CRANFIELD UNIVERSITY

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Understanding the Water Balance of Basement Complex Areas in Sokoto Basin, North-West Nigeria for improved Groundwater Management

School of Applied Sciences
Environmental Science and Technology

PhD
Academic Year: 2011 - 2014

Supervisor: Supervisor: Ian Holman
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This thesis is submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy

ABSTRACT

Understanding water balances is essential for sustainable water resource management, especially in semi-arid basement complex areas where there are large demands for water supplies, but the complex hydrogeological conditions limit groundwater development. This research presents an approach for water balance estimation based on the conceptual and computational modelling of six major landscape unit's which have been classified on the basis of their differing hydrological responses.

Detailed conceptual models of the hydrological processes operating in each of the different landscapes in a catchment and the processes that control water movement between the different landscapes are developed based on data analysis, fieldwork and literature. Two computational models (the WaSim soil water balance model and a new water balance model for bare rock) are used to estimate the daily water balance of each of the landscape units taking cognisance of their interconnectivity which includes runoff becoming run-on.

Water balance simulations were run for the individual landscapes using input data from the semi-arid Sokoto Basin in Northwest Nigeria, and outputs for representative wet and dry years are used to demonstrate the reliability of model responses. The individual landscapes outputs were subsequently integrated, taking account of their area weighted contributions, to give a catchment-scale water balance which compares favourably with the observed river discharge at Fokku.

The catchment water balance results reveal that AET accounts for the largest loss in the catchment at 72 % of the average rainfall for 37 years. This is followed by the groundwater flow to rivers, then runoff to rivers, representing 16% and 11 % of the average rainfall.

This research has provided valuable insights into hydrological behaviour of the basement complex system and the effect of landscape variability on the water balance of these areas. The research suggested a rational approach to groundwater resource management in the basement complex areas that takes cognizance of the hydrological behaviour of different landscape units, focussing on areas with deep weathered material within the catchment identified in this research. The research specifically stresses the need to apply methods of water conservation during excess rainfall for future use in the dry season

Keywords:

WaSim, Water Balance, Basement Complex, Landscape Units, Groundwater Management

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List of Acronyms

AE – Evaporation
AET – Actual evapotranspiration
AEV – Actual Evaporation
AFISS – Maximum Flow into Fissures
ASCE – American Society of Civil Engineers
BRFAC – Factor Converting ETo to PEV
DEM – Digital Elevation Model
Disch – Discharge
DSTOR – Depth of Water in Storage
EAWC – Easily Available Water Capacity
ET – Evapotranspiration
ETo – Reference Evapotranspiration
FAO – Food and Agricultural Organisation
FC – Field Capacity
FRACSTOR - Fraction of Storage – near surface storage
GIS – Geographic Information System
HRUs – Hydrological Response Units
HWSD – Harmonised World Soil Database
ITD – Inter Tropical Discontinuity
JICA – Japan International Corporation Agency
JMP – Joint Monitoring Programme
K – Saturated Hydraulic Conductivity
Kc – Crop coefficient
LAI – Leaf Area Index
LDCs – Least Developed Countries
LUs – Landscape Units
MDGs – Millennium Development Goals
MoWR – MINISTRY of Water Resources
NASA – National Aeronautics and Space Administration
NDVI – Normalized Difference Vegetation Index
NGA – National Geospatial-Intelligence Agency

NGSA – Nigeria Geological survey agency

NIMET – Nigeria Meteorological Agency

OSS – Sahara Sahel Observatory

P – Precipitation

PET – Potential Evapotranspiration

PEV – Potential Evaporation

PM – Penman-Monteith

PWP – Permanent Wilting Point

Ro – Runoff

Ron – Run-on

SARDA – Sokoto Agricultural and Rural Development Agency

SAT – Saturation

SCS - Soil Conservation Service

SMD – Soil Moisture Deficit

SRTM – Shuttle Radar Topography Mission

STOR – Storage

SWAT – Soil and Water Assessment Tool

UNDP – United Nation Development Program

UNICEF – United Children Education Fund

USDA – United States Department of Agriculture

WADROP – Water Drop Company

WaSim – Water Balance Simulation Model

WATSAN – Water and Sanitation Agency

WHO – World Health Organization

1 General Introduction

The WHO / UNICEF Joint Monitoring Programme (JMP) report, ‘Progress on Drinking Water and Sanitation 2012’ (UNICEF/WHO, 2012) reported that the Millennium Development Goal’s (MDGs) target 7c [*Halve, by 2015, the proportion of the population without access to adequate and acceptable drinking water*] had been met 5 years ahead of schedule. 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. This declaration was greeted with outcries regarding the skewedness of the reported global figures which masked massive disparities between regions and countries, and within countries.

In summary, many views are of the opinion that the target is still 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 (Pullan et al., 2014; Bradley and Bartram, 2013; Onda et al., 2012; Ford, 2012, Lake, 2012).

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 (WHO, 2011, MacDonald, 2005, Kevin and Nicholas, 2010).

Water is the major limiting constraint 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).

Nigeria is well endowed with water resources, and is well drained with a close network of rivers and streams (Ayoade and Bamwo, 2007). Most of the smaller rivers are however, seasonal, especially in the northern part of the country where the rainy season is just for 3-4 months in duration. The expanding population and the threat posed by climate change are putting the water resources under pressure and calling for new approaches for water planning and management. The Sahara Sahel Observatory (OSS, 2008) estimated that the annual withdrawals of groundwater in the Iullemeden Basin within the sub-Saharan Africa has increased from 50 million m^3 in 1970 to 180 million m^3 in 2004 due to population increase from 6 million inhabitants in 1970 to 15 million in 2000 and will probably double that in 2025.

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, geology 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., 2012; Ekpoh and Nsa, 2011; Ati et al., 2009). 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., 2007). 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.

1.1 Water balance in basement complex areas with variable landscapes

This research focus 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 geology of the area which determine the availability and accessibility of the resource (Calow MacDonald, 2009).

Many water balance studies have been conducted throughout the world for different catchments e.g. Schulz et al. (2013); De Silver and Rushton (2007); Eilers et al. (2007); Rushton et al. (2006); De Silver (2005); Scanlon et al. (2002); Flerchinger and Cooley (2000); Wesemael et al. (2000); Finch (1998); and Ragab et al. (1997). But the water balance of basement complex semi-arid catchments like the Sokoto basin presents some interesting challenges due to combine effects of climate and geology complexes. Estimating the water balance 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 study area lies within the crystalline basement complex region of northern Nigeria dominated by low and highly variable precipitation and evapotranspiration, and complex landscape units that are not addressed by most hydrologic models. Thus, this catchment presents problems to hydrologists in their water balance assessment where they occur. To overcome these, there is need to understand the interaction between different landscape features and how their spatial variability and distribution e.g. land use, topography, soils and vegetation determines the hydrological behaviour or water balance of the area.

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

1.2 Current understanding of the hydrological behaviour of variable landscapes

The characteristics of a catchment determines the partitioning of incoming rainfall into runoff, evaporation and soil moisture storage; this partitioning can be represented formally through the water balance, and is expressed in different forms of catchment response (Jothityangkoon, and Sivapalan, 2007).

A catchment-scale water balance is determined by the interactions of soil physical, climatic, and ecological factors (Potter et al., 2005). Water distribution in a catchment is influenced by complex spatial and temporal hydrological processes which are in turn related to climate and landscape surface and subsurface characteristics (Ozturk et al., 2013, Sankarasubramanian and Vogel, 2002).

Models that explain climate-soil-vegetation interactions are useful in understanding the catchment hydrological processes. Two types of hydrological models are available for spatial description of catchment processes; they are distributed and lumped models. Distributed hydrologic models have the ability to incorporate a variety of inherent spatial variability of landscape characteristics which enhances a great forecasting potential of hydrologic processes. The lumped models however usually averaged the catchment characteristics, thus ignoring the detail geometry of catchments and the small-scale variability (Carpenter and Georgakakos, 2006). Several studies report the relationship between the hydrological processes and landscape features e.g. soil and vegetation patterns (Portoghese et al., 2008; Farmer et al., 2003); land use pattern (van der Kamp et al., 2003; Yimer et al., 2008; Summerell et al., 2009); and topography and geometric patterns (Jencso et al., 2009; Sofia et al., 2013; Qin et al., 2013).

These studies and many others have demonstrated that simple distributed models can be used successfully to compute the water balance of a catchment especially when the catchment is divided into variable landscapes. Norris and Haan (1992) demonstrated the impact of various levels of landscape subdivision on runoff hydrographs and conclude that after a certain threshold (5), any further subdivision tends to have little effect in runoff hydrograph generation. Hayakawa *et al*. (1995) found that the hydrologic response of sub-catchments depend on geomorphology, size and related changes in topography within the sub-catchment. Milly (1994a) used a water balance model to explore the basis of regional variability in water balance. He demonstrates that variability in soil storage capacity and seasonal climate patterns can explain changes from long-term expected hydrological behaviour on annual water balance, involving potential evaporation and precipitation, water-holding capacity of soil, intra-annual patterns of precipitation, seasonality of potential evaporation, and the spatial variability of storage.

1.3 Study aim and objectives

Aim: The aim of this research is to improve the understanding of the water balance in heterogeneous landscapes of the basement complex areas of Sokoto Basin for groundwater management.

Objectives:

- Review the current understanding of the hydro-geomorphology of the basement complex area of the Sokoto basin.

- Identify the major landscape features that control the spatio-temporal hydrological processes in the area.

- Develop conceptual and computational models of the significant flow processes for each landscape unit within the basement complex area.

- Simulate water balance for each landscape unit to understand how input parameter values influence the plausibility of hydrological process representation.

- Integrate the simulated numerical model outputs to understand the contribution of each landscape unit to the water balance of the basement complex area of Sokoto Basin.

- Assess the credibility of the water balance results in the basement complex area.

- Give recommendations for appropriate management of water resources in the basement complex area of the Sokoto basin.

1.4 Thesis structure

The thesis contains seven chapters, with chapter one introducing the subject, aim and objectives of the study.

The description of the study area of the river Ka catchment in the Sokoto basin is given in chapter two, with an overview of the geology, and hydrogeology, soil, vegetation and land use, population and water abstraction.

Chapter three described the methodology, fieldwork and data for the research. This chapter also introduces the different water balance modelling approaches.

Chapter four presents the different conceptual models and classification of landscape units. A description of the main hydrological processes is given for each of the different landscape units and methods of quantifying each process are described.

Chapter five presents the water balance modelling with a description of inputs and outputs. The chapter shows the results of selected outputs for the individual landscape water balance simulations.

Chapter six presents the overall catchment water balance results based on the area weighted contributions of individual landscape units, also using selected outputs. This also provides a detailed comparison of the modelling outputs with the observed river Ka discharge within the catchment.

Finally, chapter seven discusses the findings of the research and provides the conclusions of the study, highlighting the credibility of the approach, major strengths and weaknesses and suggestions for further research.

It should be noted that this thesis does not include a chapter containing a literature review. However, all the relevant references are cited in the different chapters of the thesis.

2 Description of the study area

2.1 Location and physiography

The study area is part of the basement complex area of the Sokoto basin located in the north-western part of Nigeria (Figure 2.1) 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.

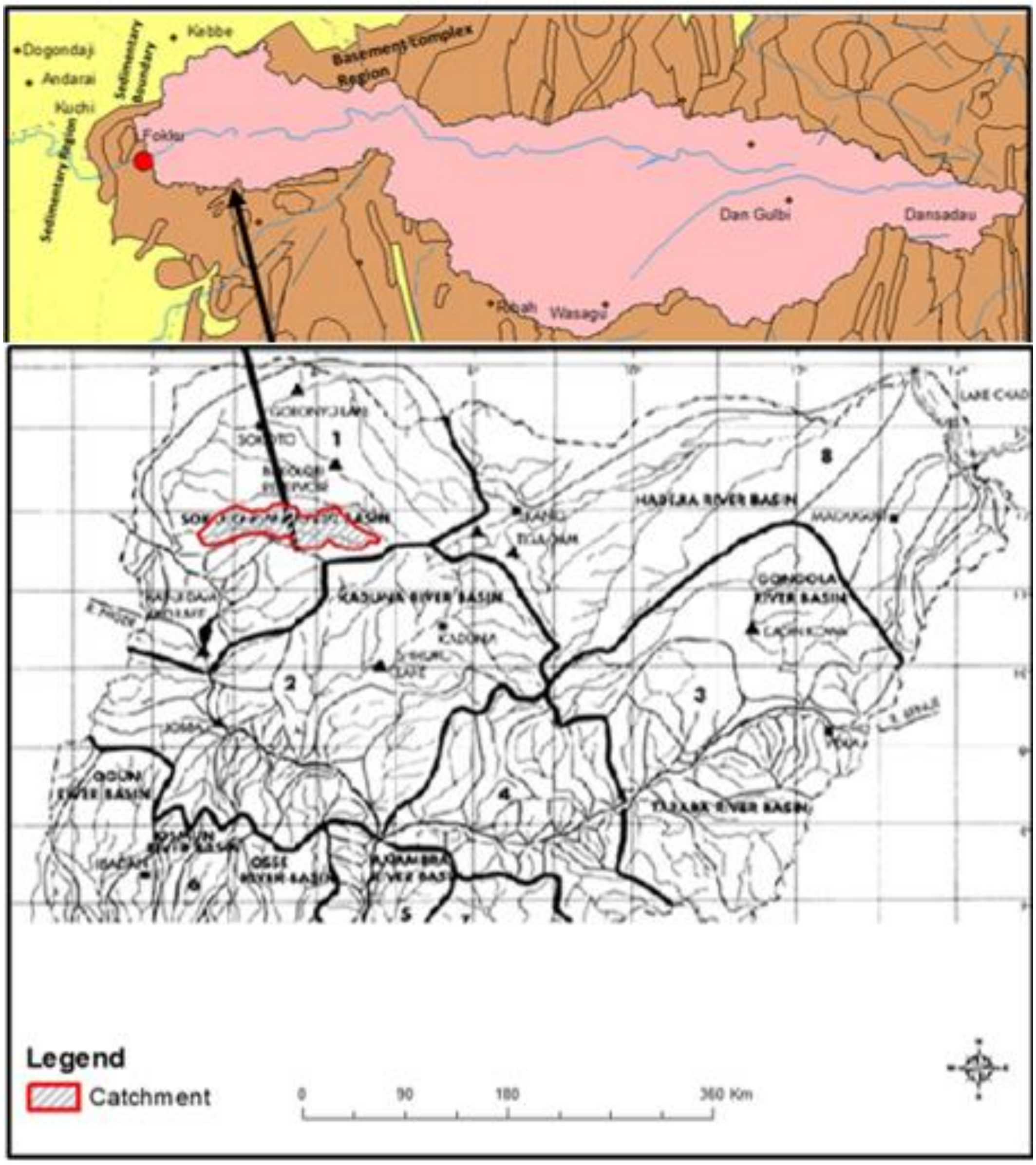


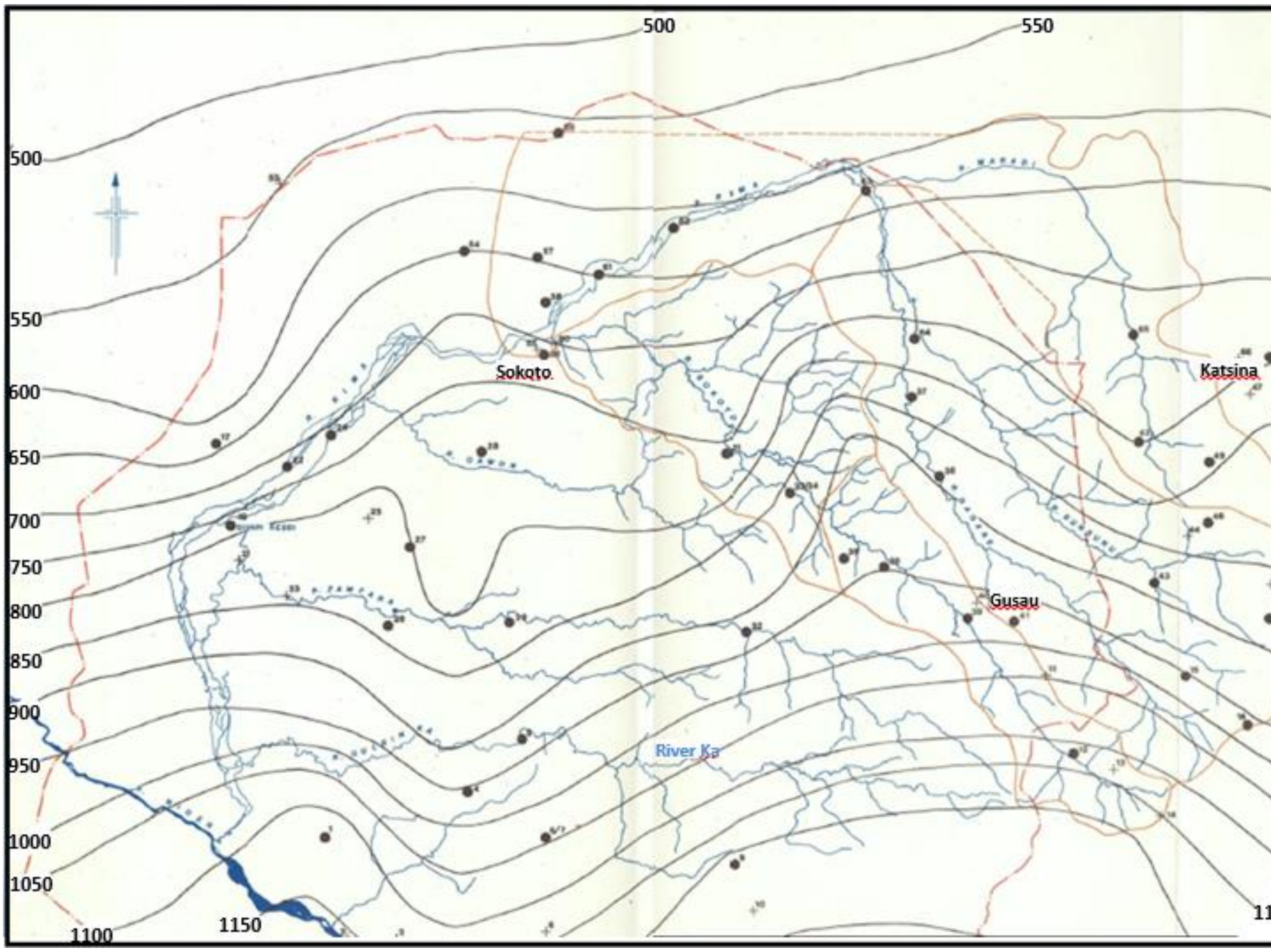
Figure 2.1: The river Ka catchment boundary within the Sokoto basin showing the contact with the sedimentary part of the basin toward the north

The study area is the catchment of the river Ka (also known as *Gulbin Ka*) at the southern end of the basement complex (Figure 2.1). 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 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).

2.2 Climate

The climate within the Sokoto Basin 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 rainfall therefore generally decreases with increasing latitude away from the Atlantic Ocean (Philip et al., 2011). 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 (Figure 2.2). The pattern of rainfall in Nigeria is reported as having a significant change in distribution and trends in the previous three decades during the 1961 – 1990 than the earlier periods (Olaniran, 2002, Philip et al., 2011).



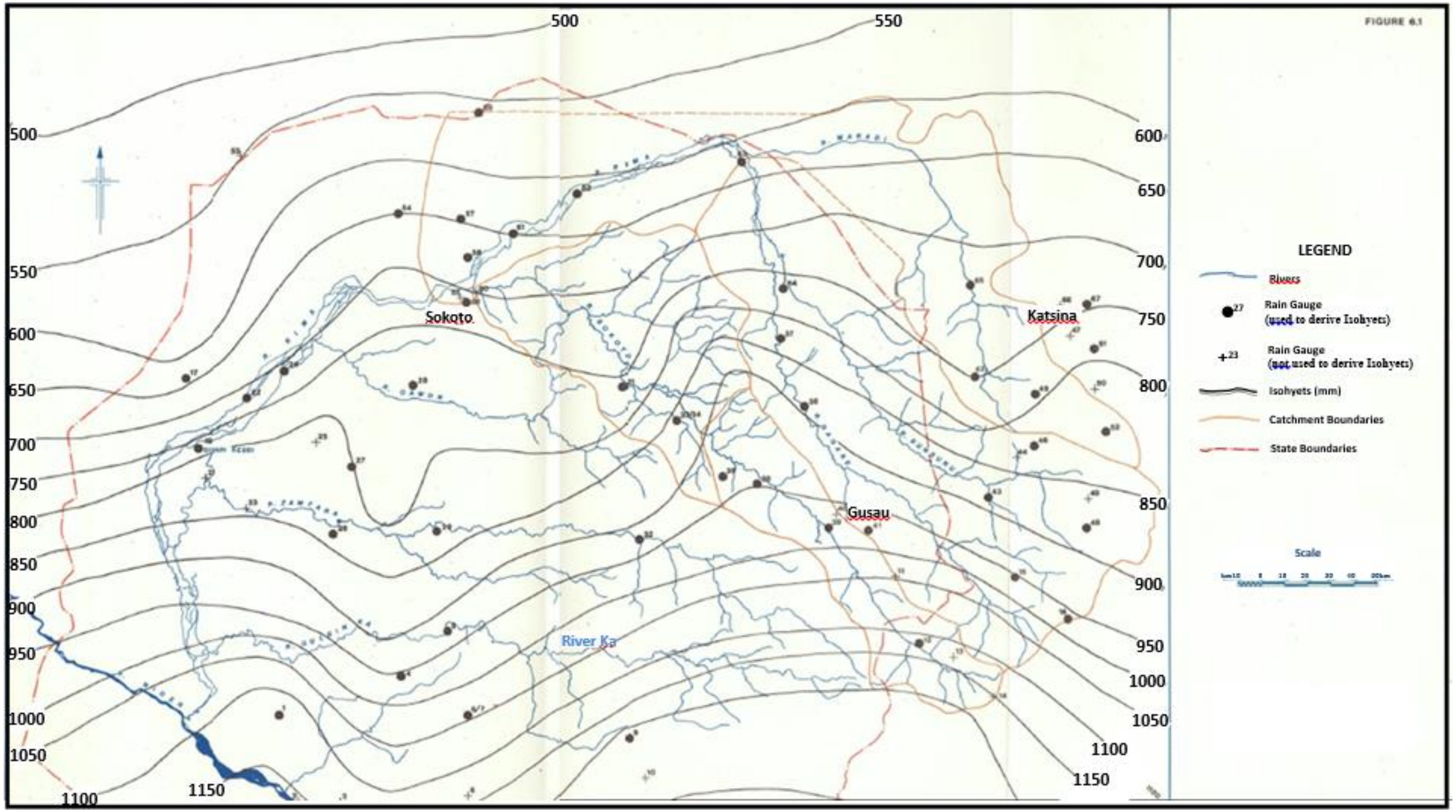


Figure 2.2: Isohyetal map of average annual rainfall in the Sokoto basin (after MRT, 1978)

Note: the rainfall contours are based on data from 1978

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 (Figure 2.3).

A 40 year rainfall records (1971 – 2010) for Gusau station given in Figure 2.3 show that the annual rainfall ranges from 1504 mm in 1994 to less than 618 mm in 2003 with mean annual of 878 mm. Note that the minimum rainfall at Gusau of 618 mm means that the rain-fed crops may have insufficient water, but if there is an additional source of water, the crops may be viable (Ati et al. 2009)

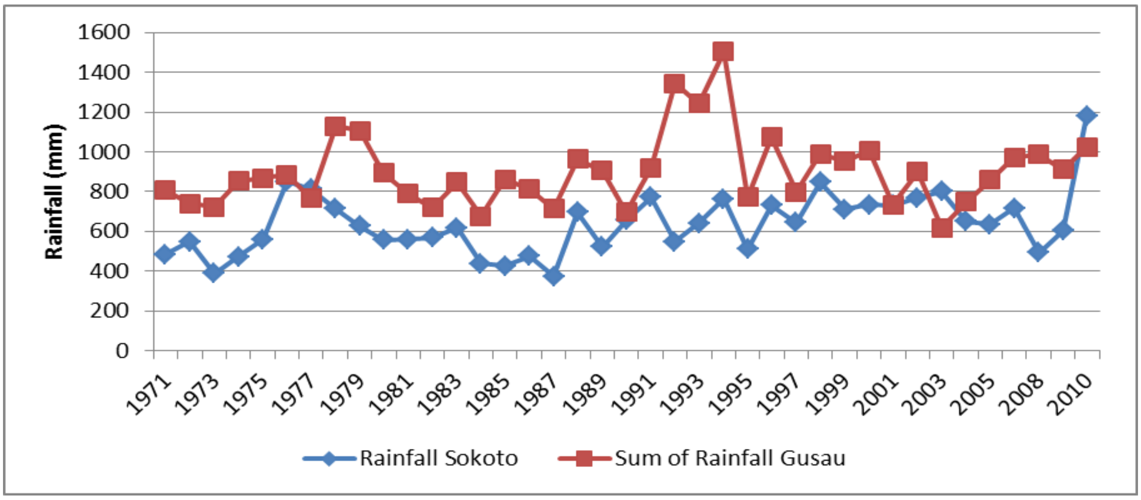


Figure 2.3: Annual Rainfall at Sokoto and Gusau stations

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 (Figure 2.4) (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.

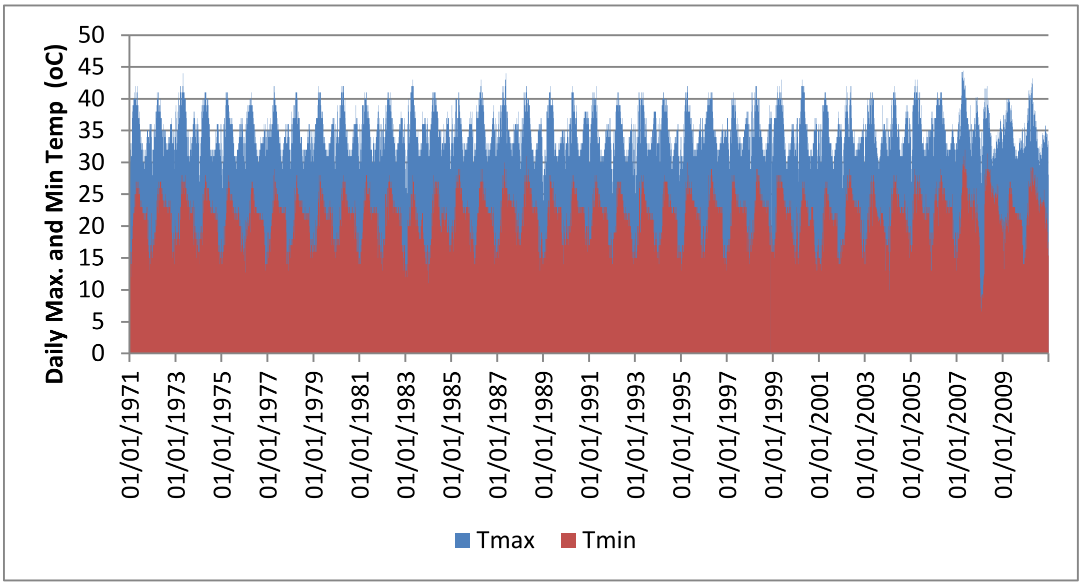


Figure 2.4: Daily Maximum and Minimum Temperatures for Gusau station (1971 – 2010)

2.3 Geology

The geology of the Sokoto basin has been described by Kogbe (1989), Anderson and Ogilbee (1973), and Offodile (2002), mostly focussing on the sedimentary part and giving a brief description of the basement complex part. Literature exists however, on the basement complex rocks elsewhere in Nigeria. 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 follows:

- 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.

These rocks have been greatly affected by repeated geo-movements which resulted in the Cretaceous plate separation with consequent development of steeply dipping joints followed by weathering. The depth of the weathered zone sometimes extends down to 50 m and the surfaces are often covered by laterites and Aeolian sands.

Several occurrences of a fayalite quartz monzonite have been described by Eborall (1976), in the north central part of Nigeria but mostly listed as ‘undifferentiated’ basement complex rocks on existing geological sheets. An observation of different rock type’s reaction to unloading stress (Eborall, 1976) shows that granites and some rock types which have a high percentage of granite occur mainly as inselbergs, whereas gneisses and high grade meta-sediment rocks often occupy deeply weathered areas in this region.

The basement complex rocks of the Sokoto basin have been described by Kogbe (1989) 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 (Figure 2.5). 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. JICA, 1990) reported similar geological observation as Kogbe and added that the basement complex occupies about 42 % area of Sokoto basin.

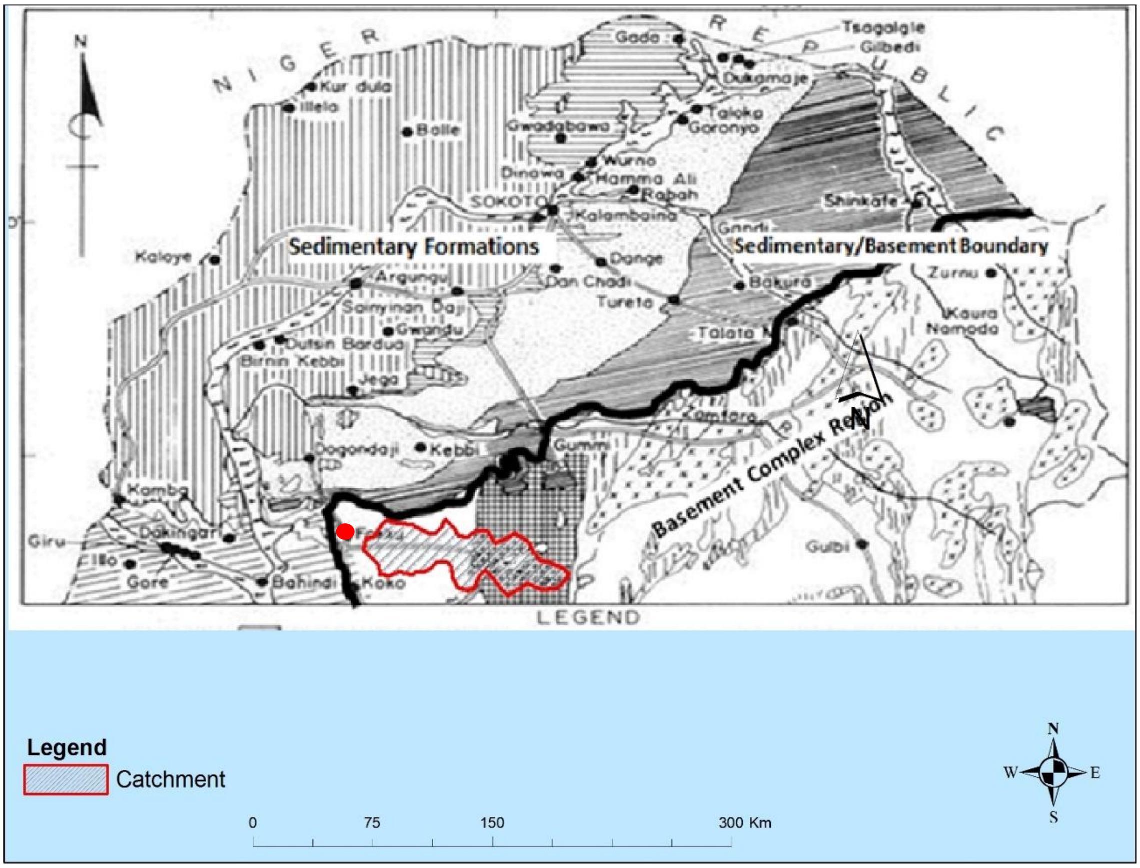


Figure 2.5: Geological map of the Sokoto Basin (Modified from Kogbe, 1981b)

The location of Fokku is indicated by red dot

2.4 Hydrogeology

The earliest hydrogeological investigation in Sokoto basin started with geological mapping of a large segment of the basin by Jones (1948) and Parker (1965) and the description of the water resources by Raeburn and Tattam (1930) and du Preez and Barber (1965). But the first important exploratory study was done by Anderson and Ogilbee (1973), who give a general description of the hydrogeology during a project to explore the artesian aquifers in the sedimentary part of the basin. Since then, a number of studies focussing on the hydrogeological characteristics, Oteze, 1979, Offodile, 2002, Adelana et al., 2006, Ndubuisi, 2007) and groundwater development (SARDA / WADROP, 1988, JICA, 1990, Graham et al., 2006) of the basin have been carried out.

Groundwater in the crystalline rocks is generally available in small quantities (Chandra et al., 2012, Robins et al., 2012) and occurs within fractures and weathered rocks (Holland, 2012, Wyns *et al.* 2004). 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 (Adams, 2009). Lloyd (1999) states that the general features that characterized the rocks irrespective of their origin or lithological type are their low transmission and storage of water due to low primary hydraulic conductivities and porosities. These features are modified where prolonged weathering has occurred or where fracture zones were altered by recent earth movements.

Du Preez (1965) compiled data on 70 boreholes in the basement rocks of northern Nigeria and reported that in 23 boreholes no water was found. He concluded that few boreholes in the un-weathered rock, usually granite or gneiss, produced more than meagre supplies of water.

The availability of groundwater in the crystalline basement rocks depends on the development of thick soil overburden (overburden aquifers) or the presence of fractures that are capable of holding water (fractured crystalline aquifers). 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).

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 fadamas 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).

Most of the previous researchers and contractors reported either low yields, no yields or high rates of borehole failure in the basement complex regions. The failure of boreholes or wells is principally caused by siting them where an insufficient depth of weathered material exist (Eduvie, 2006). In some cases however, an initially encouraging yield may later become significantly reduced or may dry up completely (JICA, 1990). JICA, (1990), reported low transmissivities in pumping tests in six boreholes, ranging from a low of 1.58 m^2d^{-1} at Ruwan Bore to a high of 38.59 m^2d^{-1} at Dauran, all within the basement complex of Sokoto basin. These results are about 10 to 100 times lower than those in the sedimentary aquifers.

Assessment of 37 boreholes show that higher yields of up to 11735 l/h are usually found in boreholes tapping saturated weathered granite and gneiss compared to boreholes tapping other weathered rock types with an average of 5300 l/h (Anderson and Ogilbee, 1973). The drawdowns during pumping test of some boreholes were as great as 62 m (Anderson and Ogilbee, 1973). The average depth of boreholes in deep weathered rock ranged between 15 - 38 m (Anderson and Ogilbee, 1973, Oteze, 1979), and the average depth to water ranged from 1 - 6 m below ground level.

Sometimes, greater depth to groundwater can be obtained in boreholes located in large fracture, weathered veins or quartz fragments (Anderson and Ogilbee, 1973, Oteze, 1979). For example, at 30 miles from Gusau, a borehole was drilled in the weathered rock to a depth of 65 m and the water table located at 52 m. The water yield from this well is however too meagre for water development.

2.5 The Soils of the study area

The available detailed soil maps for Sokoto basin only cover the fadama (UNDP-FAO, 1969) and sedimentary parts (Sambroek and Zonneveld, 1971) of the basin. Due to lack of available detailed soil mapping of the basement complex region of Sokoto basin, this section is informed by the Harmonised World Soil Database (HWSD, 2012) and Soil Atlas of Africa (2013).

Broadly, the soils within the catchment area fall within four major groups in the HWSD and Soil Atlas of Africa classifications shown in Figure 2.6. The figure however only shows the major classes and do not include soils that form a component of the depicted map units. The major soil classes are briefly described as follows.

2.5.1 Lithosols:

These are soils that are limited in depth by continuous coherent and hard rock within 10 cm of the surface (Sambroek and Zonneveld, 1971). The major sub-order found within the catchment area are the **Lithic Leptosols** (not shown in Figure 2.6) which are shallow soils having continuous hard rock close to the surface (Maduakor, 1991). Based on comparison of the soil and geology maps, it appears that this type of soil are generally found on migmatite or granite gneiss rocks e.g. between Magami and Dansadau towns (Figure 2.6).

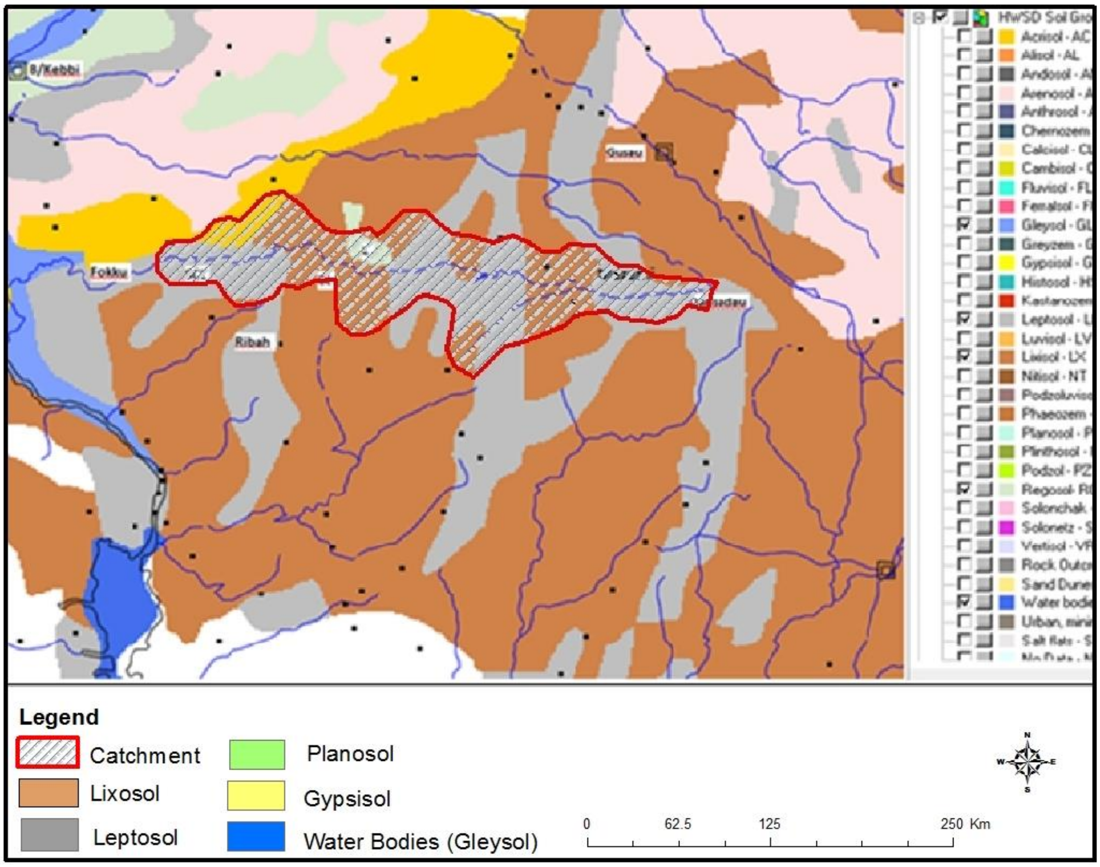


Figure 2.6: Soil map of the study area (HWSD, 2012)

Leptosols are freely drained soils free from high levels of soluble salts (Driessen and Dudal, 1991). They are shallow with low water holding capacity, but calcareous leptosols can support a high growth of natural vegetation. The soil fertility is higher on hill slopes than on level land and it has excessive internal drainage.

2.5.2 Lixisols:

These comprised of leached, slightly acid soils with clay enriched (*argic*) subsoil. The predominant sub-order in the study area is the **Haplic Lixisols** which are soils with clay-enriched subsoil showing no major characteristic. The soils are related to granite gneiss and are found around Dangulbi, Gusau and Zuru areas.

Lixisols have an *argic* horizon starting within 100 - 200 cm from the soil surface, usually overlain by loamy sand or coarser textures. The soils are mainly formed from alluvial and colluvial deposits with a low nutrient reserve. Such soils are prone to erosion due to its slackness and unstable soil structure. Most lixisols are free draining and have high base saturation, but Stagnic or Gleyic Lixisols show some evidence of a perched water table.

2.5.3 Planosols:

These consist of soils with an accumulation of iron that hardens irreversibly when exposed to air and sunlight. The most prevalent sub-order in the catchment is **Pisoplinthic Planosols** which contain nodules that are strongly cemented with iron. They are found on schist and phyllite rocks at Ribah, Zuru and Wasagu areas.

Planosols form under a variety of climatic and topographic conditions. The soil is associated with high water logging and the percolating rain sometimes may cause eluviation. The Plinthite layer formed after exposure is dense and restricts water flow and penetration of plant roots into the soil.

2.5.4 Gleysols:

These are soils in depressed areas or along the flood plains usually saturated by groundwater for long periods. The **Eutric Gleysols** are the most common sub-order in the study area which is usually water logged or alluvial deposit soils mostly used for grazing or rice cultivation. They occur almost everywhere along floodplains of river and streams within the study area.

Because of excessive wetness at shallow depth, this of soil type is deficient in oxygen for long period of time. This gives the soil a typical bluish, greenish or greyish colouration. Gleysols are poorly drained and need intensive drainage before they can be used.

2.6.Land use and vegetation

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. The vegetation is green in the rainy season with fresh leaves, but become dry during the dry season (Olorunfemi, 2012).

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.

Ajayi et al., (1981) reported that the forest areas are quite rich in terms of trees, shrubs and grass species. Tree species in the forest are mainly perennial woody plants that have many secondary branches supported by single main stem or trunk. The minimum height of the trees at maturity varies from 3m to 6m, and a minimum of 10 cm trunk diameter (Muazu, 2010).

In Kuyambana forest close to the study area, the hard wood tree (*Isoberlinia doka)* is the dominant tree species, followed by African mesquite or iron tree *(Prosopis Africana)* and Bambara tree (*Anogeissus leiocarpus).* Whereas in Kogo forest in the eastern part of the catchment with similar climatic and geologic characteristics, Bello et al. (2013) reported that the *Anogeissus leiocarpus* is the dominant tree species followed by Kwandari *(Terminalia macroptera)* and locust bean *(Parkia biglobosa)* and other species. The differences may be as a result of the slight ecological variation or over-exploitation of the woody genetic resources in the neighbouring forest area.

2.7.Population and water abstraction

According to data from the National Bureau of Statistics (2012), the population of Nigeria was about 166.2 million in 2012 (http://worldpopulationreview.com/nigeria-population-2013/). The annual growth rate varies from state to state, but for Sokoto and Zamfara states where the study area falls, it is about 2.6 %. The 2012 total population of the two states are 4,292,416 million and 3,838,160 million people respectively. Out of these figures, more than 2,000,000 people live in the basement complex areas (National Bureau of Statistics, Nigeria, 2013), which also serve as their only source of water supply.

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 use a perennial source and abstract groundwater from dug wells which are cheaper to construct than boreholes, of which there are few within the region due to their cost.

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 (Figure 2.7).

Figure 2.7: Polluted water due to refuse dump and natural vegetation growth in a typical dug well

The hand pumps boreholes like the one in Figure 2.8 are types usually found in the study area mostly constructed by State or local governments and some international agencies such as the Water and Sanitation Agency (WATSAN). The depth range of these types of boreholes is from 10-30 m and the yield is usually around 10-40 litres / min (JICA, 1990).

Figure 2.8: Typical hand pump boreholes found within the catchment

The mechanized boreholes in the study area were mostly constructed during projects undertaken by the Sokoto Agricultural and Rural Development Authority (SARDA) in 1988 and JICA in 1990. The yield from these types of boreholes is higher compared to the yield from dug wells and hand pump boreholes. However, a large number of these boreholes failed or were abandoned throughout the region due to lack of maintenance or the running cost to pump water to the elevated tanks. Examples of these types of boreholes are shown in Figure 2.9.

Figure 2.9: Non-functional mechanized pump boreholes with elevated tanks

3. Data, Fieldwork and Methods of Data Collection and Analysis

3.1.Data Availability

The problem of data scarcity is one of the greatest challenges bedevilling research in the semi-arid environment of developing countries like Nigeria (Maxwell, 2013, Olomoda, 2003). There is always the lack of maintenance and investment in monitoring equipment which usually results in lack of frequent and continuous data due to failure to collect accurate information compounded by poor record keeping. In the case of this research, a great effort was made to obtain reasonable and reliable data and key information from various sources for the study area. A summary of the data types used in this research and its sources are described below with a summary given in Table 3.1.

Table 3.1: Description of data types for the research

Type of Data	Available Records		Nature of Data/ Source	Location
	From	To		
Rainfall & Temperature	1971	2010	Daily records / (NIMET)	Sokoto, Gusau and Yelwa
Rivers Discharge	1977	1979	Daily record values of stage heights (MOWR)	Rivers Ka, Sokoto & Zamfara
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)	Soktot Basin (River Ka catchment)

3.1.1. Meteorological Data

i. Rainfall, Temperature and Evapotranspiration:

Daily rainfall and daily maximum and minimum temperature records of three meteorological stations (Table 3.1) are obtained for 40 year period (1971 – 2010). Sokoto and Katsina stations are located in flat area with a relatively homogenous rainfall while, Gusau and Yelwa stations are located in the basement complex highland areas with similar rainfall characteristics (see Figure 2.1).

This data was judged to be good and reliable because it was obtained from the Nigeria Meteorological Agency (NIMET) who uses the data for flight and air traffic control. However, there exist some missing or extreme values in the data for both the temperature and precipitation.

To check this problem, the data was exposed to quality control using the RClimDex QC Software that conducts simple quality control on the input daily data based on a very powerful and freely available statistical package 'R', which runs under both MicroSoft Windows and Unix/Linux (Zhang and Feng, 2004). The RClimDex QC performs the following procedure:

1. Replace all missing values (coded as -99.9) into an internal format that R recognizes (i.e. NA, not available).
2. Replace all unreasonable values into NA. These values include daily precipitation amounts less than zero and daily maximum temperature less than daily minimum temperature.
3. Identify outliers in daily maximum and minimum temperature, based on daily values outside a region defined as the mean plus or minus *n* times standard deviation (*std*) of the value for the day. The *std* represents the standard deviation for the day and *n* is an input from the user and mean is computed from the climatology of the day.

3.1.2. Hydrological Data

i. River Discharge records:

The daily discharge of river Ka at Fokku, river Sokoto at Gusau and river Zamfara at Anka are estimated from the gauge height records in the hydrological document (MoWR, 1981) obtained from the Ministry of Water Resources Sokoto (MoWRS), for the period 1976 – 1979. The river gauge height data collection in the basin was associated with pre-construction of Dams and water reservoirs along the major rivers which started in 1974, notably Bakolori, Goronyo and Gusau dams (Figure 3.1). Even though the rainfall data are for longer period, the gauge height data are only available for a period of 3 years.

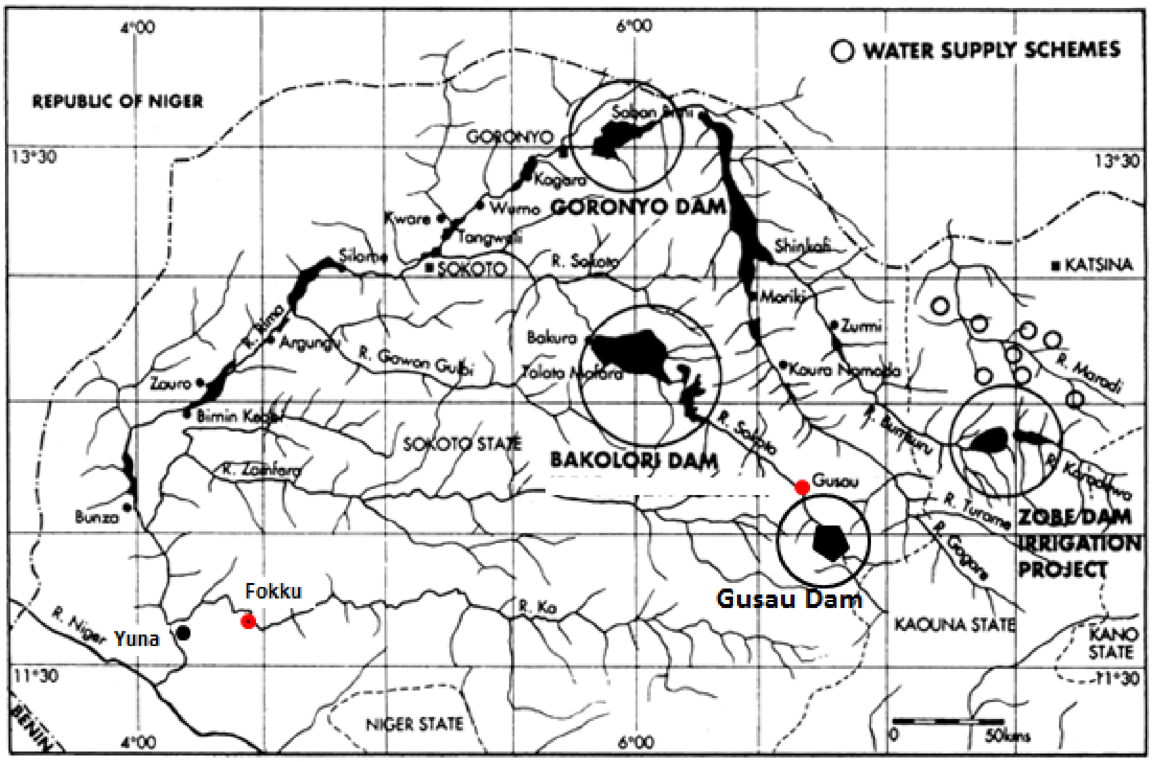


Figure 3.1: Map of Sokoto-Rima River Basin showing the major Dams

Source: http://www.fao.org/docrep/005/t1230e/t1230e06.htm
[Red dots are the river gauging stations for Gusau and Fokku]

Gauging of the River Ka took place at Fokku Bridge (Figure 3.1), with a gauge board on the upstream face of the second pier from the left hand far bank of Figure 3.2. Although not stated, it is presumed that the construction of the rating curves given in the hydrological document (Ministry of Water Resources Sokoto State, 1981) was made using the velocity-area method with velocities measured using a propeller meter. However, the photograph in Figure 3.2 indicates that this would pose many practical challenges. The river bed is characterised by sandy deposits that moves with high water velocities resulting in variability of the river bed level at different points with time. At low flows the river tends to flow in a restricted channel whereas at high flows it would not be possible to enter the river channel to make velocity measurements across the cross section of the river.

Figure 3.2: Photograph of Fokku Bridge with moderate flows in the River Ka

ii. Boreholes / Wells Data:

Over 1000 borehole records, pumping tests and borehole logs in different zones of the original Sokoto State were obtained. The boreholes are mostly located in the sedimentary part of the Sokoto basin, with only about 96 located in the basement complex region. Even though most of the boreholes are abandoned because they failed due to insufficient yield or mechanical breakdown, the data provides useful information on the lithology and depth to the bedrock in different areas of the basement complex region.

3.1.3. Geological Data

Geological map including GIS layers was obtained from Nigerian Geological Survey Agency (NGSA), while the Harmonised World Soil Database (HWSD) was used to obtain the soil map, soil types and other soil hydrological characteristics for the study area. Topographic maps of Nigeria downloaded from http://mapstor.com/map-sets/country-maps/nigeria.html in addition to the geology and soil maps were used to identify the different landscape features and soil types at different locations within the catchment.

3.2. Mapping of the catchment area and individual landscape units

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.

Based on the understanding of the complex geology of the basement complex areas described in section 2.3 and fieldwork, the hydrological processes of the basement complex region are understood to be a non-uniform process. The hydrological processes varies from one landscape unit to another depending on the vegetation, soil, topography, land use and other surface landscape features. Identification and mapping of different landscape units (LUs) was done using topographical, geology, soil and Google/Bing maps of the study area. This information was used to construct and estimate the percentage areas of the different landscapes discussed later in chapter four.

3.2.1. Delineating the catchment area from SRTM DEM

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. SRTM consisted of a specially modified radar system that flew onboard the Space Shuttle Endeavour during an 11-day mission in February of 2000.

The SRTM project is spearheaded by the National Geospatial-Intelligence Agency (NGA) and the National Aeronautics and Space Administration (NASA). The data set for regions outside the United States (including the study area) are sampled at 3 arc-seconds, which is 1/1200th of a degree of latitude and longitude, or about 90 meters (295 feet).

Some areas of missing data or voids were infilled by NASA using interpolation algorithms in addition to other sources of elevation data. The SRTM Void Filled data set used in this research is the result of this additional processing. The fill tool was run to remove some imperfection in the DEM used for this research.

Using the ArcGIS software, calculation of flow direction was done to determine the extent of floor 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.

3.3. Preliminary conceptual understanding of hydrological processes in the Basement Complex areas

Prior to the fieldwork, a simplified initial conceptual model of water movement was developed based on the description of the general hydrological behaviour of the basement complex rocks of the Sokoto basin provided in previous literature such as du Preez and Barber (1965), Anderson and Ogilbee (1973), Oteze (1979) and Offodile

(2002); in reports such as UNDP/FAO (1969), SARDA/WADROP (1988) and JICA (1990); and maps such as Parker (1964) and NGSA (2010).

3.3.1. The initial conceptual model of water movement

The initial conceptual model developed was a conventional one (Chilton and Foster, 1995) which assumes the presence of permeable strata beneath the soil zone through where potential recharge can pass. There is an input of rainfall and saturation excess runoff flowing to the river; outputs include evapotranspiration, abstraction and outflow from the hard rocks to the fadama or river downstream (Figure 3.3).

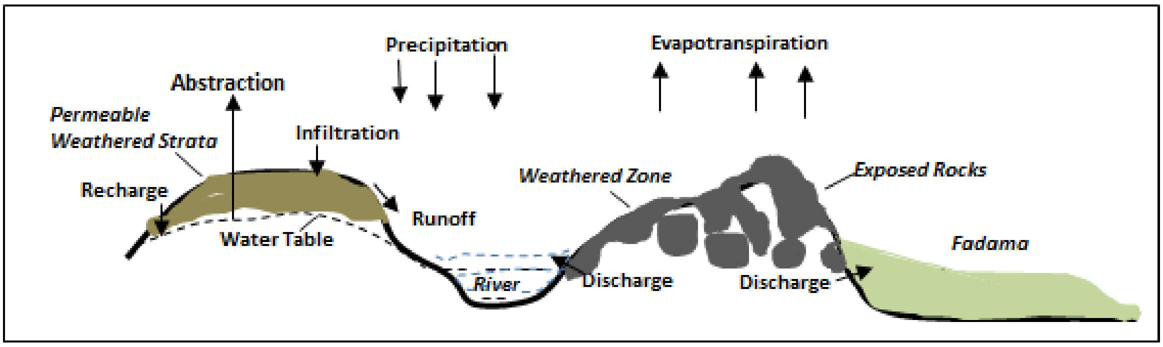


Figure 3.3: A simplified initial conceptual model of water flows in the basement complex areas

The white colour in between the dark shading of exposed rocks indicates fractured fissures in rocks

In the initial conceptual model, two key landscape areas are identified; the exposed rocks which are also assumed to have a cover of superficial deposits with lots of cracks, and the deeply weathered areas with lots of water infiltration resulting in high potential groundwater recharge.

3.4. Reconnaissance survey

The fieldwork started with a reconnaissance survey on the 17th of June, 2012 to familiarise with the environment, identify the catchment boundaries and to assess sites delineated during the desk study to see how feasible they were for the fieldwork.

3.4.1. Site selection

Three sites or areas were chosen for the fieldwork as shown in Figure 3.4 due to a number of factors. The sites are Dansadau, Ribah and Fokku areas with their surrounding environment. The factors considered in choosing these sites are:

i. Diverse landscape features

The landscape features in the area chosen for fieldwork are diverse and spatially distributed. The choice of these regions will give a good coverage of various natural features within the catchment such as different mountains, sealed land surfaces, numerous rivers and streams, dense and light forests and cultivated lands. The mountainous landscape around Dansadau forms the origin of river Ka; the largest tributary to the river Ka originates in the highland subcatchments around Ribah area; while the Fokku site is where the river gauge station is located close to the boundary between the basement complex and the sedimentary basin

ii. Accessibility

The presence of access roads to the three important towns of Dansadau, Ribah and Fokku within the catchment area and the river Ka has influenced the choice of these sites for the fieldwork. Because the research is looking at hydrological processes, much of the fieldwork is going to be conducted during the rainy season. The rocky nature and dense vegetation especially during the rainy season makes some part of the catchment inaccessible to motor vehicles. There is also the need to choose an area where adequate accommodation is available. The fieldwork sites are all located within less than 60 miles to big cities like Gusau, Zuru and Jega (see Figure 3.4) where hotel accommodation was sought during the fieldwork.

iii. Security

Insecurity is one of the major factors that led to the choice of these sites. There are lots of armed robbery gangs and also wild life living in the forest that may endanger the life, health and properties of the researcher during the fieldwork. In the alternative, the forest areas used in this research are closer to the main road (within 1 km distance).

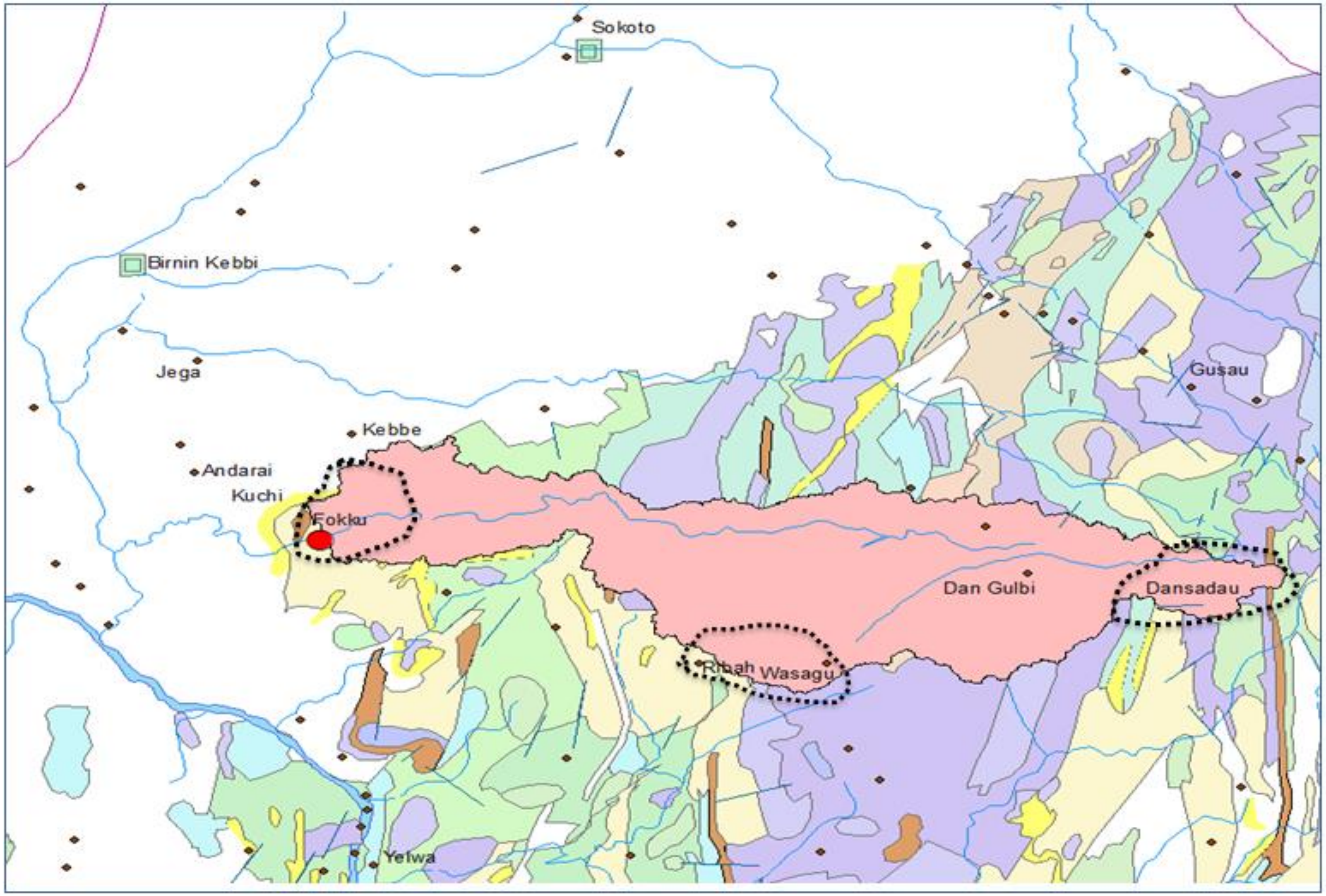


Figure 3.4: The location of fieldwork sites (dotted lines) within the River Ka catchment

During the reconnaissance, visits were made to the district heads where formal introductions and the mission statement were presented (Figure 3.5). A short structured interview (see Appendix A) with the district heads was conducted in order to obtain a brief history of the towns, the inhabitants and their activities, the water sources and the nature of soils.

Semi-structured interviews were also conducted with local people selected by the district heads, who were considered to have good knowledge of the local environment. Some of them also acted as a guide to specific sites during the fieldwork. The questions asked in the interview are purposely to tap the local people's knowledge to be used, in addition to the knowledge from literature, for interpreting the hydrological processes and modelling.

Figure 3.5: District head of (1) Fokku and (2) Dansadau with the researcher after the fieldwork interview

The general questions asked during the semi-structured interview (not in sequential order) include the following:

- The time of onset and stoppage of rainfall in the area.
- The type of crops grown and duration to harvest, and whether they obtain good yields of their crops every year.

- Duration of moisture holding in the soil after rainfall, and whether floods occur and when.
- Duration that water stays on the surface after rainfall and where the water goes afterward.
- Sources of water supply for domestic and other uses during rainy or dry season and the depth of hand dug wells in the area.

In conclusion, site visits and observations were made to some landscapes such as the river Ka, the surrounding hills, sealed land surfaces and some forest areas.

3.4.2. The Fieldwork Processes

Fieldwork was conducted in the three selected areas as described in section 3.3 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 (fractured or non- fractured) and their runoff behaviour after rainfall.

The fieldwork conducted has uncovered many issues controlling the hydrological processes within the basement complex region. It was apparent that the actual hydrological processes are much more complex than earlier thought or reported in literatures. After the fieldwork, the initial conceptual model given in Figure 3.3 was revisited and refined to reflect the new understanding of hydrological processes within the basement complex region. This resulted in developing different individual conceptual models, each representing a different hydrological response after rainfall within the study area. The different conceptual models (named as landscape models) are fully discussed in chapter four.

3.5. 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 using two different approaches for the different conceptual landscapes developed after the fieldwork. The modelling processes and model results are presented in chapter five.

3.5.1. Criteria for model selection

There are various approaches for hydrological and/or watershed modelling. The choice of appropriate model depends on the required relevant criteria and the purpose for which modelling is needed.

Based on the understanding of the hydrological processes in the semi-arid basement complex environment and the aim and objectives of this research, the model selected for this study should satisfy the following criteria.

a. The model should be able to simulate the important processes governing hydrological behaviour and portioning, based on a realistic representation of soil and vegetation properties

b. Have been used in different climatic regions especially in arid and semi-arid areas

c. Requires readily available input data and be able to be parameterised and validated with the limited datasets typically available in semi-arid environments

d. The model should be able to run using the available daily historical rainfall and reference evapotranspiration data so as to simulate the daily responses to capture short timescale runoff, ET and groundwater flow events

e. Be able to simulate daily time series of at least 30 years duration to be able to see the long term hydrological behaviour and changes.

f. Be able to represent the crop/vegetation stages of growth and bare soil conditions including up to 3 crops in rotation which is typical of floodplain semi-arid cultivation practice.

g. Be able to use ETo estimate according to the standard methods of FAO 56 – Penman Monteith, or in case of data scarcity which is common in developing countries, Hargreaves method.

h. Be able to calculate runoff either due to infiltration excess as a result of intense rainfall or due to soil saturation, both of which can occur in tropical semi-arid areas

i. Be able to represent the effect of abstraction, ponding and changes to soil and crop conditions

3.6. Review of different modelling approaches

There are many hydrological simulation models that are being used throughout the world, including in arid and semi-arid environments. They range from simple lumped and conceptual catchments models to complex distributed and physically based models. Compared with lumped models, distributed hydrological models can provide detailed descriptions of the hydrological processes and account for spatial heterogeneities in a catchment. The main disadvantage of these models is however their high demands of spatial input data.

A non-exhaustive shortlist of potential models across this range for water balance simulation of the Sokoto basement complex region have been considered against the criteria described above. These are described below and a summary of their properties given in Table 3.2.

Table 3.2: Shortlisted models and their properties for modelling hydrological processes in a semi-arid catchment

Model Name	Watershed / Hydrology Simulation	Process Representation (Conceptual / Physical)	Time step (Continuous)	Estimate runoff due to infiltration or saturation excess	Estimate ETo using Penman – Monteith or Hargreaves method	Groundwater Outflow	Representation of multiple Crops / Vegetation
Conventional Single Layer Model	√	√	X	X	√	X	X
CROPWAT	√	√	√	√	√	X	√
WaSim	√	√	√	√	√	√	√
SAMBA	√	√	√	√	√	X	X
SWAT	√	√	√	√	√	√	√
MIKE SHE	√	√	√	√	√	√	X

3.6.1. Conventional Single Layer Soil water Balance Model

The conventional single layer model is treated as a single reservoir with input of rainfall and output of evaporation and drainage at the bottom of the root zone. Runoff is not considered in this model. This approach is based on the studies by Penman (1949, 1950) and Grindley (1967), whose interest was to determine the actual evaporation and soil moisture deficit and not the actual water balance (Learner et al., 1990).

In this approach, the concept of a root constant was introduced by Penman (1950) to represent the condition of water stress in vegetation. The root constant gives the amount of water that can be extracted by the plant roots from the soil at the potential (or maximum) rate. The assumption is that, the actual evapotranspiration *AET* is equal to the potential evapotranspiration *PET* until the soil moisture deficit reaches the root constant *C*, after which *AET* is a fraction F of PET until the permanent wilting point *D* is reached.

This approach relies heavily on accurate estimation of the *C* and *D* parameters (relating to crop type and crop development stages), which are difficult to determine due to their strong empirical characteristics. This method also fails to account for the soil type and processes occurring during the dry season after rainfall stops in semi-arid environment and there is low vegetation cover or, after harvest when the roots no longer extract water from the soil.

3.6.2. The CROPWAT Model

This model was developed by the FAO (Smith, 1992), based on the methods presented in FAO Irrigation and Drainage Papers No 24 (Doorenbos and Pruitt, 1977 and No. 33 (Doorenbos et al., 1977) for the calculations of crop water and irrigation requirement. The revised method was later presented by Allen et al. (1998) in FAO Irrigation and Drainage Paper No. 56. This method used daily soil water balance to determine ET on a crop plot, starting with ETo estimation of a reference surface using the modified PM equation (Allen et al., 1996).

The potential evapotranspiration (PET) was determined using the crop coefficient (Kc) which represents different crop characteristics from the reference surface. Actual evapotranspiration (AET) is related to PE at different soil moisture condition. AET is equal to PET when the soil moisture deficit is below field capacity. Beyond this level, the crop falls under water stress and the AET reduces proportionately according to a stress coefficient Ks.

The method presented in CROPWAT is an improvement of the conventional layer model especially in ET determination incorporating important physical processes of root growth and water holding properties of soil. Although the CROPWAT model has the facility to use daily rainfall and ETo data, it can only run simulations for discrete, individual years. This makes it difficult to account for any carry-over of soil water from one year to the next.

3.6.3. Water Balance Simulation Model (WaSim)

WaSim (Hess et al., 2000), which aims to provide a reasonable compromise between detailed physical basis and minimum data requirements, was developed for use in the semi-arid environment but has been successfully applied in other climates (Hess et al., 2010, Hirekhan et al., 2007, Kunstmann et al., 2006, Stephens et al., 2001). The model is a daily one-dimensional model which simulates the soil water storage and rates of input (infiltration) and output (evapotranspiration, runoff and recharge and/or drainage) of water in response to climate, irrigation, and canal seepage.

The crops and vegetation input parameters for the WaSim model include the growth cycle of crops or vegetation over the year, the rooting characteristics and the crop coefficient for evapotranspiration. The soil input parameters include the soil profile depth and water holding characteristics. The WaSim model processes are fully described in section 5.1 of this report.

3.6.4. The SAMBA Model

This is a single layer model that incorporates the physical processes of rainfall, runoff, ET, crop growth stages, soil water distribution and potential recharge. The model was developed by Eilers (2002) based on a conventional soil water balance, but with additional allowance for the inclusion of surface runoff and condition of water stress as it affects the root water uptake of plant. The model consider the crop growth stages, plant roots water uptake and most importantly the crop planting date in semi-arid region.

The major weakness of this model is that, it fails to recognise the spatial variation of natural features in the environment such as landscape and soil types in the runoff calculation. The process of keeping some amount of water near the soil surface (near surface storage *NSS* in the model) for evaporation in the model may also be misleading, because this can only occur on particular soil type and landscape and may not be applicable in most locations within the basement complex areas e.g. areas with shallow depth of the weathered material.

3.6.5. SWAT Model

The Soil and Water Assessment Tool (SWAT) was developed by Neitcsh et al. (2002) to simulate the processes of runoff, erosion and chemical transport in soil on a daily time step at the river basin scale. The model was developed for the United States Department of Agriculture (USDA) and it has a GIS interface. The model is a widely used semi-distributed model that simulates all of the relevant hydrological processes including transmission losses, the quality and quantity of surface and ground water, and which predicts the environmental impact of land use, land management practices, and climate change. SWAT is also used in assessing soil erosion prevention and control, non-point source pollution control and regional management in watersheds.

The major strength of SWAT is the ability to incorporate a combination of upland and channel processes into one simulation package. However, each one of these processes is a simplification of reality and thus subject to the need for improvement. Gassman et al. (2007) pointed that the representation of hydrological response units *HRUs* in SWAT are simplified. The HRUs in a watershed consist of homogeneous land use, management, and soil characteristics, which also represent percentages of the sub-watershed area and are not identified spatially within a SWAT simulation. Many studies using SWAT reported that SWAT stream flow predictions were generally insensitive to variations in HRU delineations for watersheds ranging in size from 21.3 to 17,941 km^2, and also fail to represent HRUs interconnectivity [see Chen and Mackay (2004); Tripathi et al. (2006); and Muleta et al. (2007)]. In addition, Borah and Bera (2003, 2004) found that SWAT can very well predict yearly flow runoff volumes and pollutant losses, but is poor in simulating daily extreme flow events.

There is also a problem of over dependence on high resolution Digital Elevation Model (DEM) and inaccurate simulation of processes when faced with inadequate data needed to characterize input parameters, insufficient monitoring data, or insufficient scientific understanding.

3.6.6. MIKE SHE

This is an integrated model developed by Abbott et al. (1986) to simulate the land phase hydrological cycle processes. The model can be linked to GIS application, specifically ESRI's ArcView. In its original formulation, MIKE SHE can be classified as a deterministic, physically based, distributed model code developed as a fully integrated alternative to the traditional lumped, conceptual rainfall-runoff models. The physics-based code solves the partial differential equations describing mass flow and momentum transfer.

Application of physically based model like MIKE SHE is also associated with its limitations such as, large data requirement (Christiaens and Feyen, 2001) and high cost of data acquisition; substantial time needed for the execution of complex physics-based solutions; and representation of flow processes at the grid scale which are mostly valid for only small-scale experimental conditions. This makes the model difficult to use in data scarce regions.

Conclusion

The types of data available for this research and how the data was sourced through literature and fieldwork were described in this chapter. Almost all the data are relevant for the modelling process and validation of the model results. The most important being the climatic, soil and crops data which used for the modelling and the hydrological data used for model evaluation. The different modelling approaches were also reviewed and it is clear that some of them (e.g. SWAT and MIKE SHE) require extensive data for model construction that would make them be difficult to run, calibrate and validate in a data scarce region like the study area. Based on the criteria outlined in section 3.5.1, the model chosen for this research is the WaSim model (fully discussed in Chapter 5).

4. Conceptualisation of Landscape Unit Areas

This chapter describes the different landscapes Units (LUs) based on the literature and the fieldwork conducted in the study area considering the hydrological processes of water movement and exchanges between the different LUs.

Based on the understanding of the complex geology of the basement complex areas described in the literature for the study area (Chapter two) and fieldwork (described in this chapter), the hydrological processes of the basement complex region are considered to be spatially non-uniform. Individual LU area's respond differently from one another depending on the vegetation and soil types, topography, land use and other surface landscape features (Han et al., 2014; Holland, 2012; Jha et al., 2004; Guntner and Bronstert, 2004; Farmer et al., 2003; Schoorl et al., 2002; Lachassagne et al., 2001; Leavesley et al., 1983).

These catchments 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 believe that this is the best approach in assessing the hydrological behaviour of a catchment. The work by Eagleson (1978) pioneered the concept of a dynamic water balance at a point and the notion that the expected hydrological behaviour is characterized by interactions between the climate and the catchment's landscape properties. Farmer et al. (2003) reported that differences between water balances for temperate and semiarid catchments can be attributed to variability in the primary controls of the soil profile, vegetation and climate.

Jha et al. (2004) conducted similar research to see the effect of watershed subdivision on flow, sediment and nutrient predictions of the SWAT model in four Iowa watersheds. The results show that variation in the total number of sub watersheds had very little effect on stream flow but significantly affected the sediment, nitrate, and inorganic P. In contrast, Triphathi et al. (2006) evaluated the effect of watershed sub-division for the Nagwan region in eastern India and reported that the different hydrological unit responses have a significant effect on the overall water balance components of the watershed.

Han et al. (2012) looks at the effects of watershed subdivision level on semi-distributed hydrological simulations for Xiangxi River watershed in China. They reported that the simulated water balance components and runoff contributions vary among subdivision levels and that the variation decreased when the watershed was divided into more sub-watersheds.

This approach is considered more suitable in basement complex regions with variable and heterogeneous LUs like the study area. 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 (Wooldridge and Kalma, 2001). 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

4.1. Towns / Settlement/ Landscape Units

Soil compaction is a common occurrence in settlements or towns within the study area which is mainly as a result of human habitation and activities over a long period of time (Webb, 2002; Knapp, 1991).

Urbanisation has an adverse effect on the hydrological behaviour of the local soils due to the combined effect of traffic vehicles, peoples and livestock (Hollis, 1975; Garg et al., 2012). Soil compaction increases when large areas of land are rendered impervious by roads, footpaths, roofs, and parking areas. This reduces the area in which rainfall can infiltrate into the soil, and increases overland flow. Wright (1990) observed that highly compacted road surfaces and disturbed roadside margins reduce infiltration of rain water, thereby producing overland flow and allowing significant water to runoff rapidly.

Monti and Mackintosh (1979) reports that trampling of soil by humans and their livestock compact soils, thus, reducing porosity particularly the volume of macropores. This reduces the water-holding capacity of soil, except in some coarse-textured soils. Horton et al., (1994) reported that, compaction has a significant influence on soil because it leads to an increase in bulk density, which has a knock-on effect on other soil hydraulic properties (NRCS 2000).

Alessa and Earnhart (2000) have shown that plants on compacted soils may be less able to utilize available nutrients because they grow fewer lateral roots and root hairs and because cytoplasmic streaming within root hairs is reduced. This reduces the amount of water uptake by the roots and consequently reduces the AET.

The process of soil compaction may therefore be viewed as the soil's behavioural reaction to compressive forces applied by nature or humans (Johnson and Bailey 2002). The towns in the study area also experienced similar characteristics of soil compaction described above. The hydrological behaviour of towns is therefore considered as one of the heterogeneous LUs within the catchment.

4.1.1. Hydrological processes of the town LUs within the catchment

Figure 4.1 illustrate the flow processes for the town LUs which occupy about 10 % of the total land area of the study catchment. This LU is divided into two sub-units on the basis of depth of weathering. Areas of shallow weathered zone (0-3 m depth) with a shallow water table, and areas of deep weathered zone (0-10 m depth) with a deep water table. The wet season condition is illustrated in Figure 4.1a as having an input of precipitation and outputs of high actual evapotranspiration, runoff and abstraction. The dry season condition in Figure 4.1b however, has no precipitation input and the water loss is limited to small actual evapotranspiration from isolated large deep rooted trees mostly located within compounds, or direct soil evaporation due to waste water from houses; and low abstraction from the dug wells and boreholes (where available) in the deep weathered areas where the water table is present throughout the year. The wells in the shallow weathered zone dry-up during dry season (this is known based on the knowledge of the area and was confirmed during the fieldwork), while, most wells in the deep weathered zones supply water throughout the year. The major difference between the two sub-units is the depths of the weathered zone which determines the presence or absence of a water table throughout the year. The presence of large trees and well locations however is the only evidence easily identified on the surface to inform the sub-division. Groundwater in the town landscape is also lost through flow to streams (drains) or to the main river in the Fadama. Groundwater in the town landscape is also lost through flow to streams (drains) or to the main river in the Fadama.

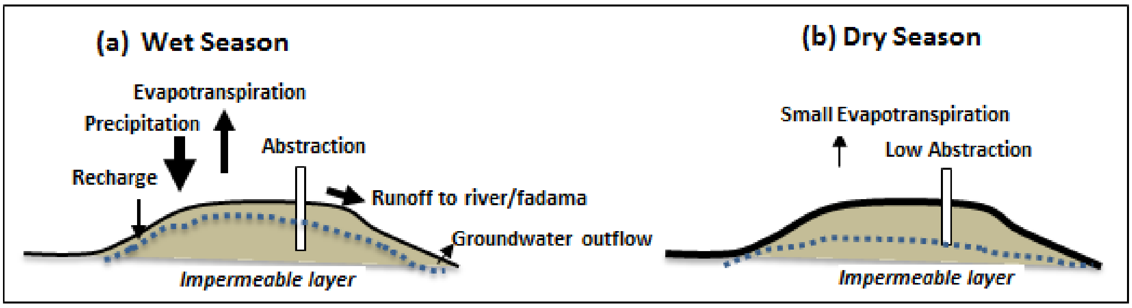


Figure 4.1: Schematic diagram showing change of the dominant flow processes during the wet and dry seasons in town landscape

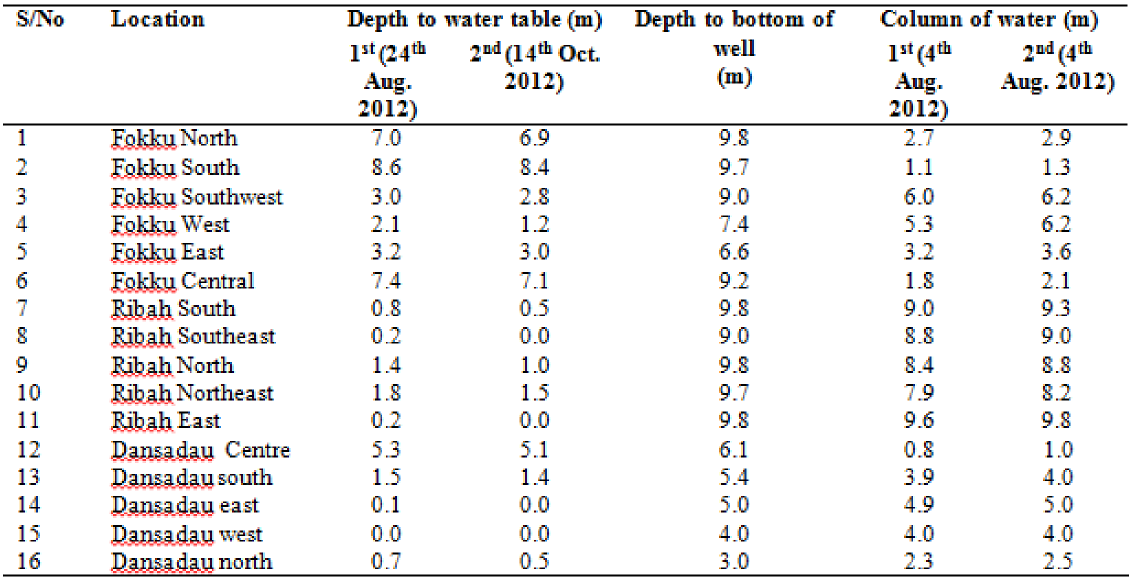
Little infiltration occurs and a lot of runoff is generated during rainfall (Figure 4.2a) either due to the slope or sealed soil surface caused by human habitation. The water generally runs off quickly within an hour of rainfall (Figure 4.2b) where slopes allow the runoff to flow downslope, unless the surface is flat, where the water remains on the surface to evaporate or slowly infiltrate into the soil (Figure 4.2c). Vegetation growth occurs during the rainy season and is mostly restricted to road sides or in small drainage channels as shown in Figure 4.2d. The vegetation is usually small grasses and increases the evapotranspiration losses from the town landscape unit.

Figure 4.2: Illustrative surface conditions in the town landscape unit showing: a) runoff occurring a few minutes after the start of rainfall; b) evidence of sediment movement with runoff 30 minutes after the cessation of rainfall; c) retention of water within localised depressions one day after rainfall; and d) completely dry surface 3 days after rainfall

In the study area, there is inadequate or a near absence of pipe borne water and the inhabitants mostly relies on hand-dug wells as their main sources of water supply; this is more affordable than boreholes. Abstraction occurs every day where the yield of the well is sustained throughout the year.

Table 4.1 gives the depth of hand dug wells measured at different locations in the study area during the fieldwork, some of which are shown in Figure 4.3. The typical depth range of the wells varies from 3-6 m in the shallow weathered zone to 6-10 m in the deep weathered zone. The depth to the bottom of shallow wells of up to 6 m is assumed to be the depth to the bedrock based on information obtained from local people. They explained that they stop at shallow depth because they were unable to penetrate further due to contact with the hard rock during the well construction. These shallow wells usually dry-up in the dry season.

Table 4.1: Dug Wells information in selected fieldwork sites



S/No	Location	Depth to water table (m)		Depth to bottom of well (m)	Column of water (m)	
		1st (24th Aug. 2012)	2nd (14th Oct. 2012)		1st (4th Aug. 2012)	2nd (4th Aug. 2012)
1	Fokku North	7.0	6.9	9.8	2.7	2.9
2	Fokku South	8.6	8.4	9.7	1.1	1.3
3	Fokku Southwest	3.0	2.8	9.0	6.0	6.2
4	Fokku West	2.1	1.2	7.4	5.3	6.2
5	Fokku East	3.2	3.0	6.6	3.2	3.6
6	Fokku Central	7.4	7.1	9.2	1.8	2.1
7	Ribah South	0.8	0.5	9.8	9.0	9.3
8	Ribah Southeast	0.2	0.0	9.0	8.8	9.0
9	Ribah North	1.4	1.0	9.8	8.4	8.8
10	Ribah Northeast	1.8	1.5	9.7	7.9	8.2
11	Ribah East	0.2	0.0	9.8	9.6	9.8
12	Dansadau Centre	5.3	5.1	6.1	0.8	1.0
13	Dansadau south	1.5	1.4	5.4	3.9	4.0
14	Dansadau east	0.1	0.0	5.0	4.9	5.0
15	Dansadau west	0.0	0.0	4.0	4.0	4.0
16	Dansadau north	0.7	0.5	3.0	2.3	2.5

A summary of the nature of the hydrological processes observed or expected in the town landscape units is as follows:

- Much runoff during rainfall events due to the high percentage of impervious and low permeability surfaces (roofs, pavements, roads etc.) as a result of human activities.
- High direct soil evaporation and small evapotranspiration due to absence of significant vegetation cover.
- Abstraction throughout the year from hand dug wells in the deep weathered zones, and abstraction from wells in the shallow zones during rainy season and lasts up to 2 months after rainfall cessation.
- Some infiltration is likely to occur in the small gully runoff channels where vegetation growth occurs in the rainy season.
- Groundwater outflow from the town LU usually goes to the river/stream or fadama due to their proximity to one another.

Figure 4.3: Pictures of hand dug wells in different locations in town landscape (a-b) shallow depth well with shallow water table and 'guga' used to withdraw the water; (c-d) deep hand dug well with deep water table and a raft across for water pulling; (e-f) shallow dug well in a house with water table close to the surface (within an arm-length); (g-h) shallow wells in town close to fadama usually of poor biological quality (note invasion of weeds and even frogs)

4.2. Cultivated Area Landscapes

The hydrological processes in the cultivated landscapes are highly influenced by anthropogenic activities. Changes in land use affect the physical, chemical and biological characteristics of soil (Shukla et al., 2003). Buytaert et al. (2006) found that the soil storage capacity of water in cultivated lands increases by 5 to 30%, and the hydraulic conductivity by 31% compared to non-cultivated lands. Buytaert *et al*. (2002) also found that the water retention of paramo soil at wilting point is reduced by 35 % due to cultivation which is significantly lower than the natural paramo soils not under cultivation.

Numerous studies have shown that the infiltration capacity of soils can be a good indicator of soil quality and health (Dexter, 2004, Shukla et al., 2006, Shougrakpam et al., 2010, Haghighi et al., 2011, Nyberg et al., 2012). Infiltration capacity is influenced by soil structure, aggregate stability, particle size distribution, land use type (Fu et al., 2003), vegetation, topographic and climatic influences (Jimenez et al., 2006). Land use change from natural vegetation to continuous cultivation and grazing has an adverse effect on soil bulk density, porosity, aeration, infiltration, storage, water transport characteristics and runoff. Most forest soils in semi-arid regions have the ability to absorb water at rapid rates, however, Cerda (1997) observed that cultivation increases soil surface storage by making a rougher (more bumpy) soil surface which increases infiltration of rainfall and as a consequence, the runoff and erosion rate is greatly reduced. This occurs not only in arid or semi-arid areas, but is also common in humid environments, e.g. Van der Kamp et al (2003) observed that an increase in the extent of cultivated land areas results in decreased discharges in the spring and autumn flood periods and a decreasing trend in the annual maximum peak discharge in Saskatchewan, Canada.

Some researchers have argued however, that cultivation decreases soil infiltration. Burt and Slattery (2006) for example argued that undisturbed soils have a much higher infiltration capacity than soils under cultivation due to compaction of cultivated soils. The compacted soil will have a significantly higher bulk density and consequently become preferential zones of runoff generation. Though Cornelissen et al. (2013) reported that only Hortonian-type of runoff occurs on cultivated lands and iron crusts surfaces but not in catchments with savannah-type vegetation. Small animal’s burrows could act as efficient water infiltration galleries which can affect the hydrological characteristics of soils. Pasitschiniak-Arts and Messier (1998) showed that the abundance of small mammal burrows and ‘mole heaps’ in the dense nesting cover increases soil infiltration compared to where there is very little activity in the cultivated fields. Giertz et al. (2005) also demonstrates that reduced activity of the soil fauna on cultivated sites leads to a reduction of macropores in the soil and reduces saturated conductivity for cultivated plots compared to the plots with natural vegetation.

The hydrological processes of the cultivated lands in the study area also vary from one area to another depending on the type of soil described in chapter two. The different hydrological behaviours are described in section 4.2.1.

4.2.1. The flow processes in the cultivated landscape within the catchment

The cultivated landscapes in the study area cover the largest land area (30 %) of the catchment and are sub-divided into four groups based on the estimated depth of the weathered material, obtained from literature (e.g. Anderson and Ogilbee, 1973; Oteze, 1979; Kogbe, 1989; JICA 1990) and physical observation during the fieldwork. The first category is the two shallow weathered zones (3-6 m deep), with one shallow zone LU receiving additional run-on from exposed non- fractured hard rocks, while the second shallow zone LU doesn’t receive any additional run-on. The second categories are the deep weathered zone (6-10 m deep), also divided into two, with one receiving additional run-on while the second one doesn’t. Figure 4.4 illustrate the flow processes in the different cultivated landscapes.

Generally, the cultivated landscapes have input of precipitation and output of evapotranspiration and runoff. The soils of this landscape are loose at the surface due to cultivation and where the depth is sufficient, the soil allow more infiltration and moisture retention compared to town landscape units. The shallow weathered zones without run-on (Figure 4.4a) do not have sufficient depth to hold all infiltrated water, so that there is a tendency for saturation conditions to occur due to low storage. The shallow weathered zones that receive additional run-on (Figure 4.4b) however tend to have more water due to saturation and even ponding on the surface. Water loss from this second LU with additional run-on and ponding is expected to be dominated by open water evaporation instead of evapotranspiration. The deep weathered zone on the other hand, have water table either at the lower level where there is no run-on input (Figure 4.4c), or at higher level close to the surface in areas that receive additional run-on input but the depth of the soil will not allow surface ponding as a consequence of saturation (Figure 4.4d). Groundwater in all the cultivated landscapes is lost through flow to streams (drains) or to the main river in the Fadama.

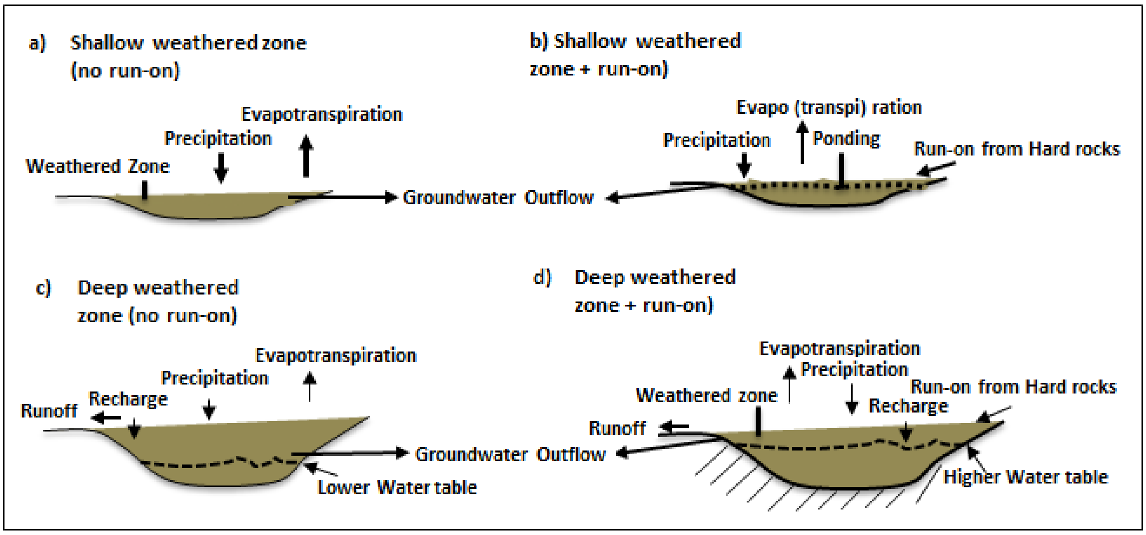


Figure 4.4: Schematic diagram showing the dominant flow processes during the wet season on (a) shallow weathered cultivated lands without additional run-on; (b) shallow weathered cultivated lands with additional run-on; (c) deep weathered cultivated lands without additional run-on; and (d) deep weathered cultivated lands with additional run-on

The researcher observed that each of the different LUs support different types of crops (Figure 4.5). Rice and maize for example are usually grown on either the shallow or deep soil cultivated lands receiving additional run-on due to their high water requirement (Figure 4.5 b & d), while Guinea Corn and Millet are grown on the shallow or deep soil cultivated lands without run-on (Figure 4.5 a & c) due to their low water requirement.

The crops will also have different seasonal cycles of evapotranspiration due to their differing crop growth timings as well as differences in evapotranspiration amounts due to vegetation differences. Evapotranspiration is higher when the crops are between the mid-stage (Figure 4.5 b & d) and maturity stage (Figure 4.5c) compared to the early stage (Figure 4.5a) of their growth because of larger crop cover and longer roots which usually coincides with the timing of the peak rainfall periods in the rainy season.

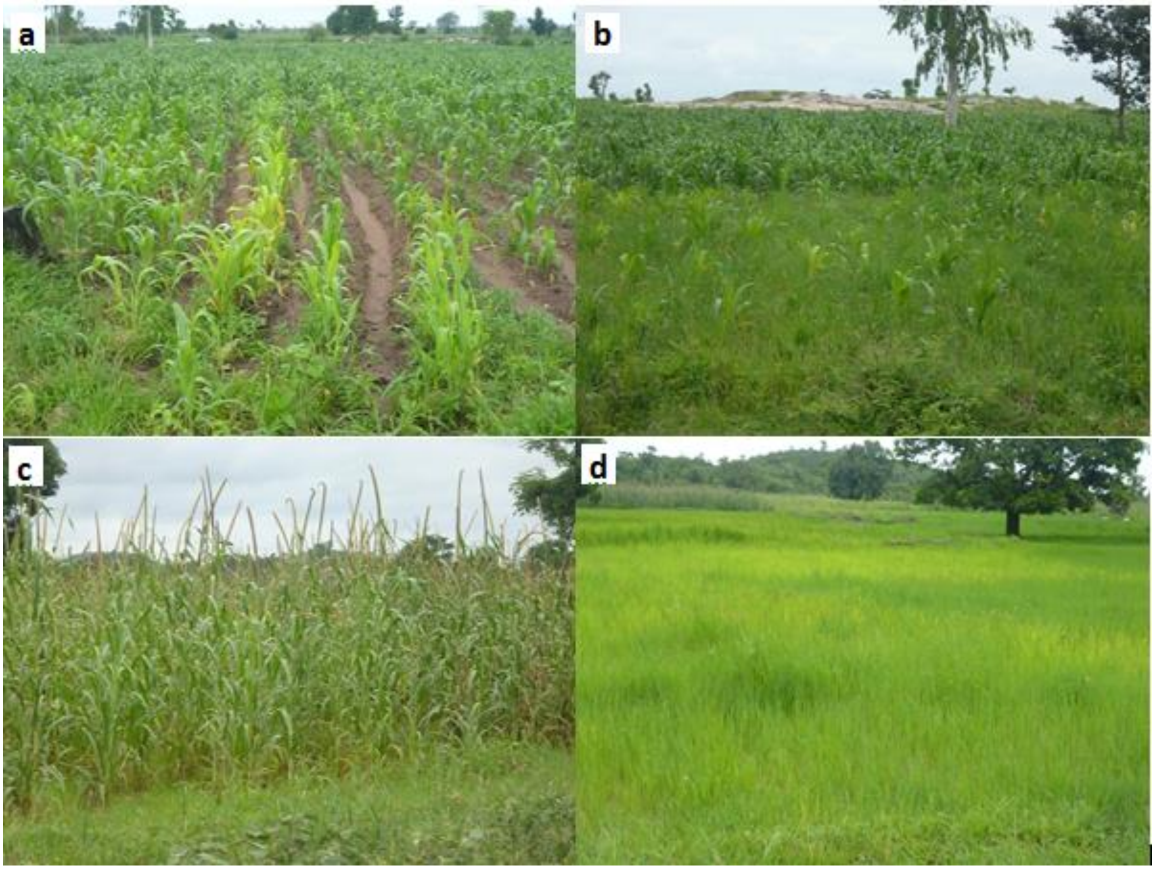


Figure 4.5: Pictures showing (a) Guinea Corn on shallow soil without run-on (early growth stage); (b) Maize and Rice on shallow soil with run-on (mid-growth stage); (c) Millet on deep soil without run-on (maturity stage); (d) Rice on deep soil with run-on crop (mid-growth stage) during the wet season

4.3. Sealed Surface Landscapes

Sealed surfaces are typically localised landscapes that occur in some areas within the catchment. The term ‘Seal’ is sometimes referred to as a crust in the literature; both crusts and seals are formed in the same way. Surface sealing can occur either due to the action of intense rainfall causing surface soil particle reorganisation or due to some form of cementation of soil particles due to chemical reaction of minerals in the soil. Valentin (1993) described the sealed surfaces as generally thin soil surface layers which are more compact and hard, when dry, than the material directly beneath.

Various researchers reported the effect of sealed surfaces on agriculture and land management in West Africa e.g., in northern Nigeria, Sombroek and Zonneveld (1971) observed that the prevailing climate of the region lead to most of the clayey soils having a tendency of becoming surface sealed. Maduakor (1991) also reported that the sealed soils have poor structure which restricts root penetration and limits the amount of available water held in the soil even when there is sufficient rainfall.

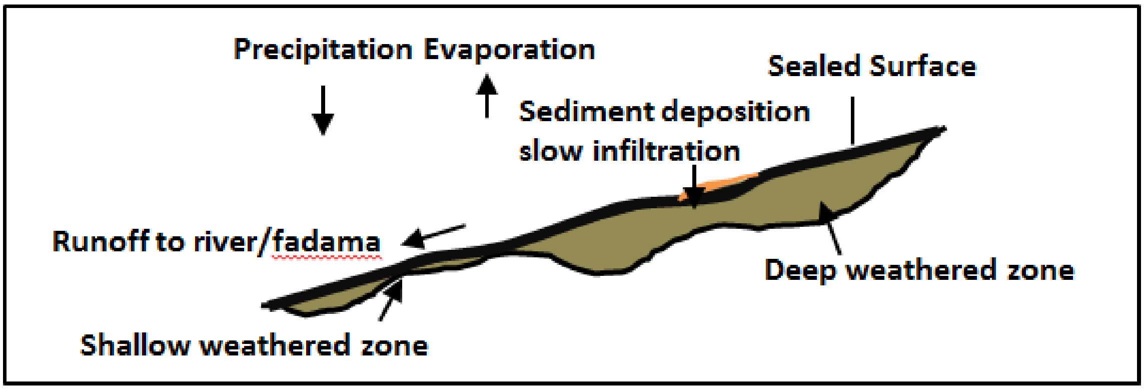


Figure 4.6: Schematic diagram the dominant flow processes in shallow and deep weathered sealed surfaces during the wet season

Figure 4.6 illustrates the flow processes in the sealed surfaces during the wet season. Water infiltration is prevented or significantly reduced due to the formation of a crust on the soil surface layer (Figure 4.6 and Figure 4.7). This can occur even in very sandy soils as observed in Niger by Valentin (1981) and in Mali by Hoogmoed and Stroosnijder (1984). In southern Togo, Poss et al. (1990) reported that even in surface sealed soils under cropping, infiltration can be as little as 20% of the heaviest rainstorm. Data analysis of 48 simulated rainfall plots in Burkina Faso showed that the presence of a crust and its type are the dominant factors influencing infiltration on bare soils (Albergel et al. 1986). Sambroek (1985) described the soil surface sealing in northern

Nigeria as the formation of a thin layer (1-5 mm) at the surface which is dense and hard when dry, without any porosity, and sometimes even water repellent with algae growth. They hamper seedling emergence, reduce infiltration and favour runoff and erosion.

Heavy runoff is commonly observed on sealed bare surface soils at the beginning of the rainy season, with runoff occurring under almost every rainstorm because the infiltration rates are frequently exceeded by rainfall intensities. Many studies have shown that the time to ponding and runoff is substantially reduced on sealed soils even when dry (Albergel 1988; Casenave and Valentin 1992). Chevallier and Valentin (1984) observed runoff occurring after only 1 mm of rainfall at 60 mm h^{-1} on a dry sandy soil in northern Burkina Faso. The soil moisture on the sealed surfaces of the basement complex areas is insufficient to grow any crop even when there is heavy rainfall. Runoff from sealed surface is generally observed to be flowing directly to the fadama or river where conditions are more favourable for infiltration. Sambroek (1985) observed that rainfall-runoff occurs on the sealed surfaces even for very gentle slopes.

4.3.1. Hydrological processes in the sealed surface LU within the catchment

Based on maps and the visual assessment described earlier, the sealed surfaces in the study area are identified as localised and spatially distributed, occupying only about 5 % of the total land area of the catchment. The depth of weathering is also variable but can be up to 3m in the deeper areas, but the surface hydrological behaviour is similar for both the shallow and deep weathered areas.

The dominant hydrological process on the landscape is rapid runoff to the river/stream and to the fadama due to low infiltration (Figure 4.7f). The runoff is conveyed via small channels (Fig. 4.7 c&d) which locally have sufficient energy to cut deep into the sealed layer (Figure 4.7e) leaving behind deposits of sediment washed and transported during rainfall (Figure 4.7a). The eroded gullies in the surface serve as possible areas of infiltration and provide sufficient soil moisture for limited vegetation growth (Figure 4.7 a-f).

Figure 4.7: Pictures showing the (a-b) Crusted/Sealed layer and lack of vegetation during the rainy season; (c-d) Runoff channels before and during rainfall showing evidence of erosion; (e-f) eroded gullies in the sealed layer providing avenue for small vegetation growth /surface stripping

Bare soil evaporation is low because little water is held within the soil due to low infiltration, and runoff removes water quickly from the surface due to low surface or depression storage (Figure 4.7c & f). Only small evapotranspiration occurs due to the lack of significant vegetation cover as seen in Figure 4.7. There is no evidence of the presence of a groundwater table in this landscape because not a single well was found in any of the sites where the fieldwork was conducted.

4.4. Hard Rock Landscapes

There are substantial arid and semi-arid areas in the world which are underlain by basement complex (hard) rocks which also forms the geology of the study area as described in section 2.3. The physical heterogeneities of these rocks control the hydrological behaviour in these regions. The occurrence of cracks or fissures on the exposed rocks provides an opportunity for storage and water movement into and out of the rocks (Dewandel et al, 2010).

The exposed basement complex rocks are divided into two landscape units in the study catchment; the fractured and non- fractured rocks. Intensively fractured rocks allow high infiltration of water into the locally extensive fissures or cracks, but are usually characterized as having low water resource potential due to their low storage capacity. The high water infiltration often results in springs forming at the bottom of the rocks. Chilton and Foster (1995) stated that a number of ephemeral springs form the only means of water supply to communities living in these types of hard rock areas. The non-fractured rocks however do not allow any infiltration of water and all the rainfall runs off with only limited evaporation.

Literature on the characteristics of crystalline basement aquifers has increased considerably over the past few decades (e.g. Lachassagne et al., 2001, Titus et al., 2002; Banks and Robins, 2002, Limaye, 2010, Mohammed-Aslam et al., 2010, Dewandel et al., 2010, Holland, 2012, Chandra et al., 2012, Teikeu et al., 2012), mostly focussing on the hydrogeological characteristics of the rocks especially the transmission and storage of water in the weathered basement or in fracture zones. Mansell and Wang (2010) explained that the moisture distribution on the bare rock surface is a function of the material properties, the surface texture, distribution of cracks and fissures and the microtopography of the surface which result in detention storage. Evaporation and infiltration in hard rock landscape depend on a dynamic interaction between the microclimate above the surface and the distribution of moisture within and on the surface (Mansell and Rollet, 2007). Cleugh et al. (2001) observed the need to determine evaporation on the paved surface or hard rock during and immediately after rainfall when the surfaces are still wet because water is rapidly lost either through evaporation or runoff.

Figure 4.8 illustrate the flow processes on the exposed hard rock landscape.

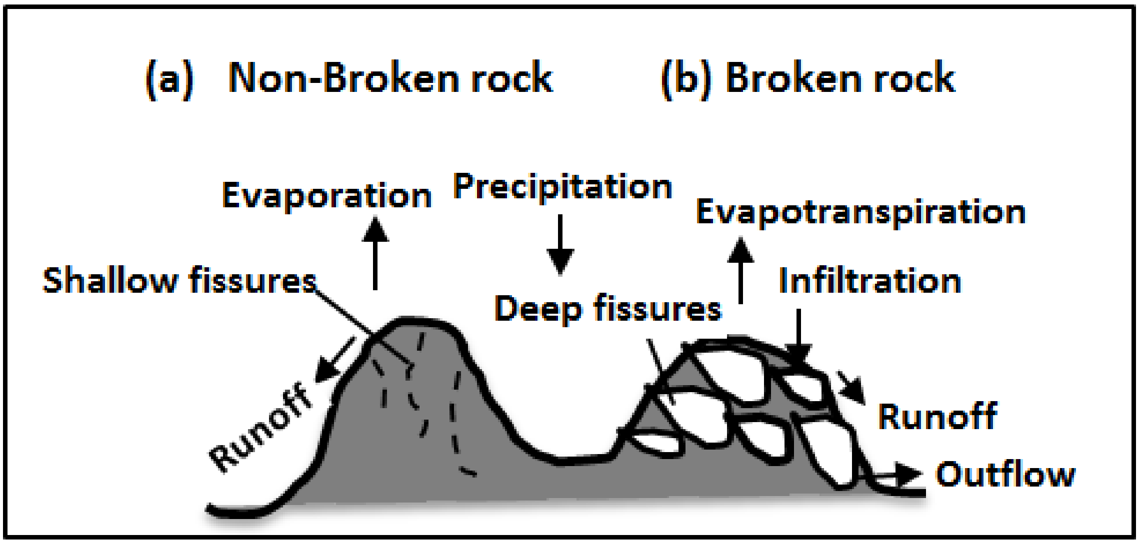


Figure 4.8: Schematic diagram of flow processes in the exposed non- fractured and fractured hard rocks in the wet season

Groundwater in hard rock occurs mainly at the top in weathered regolith and other pore spaces found in the form of cracks, joints and fractures developed due to geological processes. The aquifers in hard rock regions are usually present at shallow depth near the surface; they are considered as discontinuous aquifers as a consequence of their discrete hydraulic conductivity (Dewandel et al., 2006).

Different types of fractures are developed which favour the groundwater movement, some of which extend to a large distance horizontally as well as sub-vertically (Sukhija al.2006). The large distance horizontal flows are less significant in Sokoto basement rocks than the sub-vertical flow component due to a lack of groundwater interconnection between individual landscapes. Abstractable water can only be found in the variably weathered zone or regolith and in fractures (Hazell et al., 1992).

A typical weathering profile consists of the following layers from the top to bottom: the laterite that can be absent in some locations due to erosion; the saprolite or alterite, or regolith. There is usually a decrease in the occurrence of water bearing zones with depth below the ground surface which is attributed to the closure of tectonic fractures due to an increase in the lithostatic strain (Macdonald et al., 1995; Dewandel et al., 2006). The average depth to fresh rock is reported by Hazell et al. (1992) to be about 8 m from the surface in many locations; they are often interrupted by area of abnormally deep weathering which are the principal targets for groundwater abstraction.

A combination of the low permeability of the upper saprolite and the higher permeability of the upper layer of the collapsed zone can sometimes induce significant lateral flow (interflow) which may be discharged downslope through seeps or as baseflow to rivers or streams (Dewandel et al., 2010). There are many locations at which localised recharge can take place, streams, rivers and ponds being the most likely areas. Other locations include: the base of hills and bare outcrops.

The exposed hard rocks in the study area are divided into two; the non- fractured and fractured hard rocks (Figure 4.8) which together cover about 25 % of the total land area of the catchment. The flow processes are similar to those that have been described in the literature. In addition, the region is also characterised by the occurrence of 'Inselberg' rock types where the land is relatively flat. These are isolated hills, outcrops, or small mountains that rises abruptly from a gently sloping or virtually level surrounding plain e.g. Kotorkoshi rock around the catchment which is shown in Figure 4.9.

4.4.1. Flow processes in non- fractured hard rocks

Literature on the hydrological characteristics of exposed non- fractured rocks is lacking due to its apparent irrelevance in exploring the water resource potential of an area. Attention is given to the fractured rocks and fractured or weathered zones in the basement areas. For this research, the exposed non- fractured rock surfaces can be related to paved urban surfaces. Oke et al., (1988) and Taha (1997) described paved urban areas as consisting of a patchwork of concreted impermeable surfaces with contrasting hydrological properties that prevent water infiltration and consequently, produce more runoff than other surfaces in rural areas. The runoff water drains quickly leaving only small proportion (except in depressions) on the surface for evapotranspiration. The elements of hydrological processes in paved surfaces include evaporation and runoff (Mitchell et al., 2001).

The non- fractured hard rock landscapes within the catchment have an input of precipitation and outputs of runoff and short time evaporation due to the complete absence or presence of only small areas of vegetation on the surface (Figure 4.9 a-b). Infiltration only occurs where small fissures are present on the rocks; these fissures are usually shallow and isolated cracks as shown in Figure 4.9 c-d. The infiltrated water emerges locally as part of runoff or evaporates immediately after rainfall.

Runoff occurs only when the rock surface is completely wet, and 1 mm of rainfall is considered sufficient to initiate surface runoff on bare rock surface. Van de Ven et al. (1992) has shown that < 0.5 mm of rainfall is needed to ‘wet’ a road surface before runoff occurs; whilst, Hollis et al. (2004) assumed that the amount of rainfall needed to wet a dry road surface is 0.4 mm, not allowing for depression storage on the hard surface.

Figure 4.9: Pictures showing (a) typical non- fractured exposed rock; (b) the Kotorkoshi rock is typical of many exposed Inselbergs in the catchment (c) stripped bare rock with small depressions but no fissures; (d) hard rock with water emerging from small shallow fissures

Figure 4.9 (a-b) are obtained from: http://www.skyscrapercity.com/showthread.php?t=821770&page=2

4.4.2. Flow processes in the fractured hard rocks within the catchment

The hydrological processes in the exposed fractured hard rocks during and after rainfall include infiltration, evapotranspiration and groundwater outflow as spring discharge (Figure 4.10a). The tectonic processes that produce the structural features (cracks, fractures and fissures) are highly variable in nature (with regard to spatial extent, frequency and interconnectivity). These features are usually described as hydraulic conductors or compound conductors (depending on the intensity of fracturing) instead of aquifers which describe the storage and flow of groundwater in rocks with fractures and fissures (Gustafson & Krasny, 1994).

The difference is that while the term aquifer implies that the groundwater reservoir is related to the formation rather than the structures within it, a hydraulic conductor includes single fractures and fracture zones and is defined by its ability to transmit groundwater (Titus et al., 2009). Infiltration of water into the fractured bare rocks usually occurs along the vertical to sub-vertical cracks, with flow occurring predominantly along the horizontal to sub-horizontal cracks.

Figure 4.10: Pictures showing (e) a spring discharge from the bottom of a fractured rock landscape unit; (b) large outflow from fractured rocks to the river after heavy rainfall

The hard rock landscape with cracks in the study area are characterised by limited connectivity between fractures and fissures. The water is most often stored and transmitted through the fractures which serve as hydraulic conductors rather than the matrix due to the absence of a weathered zone. Where the rock is completely fractured, almost all the rainfall infiltrates between the large boulders and fragments resulting in small surface runoff. This produces numerous springs down slope of the fractured rocks which can form small streams or rivers (Figure 4.10 a-b). The head waters of the River Ka are formed from these types of springs.

The flow into the fractured basement complex rocks usually starts when rainfall commences in the region and ceases after the rainy season. The fractured rocks in the study area are assumed to have a water storage capacity which becomes full during the peak rainy season. When the storage capacity is exceeded due to substantial infiltration into the fissures, outflow from the store commences. The outflow occurs towards the bottom where the rocks are fractured (Figure 4.10a), and usually commences about 4-5 weeks into the rainy season and continues for up to 5 weeks after the end of the rainy season as observed during the fieldwork and further confirmed by local inhabitants (interview, 2012).

4.5. Forest Landscapes

Semi-arid environments are frequently characterised by a sparse spatial pattern of vegetation where individual ephemeral shrubs or grasses form conspicuous vegetated patches that sharply contrast with open areas of bare soil or perennial plants (Waroux and Lambin, 2012). Sufficient knowledge of hydrological processes operating at these contrasting vegetative areas can be crucial to reliable water management (Yaseef et al., 2009; Jin et al., 2011). Despite the large fraction of bare soil surface in dry semi-arid environments, there are still places where high tree density can be found especially in forested areas where there is sufficient moisture for the trees even during the dry season. The occurrence of a forest canopy has an impact on the microclimate. The levels of solar radiation, wind speed and the sunny day's temperature are lower compared to open sites. Kuuluvainen and Pukkala (1989) reported that such areas results in high heterogeneity in soil surface condition because the canopy structure and leaf area index (LAI) affect below-canopy radiation characteristics. Breshears et al. (1998) added that the surface heterogeneity can potentially influence evapotranspiration and increase its spatial variability.

It was also reported that the normalized difference vegetation index (NDVI) and leaf area index (LAI) are high and significant during the wet season (Karnieli, 2003, Vicente-Serrano et al., 2010, Sprintsin et al., 2011, Pocas et al., 2013). But the dry season condition in the semi-arid environment is characterized by reduced vegetation cover when the shallow rooted plants die (new plants germinate from dropped/dispersed seeds on the return of the rainy season) leaving only the longer root plants which are able to extract water from deeper soil horizons (Driese and Reiners, 1997). Sometimes the deep rooted plants undergo leaf senescence to conserve moisture or reduce evapotranspiration especially during a drought year (Sprintsin et al., 2011). This consequently results in variable soil moisture content, runoff production, redistribution and infiltration (Diawara et al., 1991; Morecroft et al., 1998) between different areas of vegetation density. Among all the water losses in the water balance of arid and semi-arid environments, evapotranspiration being the largest flux usually accounts for more than 90% of annual precipitation (Zhang et al., 2001) and is affected by the balance between atmospheric demand, soil water content and hydraulic conductivity.

4.5.1. Vegetation covers and flow processes in forest landscape units

The vegetation cover in the study area is much denser and luxuriant in the forest reserves than in the other landscape areas. The forest landscapes covered about 20 % of the total land area of the catchment and are divided into two; the shallow and deep weathered zones as illustrated in Figure 4.11. The shallow weathered zones are mostly characterized by shallow roots (<1.5 m deep) short trees, shrubs and grasses. The deep weathered zones however, have deeper rooted tall trees (up to 3 m deep) with dense vegetation canopy.

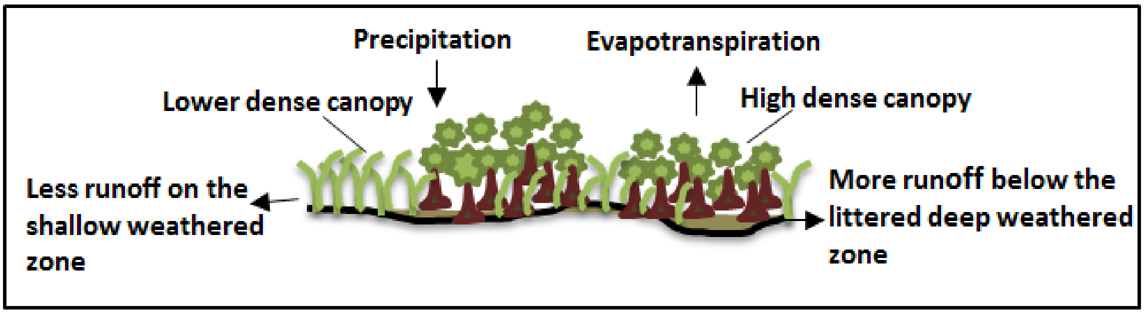


Figure 4.11: Schematic diagram of flow processes in the forest landscape during the wet season

Hoffmann et al., (1998) reported a ground cover of the grass and herbaceous layer of about 49 %, while that of the trees and woody vegetation is about 40 % in the northern part of the catchment. Non-perennial grasses are abundant and form a large ground cover during the wet season, but disappear when the dry season is severe (Eckert and Hoffmann, 1998). Rapidly maturing annual plants are predominant, although, cattle grazing and fire (bush burning) can lead to an increased dominance of perennial woody vegetation (Keay, 1949, Kueppers, 1998; Schaefer, 1998).

Where trees are present, the vegetation is denser, subsurface lateral runoff usually occur below the littered layer; while very little surface runoff occur in less dense forest areas. This is because the small grasses and shrubs have a high ground surface cover which restricts runoff compared to areas with deeper rooted large trees. The soil has a high infiltration capacity and evapotranspiration is high due to the canopy and long roots of large trees. During the rainy season, the vegetation cover is roughly about 90 % with only 10 % of bare soil patches or a mixture of bare soil and grass as seen in Figure 4.12 a-b. In the dry season however, the vegetation cover reduces significantly to about 40 % and evapotranspiration is reduced and limited to tress with long roots and drought resistant species.

Figure 4.12: Nature of forest cover (a-b) vegetation with about 90 % cover in the rainy season; (c-d) forest along the river/streams (cover is more dense where it has contact with river/stream)

There is a direct connection between the forest and the river and much of the runoff from the forest landscape goes directly into the river as shown by the pictures in Figure 4.12 c-d. Lateral groundwater flow is expected to be small to the river from the forest landscape due to the high water extraction by the roots of the vegetation.

4.6. Fadama (Wetland areas) Landscapes Units

Wetland soils are given different names in Nigeria, but Fadama is a popular *Hausa* word for wetland soils. Batjes (1992) and Ojanuga et al. (1996) described fadama as low-lying swamp areas having fluvial deposits and shallow exploitable aquifers along the river floodplains and inland valleys/depressions. They occupy about 7.2% of Nigeria's land mass (Jamala et al., 2012) and are spread from the north to the southern part of the country traversing varying climatic, geological and vegetation conditions. Anon (1993) explained that Fadamas are good agricultural areas containing land and water resources with rich mineral or organic soils that could easily be developed for irrigated agriculture.

4.6.1. Description of water flows in the fadama landscape of the river Ka catchment

The fadama landscape occupy about 10 % of the total land area of the catchment and receives input of precipitation and run-on from all the other landscape within the catchment (see Figure 4.17) and output of actual evapotranspiration, surface runoff especially where there is no ponding and irrigation abstraction especially during dry season. A large proportion of runoff from towns, cultivated lands, bare surfaces, hard rock areas, and forests is received as run-on into the river and *fadama* in addition to direct rainfall input. The soils of the fadama areas are typically *Eutric Gleysols,* (as described in section 2.5) and are mostly seasonally water logged. The alluvial soil deposits in low-lying areas along the flood plains usually became saturated by water for long periods especially when there are heavy floods as shown on the pictures in Figure 4.13 (a-c). They are mostly used for rice cultivation or grazing and they occur almost everywhere in the fadama along floodplains of rivers and streams within the study area. Despite the usual loss of crops due to heavy floods (Figure 4.13 b-c), the crops planted after flood recession usually give high yields compared to years without floods.

Figure 4.14 illustrate the different stages of annual flow processes cycle in a fadama. The main input is precipitation and run-on from other landscapes, while the water loss includes open water evaporation during the rainy season, groundwater outflow and runoff to the river especially when there is ponding. The water table in the fadama at the start of the rainy season is typically 3-5 m below the ground surface due to abstraction and evapotranspiration (Figure 4.14 - I), but as the rainy season advances, the water table rises due to increased inflows from the surrounding landscapes (Figure 4.14 - II).

Figure 4.13: Picture of fadama landscape showing (a) ponded rice field; and (b-c) heavy river floods leads to deposition of rich alluvial materials, but sometimes they result in a loss of crops in the fadama

When the rainy season reaches its peak, the water table reaches the surface and more surface runoff and outflow occurs especially during floods (Figure 4.14 - III). Evapotranspiration and evaporation during the stages in Figure 4.14 II & III respectively occur at the potential rate due to there being enough water close to the soil surface or due to ponding. After the rainy season, the water table starts declining and water abstraction directly from the river is used to supplement the growth of recession crops (Figure 4.14 - IV). During the dry season, abstraction from shallow hand dug wells for irrigation commences when the river becomes completely dry (Figure 4.14 - V).

4.6.2. Description of cropping/planting cycle in the fadama and cultivated lands

The Fadama in the study area is very important in view of its support for intensive agricultural production. Both flood recession and dry season farming are practised in the fadama areas.

The vegetation in the fadama starts growing with the onset of significant rainfall usually in May or June. Weed grasses starts growing in the fields before the planting of actual crops usually maize first then followed by rice (Figure 4.15 a-b). Maize is harvested earlier than rice and after the harvest, grass continues to grow alongside rice. After the rice is harvested, evapotranspiration still continues because of the grass but at reduced levels due to the limited moisture in the soil. Other vegetable crops such as tomatoes are grown during dry season especially when there is enough moisture in the soil or through irrigation using small hand dug wells in the fadama.

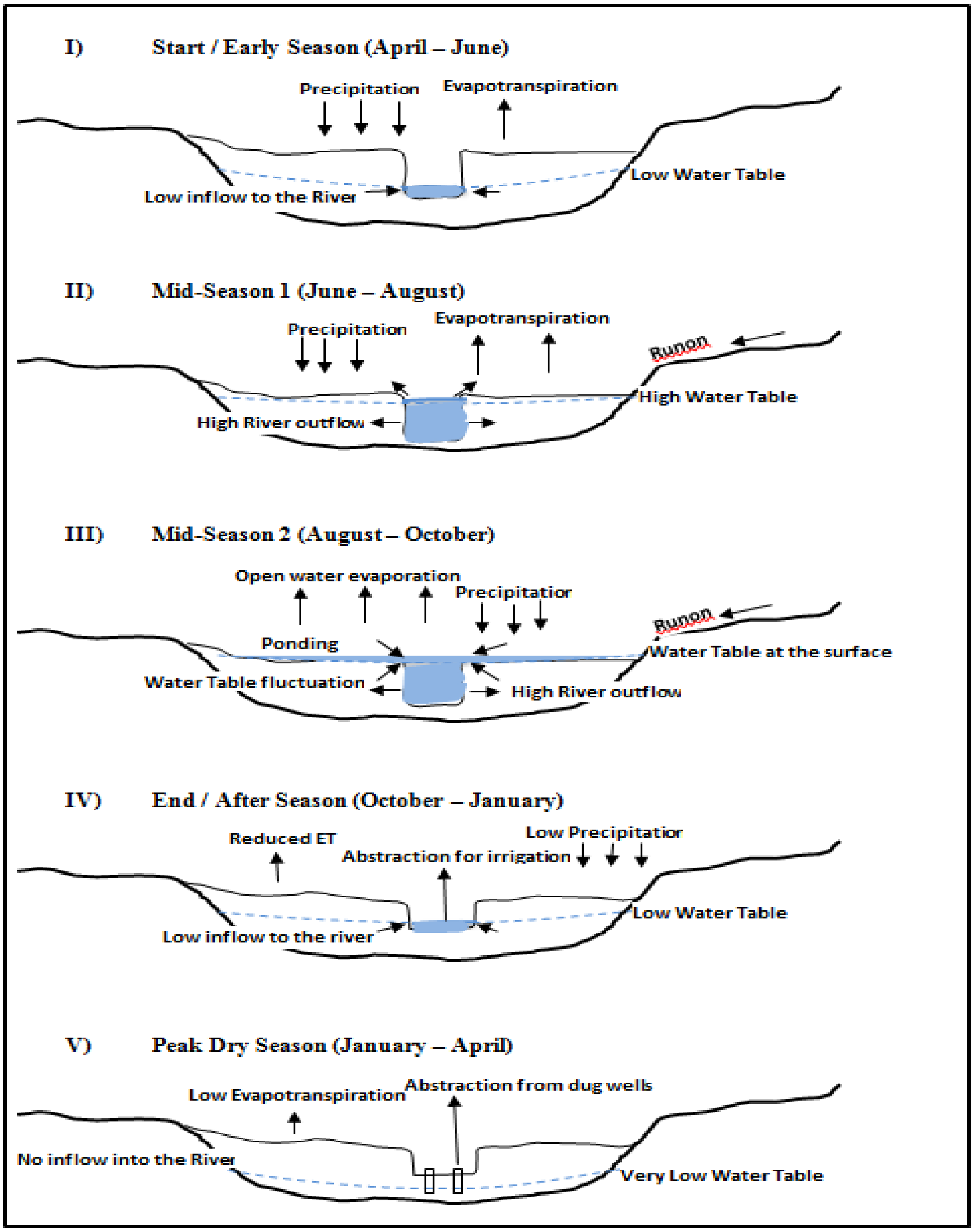


Figure 4.14: Schematic diagram of yearly flow processes cycle in fadama landscape

The major crop grown in the fadama when the rainy season is well established in the region is rice, planted usually in August and harvested in mid-December (sometimes delayed until January if there is delayed flood). The recession farming follows after rice is harvested. This involves planting crops on soils at or near field capacity in order to make use of water stored in the soils. When the annual flooding of the Ka River is timely and extensive, ponding occurs and the full range of recession crops is planted on the fadama. If the flood is delayed and limited, only the most economically rewarding crops are planted. The timing of the crop growing cycle within the fadama is given in Table 4.2 based on the information obtained from the local farmers during the fieldwork.

Table 4.2: Description sequence of cropping cycle in the fadama landscapes

Date	Crop description
1st April	Start of year, dry season mainly bare soil
1st June	Grasses in the fields, land preparation, bare soil
15th August	Crop planting
15th September	End of developing stage, rice above water
15th October	End of mid-stage, kc decreases to harvest
15th December	Rice harvest
3rd January	Recession crops planted
5th March	Recession crops (Tomato) harvest
6th March	Bare soil with low grasses
31st March	Mainly bare soil. Grass and weeds start to grow slowly

The planting of recession crops is usually timed to coincide with the rate at which the flood water retreats. This is mostly in December to early January when the temperature is relatively low, so that plants can reach maturity before the high temperatures in the later part of the year.

Figure 4.15: Picture showing Stages of cropping cycle in the cultivated and fadama landscapes (a) land preparation such as weeding and harrowing; (b) early planting stage of rice; (c) mid-growth stage of Maize; (d) Maturity growth stage in Maize

The local people seem to have good knowledge of the suitability of their soil for different crops and the alternatives to adopt in the absence of the most suitable soil. During the fieldwork, some of the local people interviewed explained that soils capable of supporting any form of natural vegetation could also support crop production. They regarded a suitable soil as the one from which high yields are expected, while less suitable soils are those with insufficient moisture and nutrients. They also knew very well when a soil is temporarily unsuitable (e.g. when the land is too wet or completely dry to work on) because it produces smaller yields than expected due to lack of sufficient soil moisture or nutrients.

4.7. Classification, interconnection and heterogeneous hydrological behaviour of different landscape areas

After a detailed geological and hydrological study and the physical fieldwork, six major conceptual models were constructed based on the landscape features within the catchment area (Figure 4.16). The six major landscape units shown by different colours in the Figure 4.16 were arrived at through careful analysis of topographic maps and google images of the catchment. The conceptual LUs were further subdivided into sub-groups taking into consideration specific site landscape features and their variability. The major divisions and sub-divisions are given in Table 4.3.

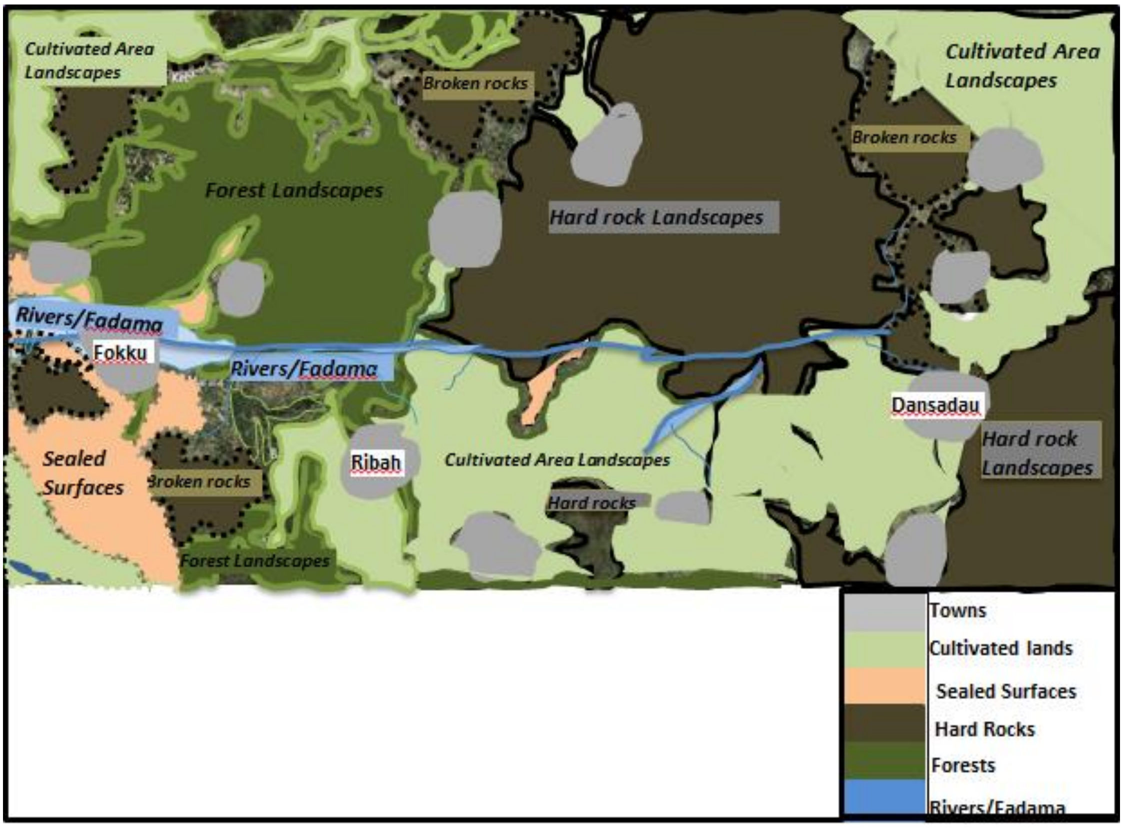


Figure 4.16: The major landscape types within the catchment

Source: obtained and modified from https://maps.google.co.uk/maps?hl=en&tab=wl

The different landscapes are interconnected with each other through the runoff processes as described in the previous sections of this chapter. The interconnectivity of runoff processes is further illustrated in Figure 4.17. The common input in all the landscapes is precipitation which is assumed to occur uniformly over the catchment. All other variables however, differ from one landscape to another e.g. runoff occurs in most of the landscapes, but the rate of runoff generation and its magnitude varies between the different landscapes as a result of heterogeneous individual landscape characteristics.

Table 4.3: Different landscape classes and sub-classes, percentage land areas and major variables

Conceptual Landscape No	**Class & Sub-Classes Name**	**Variant**	**Percentage Land Area covered (%)**	**Soil Texture**
1	**Towns**			
i	**Town 1**	Shallow Water table	3	SCL
ii	**Town II**	Deep Water table	7	SCL
2	**Cultivated**	**Soil**		
i	**Cultivated lands I**	Shallow weath zone/no runon	10	SCL
ii	**Cultivated lands II**	Shallow weath zone/ + runon	5	SCL
iii	**Cultivated lands III**	Deep weath zone/no runon	10	SCL
iv	**Cultivated lands IV**	Deep weath zone/ + runon	5	SCL
3	**Sealed Surface**			
i	**Sealed Surface I**	Shallow	2	SCL
ii	**Sealed Surface II**	Shallow	3	SCL
4	**Hard rock**			
i	**Hard rock I**	Fractured	15	-
ii	**Hard rock II**	Non- fractured	10	-
5	**Forests**			
i	**Forest I**	Shallow weathered	7	CL
ii	**Forest II**	Deep weathered	13	CL
6	**River/*Fadama***			
i	**Fadama I**	Ponding	10	CL

SCL – Sandy clay loam
CL – Clay loam

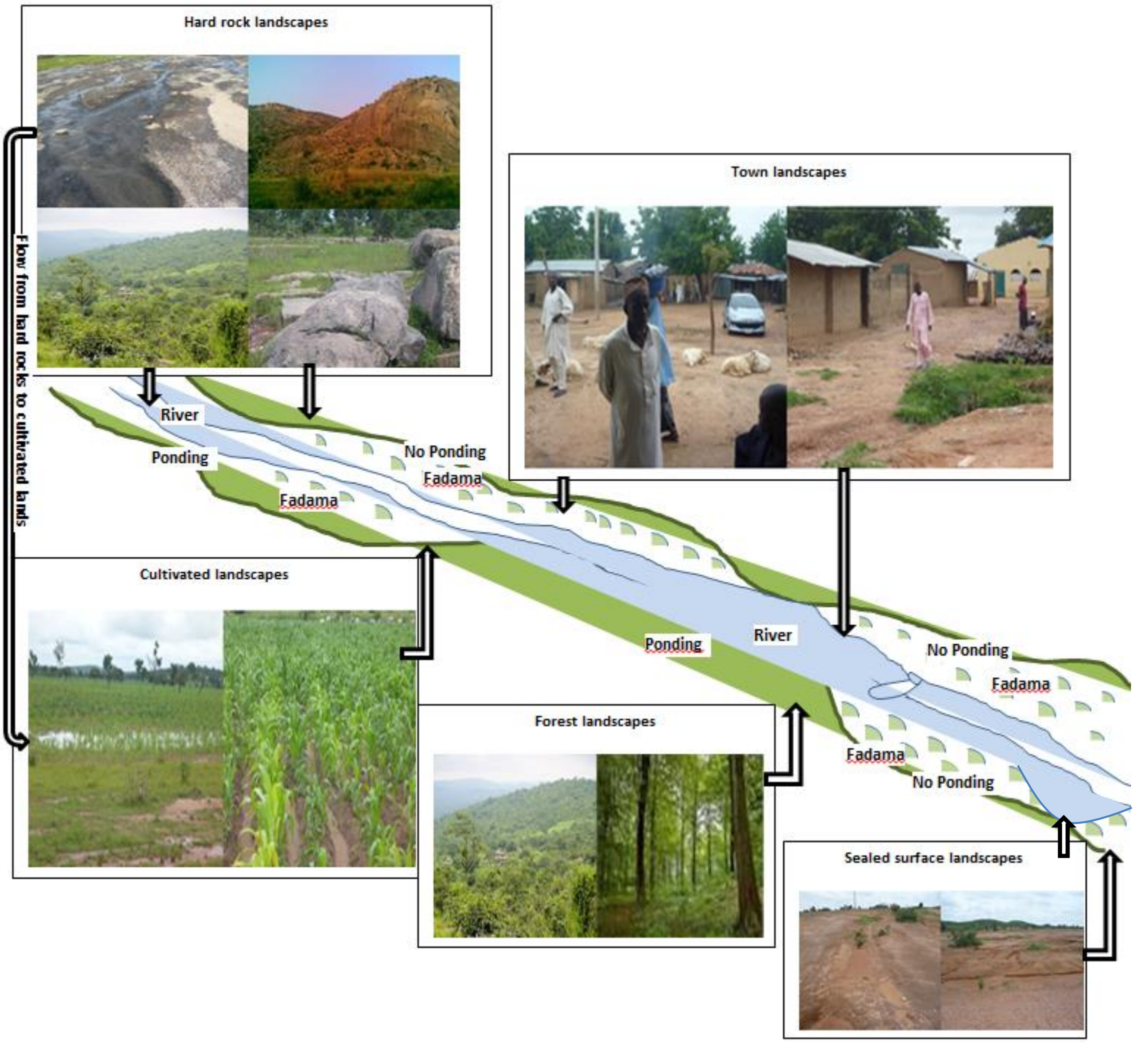


Figure 4.17: Conceptual flow interconnectivity and transfer of runoff between different landscapes within the catchment

The routing of flows from different landscapes to either the river, fadama or the cultivated lands were based on site visit observations during the fieldwork and a review of all available information including the photographs taken. It is assumed that there is no seepage, recharge or transmission losses as water flow along the channels on the way to the river or fadama. It is also assumed that all groundwater goes directly to the river or fadama and that there is no routing of the groundwater to other landscapes. Sometimes however, recharge occur in the fadama after heavy flood when the river becomes overbank. The routing is based on the assessment of the direct contact of the runoff channels from the contributing landscape to the recipient body. The degree of contact was aggregated and the percentage was estimated based on the number of runoff channels entering the river or fadama (see Table 4.5).

In the four different cultivated lands for example, equal proportion of runoff (50 %) goes to the river and to the fadama because of the distribution of farmlands within the study area which allows almost equal direct contact with the river and the fadama. The runoff from the cultivated lands however, is much higher in the shallow cultivated lands receiving additional run-on and equal amount is routed to the fadama and the river via the small natural channels or medium to large runoff channels created by the farmers (Figure 4.17).

Significant runoff from the sealed surface reaches the river (about 60 %) and the fadama (about 40 %) where they made contact with the narrow small channels conveying the water, while only a small amount of runoff from the forest reaches the fadama (about 10 %) due to low contact and absence of visible surface runoff channels, while about 90 % of the flow goes to the river because of their visible direct contact.

In town landscapes, a lot of runoff, generated during/after rainfall due to the slope or sealed soil surface caused by human habitation is routed to the fadama and in some instances the river

4.8. Two alternative water balance approaches

The hydrological behaviour of the different LUs can be summarised as shown in Table 4.4. The flow processes can be represented by one of the two water balance diagrams (A & B) in Figure 4.18, in which the major difference is the presence of a top soil layer. In diagram ‘A’, the processes of water distribution is between soil and the atmosphere; while in diagram B, the processes are between the hard rock surface and the atmosphere.

Table 4.4: Hydrological processes in different landscape units within the catchment

Name of Landscape Units	Runoff	Run-on	Infiltration	ETransp.	Evap	Abstraction	Fissure Outflow	CM Type
Towns I	√	X	√	√	√	√	X	A
Towns II	√	X	√	√	√	√	X	A
Cultivated I	√	X	√	√	√	X	X	A
Cultivated II	√	√	√	√	√	X	X	A
Cultivated III	√	X	√	√	√	X	X	A
Cultivated IV	√	√	√	√	√	X	X	A
Sealed Surf. I	√	X	√	X	√	X	X	A
Sealed Surf. II	√	X	√	√	√	X	X	A
Hard rock I	√	X	√	√	X	X	√	B
Hard rock II	√	X	X	X	√	X	X	B
Forest I	√	X	√	√	X	X	X	A
Forest II	√	X	√	√	X	X	X	A
Fadama	√	√	√	√	√	√	X	A

The rate and magnitude of the individual processes for each diagram varies, including:

- Variation of storage within the soil and fractured hard rocks;
- Groundwater outflow in soil and or fissures outflow from storage in hard rocks;
- Absence of runoff in fractured rocks; and
- Absence of infiltration in non- fractured rocks

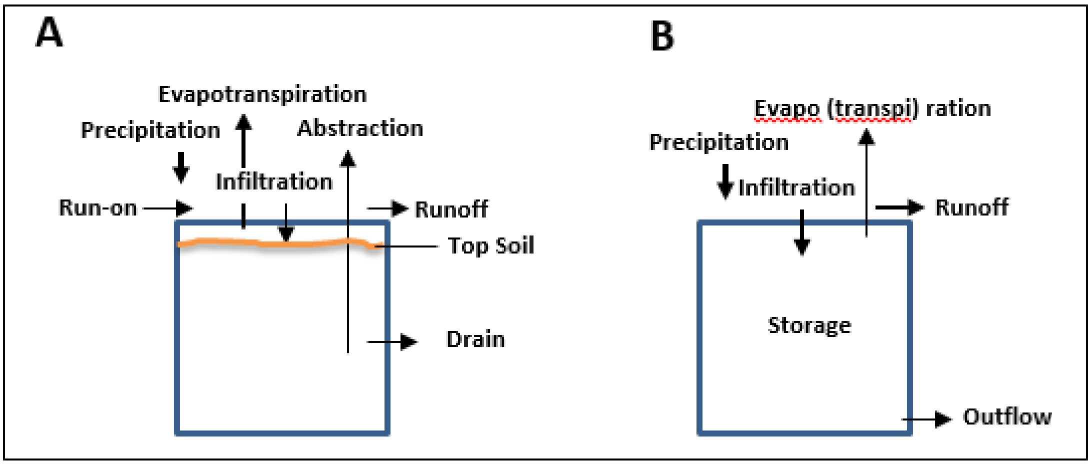


Figure 4.18: Flow processes for the two water balance approaches

All these processes occur in different landscapes, some with soil surface as in Figure 4.18A, and some without soil surface in Figure 4.18B as discussed in the previous sections. The water balances for each diagram 'A & B' in Figure 4.18 were carried out using two different approaches which are fully described in chapter five.

4.9. Quantified Conceptual Landscape Unit Models

The flow contributions of individual LU types discussed in section 4.7 to the total flow within the whole catchment is based on the percentage land area (PLA) covered by individual LUs as given in Table 4.3.

Precipitation is assumed to occur uniformly throughout the catchment; therefore, the major hydrological process connecting the landscapes is runoff. Runoff occurs from each landscape into the river and into the fadama as shown in Figure 4.17. The cultivated lands however also receive runoff from the non- fractured hard rock landscape units which is also illustrated in Figure 4.17. The percentage areas contributing flow to the different landscape units was derived from a visual assessment of study area maps informed by the observations from the fieldwork. The contributing landscape features identified on the maps were assessed according to their direct contact with the recipient landscape feature (river, fadama or cultivated lands) and the contributing area was estimated over the total individual landscape area. The fraction of runoff from each LU to the river and fadama and from the non- fractured hard rock LU to the cultivated lands is given in Table 4.5.

Table 4.5: Fraction of runoff flowing to the river, fadama and cultivated lands from different landscapes

Name of Landscape Unit	% Land area	Fraction of runoff flowing to cultivated land II	Fraction of runoff flowing to cultivated land IV	Fraction runoff flowing to the fadama	Fraction runoff flowing to the river
Towns	**10**	**0**	**0**	**0.9**	**0.1**
Cultivated I	**10**	**0**	**0**	**0.5**	**0.5**
Cultivated II	**5**	**0**	**0**	**0.5**	**0.5**
Cultivated III	**10**	**0**	**0**	**0.5**	**0.5**
Cultivated IV	**5**	**0**	**0**	**0.5**	**0.5**
Sealed	**5**	**0**	**0**	**0.4**	**0.6**
Hard rocks I	**15**	**0**	**0**	**0.375**	**0.625**
Hard rocks II	**10**	**0.45**	**0.45**	**0.0375**	**0.0625**
Forest	**20**	**0**	**0**	**0.1**	**0.9**
Fadama	**10**	**0**	**0**	**0.0**	**1.0**

Each landscape type requires a distinctive set of factors to indicate how it is connected to other landscape types and to the river in order to allow the landscape units to be modelled and their results up-scaled to the catchment. The approach is illustrated by considering the town landscapes; details of the distributions are given and the result summarized in a diagram (Figure 4.19). All the components are summed to give the final result in mm/d. The complicated distribution of runoff from hard rocks is then considered and an illustrative diagram prepared in Appendix C. The runoff is divided into contribution to the river, fadama or cultivated lands; the runoff fractions (RF) sum to 1.0.

Due to differences in the individual landscape areas, there is need for area conversion (AC) to assess the processes based on area weighted contributions. The area conversion (AC) is obtained by dividing the percentage area of a contributing landscape by the percentage area of the receiving landscape. The run-on fraction (RonF) is obtained by multiplying the AC value by the runoff factor for that landscape (RF). Table 4.6 presents the runoff factor, area conversion and runoff fraction for the different LUs. The weighted runoff reaching the fadama or river is therefore obtained by multiplying the actual model runoff (Ro) for the day by the run-on (RonF) fraction (see Table 4.6).

Table 4.6: Runoff factor (RF), area conversion (AC) and run-on fraction (RonF) to the river, fadama and cultivated lands from different landscapes

Name of Landscape Units	% LU Area	Cultivated II & IV			Fadama			River
		RF	AC	RonF	RF	AC	RonF	
Towns I	**3**	**0**	**0**	**0**	**0.9**	**0.3**	**0.27**	**0.1**
Town II	**7**	**0**	**0**	**0**	**0.9**	**0.7**	**0.63**	**0.1**
Cultivated I	**10**	**0**	**0**	**0**	**0.5**	**1.0**	**0.5**	**0.05**
Cultivated II	**5**	**0**	**0**	**0**	**0.5**	**0.5**	**0.25**	**0.025**
Cultivated III	**10**	**0**	**0**	**0**	**0.5**	**1**	**0.5**	**0.05**
Cultivated IV	**5**	**0**	**0**	**0**	**0.5**	**0.5**	**0.25**	**0.025**
Sealed Surf. I	**2**	**0**	**0**	**0**	**0.4**	**0.2**	**0.08**	**0.012**
Sealed Surf. II	**3**	**0**	**0**	**0**	**0.4**	**0.3**	**0.12**	**0.018**
Hard rocks I	**15**	**0**	**0**	**0**	**0.375**	**1.5**	**0.5625**	**0.625**
Hard rocks II	**10**	**0.45**	**0.45**	**0.9**	**0.0375**	**1.0**	**0.0375**	**0.0625**
Forest I	**7**	**0**	**0**	**0**	**0.1**	**0.7**	**0.07**	**0.063**
Forest II	**13**	**0**	**0**	**0**	**0.1**	**1.3**	**0.13**	**0.117**
Fadama	**10**	**0**	**0**	**0**	**1.0**	**10**	**10**	**0.1**

4.9.1. Run-on weighting from town landscapes to the fadama and the river

An example of run-on calculation from one of the two town landscapes to the fadama after rainfall is illustrated in Fig. 4.19 below, taking the 17th of September 2000 as an example. The run-on contribution from the town I landscape to the fadama was calculated as follows;

- The runoff leaving the town on this date is 12.57 mm over the area of the LU, which is 3 % of the catchment
- The fadama is 10 % of the catchment, so the area conversion to generate the equivalent water depth over the fadama's greater area (compared to Town I) is 10/3 = 0.33
- As 90 % of the runoff from Town I Table 4.6 flows to the fadama, the run-on fraction (RonF) = 0.9 * 0.33 = 0.27
- Therefore the depth of the run-on to the fadama on this date = Ro x RonF
  = 12.57 x (0.27) = 3.4 mm/d

Considering the runoff to the river:

- 10 % of the runoff from Town I landscape on this date flows to the river
- The runoff to the river from the Town I landscape expressed as an equivalent depth over the entire catchment
  = 12.57 * 0.1 * 0.3 = 0.4 mm/d

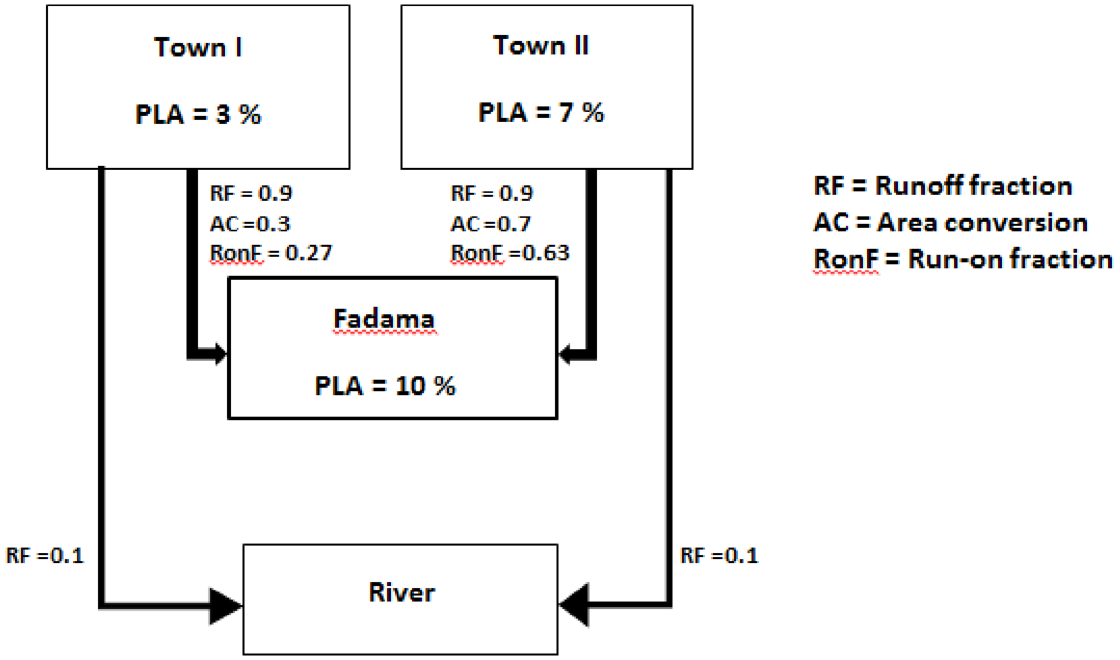


Figure 4.19: Area weighted run-on estimation from Town Landscapes

The calculations for the remaining LUs are given in Appendix C. For each landscape unit, the run-on to the Fadama represents something that is completely different to the run-on to the River. The run-on to the Fadama is given as an equivalent depth over the receiving LU; taking account of what proportion of the runoff from the providing LU arrive at the receiving LU and their differing areas

In contrast, the run-on to the river is given as an equivalent depth of water over the entire catchment. So that for example 10 mm or runoff from 3 % of the catchment is equivalent to a depth of 0.3 mm over the entire catchment. So when the sum of run-ons and groundwater flows to the river is taken, we get a mm of flow that can compare with the measured data

Conclusion

This chapter identified and classified the different landscape units within the Sokoto basement complex region. The chapter described in detail, the hydrological processes and flow behaviour of the individual landscapes based on a combination of literature review, fieldwork, careful analysis of photographs, interviews and water table depth measurements collected during the fieldwork.

In this research, six major LUs are identified within the catchment whose different surface features result in different hydrological behaviour during rainfall. The LUs were further sub-divided into sub-units as described in the following sections 4.1 - 4.6. The sub-divisions are based on variations of soil depth for all landscapes except the hard rocks and fadama. Another criteria used is the division of cultivated lands into four types based on additional run-on received. For hard rocks, there are two distinct divisions (fractured and non- fractured).

The relationship between individual landscapes is established by defining the interconnectivity and flow exchanges between various landscapes. This leads to estimates of the area weighted contributions of each landscape to the recipient landscapes. This depends on the relative areas of the contributing and recipient landscapes as illustrated in Figure 4.19 and Appendix C.

Runoff from individual landscapes is distributed according to whether it enters river or is transferred to the cultivated lands and the fadama as described in section 4.7.

Infiltration in the forest landscapes for example tends to be higher than the sealed surfaces due to absence of surface runoff. Surface runoff generation on the other hand is higher on the sealed surface landscapes due to surface sealing that slow or prevent infiltration than the cultivated or forest landscapes where high infiltration occurs.

The chapter also identified a contrasting hydrological behaviour even within the same landscape due to variations in either the soil depth or additional input of water from another landscape e.g. cultivated lands II & IV. The scale of hydrological processes such as runoff and evapotranspiration is expected to be higher in areas with additional water input. Evapotranspiration for example is expected to be higher in the fadama due to additional run-on from all the landscapes compared to town landscapes.

One significant findings of this chapter is the role of exposed hard rock landscapes in influencing the hydrological behaviour of the catchment. The hard rocks have a contrasting behaviour to all other landscapes due to their diverse nature and absence of soil surface. In the non- fractured hard rocks for e.g. there is no infiltration and all the rainfall runs off, while in fractured hard rocks, high infiltration occurs leaving only small amount of water to surface runoff.

This classification based on variability and distribution of landscape features in characterizing the hydrological processes in basement complex areas is mostly overlooked or misrepresented by most researchers in computing the water balance of a catchment. The heterogeneous features of individual landscapes must always be considered and represented in the water balance modelling of a catchment.

The next chapter provides detailed daily water balances of the individual landscapes based on the approaches discussed in section 4.8. The combine effects of the individual landscapes are considered in chapter six.

5. Water Balance Modelling

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 discussed in chapter four to better understand and quantify the importance of the different hydrological processes influencing the water balance. For each of the major units and sub-units, model inputs were used to characterize their soil, regolith and landuse based on the features identified and discussed earlier.

Two approaches are used in the water balance estimation as discussed in section 4.8. The first approach is using the WaSim (Hess et al., 2000) soil water balance model to represent the soil water balance for the towns, cultivated lands, sealed surfaces, forests and fadama landscapes. The second approach uses a newly developed methodology to estimate the water balance of hard rock landscapes due to their unique flow processes that the WaSim model does not represent. The two models inputs are daily rainfall and reference evapotranspiration, soil and crop/vegetation parameters as given in Table 5.1; while, the outputs are the runoff, evapotranspiration, groundwater outflow and abstraction. Table 5.3 give a summary of input parameters for the developed LUs and sub-units.

5.1. Description of WaSim model

The WaSim model as described earlier in section 3.6.3 is a daily one-dimensional model which simulates the soil water storage and rates of input (infiltration) and output (evapotranspiration, runoff and recharge and/or drainage) of water in response to weather. WaSim can be applied to soil water balance simulations of up to 30 years duration and up to 3 crops can be specified in rotation. The model incorporates comprehensive on-line help and is accompanied by Users and Technical manuals.

WaSim consists of several layers of soil with the upper boundary as the soil surface and the lower boundary as an impermeable layer (Figure 5.1) and water is stored between these two boundaries in five stores. The first, compartment 0, is the top soil layer compartment (0 – 0.15 m depth) which mostly consists of the weathered regolith with a mixture of loose cover sand (Aeolian sand deposits) transported and deposited by wind or water within the catchment. This is followed by an active root zone compartment 1 (0.15 m – root depth), which is considered to be the overlying regolith consisting of unconsolidated materials within the catchment; then, compartment 2 is the unsaturated compartment below the root zone (root depth – water table), which is also part of the regolith with low permeability due to high clay material; then, compartment 3 is the saturated compartment above the drain depth (water table – drain depth), which is part of saprolite; and lastly, compartment 4 is the saturated compartment below drain depth (drain depth – impermeable layer), which is considered as the saprock to consolidated bedrock.

The redistribution of the soil water in WaSim is illustrated in Figure 5.1. Soil water moves from upper layers (compartments) to layers below only when the soil water content of a compartment exceeds field capacity. In this case, the drainage flow is a function of the amount of excess water. The depth of the boundary between compartments 1 and 2 will change as the roots grow. Before plant roots reach 0.15 m, compartment 1 will have zero thickness. Similarly, the boundary between compartments 2 and 3 will fluctuate with the water table. Full details of the WaSim model can be found in the technical manual (Hess et al., 2000).

The drain flow is set in the WaSim to represent groundwater outflow from specific LUs where it occurs. The specifications needed in WaSim for the drain set-up are the drain depth, spacing and diameter (m). The values used for the drains are given in Table 5.3 for the different LUs. Drain flow occurs from the lower compartments if the water table is above the drain depth. The rate of drain flow is a function of the height of the water table above the drain. A constant daily output can be taken directly from the water table to simulate pumped abstraction.

In WaSim, ponding occurs if the water table reaches the soil surface. Once ponding occurs, the surface is treated as open water and there is no transpiration or soil evaporation loss.

WaSim has a series of input parameters as summarised in the introductory section of this chapter; some of the input parameters are listed in Table 5.3. WaSim outputs however are runoff, AET, and groundwater outflow in response to weather and irrigation where appropriate.

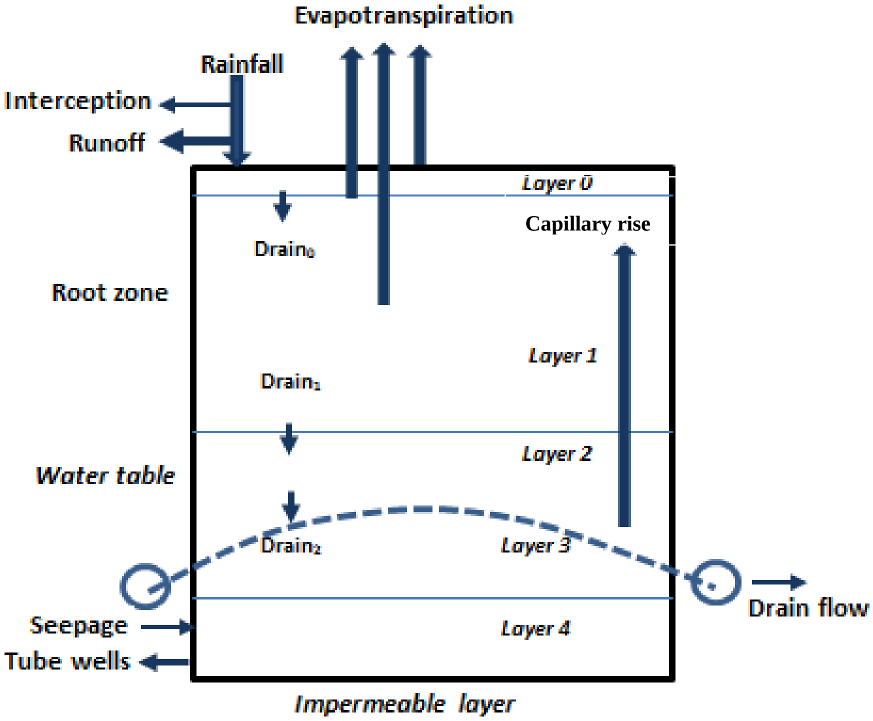


Figure 5.1: Water flow processes and distribution in WaSim (After Hess et al., 2000)

5.1.1. Weather data input

WaSim uses daily rainfall and reference evapotranspiration as inputs. The daily rainfall and temperature data mentioned in Table 3.1 for Gusau station are used. The maximum and minimum daily temperature is used to estimate the ET*o* as described in section 3.1.1. Because the data available are for 40 years and WaSim can only take 30 years data, the simulation was run into two phases; first, for the 30 year records (1971 – 2000) and secondly, for another 30 year records (1981 – 2010). This is to have an overlapping warm-up period, to ensure that the soil water conditions at the beginning of 2001 were the same as the conditions at the end of 2000.

5.1.2. Crops / Vegetation Inputs and output

The crops and vegetation input parameters for WaSim include the growth cycle of crops or vegetation over the year, the rooting characteristics and the crop coefficient for evapotranspiration. In reality, “the crop planting date is dependent on the time of rainfall onset” (Ati et al., 2009), but because planting dates in Wasim cannot be change every year, the 3rd of July was used believing that rainfall is considered to have commenced on that date all over the region as confirmed in the literature (Eilers, 2002, Bello, 1996, 1997) and verified by the local inhabitants through interview during the fieldwork. This is close to the date (14th or 15th of July) suggested by Eilers (2002) in the north east Nigeria with a similar climatic environment. Other researchers (e.g. Hess et al., 1995, Kowal and Kassam, 1978) have suggested earlier planting dates (late June to early July) because, in some years, rain can start as early as April and stops in August, which is earlier than the normal stopping period of September or early October. Table 5.1 gives the planting dates for the crops and vegetation in the different landscapes as obtained from interviews with local inhabitants. The remaining dates for the crop growth cycle were based on the FAO 56 (Allen et al., 1998) values.

The different dates in towns is for native grasses which usually starts growing soon after the rain starts, at a point where there is sufficient rainfall for crop planting. The three dates in the fadama are the periods for two crops (rice and tomatoes) and one fodder grass.

The crop cover fraction on a particular day is determined by interpolation between the dates of emergence, 20% cover, maximum cover, maturity and harvest. If the maximum cover fraction is less than 20% then the first stage is ignored (Hess et al., 2000). Senescence is simulated by a linear reduction in crop fraction between maximum cover at maturity and zero at harvest.

The root growth is limited by the water table, but is not reduced if a water table rises into an established root zone.

5.1.2.1. Estimating reference evapotranspiration (ETo)

The United Nations Food and Agriculture Organization (FAO) has adopted the Penman-Monteith (PM) method as a global standard for estimating ET*o* using four meteorological data; temperature, wind speed, radiation and relative humidity, (See Allen et al., 1998). The large data requirement of this method which is very expensive to obtain, encouraged the search for a simple, robust and practical method that was based on few readily available climatic data for computing ET*o*. The search efforts results in the 1985 Hargreaves ET*o* method which requires only measured temperature data. Where the cost of equipment is a considered and data quality is questionable, or where historical data are missing, both the FAO-PM and the 1985 Hargreaves are recommended, because the two methods are found to be equivalent over a wide range of climates (Vassilis et al., 2012; Farmer et al., 2011; Mohawesh, 2011; Bautista et al., 2009; Benli et al., 2010, Yu-Min Wang et al., 2007; Singandhupe and Sethi, 2005). The Hargreaves method was therefore used for this study. This method was ranked highest among all the methods that require only air temperature data with standard error of estimate of 0.9 mm d^{-1} compared to 0.6 mm d^{-1} of the Penman method (1963) or 0.4 mm d^{-1} of the ASCE Penman-Monteith (ASCE-PM) method (Hargreaves and Allen, 2003).

The Hargreaves equation adopted for this study is the standard Hargreaves and Samani (1985) equation as follows:

$ETo = 0.0023 \times (Tmean + 17.8)(Tmax - Tmin)^{0:5} R_a$

Where, *Tmean*, *Tmax* and *Tmin* are the mean, maximum and minimum daily temperatures respectively.

(R_a) is extra-terrestrial radiation calculated for the midday of each month using the equations from Duffie and Beckman (1980).

5.1.2.2. Estimating crop/plant transpiration

The potential crop transpiration on any day is given by:

Tm = EToi * Kcmax

where

ETo$_i$ = potential transpiration on day i, mm

Kcmax = ratio of potential to reference evapotranspiration at maximum cover.

Actual plant transpiration per unit area of plant, assumed to occur at the potential rate whilst the root zone soil water content is between field capacity (Fc) and the easily available water capacity (EAWC). For excess water, it decreases linearly to zero when the root zone soil water content reaches saturation (SAT), for restricted water supply, it decreases linearly to permanent wilting point (PWP) and remains zero thereafter. This has been shown to be an acceptable simplification for irrigated condition (Ritchie, 1972).

Actual crop transpiration was estimated using the method suggested by Brisson (1998). Open water evaporation occurs only if there is ponding on the soil surface. In this case, there is no transpiration. Soil evaporation occurs from compartment 0 only. Plant transpiration occurs from compartments 0 and 1. Capillary rise from the groundwater occur in the model through direct ‘shortcut’ simulation from the groundwater to evaporation and transpiration.

Table 5.1: Crop / Vegetation input parameters for the WaSim modelling of the river Ka catchment

Conceptual Model	Planting Date[1]	Emergence Date	20 % Cover	Full Cover	Maturity	Harvest	Maximum Root Date	Maximum Cover (%)	Crop Coeff (%)	Planting Depth (m)	Max. root depth (m)	P - fraction
Sealed surfaces and Hard rocks	**1st Jan**	**31st Dec**	**31st Dec**	**31st Dec**	**31st Dec**	**31st Dec**	**31st Dec**	**0**	**0**	**0**	**0**	**0**
Towns	**19th Apr**	**25th Apr**	**10th May**	**19th Jun**	**7th Jul**	**31st Jul**	**7th Jul**	**30**	**75**	**0.1**	**0.5**	**0.50**
Cultivated	**1st May**	**6th May**	**20th May**	**15st Jun**	**15th Jun**	**15th Jun**	**15th Jun**	**40**	**100**	**0.15**	**0.5**	**0.50**
	3rd Jul	**9th Jul**	**29th Jul**	**18th Aug**	**6th Sept**	**30th Sept**	**6th Sept**	**70**	**110**	**0.15**	**1.20**	**0.60**
Forests	**1st May**	**6th May**	**20th May**	**15st Jun**	**31st Aug**	**31st Dec**	**31st Aug**	**80**	**100**	**0.5**	**1.5**	**0.60**
	1st Jan	**1st Jan**	**15th Apr**	**15th Jun**	**31st Dec**	**31st Dec**	**31st Dec**	**70**	**100**	**1.0**	**1.5, 2.5**	**0.65**
Fadama	**4th Jan**	**18th Jan**	**2nd Feb**	**22nd Feb**	**14th Mar**	**24th Mar**	**14th Mar**	**100**	**115**	**0.10**	**1.2**	**0.40**
	1st May	**6th May**	**20th May**	**15st Jun**	**15th Jun**	**15th Jun**	**15th Jun**	**50**	**100**	**0.15**	**0.5**	**0.50**
	3rd Jul	**17th Jul**	**1st Aug**	**10th Sept**	**20th Oct**	**29th Nov**	**20th Oct**	**100**	**115**	**0.10**	**1.2**	**0.50**

Note: the values for crop coefficient, maximum root depth and P fraction are obtained from Allen et al., 1998

5.1.3. The soil data inputs

The soil input parameters needed by WaSim include the soil profile depth, soil hydrologic group and water holding characteristics such as the soil field capacity, wilting point and saturation. Soils water retention parameter values for the. fadama and forest landscapes were obtained from Abu and Malgwi, (2011) and Oyebande et al., (1993), with values for the remaining landscape areas obtained from the Harmonised World Soil Database (HWSD), (2012) based on the methods of Batjes et al, (1997); Batjes, (2002), Batjes et al. (2007) and Van Engelen et al. (2005).

Example of some soil and crop input parameters used for millet in one of the simulations are given in Table 5.2

Table 5.2: Input Parameters for millet crop grown on the cultivated landscape units

Parameter	Symbol	Value	Source
p-Fraction	p	0.60	FAO 56
Curve number	*N*	72	Runoff Curve Number method
Hydraulic conductivity	*K*	0.3 m/d	HWSD
Depth of soil profile	m	3.0	Based on literature and well measurements during fieldwork
Drain spacing	*L*	15 m	Based on literature and expert judgement
Depth to imperm. base	d_0	10.0 m	Based on literature and well depth measurement during fieldwork
Planting date	18th May	1 day	Based on literature and information from local farmers
20% cover date	13th June	27 days	Calculated from FAO 56
Full cover date	3rd July	47 days	Calculated from FAO 56
Maturity date	22nd July	66 days	Calculated from FAO 56
Harvest date	15th August	90 days	Calculated from FAO 56
Maximum root date	22nd July	66 days	Attained at maturity stage
Maximum cover	%	70	Fieldwork observation
Crop coefficient at full cover	%	100	FAO 56
Planting depth	m	0.15	Expert judgement during fieldwork
Maximum root depth	m	1.20	FAO 56

Runoff was estimated using the soil conservation service (SCS, 1972) method. The impact runoff curve number used in this study varies for each landscape unit.

Table 5.3 (a) and (b) gives the input for all the different landscapes modelled within the catchment. This includes the percentage area covered and the depth of the weathered zones for each landscape.

Table 5.3a: Input parameters used for the water balance simulation of different landscape units

CM No	Conceptual Model Name	Variant	Percentage Land Area covered (%)	Soil Texture (HWSD)	Soil Hydrologic Group	Crop / Vegetation Type	Max root depth (m)	Cover Description	Hydrologic Condition	Runoff Curve No.	Saturation (% Vol)	Field capacity (% Vol)	Wilting point (% Vol)	K (m/d)	Tau
1	Towns*		10												
i	**Town Run 1**	Shallow Weathered	3	Sandy Clay Loam	C	Bare soil	-	20% imp	Fair	79	39.8	24.1	14.8	0.3	0.10
ii	**Town Run II**	Deep Weathered	7	Sandy Clay Loam	C	Bare soil	-	20% imp	Fair	79	39.8	24.1	14.8	0.3	0.10
2	Cultivated	Soil	30												
i	**Cultivated Run I**	Shallow weathered no run-on	10	Sandy Clay Loam	B	Millet, Grass	1.2	SR+CR	Good	72	39.8	24.1	14.8	0.3	0.15
ii	**Cultivated Run II**	Shallow weathered + run-on	5	Sandy Clay Loam	B	Grass, Rice, Grass	1.2	SR+CR	Good	72	39.8	24.1	14.8	0.3	0.15
iii	**Cultivated Run III**	Deep weathered no run-on	10	Sandy Clay Loam	B	Millet, Grass	1.2	SR+CR	Good	72	39.8	24.1	14.8	0.3	0.15
iv	**Cultivated Run IV**	Deep weathered + run-on	5	Sandy Clay Loam	B	Grass, Rice, Grass	1.2	SR+CR	Good	72	39.8	24.1	14.8	0.3	0.15
3	Sealed Surface	Soil	5												
i	**Sealed Surf Run I**	Shallow weathered	2	Sandy Clay Loam	D	Bare Surface	-	Bare Soil	Poor	94	37.8	19.1	15.8	0.3	0.05
ii	**Sealed Surf Run II**	Deep weathered	3	Sandy Clay Loam	D	Bare Surface	-	Bare Soil	Poor	94	37.8	19.1	15.8	0.3	0.05
4	Hard rock	Cracks/No Cracks	25	-											
i	**Hard rock Run I**	Cracks	15	-	D	fractured Rock	-	Non-fractured	Poor	-	-	0.3	0.1	0.3	0.05
ii	**Hard rock Run II**	No cracks	10	-	D	Bare Rock	-	fractured	Poor	-	-	0.3	0.1	?	
6	Forests	Soil	20												
i	**Forest Run I**	Shallow weathered	7	Clay Loam	B	Short trees, shrubs, grass	1.5	Maximum Cover	Fair	48	46.4	32.1	11.7	0.2	0.10
ii	**Forest Run II**	Deep weathered	13	Clay Loam	B	Tall trees, shrubs	3.0	Medium Canopy	Good	30	46.4	32.1	11.7	0.2	0.10
6	River/*Fadama*	Ponding	10												
i	Fadama Run I	Ponding	10	Clay Loam	B	Tomatoes, Grass, Rice	1.0	Ponded	Good	72	42.2	20.8	10.6	0.3	0.11

CM No	Conceptual Model Name	Variant	Bottom Boundary Condition	Depth of the Weathered Zone (m)	Initial water table depth (m)	Groundwater discharge / Fissure outflow	Drain Depth/Spacing/ Diameter (m)	Well extraction (mm/d)	Added Run-on coming from CM	Ponding (cm)
1	Towns									
i	**Town Run 1**	Shallow Weathered	Impermeable	3.0	0.5	Yes	1/25/0.15	0.05	X	X
ii	**Town Run II**	Deep Weathered	Impermeable	10.0	1.0	Yes	1/25/0.15	0.1	X	X
2	Cultivated	Soil	Impermeable					-		
i	**Cultivated Run I**	Shallow weathered no run-on	Impermeable	3.0	0.5	Yes	1/18/0.15	-	X	X
ii	**Cultivated Run II**	Shallow weathered + run-on	Impermeable	3.0	0.5	Yes	1/18/0.15	-	Hard rock	2.0
iii	**Cultivated Run III**	Deep weathered no run-on	Impermeable	10.0	1.0	Yes	1/18/0.15	-	X	X
iv	**Cultivated Run IV**	Deep weathered + run-on	Impermeable	10.0	1.0	Yes	1/18/0.15	-	Hard rock	2.0
3	Sealed Surface	Soil	Impermeable							
i	**Sealed Surf Run I**	Shallow weathered	Impermeable	1.5	1.0	X	-	-	X	X
ii	**Sealed Surf Run II**	Deep weathered	Impermeable	3.0	1.0	X	-	-	X	X
4	Hard rock	fractured / Non-fractured	Impermeable					-		
i	**Hard rock Run I**	fractured	Impermeable	0.0	-	Yes	-	-	X	X
ii	**Hard rock Run II**	Non-fractured	Impermeable	0.0	-	X	-	-	X	X
6	Forests	Soil	Impermeable					-		
i	**Forest Run I**	Shallow weathered	Impermeable	3.0	0.5	Yes	1/25/0.15	-	X	X
ii	**Forest Run II**	Deep weathered	Impermeable	7.0	1.5	Yes	1/25/0.15	-	X	X
6	River/*Fadama*	Ponding	Impermeable							
i	Fadama Run I	Ponding	Impermeable	3.0	0.5	Yes	1/25/0.15	0.1	CM's (1,2,3,4, &5)	**7**

The green colour is the landscapes modelled with WaSim, while the orange colour is the hard rock modelled with a different approach (section 5.2)
SR = Straight Row, CR = Crop Rotation

5.2. Water balance for the hard rock landscapes

As mentioned earlier in section 4.4, the hard rock landscapes behave differently from the other landscapes within the catchment. The difference is due to the absence of a soil zone on the hard rocks where normal hydrological processes occur. Instead, the processes on hard rock surfaces are mainly dominated by absence of infiltration and high surface runoff on the non- fractured rocks, and high infiltration and near absence of surface runoff in the fractured rocks. The occurrence of runoff on hard rocks is not because of soil saturation or infiltration excess, but due to the presence of hard rock which prevent infiltration or due to storage being full where there are fissures on the rock during the peak rainy season. The understanding of the flow processes described in section 4.4 led to the development of an appropriate approach to model the hard rock landscapes.

The inflow into the fractured rocks (Figure 4.8) in the basement complex start with the commencement of rainfall in the area, while the outflow begins from the mid-rainy season and continue sometimes up to three months after the rainy season. The outflow occurs mostly where there are cracks or at the base of rock outcrop as springs.

The fractured rocks in the study area are assumed to have a permanent water storage capacity which is set at 300 mm which only becomes full during the peak rainy season. There is a continuous daily outflow from this store when the storage exceeds 30 mm, mostly where there are cracks or at the rock bottom as springs. The storage can go down to 10 mm in the peak dry season just before the onset of another rainy season, and the outflow during this time either ceases or is substantially reduced. When the storage exceeds 30 mm due to additional rainfall inflow into the fissures, the outflow start again and is proportionately distributed as demonstrated in Table 5.4.

5.2.1. Hard rock water balance program

The program used for the water balance estimation in hard rock landscapes incorporates the processes of actual evaporation and evapotranspiration, runoff, infiltration and outflow occurring within the hard rocks; it is based on the knowledge and observations during the fieldwork. The following abbreviations are used for the calculation:

Actual Evaporation (AEV); Potential evaporation (PEV); Reference evapotranspiration (ETo); Factor converting ETo to PEV (BRFAC); Maximum flow into fissures (AFISS); The amount of water in storage (STOR); Depth of water in storage before discharge can occur (DSTOR); The fraction by which STOR – DSTOR is multiplied to give discharge from storage (FRACSTOR). Discharge is proportional to square of storage

Input precipitation P and potential evaporation ETo: then PEV = BRFAC x ETo
where BRFAC is 0.8 (Table 5.4)

AEV = PEV when P > PEV; if P is less than PEV, AEV = P

AFISS = 19.3 mm/d, or equals (P – AEV) when (P – AEV) < 19.3, or zero when P = 0

Runoff = P – AEV – AFISS

STOR = 0.0 on Day 0, then a cumulative calculation as flow into fissures is added

FRACSTOR = 0.0007

Discharge from Storage = FRACSTOR*STOR*STOR
New STOR is recalculated by subtracting discharge from storage each day
An example of the calculation is given in Table 5.4 for 10-days period

Table 5.4: An example of 10-Day water balance of fractured hard rock landscape in the wet season

	Day 1	Day 2	Day 3	Day 4	day 5	day 6	Day 7	Day 8	Day 9	Day 10
Precipitation	49	0	20	1	0	0	47	0	17	0
ETo	5.6	6	5.8	6	6	6.3	5.7	5.7	6	5.6
PEV = 0.8*ETo	4.48	4.8	4.64	4.8	4.8	5.04	4.56	4.56	4.8	4.48
AEV	4.48	0	4.64	1	0	0	4.56	0	4.8	0
Infilr. into fissure (FISS)	19.3	0	15.36	0	0	0	19.3	0	12.2	0
Runoff	25.22	0	0	0	0	0	23.14	0	0	0
STOR	19.3	19.3	34.66	33.81	33.01	32.25	50.82	49.01	59.53	57.05
Disch from Stor	0	0	0.84	0.80	0.76	0.73	1.81	1.68	2.48	2.28
New Stor	19.3	19.3	33.81	33.01	32.25	31.52	49.01	47.33	57.05	54.77

The non- fractured rocks however do not have any storage and the calculation is more straightforward due to the absence of infiltration as described in section 4.4. All the rainfall minus actual evaporation is assumed to runoff downslope when the rock surface is completely wet and evaporation is subtracted. The computation is given in Table 5.5.

For this condition: there is input of precipitation P and potential evaporation ETo:

Then, PEV = BRFAC x ETo; AEV = PEV when P > PEV; if P is less than PEV, AEV = P

Runoff = P – AEV

The 10-days water balance given in Table 5.5 is therefore more simplified.

Table 5.5: A 10-Day water balance of hard rock surfaces without cracks using real rainfall data

	Day 1	Day 2	Day 3	Day 4	day 5	day 6	Day 7	Day 8	Day 9	Day 10
Precipitation	49	0	20	1	0	0	47	0	17	0
ETo	5.6	6	5.8	6	6	6.3	5.7	5.7	6	5.6
PEV = 0.8*ETo	4.48	4.8	4.64	4.8	4.8	5.04	4.56	4.56	4.8	4.48
AEV	4.48	0	4.64	1	0	0	4.56	0	4.8	0
Runoff	44.52	0	15.36	0	0	0	42.44	0	12.2	0

5.3. Results of the water balance of individual landscapes for three wet and three dry years

This section presents the results of the water balances for each landscape, showing the relative contribution of each of the hydrological processes to the water balance. For the purpose of presentation, only rainfall (+run-on where applicable) and selected WaSim outputs of runoff, AET and groundwater outflow are shown because they are the most important processes in the water balance. The simulated water table position is also shown where relevant.

The soil water balance simulations have been run for 40 years (1971-2010), but the results are presented in this section for three selected wet and dry sequential years to see the variations of landscapes hydrological behaviour under wet and dry conditions. The wet years are 1992-1994 with an average rainfall of 1364 mm/yr, while the dry years are 2003-2005 with an average rainfall of 742 mm/yr. The 40 year long term average is 915 mm/yr. The representative years were chosen because they are the only years within the

40 year records that occur serially. Water balances for the entire 40 years can be found in chapter six.

In Table 5.6a, the totals rainfall (+ run-on, where appropriate), runoff, AET, groundwater outflow and the difference between the water stored in the soil on the 31st of December of the third year and the water stored on 1st of January of the first year for the three selected wet and dry years are given. Table 5.6b however, gives the percentages of the water balance components for the three wet and three dry years.

For each landscape, the three year totals in Table 5.6 are examined in the following sections to identify the effect of conceptual model features such as the depth of the weathered zones, the groundwater outflow which is represented by the drain set up in the WaSim model, the rooting depth etc. Detail responses with time such as the daily rainfall event and the consequent runoff and other processes are analysed.

Table 5.6a: Water balance components for three wet and three dry years for each of the landscape units

No	**Conceptual Landscape**	**Totals for Wet Years (1992 – 1994)**					**Totals for Dry Years (2003 – 2005)**				
		Rain (mm)	**Runoff (mm)**	**AET (mm)**	**Groundwater discharge / Outflow (mm)**	**Change in Storage (mm)**	**Rain (mm)**	**Runoff (mm)**	**AET (mm)**	**Groundwater discharge Outflow (mm)**	**Change in storage (mm)**
1	**Town I**	4091	1348	2002	812	-72	2226	398	1781	51	-5
2	**Town II**	4091	1371	2009	783	-73	2226	398	1784	49	-5
3	**Sealed surface I**	4091	2558	1525	-	7	2226	1047	1169	-	10
4	**Sealed surface II**	4091	2558	1525	-	7	2226	1047	1169	-	10
5	**Forest I**	4091	222	3507	0.0	362	2226	6	2236	0.0	-16
6	**Forest II**	4091	258	3449	0.0	383	2226	165	2242	0.0	-30
7	**Hard rock I**	4091	1297	839	1931	24	2226	345	665	1223	-7
8	**Hard rock II**	4091	3252	839	-	-0.1	2226	1560	665	-	0
9	**Cultivated I**	4091	1074	2206	797	12	2226	241	1965	38	-8
10	**Cultivated II**	5554*	1779	2431	1193	143	2927*	263	2506	251	-88
11	**Cultivated III**	4091	1063	2193	822	12	2226	240	1961	43	-8
12	**Cultivated IV**	5554*	1718	2419	1259	144	2927*	260	2505	2565	-88
13	**Fadama**	9668*	4095	3519	1877	144	4115*	182	3439	552	-46

*** includes run-on**

Table 5.6 (b): Water balance components as percentages for three wet and three dry years

Conceptual Landscape	Wet Years (1992 – 1994)				Dry Years (2003 – 2005)			
	Runoff (%)	**AET (%)**	**Groundwater discharge / Outflow (%)**	**Change in Storage (%)**	**Runoff (%)**	**AET (%)**	**Groundwater discharge / Outflow (%)**	**Change in Storage (%)**
Town I	33.0	49	20	-2	18	80	2	-0.2
Town II	33.5	49	19	-2	18	80	2	-0.2
Sealed surface I	63	37	-	0.2	47	53	-	0.4
Sealed surface II	63	37	-	0.2	47	55	-	0.4
Forest I	5	86	-	8	0.3	101	-	-1
Forest II	6	84	-	9	1	101	-	-1
Fractured Hard rock I	32	21	47	1	16	30	55	-0.3
Non- fractured Hard rock II	80	21	-	-0.0	70	30	-	0
Cultivated I	26	54	20	0.3	11	88	2	-1
Cultivated II	32	44	22	3	9	86	9	-4
Cultivated III	25	54	20	0.3	11	88	2	-1
Cultivated IV	31	44	23	3	9	86	9	-4
Fadama	42	36	19	2	4	86	13	-3

5.3.1. Towns Landscape

The most important hydrological processes in the town landscape as described in section 4.1 are runoff, evapotranspiration, groundwater outflow and abstraction. The difference between town I and II landscapes is the soil depth and rate of abstraction (Table 5.3). In town I, the soil depth is moderate (3 m) and the rate of abstraction is set at 0.05 mm/d. An examination of the detailed WaSim output shows that the water table is absent in the dry season which represent a realistic condition in the area, because the dug wells became dry during some part of the year. In town II however, the soil is deep (10 m) and abstraction is put at 0.1 mm/d due to the presence of water table throughout the year in the dug wells.

For the town landscapes, the results are presented in Table 5.6 (a & b) and 3 set of graphs Figure 5.2 - Figure 5.4)

Figure 5.2 - Figure 5.4 presents the graphs in different colours such as daily rainfall (blue), runoff (red), AET (green), ETo (light blue), groundwater outflow (purple) and water table depth (orange) for the town landscapes during the wet and dry years. The same colours will be used in all similar graphs presented in this chapter.

The major observations in town landscapes are:

- There is little difference in the water balance results between the two town landscapes for the wet years (Figure 5.2a & Figure 5.3a) and for the dry years (Figure 5.2b & Figure 5.3b); most of the following discussion is therefore, applicable to both landscapes.

- The water loss through runoff for both town landscapes I and II during the three wet years is about 33 % of the rainfall (Table 5.6b).

- In the three dry years, the water loss due to runoff is only 18 % in the two town landscapes (Table 5.6b) occurring mostly when there are high rainfall events.

- Apart from 6th September 2003, runoff is below 20 mm/d throughout the dry years; see Figure 5.2 & Figure 5.3b. However, in the wet years there are many days when runoff is over 20 mm/d, see Figure 5.2 & Figure 5.3a.

- The AET is even higher than runoff in the wet years equalling about 49 % of the rainfall.

- The AET in dry years is however higher than runoff (Table 5.6a), taking about 80 % of total rainfall.

- In Figure 5.2 (a), runoff occurs as a consequence of each rainfall events in the wet years, but when there are 7 or more days without rainfall, very small or no runoff is produced when rainfall resumes.

- The low infiltration of the shallow soil zone on this landscape leads to substantial runoff generated during periods of intense rainfall or in peak rainy season when the soil moisture is high and the water table is close to the surface (Figure 5.4).

- The groundwater outflow indicated in Figure 5.2 & Figure 5.3 for the three wet years, for both shallow and deep weathered zones also have similar results, representing about 20 % and 19 % respectively. The outflow in dry years is however very low, having just about 2. % each for the shallow and deep zones (Table 5.6b).

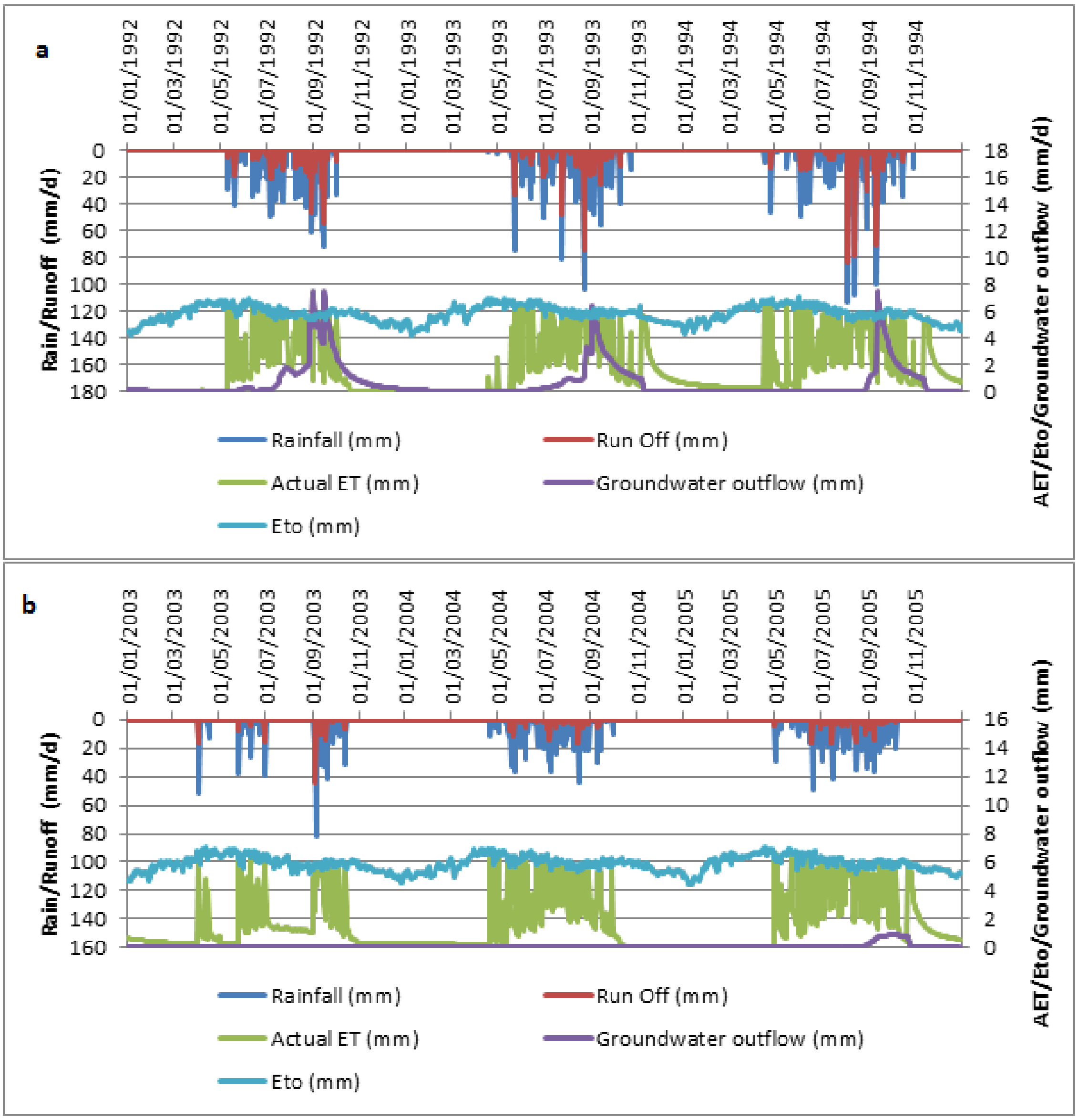


Figure 5.2: Daily rainfall, runoff, AET and ETo for Town I LUs in the wet and low rainfall years

In Figure 5.2 (a & b), any rainfall above 30 mm/d produces simulated runoff even in the early rainy season. This is consistent with the nature of the surfaces in town landscape (such as roofs, tarred and paved surfaces) represented in the model set up by the curve number which produces much runoff due to limited infiltration.

In dry years however, runoff also occurs typically after any rainfall above 30 mm/day. In the middle and towards the end of the rainy season when the soil moisture deficit is very low, rainfall events below 10 mm/d produce some runoff as seen in Figure 5.3 (a & b). This rarely occurs in the early rainy season due to high soil moisture deficit.

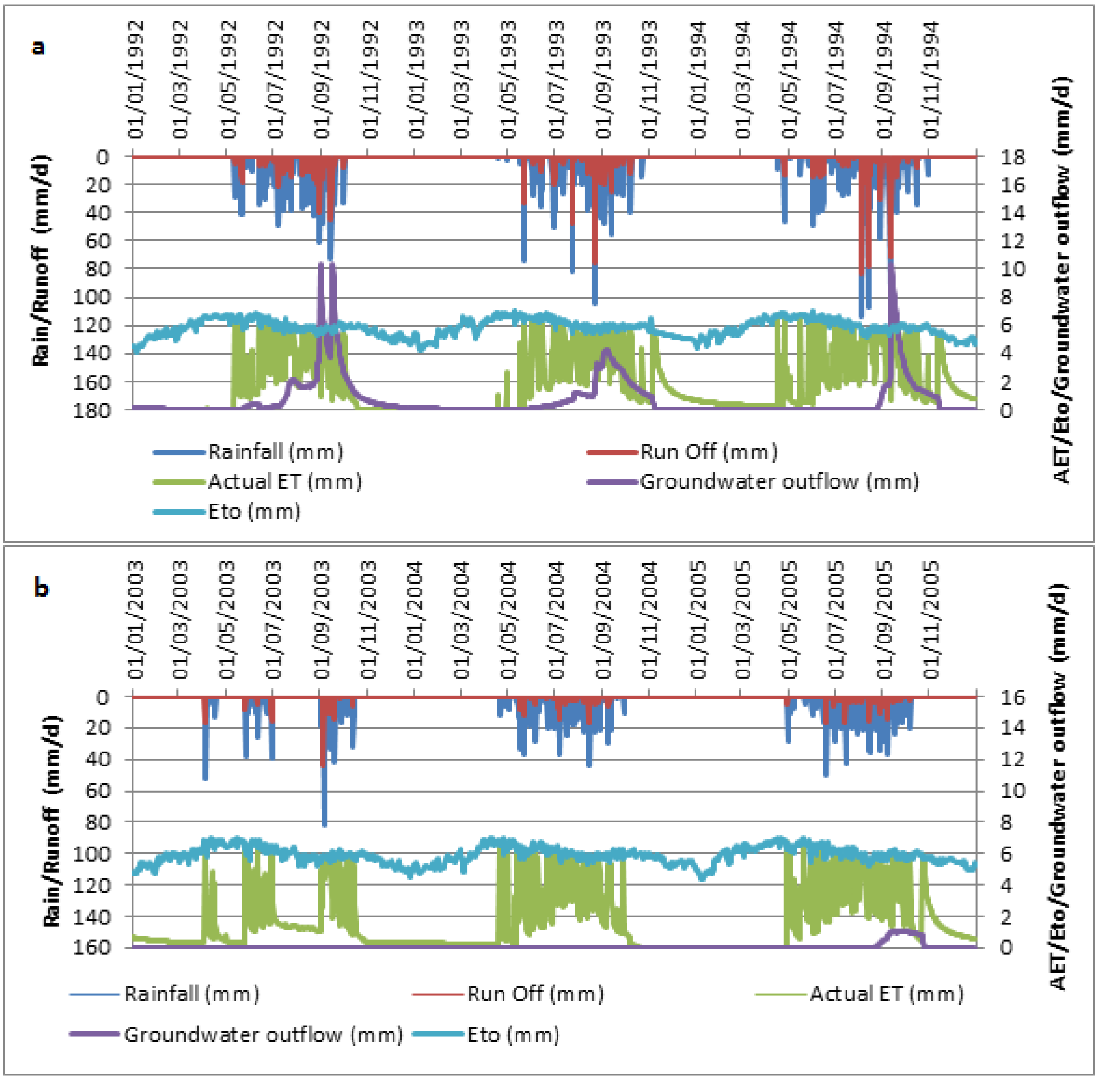


Figure 5.3: Daily rainfall, runoff, AET and ETo for Town II LUs in the wet and low rainfall years

The runoff in the deep weathered zone in all the Figure 5.2 & Figure 5.3 presented in this section slightly differs to the shallow weathered areas as seen in the results of Table 5.6. The runoff for the two town surfaces in WaSim is calculated using the SCS curve number method and the antecedent soil moisture condition. Because they have the same surface characteristics, this result in similar amounts of runoff generated.

Both the shallow and deep weathered zones have the same type of vegetation (small grasses) with the same percentage surface cover. The maximum root depth for the grass is 1.0 m; meaning that the rate of water extraction is the same for the shallow and deep zones. The maximum depth to the impermeable layer is 6 m for the shallow zone and 10 m for the deep weathered zones (Table 5.3) which did not exceed the maximum root depth in all the landscapes. This also resulted in similar amount of AET for the two town landscape areas.

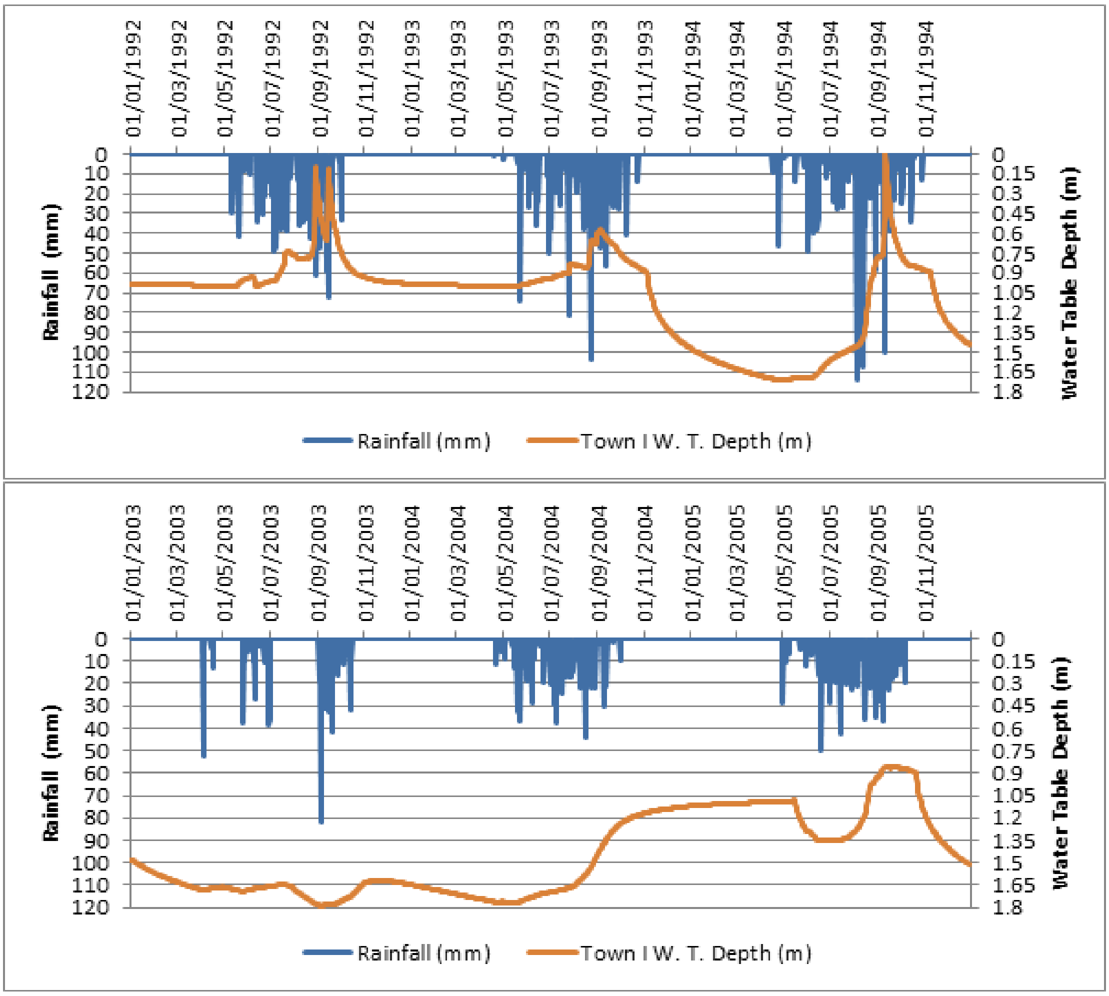


Figure 5.4: Daily rainfall and water table depth for Town I landscape in the wet and low rainfall years

The difference in the weathered zone depths and height of the water table may also be the reason for the slight variations in the groundwater outflow for both the shallow and deep weathered areas as shown in Table 5.6a. The WaSim model only gives a response of an average water table decline and therefore cannot represent the cone of depression for an individual pumped well.

5.3.2. Sealed surface landscape

This section observes the differences in hydrological processes between the two sealed surfaces conceptually developed as shown in Figure 4.6. The discussion is centred on the variations of output (such as runoff and AET) for the shallow and deep weathered areas of the sealed surfaces. The reasons for the variations are also explored and assessments given based on the resultant outputs.

The hydrological behaviour of the sealed surfaces is quite different from other landscapes due to the crusting effect of the soil surface. Water infiltration is determined by the soil seal which controls the amount of water entering the soil, resulting in higher rates of overland flow. The physical feature that affects infiltration for this landscape is assumed to occur at the soil surface in the form of a thin surface seal. Other processes such as compaction and washing-in of sediment may further reduce conductivity below the seal. This research however, acknowledges the possibility that, with sediment movement and surface seal formation, physical changes may occur below the thin surface layer.

The parameters used for this landscape are given in Table 5.3. Surface runoff is the dominant process for the sealed surfaces and evaporation is mainly from the bare soil surface due to the dearth of vegetation. The high runoff is achieved in WaSim by using a high curve number of 94 (the towns and cultivated lands are less than 80) which is higher (Table 5.3) than all the landscapes (except the non- fractured hard rock which was estimated using a different approach).

From the Table 5.6, in the wet years runoff is very high due to the high curve number. Apart from the hard rocks, it has the lowest value of AET because so much water runs off. In dry years, the runoff is more than double other landscape values and the AET is lowest apart from the hard rocks. The bare soil evaporation calculated from the method of Ritchie, 1972 (section 5.1 in the WaSim technical manual) does not appear to take account of the three stages in the soil evaporation process. The processes are an initial constant rate, an intermediate falling rate and effectively no evaporation when the total evaporable water has been lost (Rushton, 2003). As a result, the sealed surfaces I and II (shallow and deep weathered zones) produce identical results because they have the same curve number and the same equations for evaporation.

The diagrams Figure 5.5 and Figure 5.6 for both the wet and dry years indicate that almost all rainfall events above 3 mm produce runoff usually in the middle and towards the end of the rainy season when the soil moisture is higher. In the early rainy season however, because of the high soil moisture deficit, only rainfall above 5 mm can initiate runoff.

Figure 5.5a show that the runoff is much higher in the wet years especially during the peak rainy season than in the dry rainfall years in Figure 5.5b because of lower rainfall.

Depending on the soil moisture condition, about 60-70 % of the rainfall usually goes to runoff on the sealed surfaces as shown by the graphs in Figure 5.5a & Figure 5.6a. The runoff generated is therefore significantly higher even during the dry years than other landscapes.

As the bare soil evaporation is controlled by both the ETo and the short term availability of water from rainfall events, the AET is usually higher than runoff if the rainfall is small.

The results in Table 5.6 for the wet years show that runoff is about 63 % of the total rainfall and AET is 37 %; while, in the dry years runoff is about 47 % and AET is 53 % of total rainfall. Of the total rainfall (4090 mm) for the three wet years (1992-1994) shown in Figure 5.5a & Figure 5.6a, about 2558 mm is runoff while 1525 mm is AET.

Actual evapotranspiration always occur when there is rainfall or for the short period after when there is elevated moisture in the topsoil. Limited infiltration of water in this landscape leads to high soil moisture deficit in the soil. In low rainfall years, a significant part of the rainfall is lost through runoff (Figure 5.5b & Figure 5.6b), and the AET only occur during and immediately after rainfall and not long afterwards.

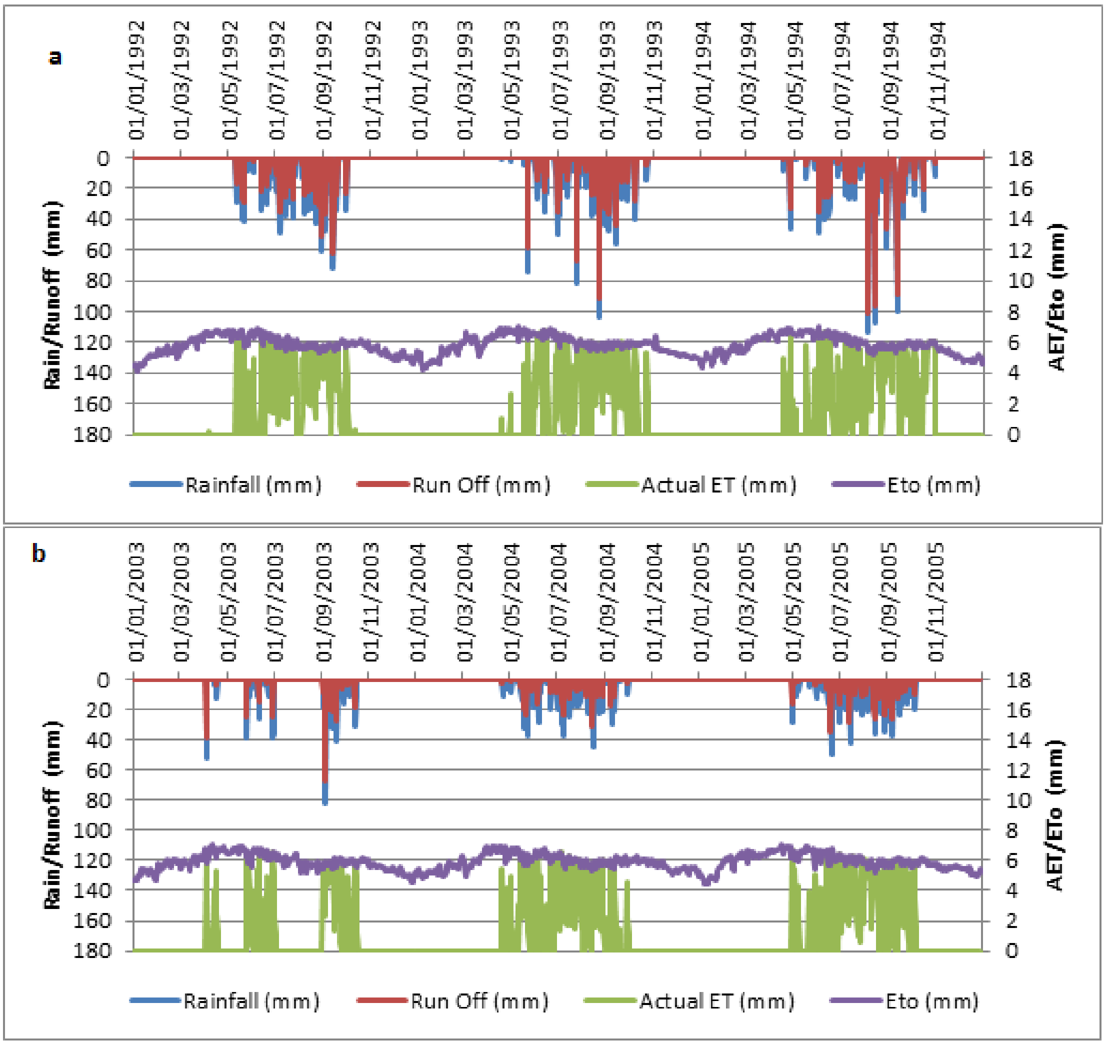


Figure 5.5: Daily rainfall, runoff, AET and ETo for sealed surface I landscape in the wet and low rainfall years

The total rainfall is about 2226 mm for the three low rainfall years (2003-2005) in Figure 5.5b & Figure 5.6b, runoff and AET is 1047 mm and 1169 mm respectively. This leaves only about 7 mm and 10 mm for the three wet years and three low rainfall years as change in soil moisture storage on these landscapes.

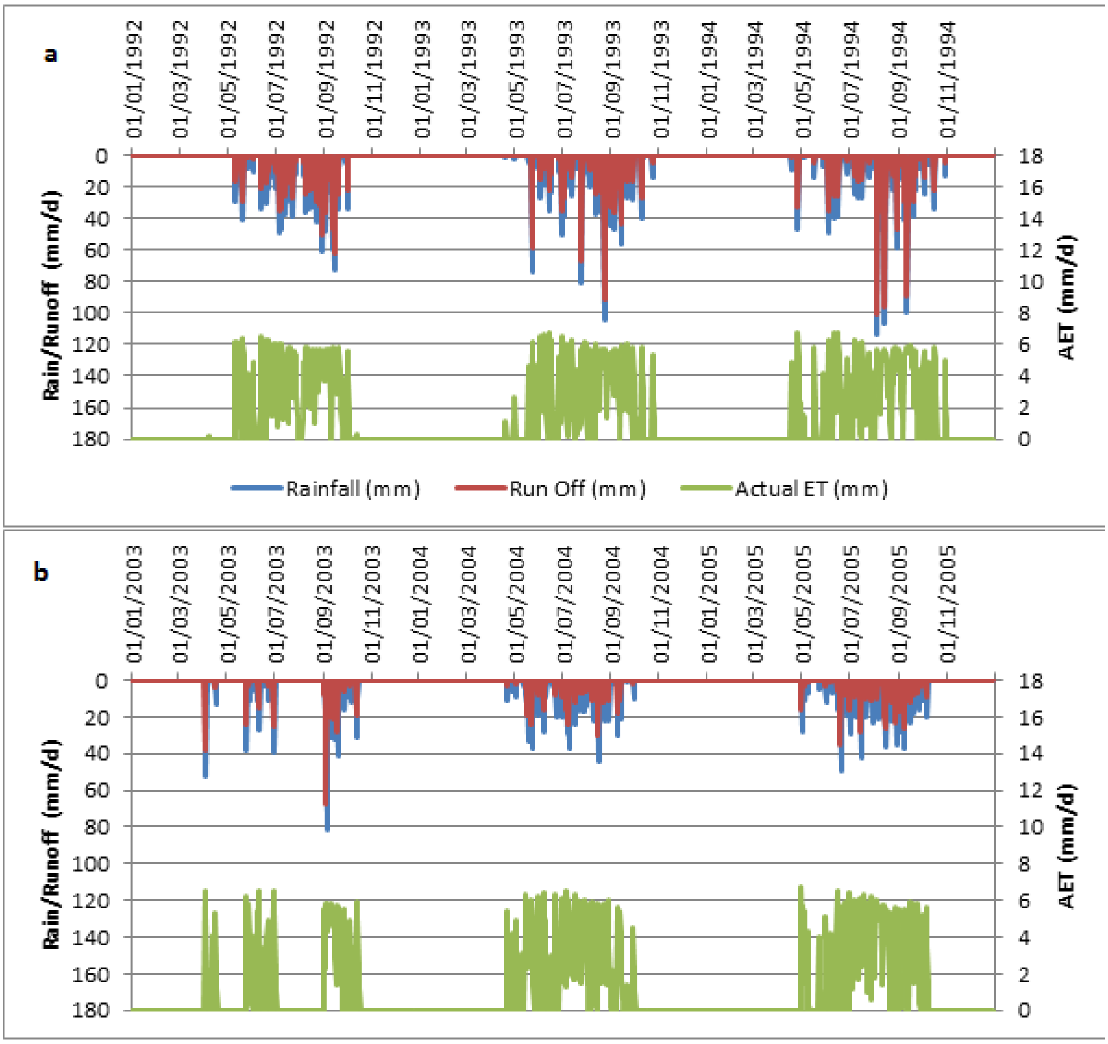


Figure 5.6: Daily rainfall, runoff, AET and ETo for sealed surface II landscape in the wet and low rainfall years

5.3.3. Cultivated Landscapes

The cultivated lands are divided into four modelling units as described in chapter four and they behave differently from one another in terms of the scale and magnitude of hydrological responses after rainfall. The discussion of this section will focus on the differences in hydrological processes between areas with and without additional run-on and the variations of processes in deep and shallow weathered zones.

The rainfall input to the cultivated lands II and IV that is shown in Table 5.6 is the sum of actual rainfall and the run-on received from the hard rock II. The total runoff from the water balance on the cultivated lands II & IV receiving run-on form hard rock is higher than cultivated I and III that does not receive any run-on.

Runoff from the cultivated landscapes is generally lower than for the towns and sealed surfaces discussed earlier in this section, because the runoff curve number used is lower and consequently the water infiltration into the soil is higher. Groundwater outflow (Drain flow) is also higher in the wet years such as in Figure 5.7 (a-b) and in areas receiving run-on such as in Figure 5.8 (a-b) usually occurring after heavy rainfall. Some groundwater outflow occurs (approx. 1 mm/d) if there are a series of rainfall events even in dry rainfall years such as 2004 and 2005 in Figure 5.8 (a-b) and Figure 5.10 (a-b). The observations from Table 5.6 for the cultivated landscapes are summarised below:

- Runoff on Cult I & III represent about 26 % of the total rainfall while AET is about 54 % and drain flow is about 20 % in the wet years (Table 5.6b).

- Runoff for Cult II & IV represents about 32 % of rainfall plus run-on, while AET is about 44 % and groundwater outflow is about 23 % for the wet years.

- In dry years for cult I & III, the water loss is mainly from AET representing about 88 %, while, runoff and drain flow accounts for only about 11 % and 2 %.

- For cult II & IV dry years, the water loss through AET is about 86 %, while runoff and drain flow both represent only about 9 % of the total rainfall with about 3 % provided by soil storage.

- Even though the differences in runoff and AET between Cult II and Cult IV are small in the wet years, it can be seen in Table 5.6 that the amount of runoff generated in Cult II is more than in Cult IV. This arises because the smaller storage capacity in Cult II allows the profile to become saturated.

- The groundwater outflow however is higher in cult IV due to the greater depth and high storage capacity than in cult II with shallow depth of the weathered material. Similar observation is also made between the shallow (Cult I) and deep (Cult III) weathered zones (Table 5.6).

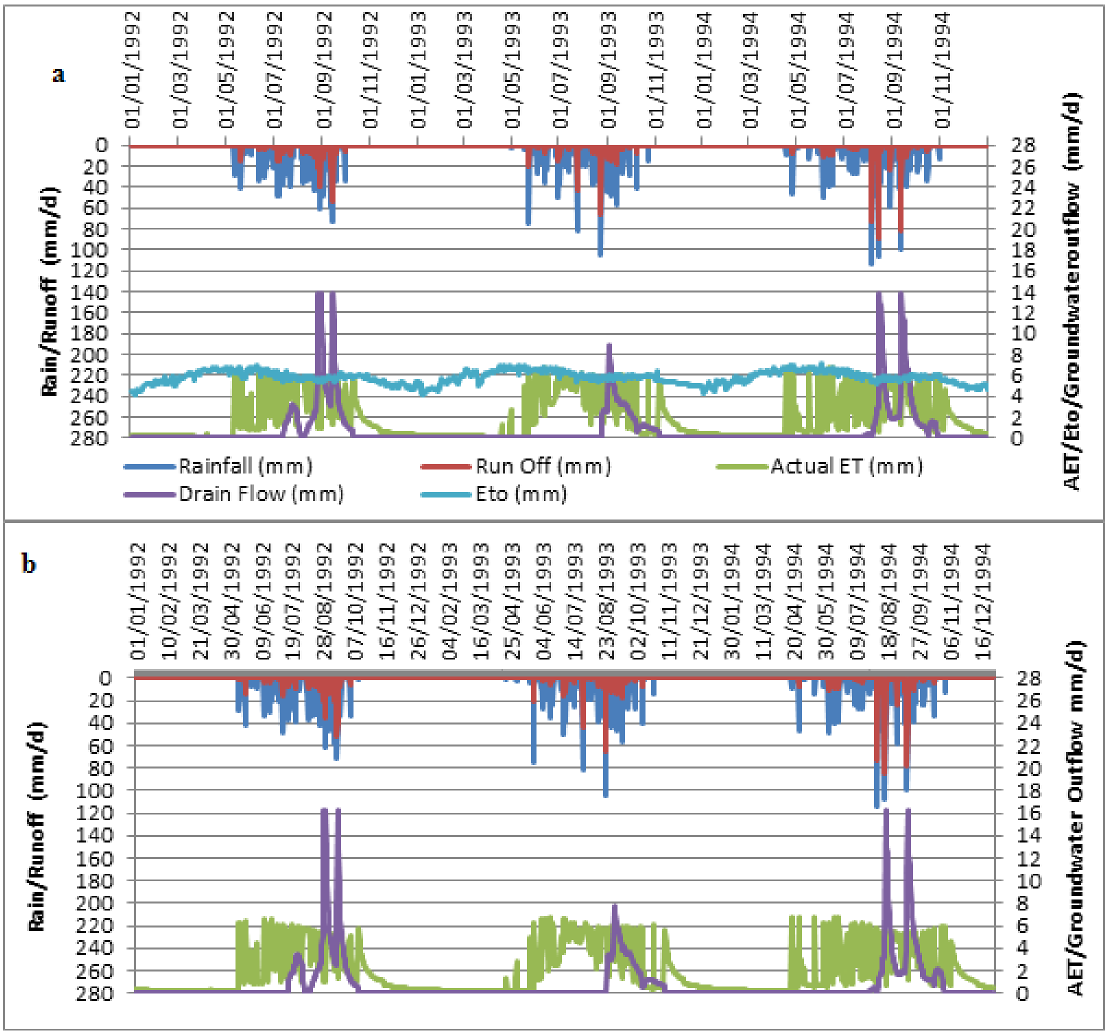


Figure 5.7: Daily rainfall, Runoff, AET, Groundwater outflow (Drain flow) and ETo for Cultivated landscape I and III without additional run-on in the wet years

In dry rainfall years, the soil only becomes saturated for short periods and a small amount of runoff and groundwater outflow occurs unless the rainfall intensity is high enough to allow for infiltration excess runoff as shown in Figure 5.8 and Figure 5.10.

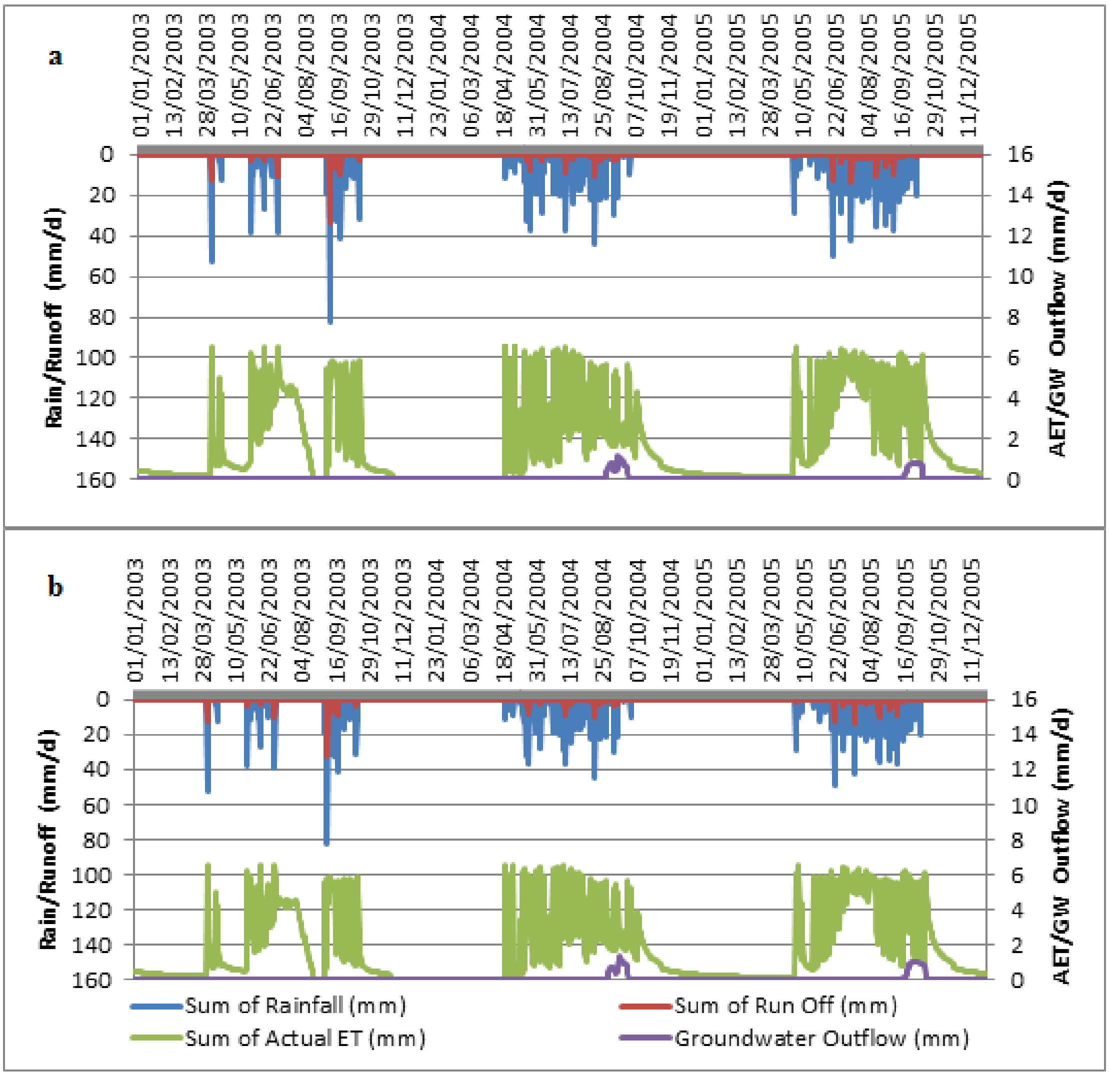


Figure 5.8: Runoff, AET and Groundwater outflow (Drain flow) for cult I & III during the low rainfall years

Figure 5.9 & Figure 5.10 refer to cult II and IV where run-on occurs. The total runoff sometimes has same order of magnitude with the total rainfall + run-on input; this indicates that the soil moisture deficit is zero on that particular day and all the input equals output. Example of this is shown in Figure 5.9 (a-b) on the 30th August 1992 and the 11th of September 1994 with total rain + run-on of 86.6 mm and 142.6 mm respectively. The corresponding runoff is the same totals with the rainfall-run-on input and AET on those days equals zero. The drain flow occurs from deeper soil zone.

The annual AET is higher in the cultivated landscapes that receive run-on from hard rocks because of higher moisture availability in the soil especially in 1993 (Figure 5.9). This is expected because in reality, the vegetation and crops grown on these areas is always greener and higher yielding compared to areas not receiving any additional run-on.

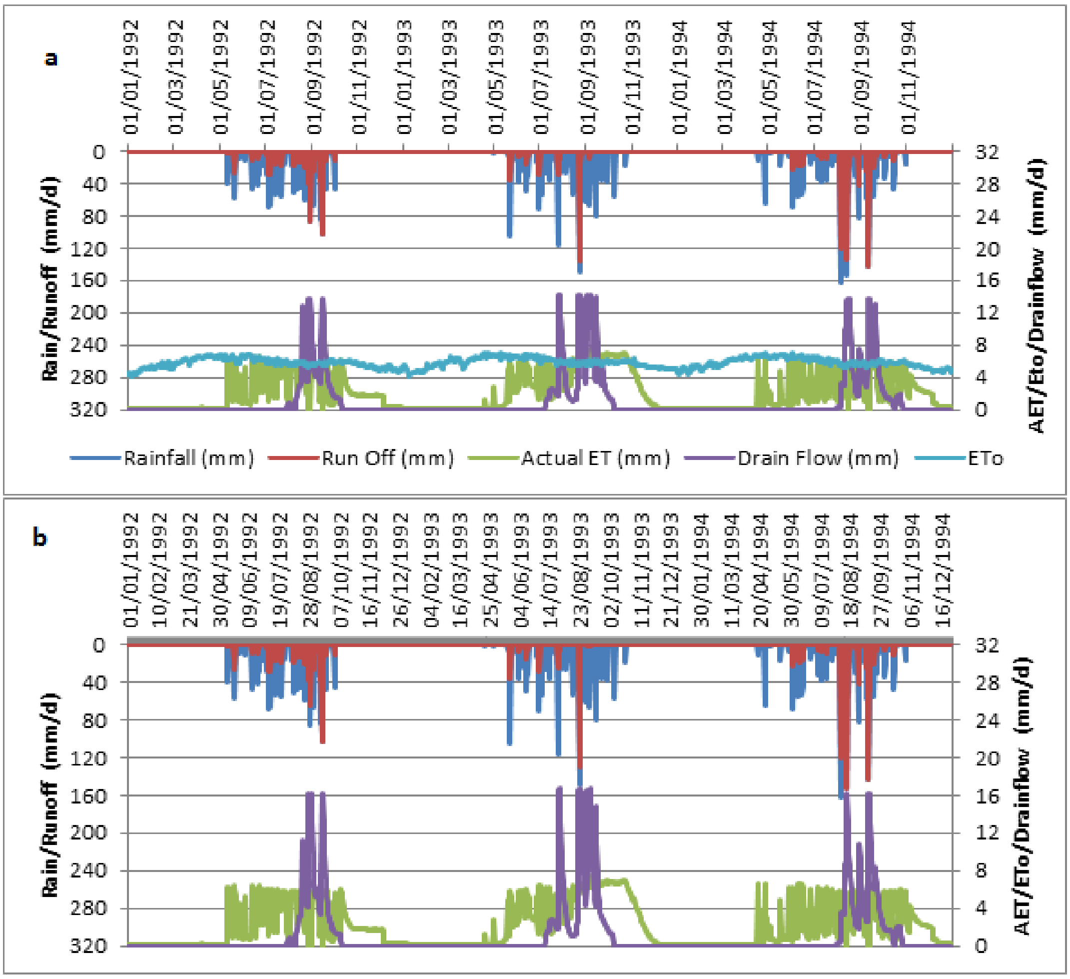


Figure 5.9: Runoff, AET and drain flow for cult II & IV with additional run-on in the wet years

A detailed analysis of the WaSim output shows that during the peak rainy season, simulated ponding occurs in the cultivated lands receiving additional run-on, and open water evaporation instead of AET occurs.

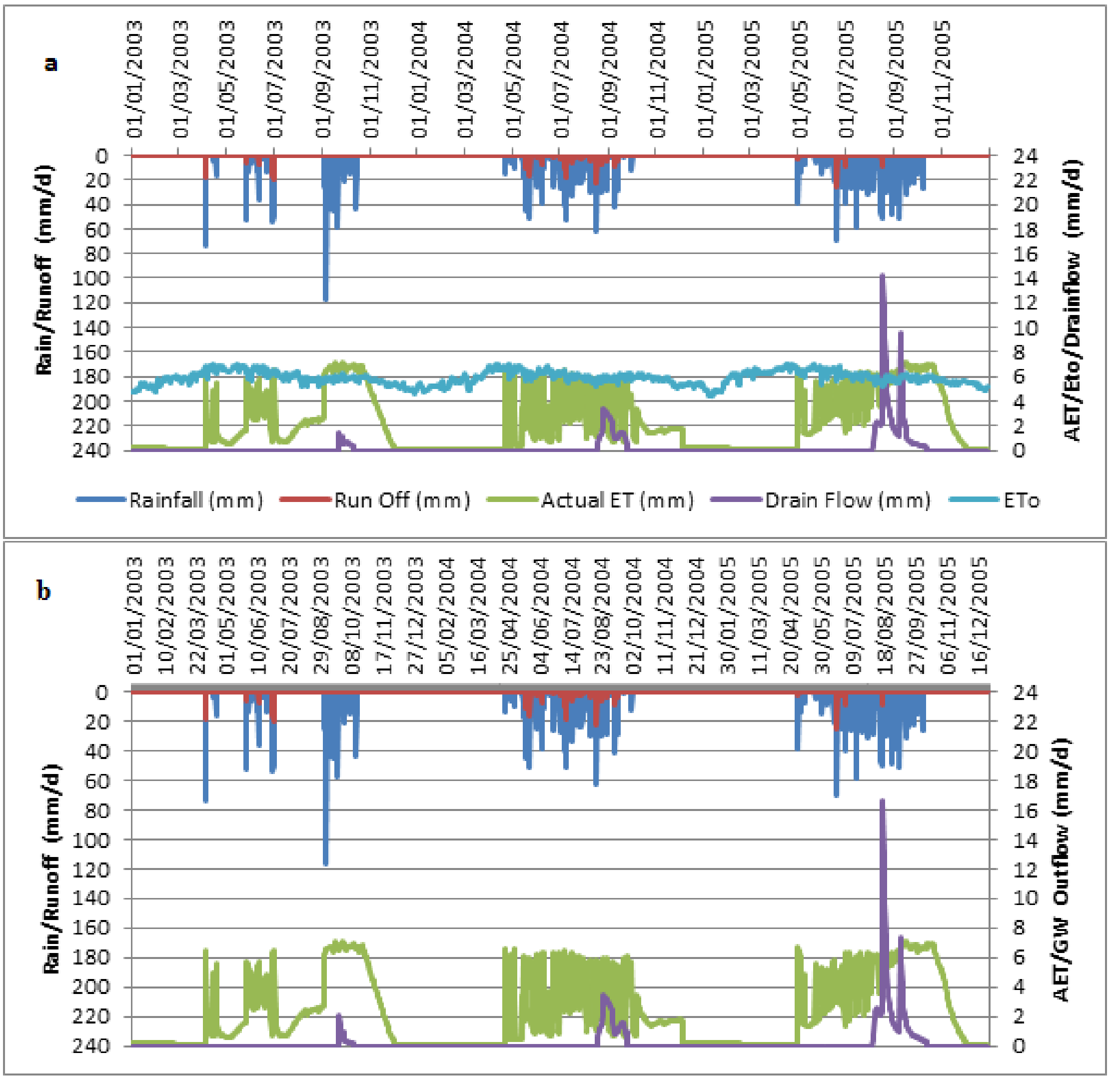


Figure 5.10: Runoff, AET and Groundwater Outflow for cult II & IV with additional run-on in the low rainfall years

5.3.4. Forest landscapes

This section examines the water loss in the forest landscape mainly dominated by evapotranspiration and the small variability between the shallow and deep weathered areas. The behaviour of the forest is assessed and the differences between the wet and dry rainfall years explored.

The parameters used to represent the forest landscape in the study area are given in Table 5.3. There is uncertainty in the representation of the vegetation in the forest CM because of the temporal variability in vegetation cover observed during the year, both with regard to the ground vegetation and the tree canopy. Trees and shrubs are the dominant plants in the forest landscape, but in the rainy season there is abundant grass covering the remaining patches of the forest and increasing the vegetation canopy from about 40 – 50 % in the dry season to 80 or 90 % as discussed in section 4.5. Sequences of experimental runs were made by changing the maximum root depth and percentage vegetation cover to assess the model behaviour against the expectation that actual evapotranspiration during the dry season is far lower than during the wet. It was found that AET is most sensitive to the percentage vegetation cover. The initial simulation condition (planting date) in WaSim considered for the forest landscapes is the 1st of January.

In Figure 5.11, the vegetation cover in the shallow weathered zone conceptual model (A) reaches upto 80 % in the rainy season because the plants are dominated by medium trees, shrubs and lots of grasses in the lower layer giving it substantial bushy cover compared to the deep weathered zone (B) with maximum vegetation cover of 70 % dominated by tall trees without much lower layer cover as described by Ajayi et al. (1981), Muazu (2010) and Eyre (2013).

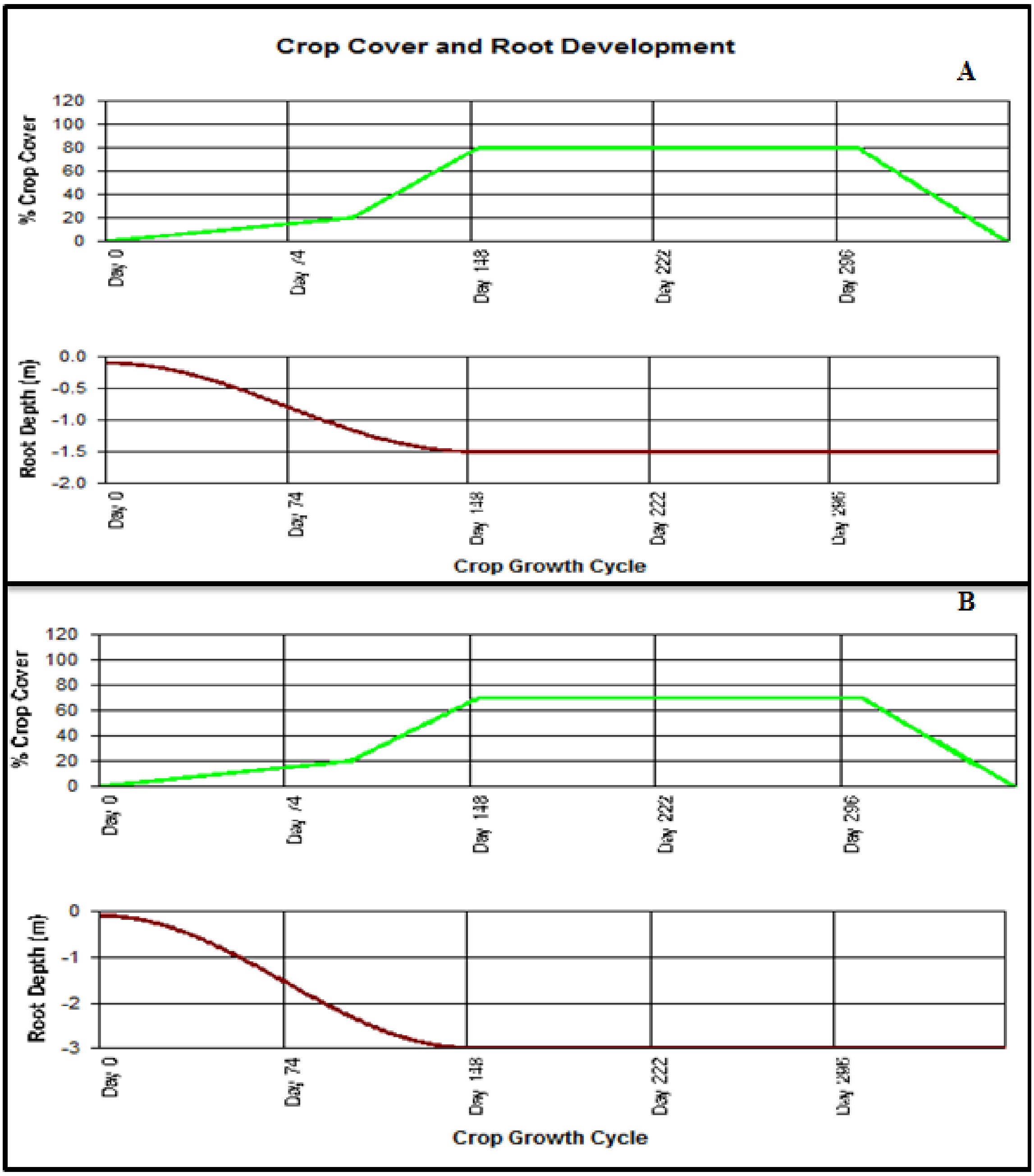


Figure 5.11: The percentage annual vegetation cover and root depth cycle for the (A) forest I shallow weathered zone and shallow root depth; and (B) forest II deep weathered zone and deeper root depth

Note: Day zero does not mean that there is no vegetation cover, but showing a significant reduction in vegetation cover before the commencement of the rainy season

Figure 5.12 & Figure 5.13 present the graphs of rainfall, evapotranspiration and runoff in the forest landscapes. The runoff and AET are similar for both the shallow weathered (diagrams Figure 5.12 (a) and deep weathered zones in diagram Figure 5.12 (b). The result in the figures shows that AET is high in the wet season and low during the four months of the dry season every year due to the low water fraction in the soil. Sometimes early onset or extended rainfall to late September or early October makes the AET for that year to be higher than during the normal years when rainfall stops early by mid-September. The water table in most of the years is below the root zone and therefore no groundwater outflow is obtained in all the years.

Little surface runoff occurs for most of the years, but during individual high rainfall events, small runoff events occurs. The graphs for forest I and II shown in Figure 5.12 (a & b) indicate that small amount of surface runoff (< 0.5 % of rainfall) is produced in the forest even in the wet years (1992-1994). Most of the runoff produced in Figure 5.12 (a & b) is after very large rainfall events usually above 100 mm/d. Some runoff also occurs when there are consecutive days of rainfall above 60 mm/d. The runoff occurrence is typically higher from the middle and towards the end of the rainy season when the soil moisture deficit is low.

The runoff for both the shallow and the deep weathered zones during the wet years is similar due to similarities in surface condition. In the deep weathered zone the runoff is 6.2 % of total rainfall compared to 5.4 % of the shallow zone. The slight difference is due to the abundant grass cover on the surface layer in the shallow zone which dries out the soil leading to reduced curve number and runoff.

There is some interesting dry season AET behaviour; after dropping down to zero, the AET slowly increases until the rains arrive. This is because the vegetation cover starts increasing in the model from planting date set in the WaSim model.

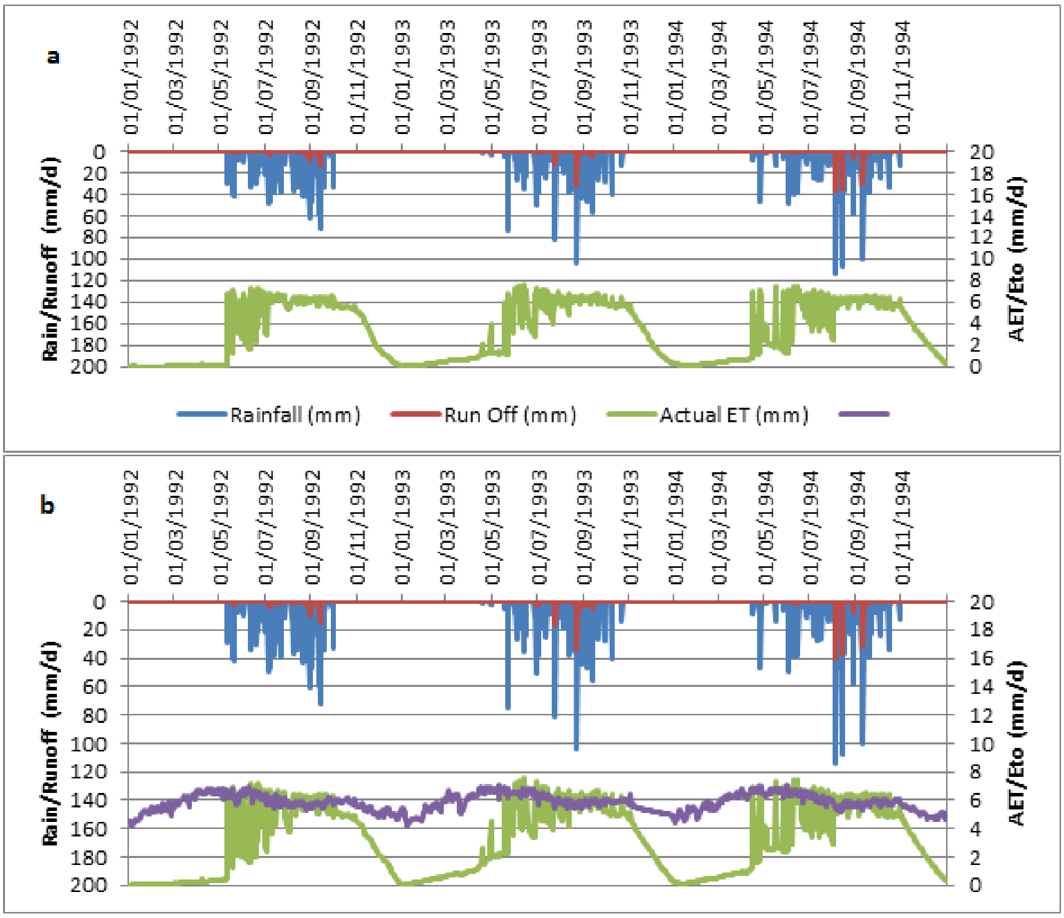


Figure 5.12: Daily rainfall, runoff, AET and ETo in the wet years for (a) forest I and (b) forest II landscapes

The AET in the wet years is also similar for the shallow and deep weathered areas with 85.7 % and 84.3 % in that order. The slight difference in the percentage vegetation cover given in Table 5.3 account for the small variation in the AET for the two zones under sufficient moisture condition. About 8.8 % and 9.4 % of the total rainfall is due to changes in storage for the shallow and deep areas. The storage is slightly higher in the deep zone because of greater weathered zone of 7 m compared to only 3 m depth in the shallow zone.

There is little surface runoff in dry years like 2003 and 2004 as shown in Figure 5.13 (a-b). When runoff occurs, it is very small. The total runoff for the three dry years given in Table 5.6b represents only about 0.3 % and 0.7 % of the total rainfall for the shallow and deep weathered areas respectively. The AET however is marginally higher than the total rainfall for those years; the water stored in the soil provides the additional water needed for AET (See Table 5.6). The AET is very low during the dry season as shown by the drop in the AET graphs in all the figures, indicating a significant reduction in the vegetation cover and high soil moisture stress. The AET and the soil water deficit is slightly higher in the deep weathered zone due to the longer roots of trees extracting water from deep soil storage up to 3 m or more.

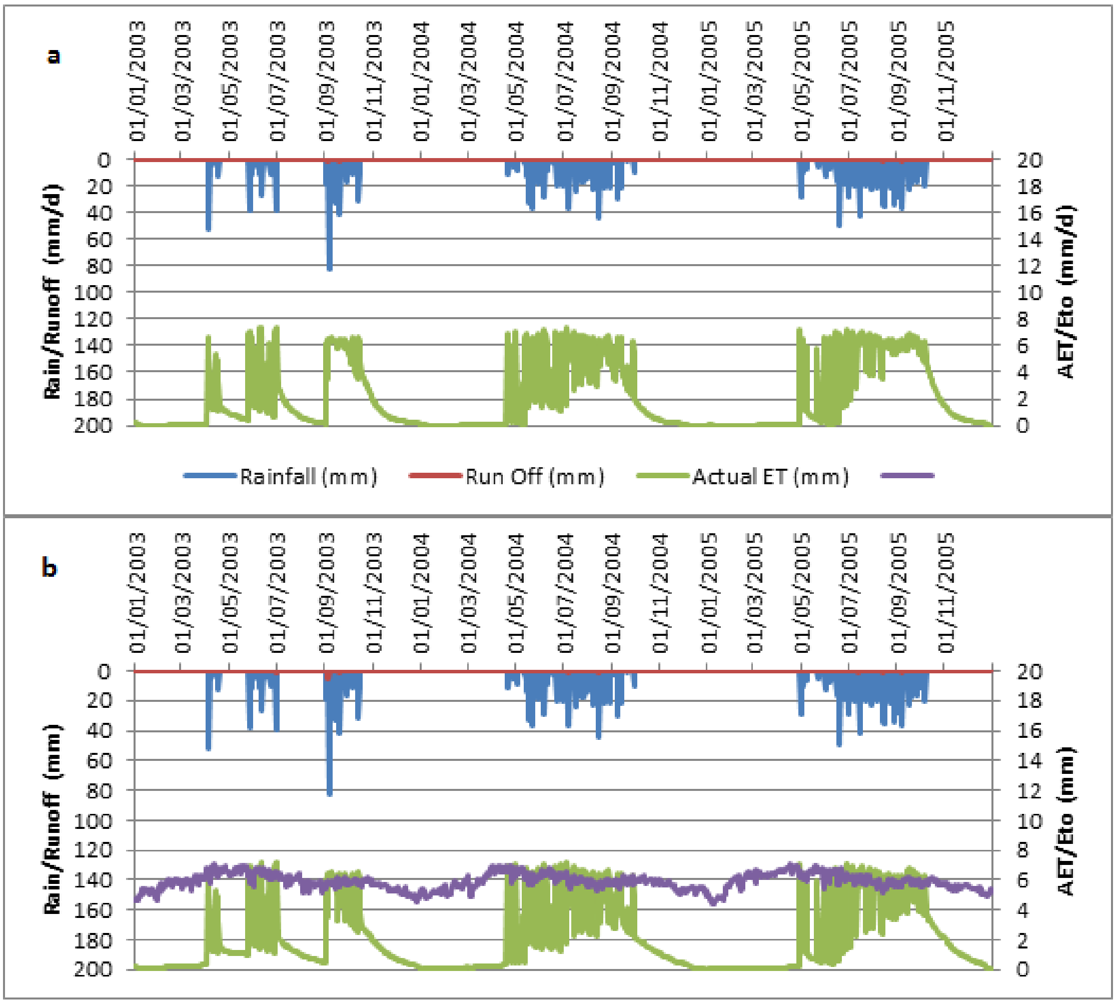


Figure 5.13: Daily rainfall, runoff, AET and ETo for forest I and II landscape in the dry years

The AET in dry rainfall years occurs at reduced rate due to insufficient moisture, and usually all the water is transpired back to the atmosphere after rainfall. The total AET for the three dry rainfall years is 100.5 % and 100.7 % of rainfall for the shallow and deep weathered zones, with a reduction in storage of -0.8 % and -1.4 % respectively.

5.3.5. Fadama landscape

The fadama landscape has more complex hydrological processes due to run-on received from different landscapes within the catchment. The parameters used in the simulation for the fadama are given in Table 5.3. The soil is a clay loam and is usually saturated for most of the rainy season as described in section 2.5. The runoff curve number used for this landscape is higher soil moisture condition as a result of additional run-on input than that of the forest. The relative small land area of the fadama landscape (10 %) compared to the forest and hard rocks (20 and 25 % each) and cultivated lands (30 %) which contribute run-on to the fadama leads to the large volume of runoff and the outflow of water.

Groundwater outflow and ponding occurs in the fadama, especially in high rainfall years; the drain depth, diameter and spacing represent an interaction with the river, and the maximum ponding is set as 7cm. The values used for the drain depth of 1 m, drain spacing of 25 m and diameter of 0.15 m (Table 5.3).

The results for the fadama landscape can be found in Table 5.6. The rainfall and additional input of run-on from other landscapes in the catchment results in high runoff produced in the fadama during the wet years. The high total AET for the fadama is second only to the forest areas owing to additional run-on and the fact that the crop cover in the fadama extends over a longer period due to available moisture in the soil for several months after the rainy season, and also due to irrigation in the dry season. The two crops and the grass grown in the fadama dominate the different planting cycle described in section 4.6.

Figure 5.14 (a-b) presents the daily runoff, AET and drain flow in the fadama landscape for three wet and three low rainfall years.

The results of the fadama water balance shows that AET is high when there is high rainfall in a year e.g. 1994 (Figure 5.14a), while it is lower in the dry years (Figure 5.14b) due to limited moisture for evapotranspiration to occur at potential rate.

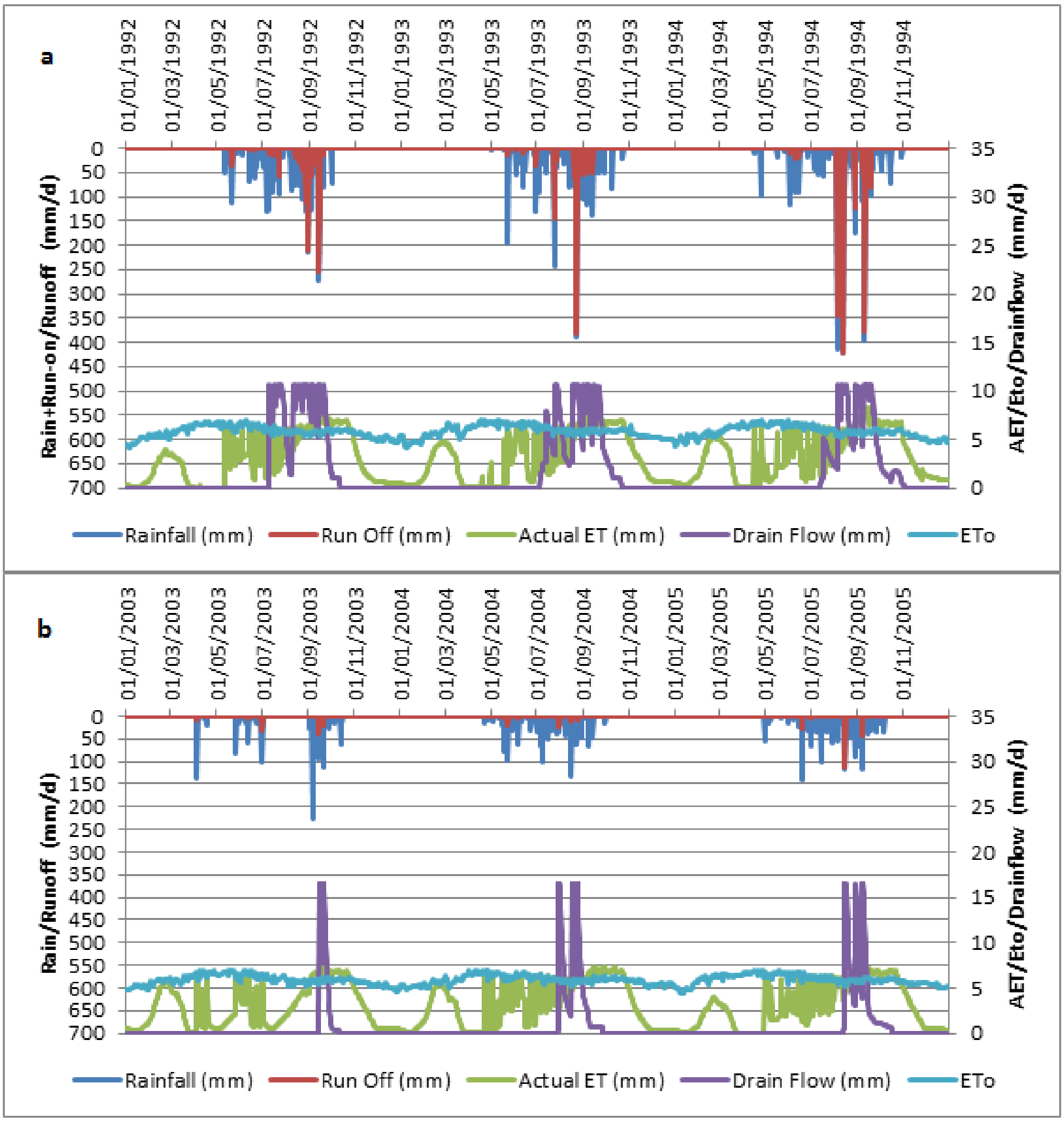


Figure 5.14: Daily rainfall, runoff, groundwater outflow, AET and ETo for fadama landscape in the wet and low rainfall years

The results given in Table 5.6 shows that the total runoff represent about 42 % of the total rainfall plus run-on received, the AET is about 36 %, while the groundwater outflow is about 19 % in the wet years (1992-94). The remaining 3 % is the change in storage.

Significant simulated runoff and groundwater outflow are found to occur typically from late August to early October even in the dry years; this corresponds to the period when ponding occurs. About 100 % of a single rainfall event can become runoff when there is ponding in the fadama (Figure 5.14a).

When the soil in the fadama is saturated, any additional rainfall input will go to runoff as seen in Figure 5.14a on 23rd August 1993 and 14th August 1994, the total rainfall + run-on input into the fadama is 810 mm, while the total runoff produced is 803 mm and; leaving only about 10 mm to AET.

In dry rainfall years however, runoff hardly occurs in the fadama (Figure 5.14b) because the additional run-on from contributing landscapes are small and all the water infiltrates into the alluvial soil in the fadama as described in section 4.6.

The runoff totals for the three dry years is only about 4 % of the rainfall + run-on, while the AET which represent the highest water loss in dry rainfall years has about 84 %, while 13 % of the total rainfall received goes to groundwater outflow (see Table 5.6).

The groundwater outflow is a function of the mid-drain water table height and occurs when the water table position is above the drain depth. The outflow is from saturated zone of the soil. Ponding occur when the water table (Figure 5.15) position comes to the surface or when there is too much run-on from other landscapes.

Figure 5.15 shows the position of the water table in the three wet years. In dry season the water table can go below 2 m.

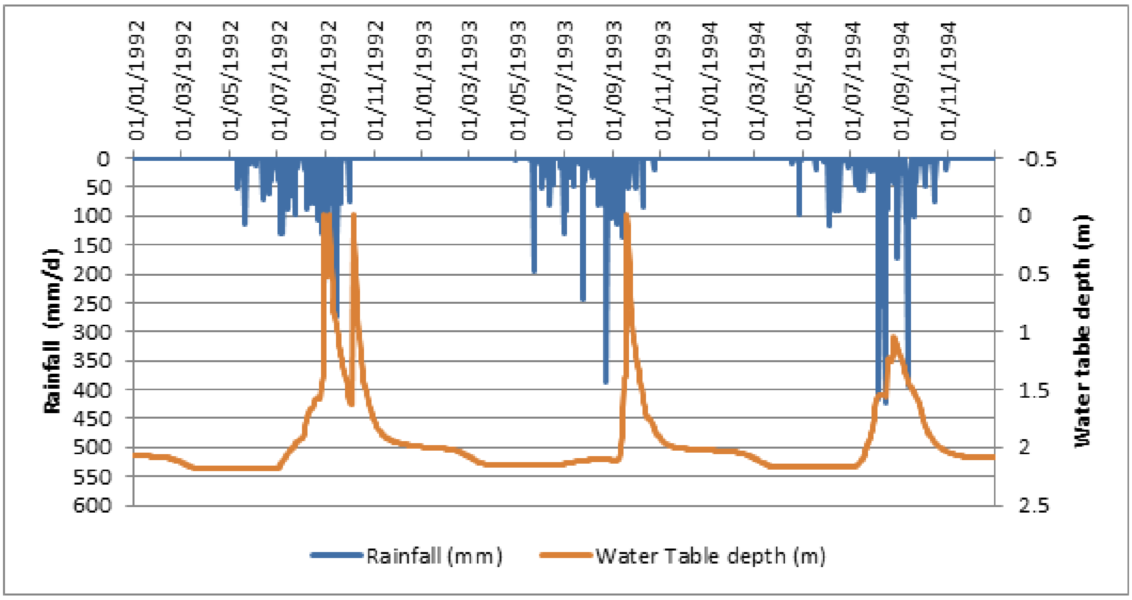


Figure 5.15: Position of the water table depth in the fadama landscape showing periods when ponding occurs in the three wet years

The water table movement shown in Figure 5.15 indicate that the response is not dependent on only rainfall occurrence, but also the density by which it occurs. In the year 1992 for example, the density of rainfall occurrence is high than remaining two years. From the 5th of August to 21st of September there are only a few breaks in rainfall; and even as such, the breaks hardly exceed 2 – 3 days. This resulted in significantly high groundwater outflow seen in Figure 5.14a. The year 1993 has similar occurrence but this time the density is just for a short period from 28th August to 29th September with more break intervals of two to three days than 1992; and the result in Figure 5.15 shows that the water table reaches the surface only once. In 1994 however because of frequent breaks between rainfall events, the water table could not reach the surface and no ponding occurs, but there are still lots of runoff and groundwater outflow due to infiltration excess.

The significant proportion of rainfall going to the groundwater outflow is not unexpected considering the large storage potential of the fadama. The water stored in addition to outflow from other landscape is what sustains the small hand dug wells used for irrigation during dry season in the fadama.

The large AET in the fadama landscape is not only due to rainy season water influx but also due to dry season water loss through evapotranspiration by dry season crops grown in the fadama e.g. tomatoes and also grass cover which is abundant throughout the landscape due to some moisture availability. The crop cover can therefore extend throughout the year due to available moisture and capillary rise from the groundwater table and presence of vegetation and plant roots extracting water and increasing water loss to evapotranspiration. Figure 5.16 shows the percentage crop cover and the root depth for the three major crops grown in the Fadama and the length of growth period when the cover is available.

The initial planting date (zero days) for each crop varies based on the sequence by which they are grown within the year. The zero day for rice which is the first crop grown in the calendar year is on the 3rd of July when rainfall has properly commenced. The initial planting (zero days) for a tomato which is the second crop is on the 4th of January which is actually in the dry season when no rainfall occurs in the region. The third vegetation is weed grass which starts on the 1st of May which is a period when rainfall did not commence properly in the region. This shows how water is continuously lost in the fadama as shown by the different AET peaks in Figure 5.16.

Rice crop has the longest growing period with about 150 days from planting to harvest followed by tomatoes with 80 days and lastly the grass with only 46 days. The grass cover graph in Figure 5.16 shows a continuous rising limb and a sudden cut without recession to indicate maturity or harvest. This is because the grass is usually weeded to prepare the land for rice planting.

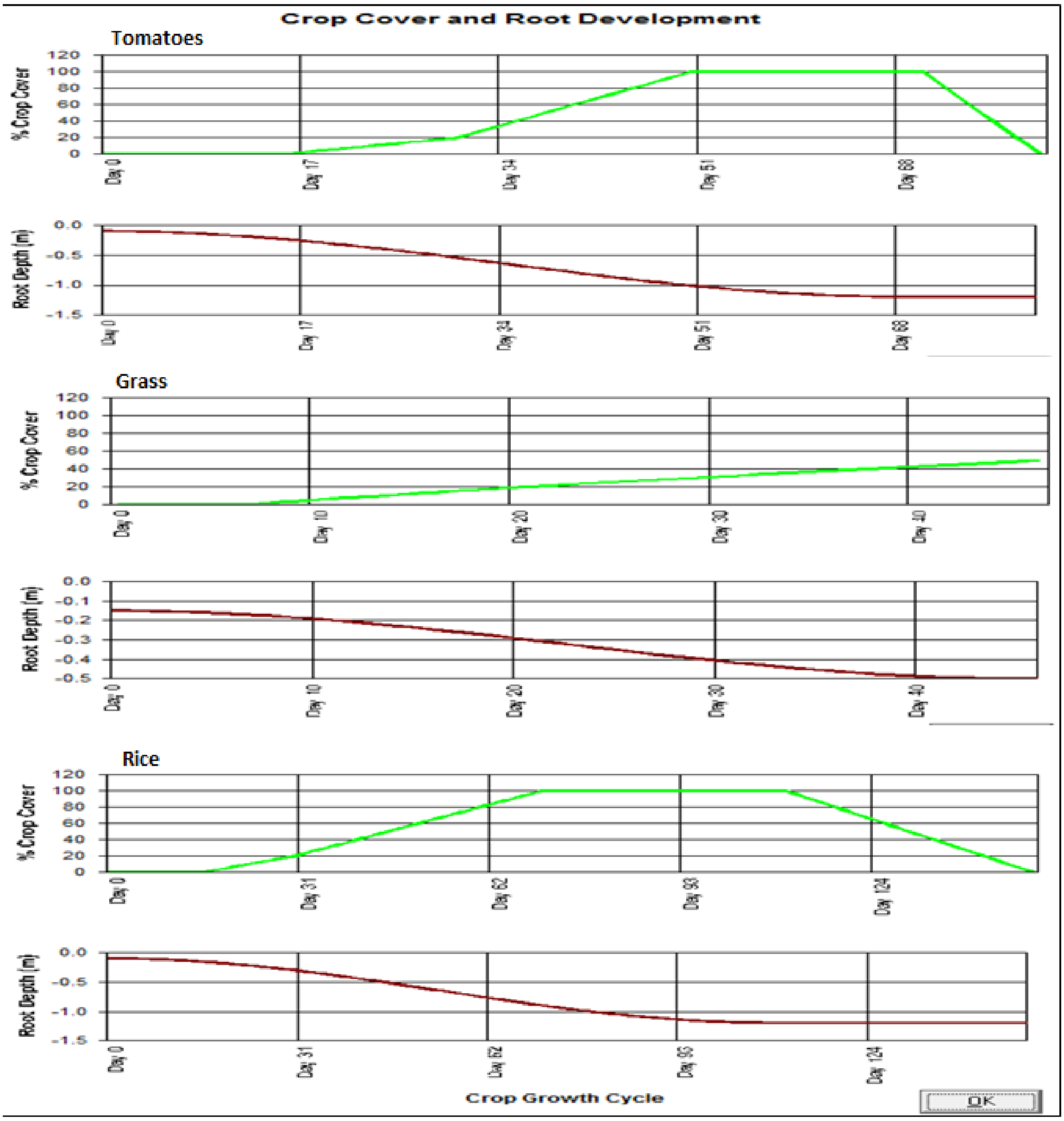


Figure 5.16: The percentage crops cover and root depths for 3 crops grown in the Fadama

5.3.6. Hard rock landscapes

As discuss earlier, the water balance for the hard rock landscape was done using a new methodology described in section 5.2. Figure 5.17 (a & b) shows the daily runoff, AE and fissure outflow from fractured hard rocks for the three wet and dry years. The totals given in Table 5.6a shows that outflow is the dominant process and represent the highest water loss on this landscape compared to runoff and AET for both wet and dry years. In Table 5.6a, the outflow from fractured rocks in the three wet years is 47.2 % of the total rainfall, the runoff is 31.7 % and the AET is about 21 % while, the remaining 0.6 % is change in storage. In the dry years, the outflow is even higher with about 55 % followed by the AET with 30% and then runoff with 15.5 %. The AET is higher than runoff in dry years due to the fact that the fissure storage hardly gets filled up to produce much runoff like in the wet years. The runoff produced for the three dry years is only about half of the AET (Table 5.6), while negetive change in storage (-0.3 %) is obtained.

In Figure 5.17 (a & b), fissure outflow starts mid-way into the rainy season, peaking around late August to September and continues sometimes up to the end of February. The outflow is high in the wet years as shown in Figure 5.17 (a) and extends far (up to 3-4 months) into the dry season. This is consistent with the actual outflow behaviour of fractured hard rocks within the catchment. The simulated outflow sometimes can reach up to 7.6 mm/d when there is high rainfall e.g. on 16th September 1992 and 22nd September 1994 in Figure 5.17a; and the outflow can also be as low as 0.1 mm/d during the dry or early rainy season such as on 11th of May 1992 and 22nd may 1993 in Figure 5.17b. The discharge from fissures in the wet years (Figure 5.17a) can reach up to 8 mm/d during the peak rainy season when the storage is over 300 mm, but decline gradually as the storage reduces. In the dry years, the fissure outflow hardly exceeds 3 mm/d due to low fissure storage of about 150 – 200 mm (Figure 5.17b).

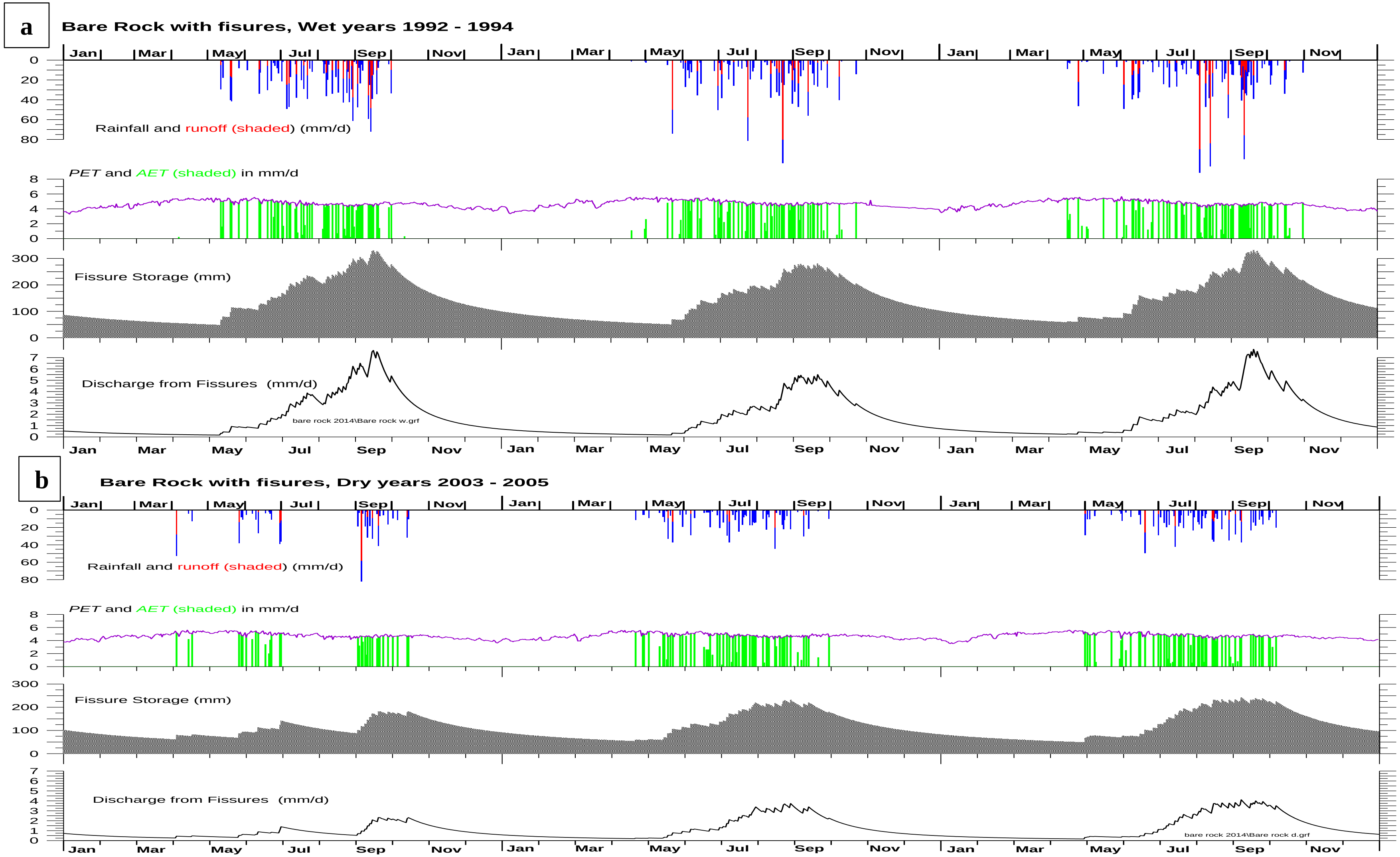
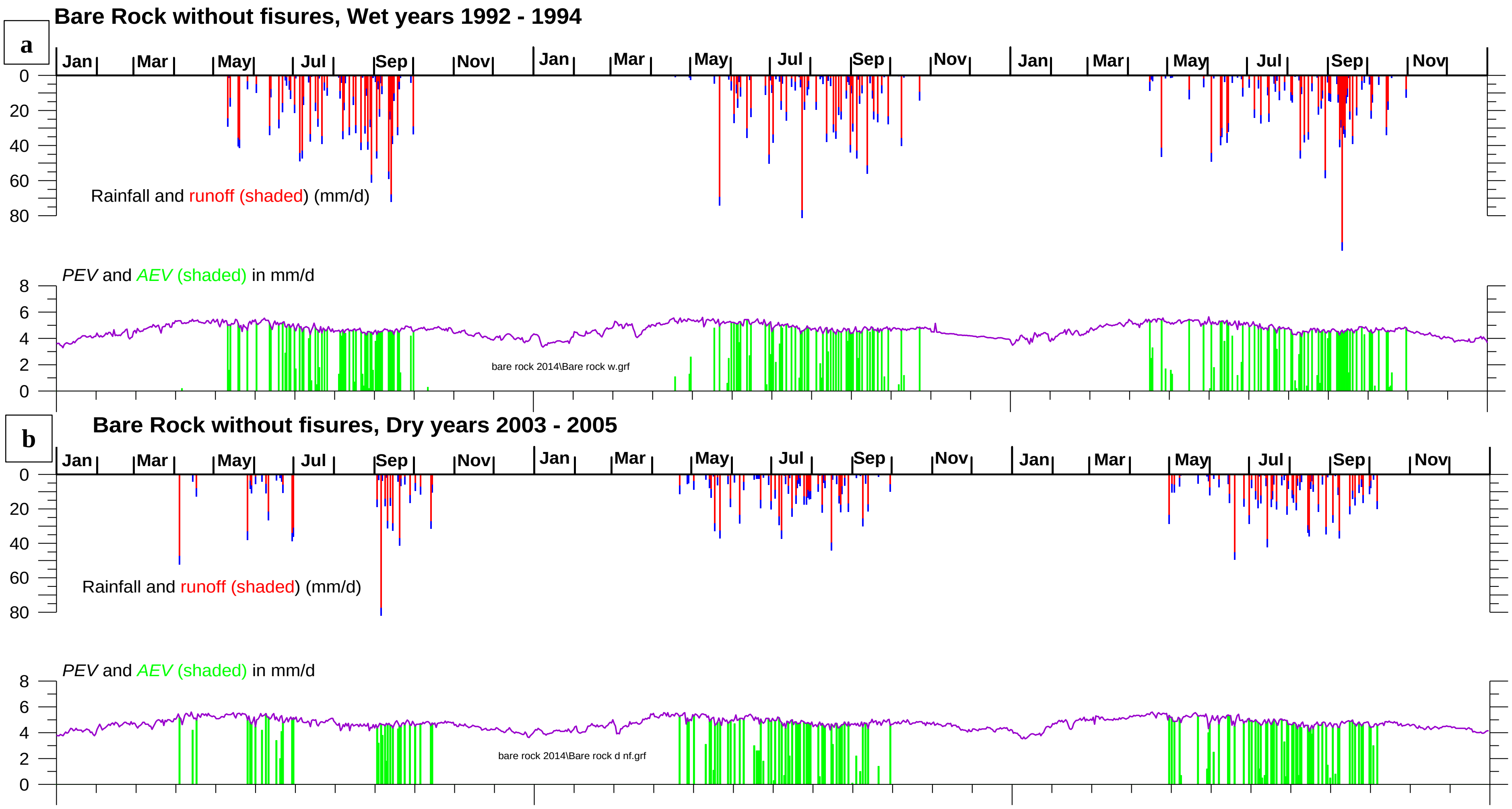


Figure 5.17: Daily rainfall, AET, PET and Outflow from fractured hard rock landscape for three wet and three dry years

For the non- fractured rock landscapes however, there is no storage as described in section 5.2 and the flow processes are mainly through runoff and evaporation. Figure 5.18 (a & b) shows the daily runoff, ETo and AE from non- fractured hard rock for the three wet and three low rainfall years. The hydrological processes on the non- fractured rocks shows that in the wet years, runoff is extremely high and represent about 79.5 % of the total rainfall, while AET represent the remaining 20.5 %. In the dry years however, runoff is still high with 70 % of the total rainfall and AET is 30 %.



Bare Rock without fisures, Wet years 1992 - 1994

Bare Rock without fisures, Dry years 2003 - 2005

Figure 5.18: Daily rainfall, AET, ETo and outflow from non- fractured hard rock landscape for three wet and three dry years

Conclusion

This chapter present the modelling results of individual landscape with a detail analysis of the variations of different output of runoff, AET/AE, groundwater discharge / outflow. It was acknowledged that the variations in the hydrological responses are mostly caused by the distribution of physical features such as the vegetation and topography as well as man-made induced changes due to land use.

A technique is devised for estimating run-on in which account is taken of the area of landscape providing water and the area of the landscape receiving.

Certain landscapes require significant modifications to the input parameters to reflect the real physical landscape characteristics. For example, for the forest landscape, the depth of the soil determines the nature of the vegetation. For shallow soils, the vegetation is dominated by small shrubs with abundant grass cover which occurs only during the rainy season. However, for the deep soils, the vegetation is dominated by large, deep rooted tress whose vegetation cover reduces significantly in the dry season. When these different vegetation conditions are incorporated in the water balance model, there is sufficient soil water to meet the contrasting demands for the shallow and deep weathered forest zones reflecting the observed behaviour of trees in this landscape.

The cropping pattern of the cultivated landscapes varies according to whether or not there is additional run-on. High water demanding crops e.g. rice is grown on cultivated lands with additional run-on, while low water demanding crop such as millet is planted in cultivated lands without run-on. The allowance made for 2 cm ponding in areas with additional run-on also controls the scale of some hydrological processes such as runoff and AET. Figure 5.7 to Figure 5.10 demonstrates that for most years the AET is sufficient to maintain successful crop growth. An exception is 2003 when the AET is less than the potential for extended periods.

The results revealed that individual landscapes tend to have different fluxes in their responses e.g. while the highest AET is mostly generated on densely vegetated or open water areas such as the forest, cultivated lands and fadama, the highest runoff on the other hand is produced in areas where infiltration is less such as the hard rocks and sealed surfaces.

The model results shows that the forest landscape generates the highest AET, the non-fractured hard rocks produces the highest runoff while the fractured rocks produces the highest outflow depending on the natural features and other factors. The interaction between different landscapes is found to have great influence on the rate and magnitude of the hydrological process at individual scale. The fadama for example have a small area proportion, but produces some of the highest responses due to interaction with all the different landscapes.

The results of individual landscape units presented in this chapter have demonstrated that most of the model behaviours match the real hydrological processes within the catchment.

The total contribution of each landscape to the overall water balance of the catchment is presented in chapter six

6. Catchment-Scale Water Balance and Contributions of Unit Landscapes

This chapter presents the basin-scale water balance based on an up-scaling of the contributions of the different unit landscapes simulated in the previous chapter. This involves analysis of the total contributions from the different landscape for the 40 year period of the simulation (1971 – 2010). The analysis will however present only results for 37 years (1974 -2010). The first 3 years are removed to avoid any inconsistencies in the model initialization. The chapter also examines the stage-discharge relationship of the river Ka at the Fokku gauge and relates it to another river gauge at Gusau within the basement complex area. Finally, comparisons are made between the model outputs of runoff to the river plus groundwater outflow with observed river discharge of river Ka.

6.1. Contribution of individual landscape water balances to the total catchment water balance

The simple water balance assumption for this research consists of a catchment with precipitation as the only input and evaporation/evapotranspiration, runoff, groundwater outflow and abstraction (integrated in the model simulation) as the outputs. This can be expressed using the following equation in the context of climate-landscape influences as:

ΔS = P (climate) - E (climate, soil, vegetation) – Ro (soil/geology/topography) - GWo (soil/geology/topography)

Where ΔS = change in storage, P = precipitation, E = evaporation/evapotranspiration, Ro = runoff, and GWo = groundwater outflow

The summed contributions from the individual landscapes to the total water balance of the catchment over the 37 year period are recorded in Table 6.1a, showing the total output of runoff, AET and groundwater outflow. The total catchment values are calculated by summing the area weighted contributions of individual landscapes as presented in Table 6.1b.

The rainfall's input for the Cultivated II and IV and the fadama in Table 6.1 is the sum of actual rainfall and run-on from the contributing landscapes as described in section 5.3.

Table 6.1a: The unit area water balance of each individual landscapes for 37 years

No	Conceptual Landscape	Totals for 37 Years (1974 – 2010)				
		Rain (mm)	**Runoff (mm)**	**AET (mm)**	**Groundwater / fissure outflows (mm)**	**Storage change (mm)**
1	**Town I**	33865 (915 mm/yr)	7791 (221 mm/yr)	23864 (645 mm/yr)	2220 (60 mm/yr)	10
2	**Town II**	33865 (915 mm/yr)	7821 211 mm/yr)	23759 (642 mm/yr)	2339 (63 mm/yr)	54
3	**Sealed surface I**	33865 (915 mm/yr)	17504 (473 mm/yr)	16215 (442 mm/yr)	0	146
4	**Sealed surface II**	33865 (915 mm/yr)	17513 (473 mm/yr)	16682 (443 mm/yr)	0	330
5	**Forest I**	33865 (915 mm/yr)	721 (19 mm/yr)	33224 (898 mm/yr)	0	80
6	**Forest II**	33865 (915 mm/yr)	960 26 mm/yr)	32953 (891 mm/yr)	0	48
7	**Fractured rocks I**	33865 (915 mm/yr)	6920 (191 mm/yr)	9106 (246 mm/yr)	17650 (477 mm/yr)	189
8	**Non- fractured rocks II**	33865 (915 mm/yr)	24587 (667 mm/yr)	9106 (246 mm/yr)	0	172
9	**Cultivated I**	33865 (915 mm/yr)	5260 (145 mm/yr)	25785 (686 mm/yr)	2887 (81 mm/yr)	67
10	**Cultivated II***	44929 (1214 mm/yr)	7595 (212 mm/yr)	30096 (813 mm/yr)	6906 187 mm/yr)	332
11	**Cultivated III**	33865 (915 mm/yr)	5238 (142 mm/yr)	25441 (690 mm/yr)	3006 (81 mm/yr)	180
12	**Cultivated IV***	44929 (1214 mm/yr)	7406 (203 mm/yr)	30054 (812 mm/yr)	7133 (198 mm/yr)	336
13	**Fadama***	68072 (1840 mm/yr)	13024 (355 mm/yr)	42528 (1149 mm/yr)	12370 (335 mm/yr)	150

***Rain + Area Weighted Run-on**

***Storage change refers to the difference in water stored between the start and end point of the water balance over the 37 years**

Table 6.1b: Area weighted components of individual landscapes water balance for 37 years

	Conceptual Landscape	**% Land Area**	**Area Weighted Totals for 37 Years (1974 – 2010)**					
			Area weighted Rain (mm/37years)	**Factor to river**	**Area Weighted AET (mm/37years)**	**Area Weighted Runoff to river (mm/37years)**	**Area Weighted Groundwater / fissure outflows (mm/37years)**	**Contribution to run-on (mm/37years**
1	**Town I**	3	1016 (27 mm/yr)	0.1	716 (19 mm/yr)	23 (0.6 mm/yr)	67 (1.8 mm/yr)	210
2	**Town II**	7	2371 (64 mm/yr)	0.1	1663 (45 mm/yr)	55 (1.5 mm/yr)	164 (4.4 mm/yr)	493
3	**Sealed surface I**	2	677 (18 mm/yr)	0.6	324 (8.7 mm/yr)	211 (5.7 mm/yr)	0	141
4	**Sealed surface II**	3	1016 (27 mm/yr)	0.6	501 (14 mm/yr)	312 (8.4 mm/yr)	0	208
5	**Forest I**	7	2371 (64 mm/yr)	0.9	2326 (63 mm/yr)	40 (1.1 mm/yr)	0	4
6	**Forest II**	13	4402 (119 mm/yr)	0.9	4284 (116 mm/yr)	112 (3 mm/yr)	0	12
7	**Fractured rocks I**	15	5080 (137 mm/yr)	0.625	1366 (37 mm/yr)	649 (18 mm/yr)	2648 (72 mm/yr)	389
8	**Non- fractured rocks II**	10	3387 (92 mm/yr)	0.0625	911 (25 mm/yr)	154 (4.2 mm/yr)	0	2305
9	**Cultivated I**	10	3387 (92 mm/yr)	0.5	2578 (70 mm/yr)	263 (7.1 mm/yr)	289 (7.8 mm/yr)	263
10	**Cultivated II**	5	2246* (61 mm/yr)	0.5	1505 (41 mm/yr)	190 (5.1 mm/yr)	345 (9.3 mm/yr)	190
11	**Cultivated III**	10	3387 (92 mm/yr)	0.5	2544 (69 mm/yr)	262 (7.1 mm/yr)	301 (8.1 mm/yr)	262
12	**Cultivated IV**	5	2246* (61 mm/yr)	0.5	1503 (41 mm/yr)	185 (5 mm/yr)	357 (9.6 mm/yr)	185
13	**Fadama**	10	6807* (184 mm/yr)	1.0	4253 (115 mm/yr)	1302 (35 mm/yr)	1237 (33 mm/yr)	0
	Totals	**100**	**38393 includes run-on**		**24474 (661 mm/ yr)**	**3758 (102 mm/yr)**	**5408 (146 mm/yr)**	**[4658]**

6.1.1. Runoff contributions from different landscapes to the catchment-scale water balance

The results of total runoff to the river contributed by each landscape for 37 years are given in Table 6.1 (a) and the area weighted totals in Table 6.1 (b). As described in section 4.9, the runoff contribution is the area weighted totals from different landscapes to the river. The depth of runoff from cultivated lands II and IV to the fadama and river is influenced by the run-on from the non- fractured hard rocks added to the actual rainfall; also, the runoff from the fadama to the river is influenced by the run-on from all the five landscapes added to the actual rainfall (see section 4.9.1).

Figure 6.1 shows the area weighted runoff totals to the river recorded in Table 6.1b, which are expressed as a depth over the entire catchment (rather than over the landscape unit). In Figure 6.1, the fadama has largest runoff contribution equalling about 34 % of the runoff received by the river. The fadama receives large amount of run-on from other landscapes, some with three time bigger land area as described in section 4.9. The fadama area is smaller than some of the contributing landscapes in addition to the fact that it doesn’t contribute flow to any landscape apart from the river; this results in high runoff from the fadama to the river.

The fractured hard rock has the second highest individual landscape contribution of runoff to the river in the 37 year water balance having about 18 % of the total runoff to the river. This is not unexpected in view of the fact that the fractured hard rocks occupy about 15 % of the total land area and a significant proportion of runoff from this landscape goes directly to the river (Table 6.1). In contrast, the non- fractured hard rocks contribute only about 4 % of the runoff to the river in the 37 year water balance despite much runoff generated from this landscape due to lack of infiltration. However, 90 % of the runoff from non- fractured rocks goes to the cultivated lands as run-on and only small amount goes directly to the river and fadama as described in section 4.9 (Table 4.5).

Despite the large total runoff from the two sealed surface landscapes (column 5 of Table 6.1a), 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 24 % runoff to the river (Figure 6.1).

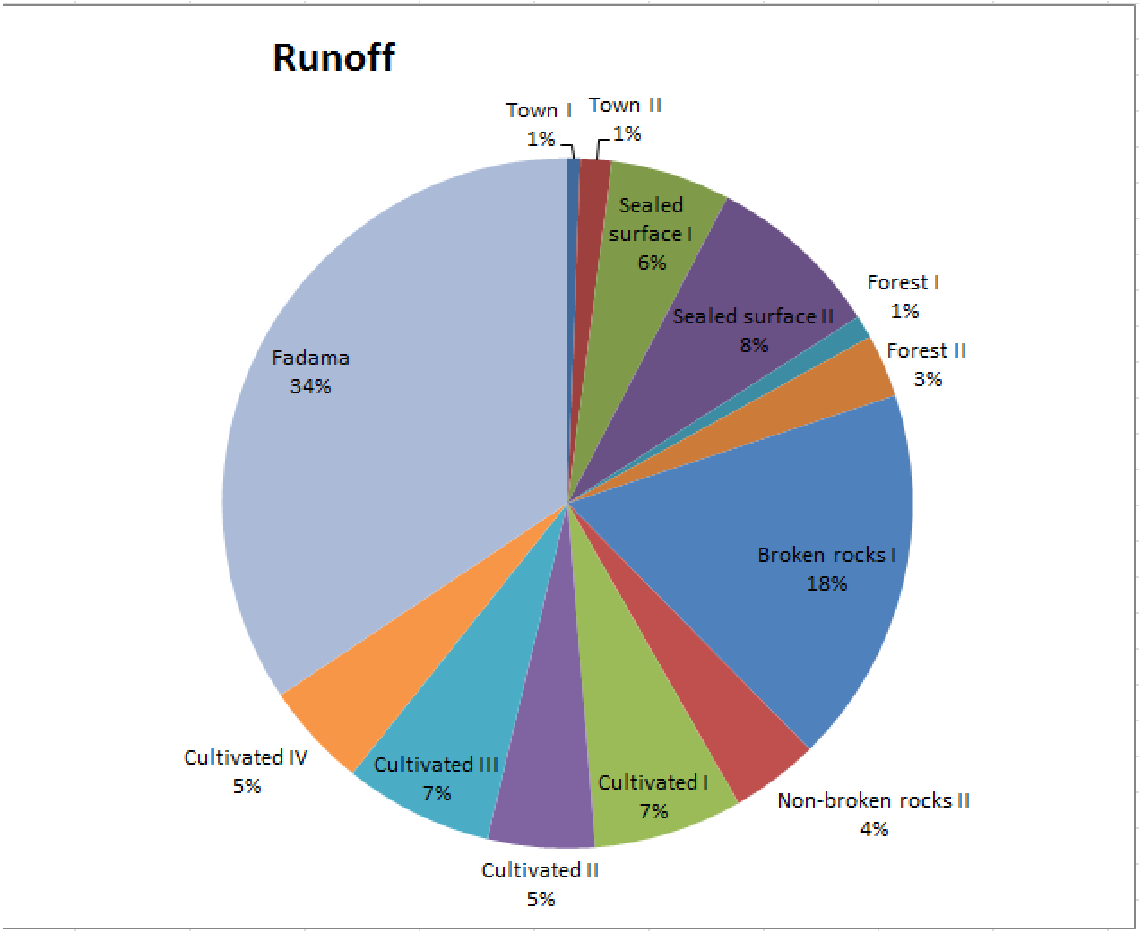


Figure 6.1: Percentage 37 year area weighted runoff contribution to the river from individual landscape unit (Totals runoff to the river = 3758 mm)

The effect of variations in percentage size of land areas can also be seen in the results of cultivated lands I to IV in Table 6.1. Although the total per unit area runoff from cultivated II & IV is higher than that of cultivated I & III, the area weighted runoff to the river however is higher for Cultivated I and III due to their larger areas than Cultivated II & IV (7 % each compared to 5 % each), despite the latter having additional run-on from non- fractured hard rock. The 2 cm ponding allowed in the WaSim runs for cultivated II & IV provides additional storage, lessening the effect of the additional run-on on runoff to the river for the two landscapes. The 2 cm ponding provides more space to accommodate water on the surface and reduce runoff. The water instead will be lost to AET and infiltration or groundwater outflow.

The total runoff contributions from town landscapes to the river are very small (Figure 6.1), equalling only about 2 % of total runoff to the river. This is due to the fact that the high runoff from town landscape discussed in section 5.3.1 goes to the fadama instead of the river and contributes to the large runoff volumes from the fadama to the river. It was observed during the fieldwork that most towns within the catchment are located close to the fadama because it serves as their source of water supply for irrigation and domestic use especially in the dry season.

Even though, the total land area of forest landscapes is twice the size of towns landscape, the contributions of runoff from the two forests to the river are also small equalling about 4 % of the total rainfall (Figure 6.1). As noted earlier from the results in Table 6.1, the forest surface allows more water infiltration and consequently higher soil water storage which is later intercepted and utilized by plant roots for evapotranspiration. The resultant high AET on these landscapes discussed in section 5.3.4 explains the reason for the low runoff generated (see Table 6.1).

6.1.2. The total AET on different landscapes

The percentage area weighted AET contributions to the water balance are recorded in column 8 of Table 6.1b and given in Figure 6.2.

The cultivated landscapes I - IV in Figure 6.2 contribute the highest area-weighted AET in the catchment water balance. The four landscapes together occupy about 30 % total land area of the catchment and contribute about 33 % of the total AET.

The forest has the second highest contribution equalling about 27 % of the total AET. This is expected because forest landscape also is large in terms of land area (20 %) and has the highest Kc with roots extracting water from a greater soil depth and evapotranspiration occurring even in the dry season as described in section 5.3.4.

Despite the large AET contribution from the fadama of about 17 % in the water balance (Figure 6.2), its relatively small land area (10 %) compared to cultivated lands I-IV or forests I & II makes its contribution smaller than the former two.

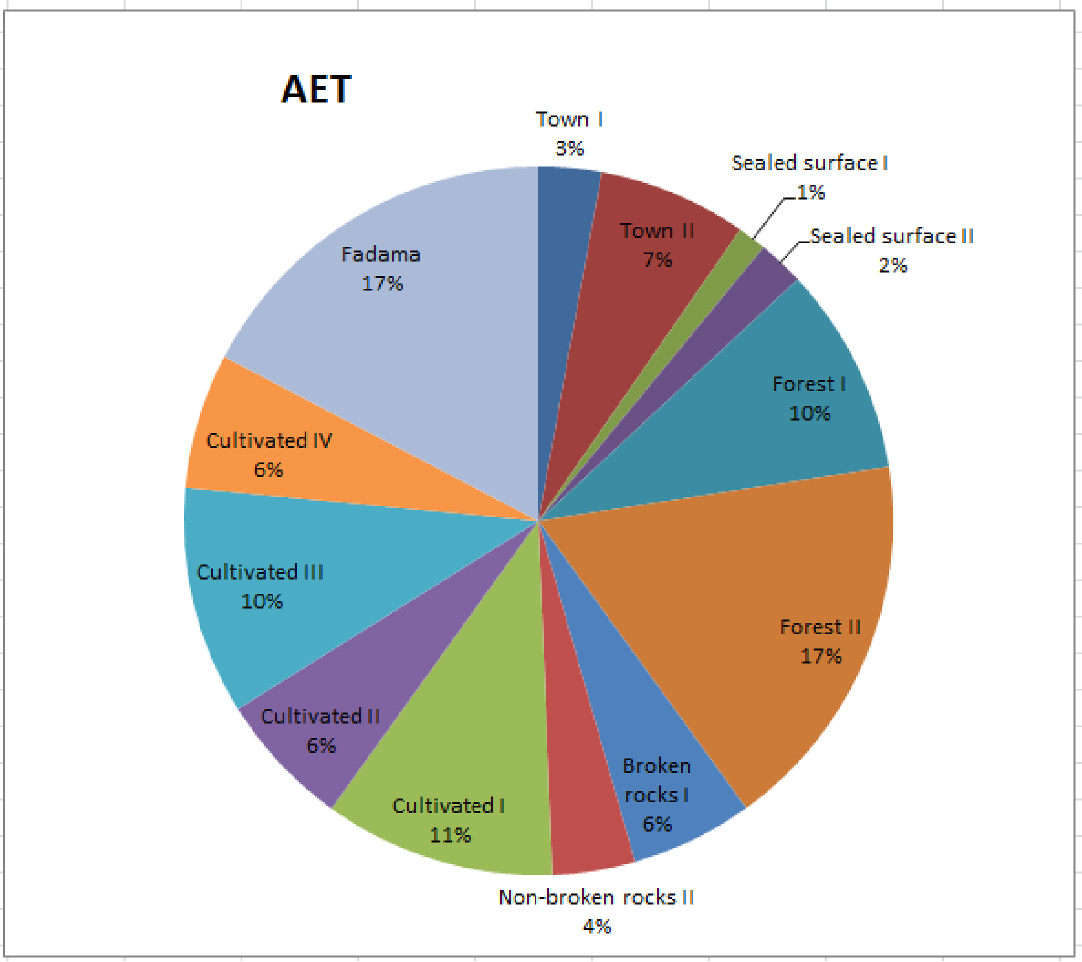


Figure 6.2: Percentage 37 year area weighted AET contribution from unit landscapes (Totals = 24474 mm)

The towns and hard rocks contributes similar amount of AET (10 %) in the basin water balance despite the fact that hard rocks (fractured and non- fractured) 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 as described in section 4.4. 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 as described in section 4.3

6.1.3. Total groundwater / fissures outflow from different landscapes

Groundwater outflow to the river occurs from towns, cultivated lands, forest and fadama landscapes, while fissure outflow occurs from fractured hard rocks. The results of groundwater / fissure outflows are recorded in column 9 of Table 6.1 and the percentages are shown in Figure 6.3. The total area weighted groundwater outflow for 37 year period is about 5408 mm accounting for about 14 % of the rainfall for the same period. It is important to note that runoff and AET totals are 3758 mm and 24474 mm, which represent 10 % and 64 % of total rainfall respectively (Table 6.1). The groundwater outflow therefore has the second highest contributions in the catchment-scale water balance.

Figure 6.3 shows the percentage groundwater outflow contributions in the total basin water balance. The highest contribution is the fissure outflow from fractured hard rocks alone accounting for about 49 % of the 37 year groundwater outflow. The non-fractured rocks in Figure 6.3 do not have any outflow contribution to the water balance because the rainfall is annexed to runoff and evaporation as described in section 4.4.1.

The cultivated lands (I-IV) and fadama contribute similar groundwater outflow (24 & 23 % 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 (4 %) to the basin water balance because runoff and AET takes a larger proportion of the rainfall.

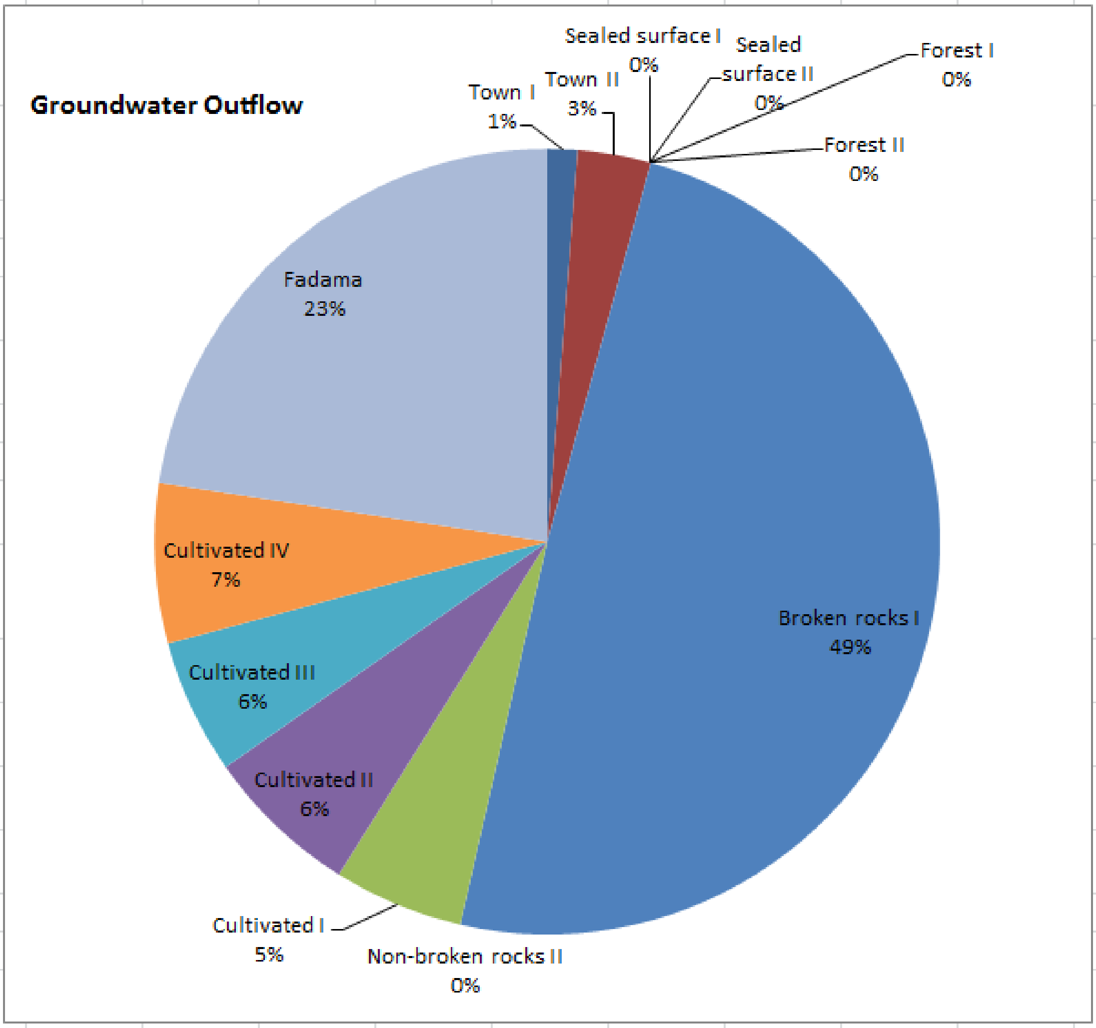


Figure 6.3: Percentage 37 year groundwater outflow contributions from individual unit landscapes

The forest landscapes however, did not produce any groundwater outflow because the high AET utilizes much of the water on these landscapes as discussed in section 6.1.2. The drain flow in WaSim (represented as groundwater outflow) is a function of mid-drain water table elevation, which in the catchment is regarded as river valleys (channels). The water table in forest runs for most of the years is below the root zone and no groundwater outflow is obtained in all the years (section 5.3.4). Groundwater outflow is not allowed in the WaSim model runs for the sealed surfaces due to the surface nature of the landscape (see section 4.3).

6.2. Comparative analysis of the model output and observed river discharge

This section evaluates the stage-discharge relationship of river Ka at Fokku based on three years hydrological records obtained from the Ministry of Water Resources, Sokoto State (MoWRS records) mentioned in section 3.1.2. The validity of the river discharge estimated using a stage discharge-relationship established by the Ministry of Water Resources is assessed prior to comparisons of the river discharge at Fokku with modelled runoff plus groundwater outflow to the river. River Ka was chosen because it is the only river that originates and ends within the study catchment at Fokku gauge before entering the sedimentary part of the Sokoto basin, with a complete river stage record.

The Hydrology & Borehole Section of the Ministry of Water Resources produced a document [Hydrological Data, for available periods 1976-1979] with daily readings of stage heights at different gauge locations in Sokoto State, northwest Nigeria. River stage data for Fokku and Gusau stations for the hydrological years 1976-77, 1977-78 and 1978-79 were obtained from this document (MOWR, 1981) as described in section 3.1.2.

6.2.1. Stage-Discharge Relationship for Fokku Gauge

The historical gauging of the River Ka was done at Fokku Bridge shown on the picture in Figure 3.2. The flow behaviour of river Ka is complex since it can be affected due to rainfall occurrence either locally or further upstream within the catchment. It was observed during the fieldwork that the river level can rise above the Fokku Bridge either due to rainfall within just 10 km^2 of Fokku town or due to continuous rainfall at a long distance (up to 250 km upstream). These are common occurrences in semi-arid areas with high storm rainfall (Zhang et al., 2011, Bello. 1997).

Figure 6.4: Photograph of Fokku Bridge with high flows in the River Ka

The stage-discharge relationship for the River from the MoWRS records is plotted in Figure 6.5 as red line. The plots are given as two curves; the first is representing low flows which are proportional to a stage raised to the power of 1.5 ($H^{3/2}$) for a rectangular weir, and the second representing high flows which show a linear stage-discharge relationship. These stage-discharge curves are faulty due to number of issues; first, the continuous linear increase in discharge as a result of stage increase may be appropriate under low flows but not at high flows (Heschy, 1985). Secondly, the zero flow in the curve is at a stage reading of about 1.32 m, which is lower than the minimum actual gauge reading in the hydrological document of about 2.0 m. this indicates that the lower stage is either incorrect or the stage may have been defined during an earlier drier period.

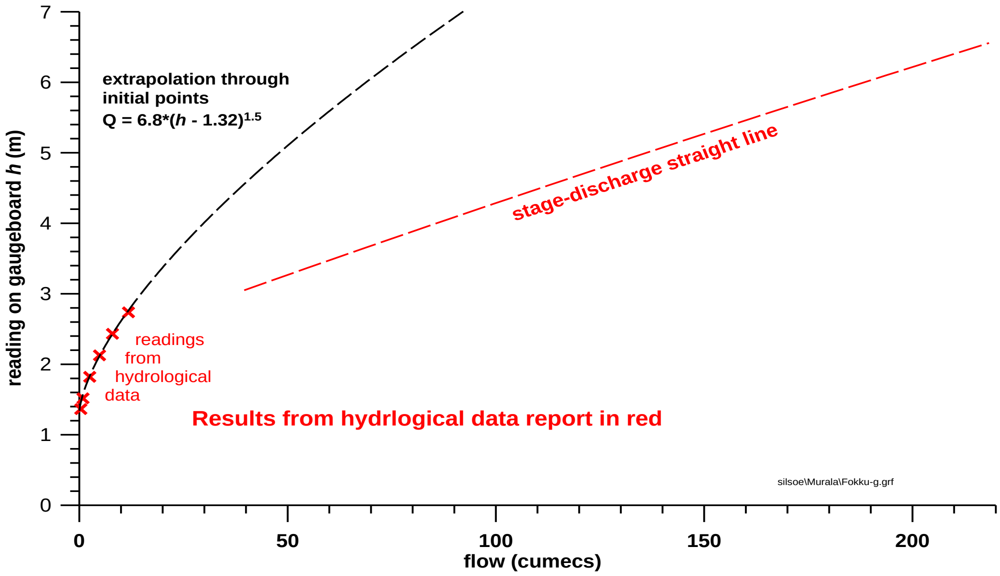


Figure 6.5: Stage-discharge relationships for the river Ka at Fokku

The red line refers to the results quoted in the Hydrological data document

Lastly, even though occasional high flows sometimes occur after heavy rainfall as described in section 6.2.1, the extremely high stage readings especially in 1978/79 seem to be non-realistic representation of flow over the bridge. The stage gauge height at Fokku is located at the bridge level based on confirmation from the local inhabitants during the fieldwork. Table 6.2 gives a summary of the minimum and maximum stage readings for the three year records in the hydrological document from MoWRS.

Table 6.2: A summary of river Ka stage readings from stage-discharge curve and readings in the hydrological document from MoWRS

Year	Rainfall (mm)	Minimum recorded stage (m)	New Minimum Stage (m)	Maximum recorded stage (m)
1976-77	884	1.30	2.0	5.6
1977-78	766	1.46	2.0	7.3
1978-79	1128	1.66	2.0	9.3

From Table 6.2, the minimum stage started from 1.3 m in 1976/77, while the maximum is 9.3 m obtained in 1978/79. The minimum stage considered as zero flow corresponds to a stage of 1.32 m, this is below the lowest actual stage reading of 2.0 m in the hydrological document. The maximum stage of 9.3 m and 8.1 m also look very high and probably represents the flow over bridge.

6.2.2. Comparison of rainfall and river stage

Stage heights have also been obtained for Gusau station for comparison. In Figure 6.6, stage heights at Gusau and Fokku are plotted together for 1977/78 to see if there are similarities in the two gauge responses. The motive is to see whether the two gauges responds similarly to rainfall from Gusau station. The zero flow stage is taken as -0.2 m at Gusau gauge and 2.0 m for Fokku gauge based on hydrological records in MoWRS document. The different vertical scales of stages for Gusau (left hand side) and Fokku (right hand side) are chosen to give similar maxima based on the stage readings in the hydrological document.

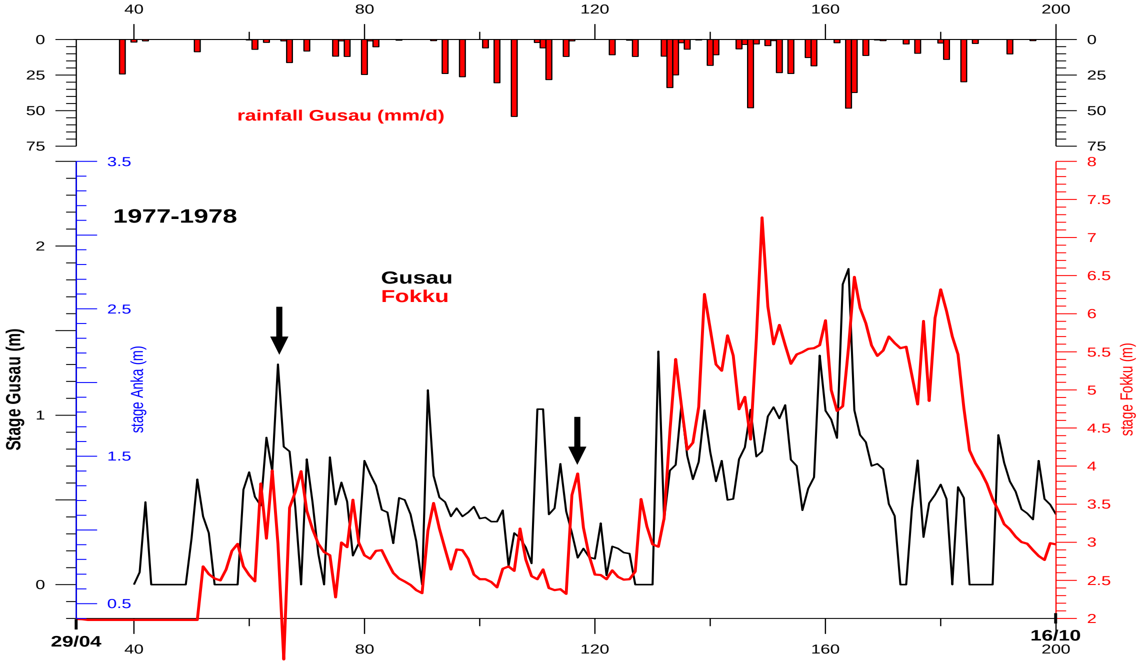


Figure 6.6: River stages at Gusau and Fokku with rainfall from Gusau station for the year 1977/78

[The red line is Fokku and the black line is Gusau. The arrow is indicating a mismatch of Fokku stage with Gusau rainfall]

Figure 6.6 confirms a good correlation between the rainfall and the gauge readings at Gusau and Fokku in terms of timing. There is always increase in stage after significant rainfall, and low stage after low rainfall with a time difference of not more than two days. There are a few periods however when the high stage values does not actually match rainfall occurrence in Figure 6.6. These high stage values are believed not to be real as no rainfall is recorded during that period at Gusau station. However, there is a possibility of rainfall occurrence elsewhere in the catchment which is not recorded at Gusau station. The high increases in stage with high rainfall occurrence is also similar for the remaining two years (1976/77 and 1978-79), even though fluctuations in stage are larger in 78/79 (see appendix).

6.2.3. Correction of low stage values for all years and extreme stage values for 1977-78

For 1977-78, the extreme values in table 6.2 are rejected because they did not reflect the nature of responses with similar rainfall amount in the other two years (see Figure 6.6); despite having lower rainfall, instead, the original stage values in feet were modified using a set of conditions. First, 2.0 m is taken as the minimum stage based on the values given in the hydrological document from MoWRS. Any stage values below the minimum are considered equal to 2.0 m (Table 6.2). Secondly, all extreme values that did not coincide with high rainfall occurrence are reduced by 1.52 m. This helps in correcting the extreme stage values to fall within the highest possible range.

Figure 6.7 presents the plots of the original stage and the modified stage readings for 1977/78. The new maximum stage obtained after modification is 5.7 m which reflects the amount of discharge amount expected because 48 mm of rainfall occurs two days before the high stage is obtained.

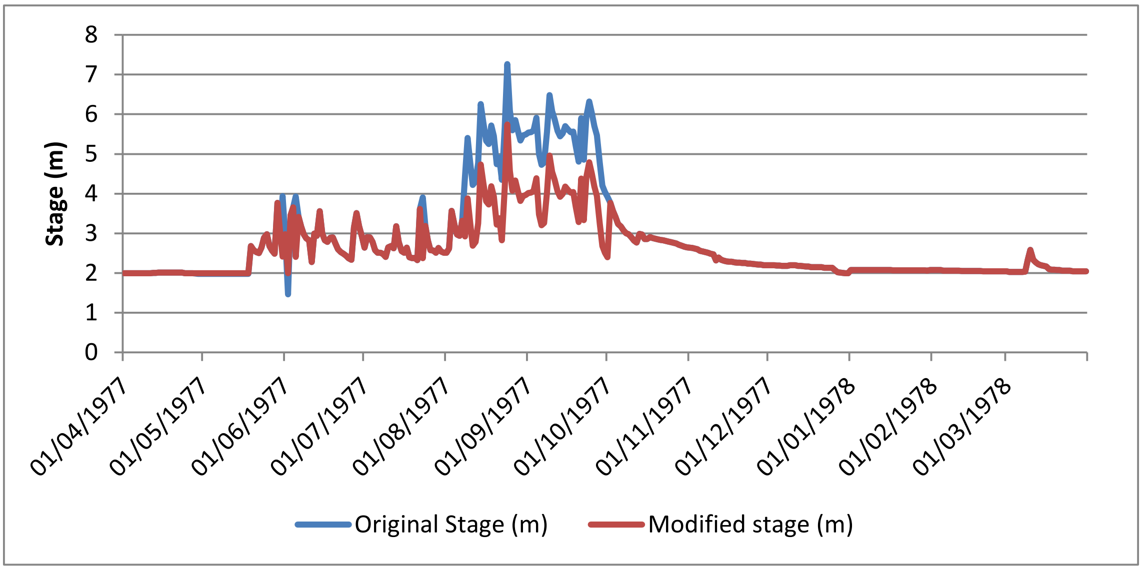


Figure 6.7: Original and modified stage readings at Fokku gauge for 1977/78

6.2.4. Estimating river discharge from river stage

In view of the inconsistencies observed and since no reliable stage-discharge graphs are available, an equation is deduced using the rectangular weir equation as an alternative approach to derive the stage-discharge relationship for Fokku gauge.

The velocity area method is commonly used to derive the stage-discharge curve in many areas around the world (Herschy, 1985). For areas with occasional high flows e.g. Fokku gauge, this is very difficult because of doubts in the water levels measurement and the high velocities under high discharge conditions. This uncertainty can affect the estimated discharge due to the exponent (power) of heads in the equation.

There is no information however, on how the published stage-discharge relationship in MoWRS hydrological document at Fokku gauge was obtained, but from Figure 3.2, the flow at Fokku Bridge looks similar to a rectangular section. The normal flow equation for a rectangular weir is given by Herschy (1985) as:

$$Q = C(h + a)^{n} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

where C is a coefficient depending on the weir dimensions and geometry, h is the measured stage and a is a correction where zero does not match to zero value of stage. The exponent n depends on the shape of the weir (or channel); for rectangular weir, n = 3/2.

From the rectangular weir equation, the flow equation is:

$$Q = \frac{2}{3} C_d \sqrt{(2g)}\ b\ H^{3/2} \quad \text{………………………..(2)}$$

where Q is the discharge in m^3/s, b is the width of the weir (m), H is the height of the river above the zero flow elevation (m) and Cd is a coefficient of discharge which allows for the reduced area of flow compared to the total width. For a well-designed weir, maximum Cd = 0.6

In order to obtain a good stage-discharge relation, the discharge through the measuring section should always occur within the boundaries of the channel. The flow behaviour at Fokku Bridge is however unlike the normal situation since the flow sometimes can go above the bridge or over the river banks causing abnormal flow. Herschy (1985) also suggested that the river stage should be measured away from any disturbance; but the measurement of stage at Fokku Bridge is not very reliable due to the flow behaviour. The river channel at Fokku Bridge is also not stable and has a sand-bed channel with a continuous fluvial sediment movement which further makes the normal rectangular weir stage-discharge relation difficult to determine. The downstream water level is the same with upstream at Fokku Bridge without any ideal indication of a nappe forming after water passes through the bridge. Based on the absence of the ideal flow conditions at Fokku Bridge, the weir equation used will therefore have a coefficient of discharge which reflects the abnormal flow.

The width of the weir at Fokku is estimated to be 45 m (from google map) and the Cd chosen is 0.48 (Rushton, 2013 - personal communication). The stage-discharge equation becomes:

$$Q = 63.8H^{3/2} \quad \text{……………………………….(3)}$$

where ‘H’ is the reading on the gauge board minus 2.0 m.

Based on this equation, the new stage-discharge curve is plotted in Figure 6.8. The blue line in Figure 6.8 is the original plot from hydrological data stage-discharge curve, while the red line is the stage-discharge relationship using equation 3. The red line equation is considered to be more reliable for Fokku stage-discharge relationship because it shows a steady increase in flow in response to increase in head.

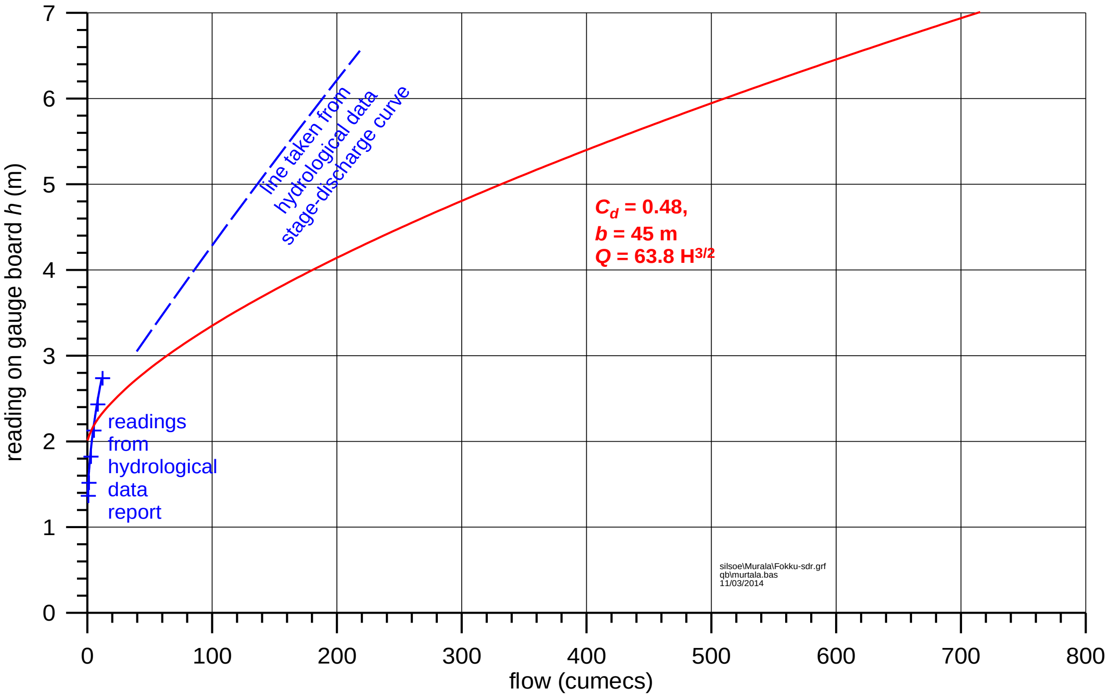


Figure 6.8: Established stage-discharge curve for Fokku

[Red line is best stage-discharge curve]

6.3. Comparison of modelled catchment contributions to river flow with estimated discharge at Fokku Bridge

From the runoff-run-on interconnection described in section 4.7, the simulated flows into the river are assumed to be the sum of runoff plus groundwater outflow from different landscapes. The total modelled runoff plus groundwater outflow to the river from 1974-2010 is about 248 mm/yr, representing about 24 % of the total rainfall of 915 mm/yr for the same period. Japan International Corporation Agency (JICA, 1990) conducted a water balance and gave an estimated average surface runoff in the Sokoto basement complex region (with a much larger area) as 17 % of total rainfall for 32 years. This is a useful approximation as it gives an insight of the likely percentage of rainfall that contributes to river discharge in the Sokoto basement area.

The total simulated contributions to river flow (runoff and groundwater outflow) and observed river discharge for the three years are given in Table 6.3. The rainfall for the three years for which the stage data are available is slightly above the average rainfall for the 37 years. For the three discharge years (from 1st April 1976 – 31st March 1979), the total rainfall is 2799 mm and total modelled runoff plus groundwater outflow to the river is 661 mm (Table 6.3), representing about 23 % of total rainfall for the three year period. The total observed river discharge (based on the revised stage-discharge relationship) for the three years is however about 526 mm (Table 6.3) which is about 19 % of rainfall and about 80 % of runoff plus groundwater outflow to the river. This difference is considered further in section 6.4.

Figure 6.9 shows the plots of modelled runoff plus groundwater outflow and observed river discharge for the three discharge years.

Table 6.3: A summary of annual totals of rainfall, runoff and river discharge for the three years

Year	Total Rainfall (mm)	Total Modelled Runoff + G/Water Outflow (mm)	Total Observed River Discharge (mm)	Runoff + G/Water Outflow as % rainfall	Discharge as % rainfall	Discharge as % of modelled runoff + outflow
1976/77	884.2	195.6	137.7	22.1	15.6	70.4
1977/78	776.6	161.3	140.1	20.7	18.0	86.9
1978/79	1137.7	303.9	248.1	26.7	21.8	81.6
TOTALS	**2799**	**661**	**526**	**23.2**	**19**	**79.6**

For the three hydrological years in Figure 6.9 (a, b & c), the total observed discharge ranged between 16 and 22 % of rainfall and 70 – 87 % of modelled runoff + groundwater outflow (Table 3.1Table 6.3). A detailed comparison of modelled output of runoff plus groundwater outflow to the river with the observed river discharge is given in Figure 6.9 (a, b & c): the observations are summarised below:

- In many instances, the observed discharge is not responding to rainfall which is indicated by the modelled runoff and groundwater outflow on the day of occurrence until few days after, sometimes up to 5 - 7 days.

- The discharge is usually spread through the following days after rainfall. Discharge after heavy rainfall for e.g. can spread for up to 5 - 7 days, while discharge after small amount of rainfall can spread for between 3 - 5 days.

- The observed peak discharge in many cases does not coincide with the days of simulated peak runoff plus groundwater outflow, but occur some days after. The discharge usually peaked on the second day after rainfall (Figure 6.9).

- The observed peak flow usually occurs on the third day and the flow decreases subsequently until the last day.

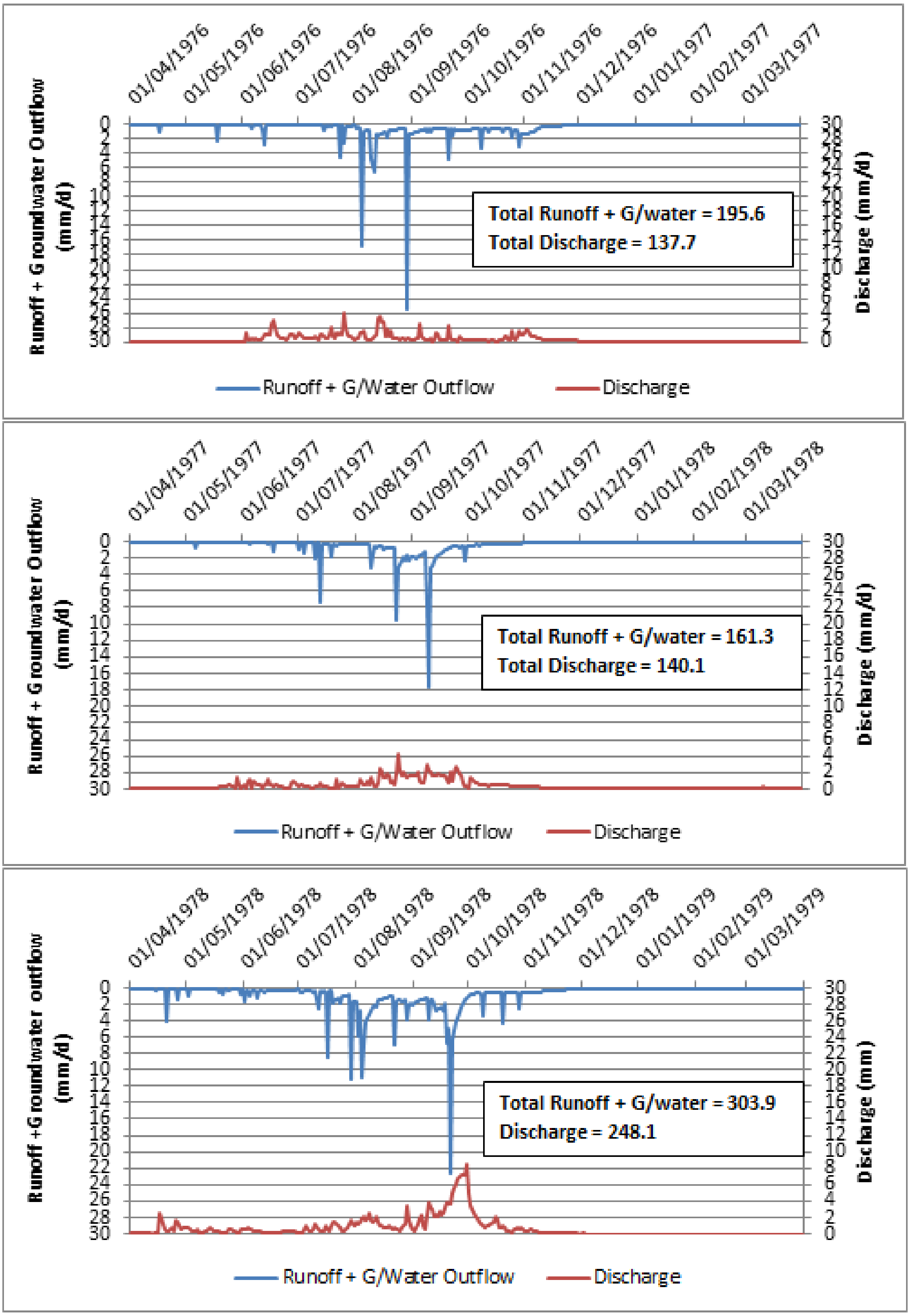


Figure 6.9: Modelled runoff + groundwater outflow and observed river discharge at Fokku for the three years

Considering the fact that WaSim is not a catchment hydrological model and therefore, does not consider routing and the time-lags associated with water moving through the landscape and down to the river networks. Runoff plus groundwater outflow in WaSim is assumed to reach the river on the same day, while in reality this is not the case.

Based on the observations of delays between rainfall and water reaching the gauging at Fokku, an equation is devised which attempts to represent the real physical observations of delays in runoff plus groundwater outflow reaching the river outlet at Fokku after rainfall. The modelled runoff + groundwater outflow is distributed over seven days as follows:

First day = 15 %; second day = 22.5 %; third day = 25 %; fourth day = 20 %; fifth day = 10 %; six day = 5 %; seventh day = 2.5 %

The lag-equation was arrived at after looking at the river response to isolated large rainfall events in the measured period and also based on the observations of delays between rainfall and water reaching the gauging at Fokku during the fieldwork.

Figure 6.10 presents the revised plots of modelled runoff plus groundwater outflow to the river and the observed daily discharge. The revised plots have taken care of the extreme events and show a more reasonable match and consistency with the observed river discharge.

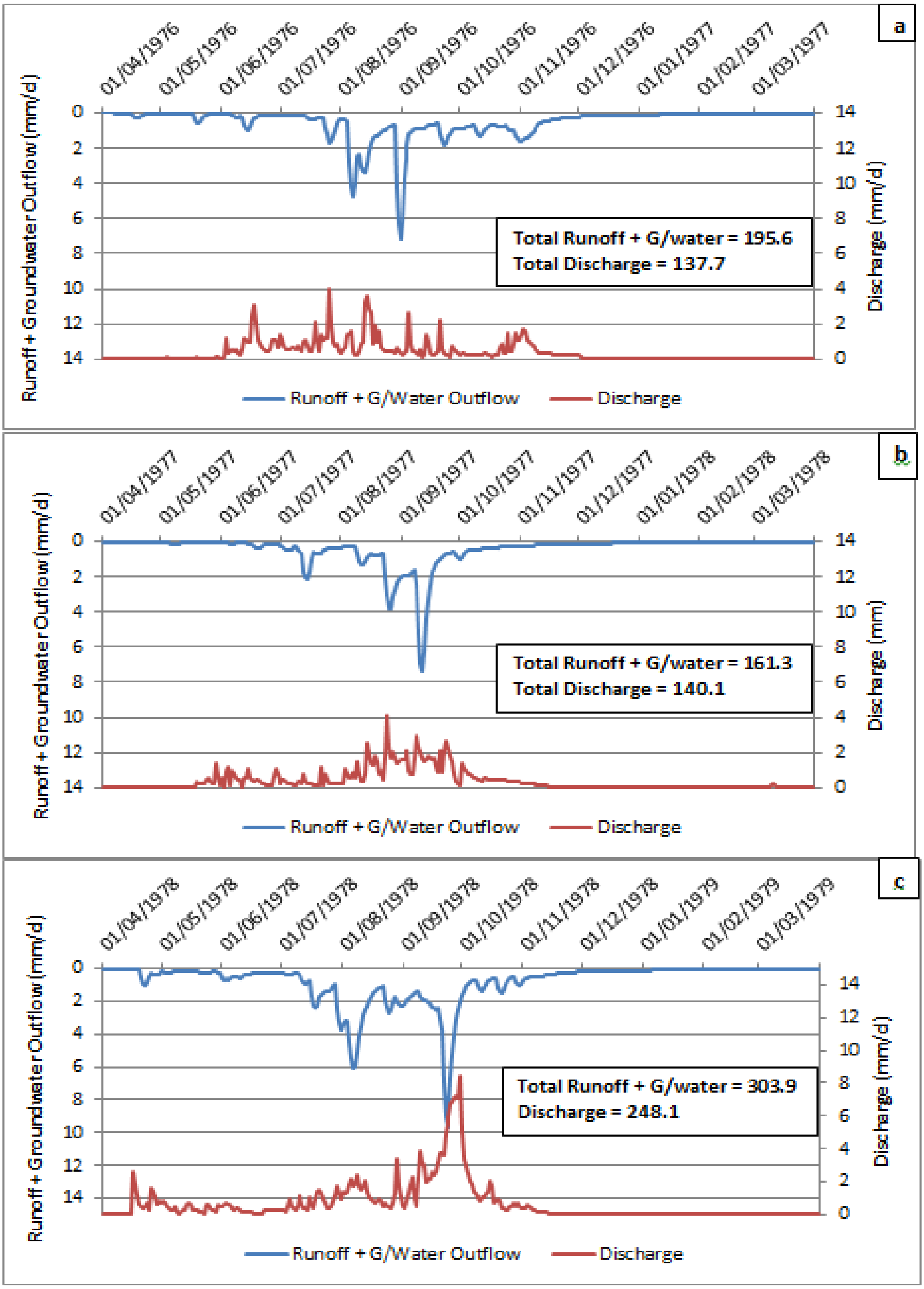


Figure 6.10: Spread modelled runoff + groundwater outflow and observed river discharge at Fokku

6.4. Possible reasons for the difference between annual modelled runoff to rivers plus groundwater outflow and estimated discharge at Fokku.

As pointed out earlier in section 6.3, the measured annual discharge at Fokku is about 80 % of the simulated annual water reaching the river from the modelled runoff plus groundwater outflow.

For the three water years (1976 – 1979), the average annual modelled runoff plus groundwater outflow is 661 mm/year and the average gauged flow at Fokku is 526 mm/year. The difference is 135 mm/year. The possible reasons for this difference are explored and presented below to see whether any of their contributions are significant.

6.4.1. Direct evaporation from the river and its tributaries

The landscape classification and the water balance conducted did not take into account evaporation directly from the river surface and its tributaries. All river channels are subject to some losses at one point or another regardless of soils, geology, or geometry. Direct evaporation from rivers and their tributaries have been identified as an important process of increased losses in the water balance. Maheu et al, 2013 for example estimated water loss from direct river evaporation of 3 mm/d in a large river (80 m wide and 0.55 m deep) and 1 mm/d in a small river (8 m wide and 0.21 m deep) in Canada during summer.

Water is lost through direct evaporation from the river Ka and its tributaries. The length of the river is about 250 km and the width varies from 30 m to 2 km.

Assuming that the large and small tributaries have a combine length that is four times the main river (1000 km) and have an average width of 5 m, and that evaporation of 6 mm/d occurs for 220 days within the year. Then,

$$Q = [(250 * 10^3 * 30) + (1000 * 10^3 * 5)] * 0.006 * 220 = 16500 * 10^3 \text{ m}^3\text{/year}$$

The 6 mm/d used represent the highest average water loss through direct evaporation from a river surface in the catchment. This is indicated in most figures presented in section 5.3.1 – 5.3.6 where reference and actual evaporation is shown.

Converting this to mm/year over the catchment area, we divide by the area of the catchment = 9631 km^2

Q = 1.7 mm/yr

This estimate shows that about 1.7 mm/year is lost from the river Ka and its tributaries, which represents only about 1% of the annual difference.

6.4.2. Rainfall variability between Gusau and Fokku

Considering the high spatio-temporal variability of precipitation in northern Nigeria, it should be noted that even the best point measurements are only representative of a limited area. Rainfall variability is one major factor that causes the observed river discharge at Fokku to be lower than the modelled runoff. Despite the fact that the larger catchment is within the basement complex region close to Gusau, the actual rainfall recorded at far distance such as around Fokku located 249 km away may be lower than that recorded at Gusau. This can be seen in the rainfall-stage graph comparison between Gusau and Fokku presented in Figure 6.6 where some stage responses at Fokku did not coincide with rainfall and stage rise in Gusau.

The northern Nigeria basement complex area has a tropical climate characterised by rainy season with high variability in rainfall amount, time and duration, intensities and spatial coverage. The large variability in altitude, slope and aspect increases the variability by means of processes such as rain shading and strong winds. Ati et al. (2002) described that the large inter-annual and intra-annual variability of rainfall in northern Nigeria resulted in frequent dry spells with widespread consequences of severe droughts. Ngongondo (2006) observed a general decline in rainfall with alternating wet and dry years detected since 1954 in southern Malawi.

Adejuwon et al. (1989) and Obadaki (2013) demonstrated that variability is observed in amounts and spatial coverage even within small distances. Oladipo (1989) and Sawa (2002) reported that rainfall may be above average at one place and below average at another within the same catchment for a particular period. None of these references however quantify the actual rainfall variability and its implication to the water balance for different locations within the catchment. Understanding the variability and amount of rainfall from point to point within the same catchment area is therefore crucial to appropriate water balance.

The best way to improve the quality of spatial rainfall information in the catchment is to increase the density of the monitoring network. Bhowmik and Das (2007) and Mishra et al. (2011) stated that the level of rainfall accuracy is highly dependent on density and distribution of rain gauge stations over a region. Unfortunately, this is lacking in the study area due to the high cost involve. Goovaerts (2000) added that even where there are dense networks, interpolation is necessary to calculate the total rainfall over a certain area.

The World Meteorological Organisation (WMO, 1981) recommended the minimum gauge density of 25 km^2 per gauge for small mountainous islands; 100-250 km^2 per gauge in mountainous areas; 600-900 km^2 in flat areas; and 1500-10 000 km^2 per gauge for arid and polar climates (Ward and Robinson, 2000). In Sokoto basin, only four reliable rainfall gauging stations can be found as pointed in section 2.2. Two of the stations are located within the basement complex, while the remaining two are located in the sedimentary part of the basin. None of the four stations is however located within the river Ka catchment.

A sensitivity analysis was carried out to see the effect of rainfall variability on runoff plus groundwater outflow reaching the river (see Table 6.4). The total runoff to the river plus groundwater outflow to the river for 27 years (1974-2000) obtained using actual Gusau station rainfall is 7223 mm (268 mm/year). A new simulation was run assuming that the rainfall at Fokku is 10 % less than that of Gusau (Table 6.4). The result shows that a decrease of 10 % rainfall decreases the total runoff + groundwater outflow to the river for 27 years to 5758 mm (213 mm/year), with a difference of 1465 mm which represents about 54 mm/year. This is about 20 % lower than the original values.

The annual modelled flow to River Ka therefore decreases by about **54 mm/year** if the catchment average rainfall is decrease by 10 %.

The actual water balance and the new sensitivity water balance results are presented in Table 6.4. The results of the sensitivity analysis show a decrease in all the modelled outputs of runoff, AET and groundwater outflows. The sensitivity modelled results of the three discharge years given in Table 6.4 also show a decrease in the modelled total runoff plus groundwater flow to the river. Table 6.5 also shows that the modelled annual flows almost equal the actual observed river discharge at Fokku for two years. However in 1977/78), the modelled flow is higher than the observed discharge. This is the year that the extreme values were corrected as shown in Figure 6.7 due to inconsistency with rainfall.

6.4.3. The temperature (and hence ETo) is higher at Fokku than at Gusau

The variation in elevation causes differences in daily temperatures and reference evapotranspiration between Gusau and Fokku. Gusau is located at lat. 12^o 16’ and long. 6^o 40’ at elevation of about 453 m. Fokku on the other hand is located at lat. 11^o 39’ and longitude 4^o 30’ with elevation of about 190 m above sea level. The average temperature drop per 100 m of altitude is at least 0.65 degrees Celsius (Chapman et al., 2001, Crippen et al., 2007, Eneva and Coolbaugh, 2009). The daily maximum temperatures at Gusau are between 26 to 33^{o}C, while at Fokku it is between 33 to 41^{o}C (Ekpoh and Nsa, 2011; Olusina and Odumade, 2012).

The Fokku area is always warmer with a temperature at least 2 – 3 degrees higher than Gusau area and therefore is likely to have higher water losses through evapotranspiration and evaporation from rivers and stream surfaces.

A sensitivity analysis was also carried out to see how temperature variability affects the reference evapotranspiration (ETo), runoff and groundwater outflow to the river when incorporated in the water balance models revised. The mean daily temperature was increased by 3^{o}C, which resulted in a significant decrease in runoff plus groundwater outflow to the river as shown in Table 6.4. An increase of 3^{o}C temperature increases the ETo by about 6 % but decreases the total runoff + groundwater outflow to the river to 5728 mm from the original value of 7223 mm (Table 6.4), which is about 21 % decrease.

This represents about **55 mm/year**.

Table 6.5 shows the new comparison of actual water balance with 10 % rainfall decrease sensitivity water balance for the discharge years (1976-1979).

Table 6.4: Actual water balance with 10 % rainfall decrease or 3oC temperature sensitivity water balance (1974-2000)

Variable		**Rainfall (mm)**	**AET (mm)**	**ETo (mm)**	**Ro (mm)**	**GW Outflow (mm)**	**Ro + GW Outflow (mm)**
Base Values	**No Change**	25089 **(929 mm/yr)**	17694 **(655 mm/yr)**	61075 **(2262 mm/yr)**	2999 **(111 mm/yr)**	4224 **(156 mm/yr)**	7223 **(268 mm/yr)**
Precipitation Decrease	**-10 %**	22589 **(837 mm/yr)**	16570 **(614 mm/yr)**	61075 **(2262 mm/yr)**	2166 **(80 mm/yr)**	3592 **(133 mm/yr)**	5758 **(213 mm/yr)**
Difference		2500 **(93 mm/yr**	1124 **(42 mm/yr)**	0	833 **(31 mm/yr)**	632 **(23 mm/yr)**	1465 **(54 mm/yr)**
Temperature Increase	**3 ºC**	25089	18373 **(684 mm/yr)**	65221 **(2416 mm/yr)**	2689 **(100 mm/yr)**	3039 **(156 mm/yr)**	5728 **(256 mm/yr)**
Difference		0	-679 **(-25 mm/yr)**	-4146 **(-154 mm/yr)**	310 **(11 mm/yr)**	1185 **(45 mm/yr)**	1495 **(55 mm/yr)**

Table 6.5: Comparison of actual water balance with 10 % rainfall decrease sensitivity water balance for the discharge years (1976-1979)

Year	**Total Rainfall (mm)**	**Sensitivity Total Rain fall (mm)**	**Total Modelled Runoff + Outflow (mm)**	**Sensitivity Runoff + G/water Outflow (mm)**	**Total Observed River Discharge (mm)**	**Runoff + G/Water Outflow as % rainfall**	**Sensitivity Runoff + G/Water Outflow as % rainfall**	**Discharge as % rainfall**	**Discharge as % of Sensitivity rainfall**	**Discharge as % of Modelled runoff + outflow**	**Discharge as % of Sensitivity runoff + outflow**
1976/77	884.2	796	195.6	139	137.7	22.1	17.5	15.6	17.3	70.4	99.1
1977/78	776.6	689	161.3	115	140.1	20.7	16.7	18.0	20.3	86.9	121.8
1978/79	1137.7	1051	303.9	223	248.1	26.7	21.2	21.8	23.6	81.6	111.3
TOTALS	**2799**	**2536**	**661**	**477**	**526**	**23**	**19**	**19**	**21**	**80**	**110**

6.4.4. Areas allocated to landscapes may be incorrect

Since the 1970s, dramatic changes have taken place in land use patterns characterized by the persistent expansion of cultivated lands and continuous decrease in natural forest in the Sokoto basin. As a consequence, the hydrological processes within the basin have been substantially altered. On a catchment scale, such impacts are reflected in fluctuations in supply and demand relations of water resources, which in turn will significantly affect the ecosystem, environment and economy. It is important to assess the effect of such landuse change on the water balance of the basin for water resource management and sustainable development on the catchment scale.

The ultimate goal of deliberate landuse practices is the acquisition of natural resources for immediate human needs, often at the expense of degrading environmental condition. Land use change can affect regional climates through changes in the hydrologic cycle, surface energy and water balance. Land use change can disrupt the surface water balance and the partitioning of precipitation into evapotranspiration, runoff, and groundwater outflow. Surface runoff and river discharge generally increase when natural forests are cleared. Change in land use and increased water withdrawals within the catchment as a result of increased population result in reduced flow of the major river Ka and its tributaries especially in upland region.

Since the river gauging is for the late 1970s while the water balance is for the landuse in the 2010s, the sensitivity analysis based on changes in areas allocated to different landscape presented in section 6.4.4 addresses some of the possibilities of the effect of land use change on the water balance of the catchment. By clearing forests for example to increase fractured rock areas or cultivated lands by 50 %, the amount of runoff from forest to the river (given in the example in section 6.4.4) is reduced from a total of 157 mm to 79 mm; while runoff to the river from fractured rocks is increased by almost 50 % from a total of 649 mm to 1081 mm for the 37 year period depending on the percentage increase or decrease in the actual area of the landscape and the type of land use changes (see section 6.4.4).

A sensitivity analysis was also carried out to estimate the water balance components in the 1970s before any deforestation. The simulation was run with an assumed forest cover of 100 % and the result shows an extremely high AET (about 100 % of the total water balance) while no runoff (<0.2 %) or groundwater outflow occurs (<0.01 %).

The area covered by the different landscapes in the catchment was arrived at using topographical maps and google images; therefore, there are uncertainties in these estimates. A change in the land area of individual landscape might affect the total output from the landscape to the river or to overall catchment water balance. It was observed that surface runoff increases due to decrease in vegetation cover (Ge Sun et al., 2006, Mohammad and Adam, 2010), while increased vegetation cover leads to reduced runoff (Peel et al., 2002; Ger Bergkamp, 1998; Dunne et al., 1991) and increased evapotranspiration (Wang et al., 2012; Liu et al., 2008; Zhang et al., 2001).

For example, if 50 % of the area of forest landscape is allocated to fractured rocks, this means that the actual runoff to the river from fractured rocks will increase by 50 %. This is expressed as follows:

Area of forest I & II is decreased from 20 % to 10 % of the total area, while area of fractured hard rock is increased from 15 % to 25 %. Runoff to the river from the forest is reduced from 157 mm to 79 mm; while runoff to the river from fractured rocks is increased from 649 mm to 1081 mm for the 37 year period.

This gives an increase of **29 mm**/year.

6.4.5. Water in the Fadama or river by-passing Fokku gauge

Another possibility is that some water is by-passing the Fokku gauge especially during high flows. This usually occur whenever there is high flow like the one described in section 6.2.1, lots of water by-passes and is missed by the gauge.

Assuming the width of fadama and river combine together in a section on a line through bridge = 8 km, depth of fadama section = 7 m, hydraulic conductivity = 3 m/d, groundwater gradient 3m per km = 3×10^{-3},

When we apply Darcy's Law

Q = cross-section area x K x head gradient = $([8 \times 7 \times 10^3] \times 3 \times 3 \times 10^{-3} \times 365)$ = 184×10^3 m^3/year

The value of K was chosen as being representative of the type of material making up the fadama (3 m/d), with a value taken from Todd and Mays (2005).

If we convert this to mm/year, by dividing by the area of the catchment = 9631 km^2

Q = 0.019 mm/year

This is considered too small to be significant even with high parameter values.

6.4.6. Water loss to the northern sedimentary boundary

The basement complex region is bordered to the north by the Sokoto sedimentary basin. The modelling has assumed that all groundwater outflows occurring in the catchment contribute to the flow in the river Ka, but it is possible that the transfer of water to the sedimentary rocks could be significant especially towards the northern boundary (See Figure 6.11).

Around 3 % of the catchment is underlain by sedimentary rocks and it is possible that there is a flow down-gradient through the sedimentary rocks induced by major abstraction in the nearby towns of Kebbe, Kuchi, Andarai and other small villages located within the sedimentary part as shown in Figure 6.11. This means that water is transferred down gradient. Assuming that there is a loss of 2 mm/d, then,

Q = 0.03 x 2 x 365 = **21.9 mm/year**

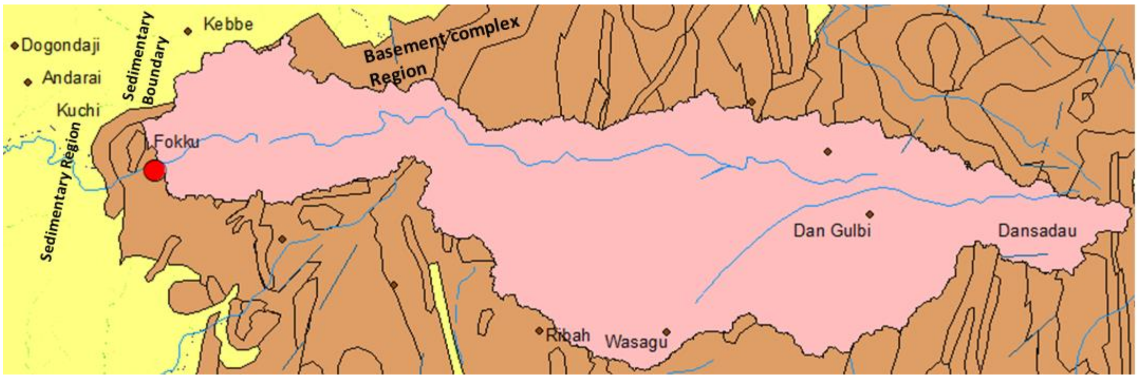


Figure 6.11: River Ka catchment showing area of contact with sedimentary rocks (yellow colour to the North-West)

6.4.7. Small abstractions from non-town areas

There is also the possibility of small abstraction occurring in other landscape areas apart from the towns and fadama. It is assumed that abstraction is carried out by 250,000 people using 20 litres per head per day. Thus,

$Q = 0.25 \times 10^6 \times 0.02 \times 365 = 1825 \times 10^3\ m^3/year$

Converting it to mm/year we divide this by the area of the catchment = 9631 km^2

Q = 0.19 mm/year

This process also does not appear to be significant.

6.4.8. Discussion of possible reasons

The Seven possible reasons given for the differences between modelled output and observed discharge may not be exhaustive, but are the likely reasons for the catchment. Many of the reasons such as water loss to the sedimentary boundary and rainfall and temperature variability are significant, while some of them e.g. direct evaporation from river and its tributaries, small abstraction in non-town areas and water bypassing Fokku gauge are insignificant.

The most significant is the rainfall and temperature variability. (Table 6.4) shows encouraging agreement for two of the three discharge years. The water loss to the northern sedimentary boundary is another significant aspect that requires a detailed field investigation to ascertain.

The actual area sizes of individual landscapes are crucial in the water balance computation because it determines the amount of output contribution by the landscape as demonstrated in section 6.4.4 where a 50 % increase in the hard rock area results in 29 mm increase flow to the river.

Even though not quantified, interception loss is another significant process through which water is lost to the atmosphere especially from forest surfaces. When rain falls on to a vegetated surface, part of it is intercepted by the forest canopy and evaporated directly back into the atmosphere as interception loss. The remainder of the rainfall reaches the ground either by through flow or by dripping from the leaf falls, or by stemflow (David et al., 2006). Interception loss is conventionally measured as the difference between the incident gross rainfall, and the sum of throughfall and stemflow. It is usually a significant component of the overall evaporation and may play an important role in catchment water balance. The total amount of interception loss depends on the rate of evaporation from the wet canopy, the canopy storage capacity, and the distribution and intensity of rainfall (David et al., 2006).

Considering the percentage land area covered by the forest landscape within the river Ka catchment (20 %), significant amount of water is believed to be lost through interception loss after rainfall. This may also be part of the possible reasons for the short fall in the water balance of the catchment.

Conclusion

This chapter brings together the overall modelled results of individual landscapes in the catchment with a detailed analysis of variations in the different simulated hydrological outputs. The catchment scale water balance was achieved by using the area weighted concept where all the individual landscape contributions are integrated.

The catchment water balance results revealed that AET accounts for the highest water loss in the catchment with an annual average of 660 mm/year which represent about 72 % of the annual average rainfall for the 37 years simulated. This is followed by the groundwater outflow with 146 mm/year (16 % of annual rainfall); and lastly, the runoff total is about 101 mm/year, representing only about 11 % of the total rainfall in the catchment water balance.

The chapter also analysed the observed river flow at Fokku and the uncertainty (extreme and minimum values) in the flow data was corrected. The river flow data was also compared with river flows at the Gusau gauging station to assess whether there is a similarity in their behaviour over time with rainfall. A new stage discharge was later devised for river Ka at Fokku.

The actual comparison of the model output of runoff plus groundwater outflow to the river with observed river Ka discharge for 3 hydrological years revealed that the individual daily model result is much higher that the observed discharge. But after the modelled runoff plus groundwater outflow to the river was spread over a number of days to reflect travel times (section 6.3), the comparison of the model and observed improved greatly (Figure 6.10).

About 80 % of the runoff plus groundwater outflow is recorded as discharge in the river Ka, while the remaining 20 % are lost through various processes described and approximated in the sub-sections 6.4. No single rain gauge is located within the catchment of river Ka. The rainfall used is that of Gusau station located about 50 km away from the upper reaches of the catchment.

Gusau rainfall is suspected to be greater than the Ka catchment because the results of sensitivity analysis show that a 10 % decrease in rainfall for the 3 discharge years leads to close agreement between observed and model flows (Figure 6.10) for two years. However, for 1977/78, the model result is less than the observed despite the fact that the extreme values for this year was corrected as shown in Figure 6.7 due to inconsistency with rainfall.

7. Discussion and Conclusions

The aim of this research is to improve the understanding of water balance in heterogeneous landscapes of the basement complex areas of Sokoto Basin. The river Ka catchment within the Sokoto basement complex region was chosen as the study area, because it is the only catchment that originates and nearly ends within the basement, with relatively enough data for hydrological modelling. By reviewing different hydrological processes within the Sokoto basement catchment, it is realized that the hydrological processes are highly variable and dependent on different landscape unit's distribution. There is therefore the need to consider this complex variability in modelling the hydrological balance of the basement complex regions around the world.

7.1. Water balance modelling in the basement complex areas of Sokoto basin using different landscape units approach

In this thesis, water balance modelling has been carried out in the Sokoto basin basement complex region. The approaches used in the research led to:

i. Classification of the catchment into different landscape units, including intrinsic sub-division of individual units based on the depth of the weathered zone.

ii. Developing new approaches to compute the water balance of individual LUs including the fractured and non- fractured hard rocks based on realistic physical understanding of their hydrological processes.

iii. Developed flow interconnectivity between different landscape units and estimate their area weighted hydrological responses

iv. Integrating different landscape units to achieve a catchment-scale water balance

v. Assess the plausibility of the modelling approaches using the observed river discharge data

The first objective of this research is *"to review the current understanding of the hydro-geomorphology of the basement complex areas"*. This was achieved through the development of soil water balance using the conceptual landscape models presented in chapter four. The conceptual models introduce new approach for better understanding of hydrological processes in the basement complex regions.

By developing and classifying the different landscapes and their hydrological processes in chapter four fulfilled the second and third objectives of this research "*to identify the major landscape features that control the spatio-temporal hydrological processes in the area*"; and, "*to develop conceptual and computational models of the significant flow processes for each landscape within the basement complex area*.

The hard rock water balance was computed using a different approach. This is to fulfil one of the objectives of the thesis "*to Simulate soil water balance for different landscape conceptual models to understand how input parameter values influence the plausibility of hydrological process representation*".

The basin-scale water balance result presented in chapter six achieved one of the objectives of this research "*to integrate the simulated conceptual model outputs to understand the contribution of each heterogeneous landscape to the water balance of the basement complex area of Sokoto Basin*".

In chapter six, comparative analysis of model output of runoff to the river and observed river discharge was presented to achieve the thesis objective of "*assessing the credibility of the water balance model results in the basement complex areas*". This approach is most valuable in developing countries where data is scarce due to poor monitoring and record keeping because it allows for the qualitative analysis of the model output in order to assess its credibility. The concept is a functional approach usually applied in the water balance modelling. For this research, the credibility analysis uses the observed river discharge data at Fokku Bridge to assess the model behavior.

7.2. Credibility of the approach

The division of landscape units approach used for this research has been used widely around the world (Farmer et al., 2003; Jha et al., 2004; Triphathi et al., 2006; Portoghese et al., 2008; Yimer et al., 2008; Han et al., 2014). Most of these references however, pay little attention to the local variations of individual LUs such as the depth of the soil or overburden material or the interactions or connectivity between hydrological processes of individual LUs. The major focus is always on the principal landscape heterogeneous features such as variations in vegetation types, density and cover (Portoghese et al., 2008; van der Kamp et al., 2003), different climates, soil landscape interactions (Farmer et al., 2003), different topography (Hayakawa *et al*. 1995), or different catchment geometric properties (Goodrich, 1992).

A significant merit of this work however, is the integration of the entire variable processes at individual scale to a unified large-scale system by incorporating real understanding of physical hydrological processes and descriptions, thereby providing a scientific exploration approach easily practicable in modelling processes. The research considers all the major landscape features and minor landscape variables that control the hydrological behaviour of the basement complex areas.

The conceptual models chosen for the water balance of the catchment are based on satisfying the set criteria outlined in section 3.5.1. The approach considers the physical knowledge of the study area with data availability to improve the physical robustness of the water balance conducted in the basement complex region. The climate data used are obtained from reliable agencies and the parameters used for the various landscapes are obtained from literature and researcher's knowledge and experience of the area.

The overall catchment area above Fokku gauging station is given as 15000 km^2 by JICA (1990) and Anderson and Ogilbee (1973). The catchment area was recalculated using RSTM DEM with 90 m resolution recommended for representation of complex regions such as the mountainous areas. The results obtained the actual catchment area above Fokku gauging station to be 10179 km^2. It is recommended therefore that anyone doing catchment studies should not only rely on existing information.

In order to avoid any uncertainty in early or late onset of rainfall, the planting date chosen consider the timing when cultivation has started throughout the region based on local knowledge and literature. In reality, the actual planting date can vary by 30 days, but the nature of WaSim software package has restricted this research to consider single planting date throughout the thirty year simulation period.

The sensitivity analysis carried out to see the effect of early or late planting on the water balance of the catchment shows that when crops are planted a month earlier than actual chosen date, there is high tendency of re-planting, low yield or losing the crops because early planting is often followed by dry spells and the soil moisture deficit becomes high. Crops planted early such as millet would also be harvested during the peak rainy season around August which will affect the ripening process. Late planting however usually results in low yield due to wilting and stunted growth associated with too much water at planting and development stages, or early cessation of rain before crops reaches maturity. This is largely due to the high seasonal variation in onset and cessation of rains in the region (Bello, 1989; Oguntoyinbo, 1981). The sensitivity analysis found that only the water balance of cultivated LUs is sensitive to the changes in planting date e.g. by reducing the AET and increasing runoff either due to absence of crops at the right time to utilize the water, or the crops was harvested earlier. The excess water not utilized by the crop will be added to either the runoff, AET or groundwater outflow in the water balance.

The runoff curve number used in the model largely determines the volume of runoff generated. The curve number method was used due to its consideration of other catchment attributes such as the soil type, surface characteristics, land use and antecedent condition. Since its inception in 1954 by the USDA SCS (Rallison, 1980), the runoff curve number method has gained global recognition and acceptance in hydrological practice such as flood design and water balance calculation (Soulis and Valiantzas, 2012; Abon et al., 2011; van Dijk, 2010; Steenhuis et al., 1995). The results of runoff volume from individual landscapes are consistent with the expected behavior after rainfall. Runoff generally increases through the rainy season as the soil moisture deficit becomes lower.

This behavior is however different in the sealed surfaces with low infiltration where high curve number of 94 was used (100 is maximum), and non- fractured rocks with only evaporation and no infiltration where a different approach was used (section 5.2). Consideration of variations in surface sealing and depth of the weathered material is necessary in modelling individual LUs because it affects hydrological processes in some landscape e.g. surface runoff in sealed surfaces, while it doesn't have any effect on others e.g. forest or cultivated landscapes.

The results of AET from individual landscapes water balance are also consistent with real field expectations. The forest landscape produces the highest AET due to large vegetation and high Kc throughout the year compared to cultivated lands where AET is only during part of the year.

The land area of individual landscapes plays a significant role when it comes to the overall catchment water balance. Some landscapes produces massive output at individual unit scale, but when it comes to overall catchment scale, their percentage contribution is very small compared to other landscapes with larger size area (see Table 6.1a). This has exposed the real physical interaction of hydrological processes in a basement complex and their effect on the catchment water balance. The assumption that all the run-on from contributing landscapes reaches the recipient landscapes on the same day may not be realistic.

The overall 37 year water balance presented in section 6.1 shows that runoff represents about 12 % of total rainfall, while AET and groundwater outflow represents about 72 % and 16 % of the total rainfall. About 0.2 % error is obtained for the overall 37 year water balance of the catchment. Wright (1992) give the runoff total range between 7 – 32 % of annual rainfall in the basement complex areas of Malawi, and a range of between 0.3 – 17 % in Zimbabwe. Deus et al. (2011) obtained an average AET of 665 mm/yr for Lake Manyara catchment in Tanzania. This is similar to 661 mm/yr obtained for this research.

The errors in the water balance highly depend on the quality of data and can occur either due to uncertainties in input data (e.g. precipitation and reference evapotranspiration) as observed by Førland *et al*. (1996), or uncertainties in model parameters such as inaccuracy in soil and crop input data (Engeland et al., 2005). Several studies indicate that precipitation is the most important uncertainty factor in the water balance modelling compared to the model parameters (e.g. Thorsen *et al*., 2001; Storm *et al*., 1988). Rodda and Smith (1986) stated that errors of up to 5% can occur in the measurement of rainfall above a forest canopy.

The overall catchment area is about 10000 km^2, while the fieldwork was conducted on only three locations (averaging about 200 km^2) to represent the whole catchment. There may be other areas within the catchment with different hydrological behaviour that is not captured by this research. The densely forested areas such as the ‘Kuyambana forest’ are particularly avoided due to insecurity in the region posed by armed bandits and wild animals.

There are also some complicated hydrological processes observed during the fieldwork such as surface depression storage on different landscapes and in the river channel that cannot be incorporated into the model.

7.3. Implication for groundwater resource management

The implication of the research findings to water resource management is the major focus of this study. There is little actual water resource management practiced in the Ka river catchment because people are in most cases left with the responsibility for their own water supply despite the functional government agencies (e.g. SRRBDA, State Water Boards and other NGOs) responsible for water resource management. Most of the water supply programmes established by these 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 (discussed in section 4.1.1) constructed in many households.

Water resources management may be regarded as the modification of the hydrological cycle for the benefit of mankind. It involves not only the beneficial uses of water resources but also the prevention, avoidance or minimization of the effects of water excess e.g. flood or deficiency such as drought (Douglas, 1973).

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. Generally in prospecting for groundwater in basement complex areas, there is need to

1. Determine the lateral and vertical extents of the weathered zones and features like faults, fractures, joints and shears.
2. Estimate quantitatively, the porosity and permeability of rock samples.
3. Employ geophysical methods to locate zones of weakness and of deep weathered areas in the region.

Specifically, this research explores the likely suitable areas for groundwater prospecting and exploitation. These are the deep weathered zones of various landscape discussed in previous chapters except the sealed surfaces, forests and non- fractured hard rocks. 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. The number, distribution and discharge of springs in the basement complex rocks of Nigeria are good indications of the occurrence of groundwater (Ayoade, 1975). Azeez (1972) pointed out that the large number of shallow hand-dug wells in the rural areas as the only source of water supply is an indication of huge groundwater storage of the basement complex region. It is not unexpected therefore to see that about 90 % of the towns in the basement complex areas are located close to the fadama or fractured rock landscapes.

Population increase and demand for more water in the catchment is putting more pressure on the already stressed available water resource. The frequent failure of boreholes and dryness of hand dug wells reported by Oteze (1979), JICA (1990), Oduvie (2006) and Offodile (2002) is not only associated with decrease in rainfall but also due to over abstraction in the catchment. During the fieldwork interview, the local people confirmed that 10 – 20 years back, some of the hand dug wells that dry up in the dry season used to have water throughout the year. When the current population (2013) of the area was compared with that of 15 years back (1991), it shows that the population almost triple, implying triple increases in water demand.

The actual recharge into the underlying aquifer cannot be measured. A soil moisture balance was carried out from which recharge is estimated. This recharge enters an aquifer system which is exploited for domestic purposes, for livestock and for irrigation. The Wasim model represents both the soil moisture zone and the aquifer with its storage as a single unit.

The rate of abstraction in town landscape is estimated at 0.1 mm/d and 0.05 mm/d for the deep and shallow weathered zones respectively. This amounts to 36.5 mm/year in the deep weathered areas and 9.15 mm / ½ year in the shallow weathered areas (due to dryness of wells throughout the dry season). The mean annual groundwater outflow obtained from the model in Table 6.1a is 63 mm and 60 mm for the deep and shallow zones. Assuming all the groundwater outflow amount is due to recharge, there is still going to be 27.5 mm and 50.8 mm left as outflow when you subtract the amount abstracted. However when we compare the results in Table 5.6a, abstraction in town landscape throughout the year is only possible during the high rainfall years and cannot be sustained during the low rainfall years especially in shallow hand dug wells.

When the shallow wells in the upland areas e.g. Fokku town go dry, water is collected from the river or dug wells in the fadama for the remaining part of the year. The fadama landscape is therefore the most reliable source of water within the catchment. However, environmental changes especially landuse (e.g. deforestation) may affect the amount of run-on to the fadama with a consequent increase in the amount of AET, runoff and groundwater outflow from this landscape.The rate of dug wells abstraction is higher in the Fadama landscape due to the presence of water throughout the year compared to the town landscape. Abstraction in the Fadama is put at 0.1 mm/d, because it occurs for only a few months within the year after the dug wells in the town landscapes dry up or during dry season irrigation. This will equally amount to 36.5 mm/d. However, the mean annual groundwater outflow to the river in the fadama landscape is very high (335 mm/yr) compared to just 63 mm/yr of town II landscape. When you subtract the amount abstracted from dug wells, there would still be substantial amount of water left in the fadama landscape (about 299.5 mm). This implies therefore that environmental changes that causes a reduction in recharge equivalent to the annual amount abstracted would result in serious overdraft in the water balance especially in low rainfall years.

To ensure a sustainable water supply throughout the year for the local people especially where fadama or natural springs are not available or inadequate, there is need to apply methods of water conservation during excess for future use in the dry season. This involves taking advantage of the high levels of runoff not captured by natural recharge during rainy season for augmentation of groundwater resources through artificial recharge of aquifers in the deep weathered zones; or capturing and storing surface runoff by building small earth dams.

Artificial recharge is a method being used extensively in areas with similar hydrological condition around the world e.g. the development of sand dams in Kenya, Ethiopia, Namibia, Burkina Faso and India. It provides the cheapest form of new safe water supply for towns and small communities (Dillon, 2005, Bouwer, 2002). Artificial aquifer recharge is the enhancement of natural ground water supplies using man-made conveyances such as infiltration basins or injection wells (Rushton and Phadtare, 1989; Durham et al., 2002; Dillon et al., 2009; Dillon, 2009).

The term “Managed Aquifer Recharge” (MAR) is now globally recognised as the best practice for increasing aquifer recharge. This method has also successfully been used widely in Argentina where two artificial recharge experiments have been conducted; in Jamaica where excess surface runoff is treated and discharged into sinkholes in karstic limestone aquifers; in India, where runoff from roof tops is passed through PVC pipes into an aquifer via a recharge well.

A field investigation in a semi-arid area of New Mexico found that capturing runoff from a hardscape area and diverting it into unlined retention ponds increased the recharge from about 1% to about 50% of mean annual precipitation, creating a groundwater mound beneath the ponds. JICA (1990) observed a groundwater mound around Sokoto town in the Rima Group Aquifers due to increased infiltration from Goronyo dam upstream of river Rima.

Groundwater recharge dams are also essential as source of aquifer replenishment (Abdalla and Al-Rawahi, 2012). Dams are widely used in Saudi Arabia, United Arab

Emirates and Oman, Syria and Jordan. There are many Dams in Nigeria and about three large Dams and one small earth Dam in Sokoto basin. The Gusau Dam was built purposely to capture and store excess runoff during rainy season for utilization in the dry season. Unfortunately, siltation has greatly reduced the storage capacity of the Dam and the water can only last for 2 – 3 month after rainy season. Large quantities of the surface water would otherwise have ended up flowing into the sea or into the desert areas or impermeable plains, all of which would promote water loss because of the small water infiltration capacity in these areas, relative to the volume of flowing surface water.

This research is suggesting that small earth dams should be built to capture excess runoff from the sealed surfaces and non- fractured hard rocks for use during the dry season. This will help not only in preventing the occurrence of flash floods but also alleviate the water shortage problems faced by the local people in the dry season.

This research has demonstrated the important role of forest in the overall water balance of the catchment, because of their high AET. Apart from high AET, forest also has a crucial role in the water balance of the basement complex areas by regulating the water flow. The forest ecosystems represent a major route through which water in soils and groundwater aquifers re-enters the hydrologic cycle. Surface runoff hardly occurs in the forest areas, and when it does, it usually reaches the river or fadama slowly with less devastating effect. Rainfall on forest landscape hardly has time to rest. Much is evaporated from the soil surface or sucked up by plant roots. Plants retain some of this water to hydrate their cells, but they let most of it escape through their leaves and back into the atmosphere as seen in the high AET amount in the model results.

The north-eastern part of Sokoto basin is threatened by desert encroachment. The method employed by community for reversing desertification is tree planting. The effect of tree planting in arid areas was however debated because trees may consume more water than they provide to the water cycle. The larger the area of forest landscape, the more water they transpire. In areas where trees utilize all the rainwater, it may be considered better to harvest this water through a bare watershed, store it in a reservoir and use it for water supply. In Yatir, Israel for example in the early 1960s, Rueff and

Schwartz (2007) reported that more than 3 000 ha of rain-fed forest were planted under a large-scale afforestation project while the average precipitation is only 270 mm/yr. Despite the benefits of this project to the livelihoods of nearby communities (e.g. source of fuel wood, fodder, medicinal and aromatic plants) and carbon sequestration, the forest uses all the rainfall water and altered the biodiversity of the region. The water used by the forest would alleviate the water scarcity and poverty better if it had been used for agriculture and not for afforestation.

The annual average rainfall in the study area is around 900 mm, sometimes falling to as low as 500 mm during low rainfall years. Despite large water loss through high AET from forest landscape, the forests in the study area improve the water cycle by reducing excess runoff and increasing infiltration. The annual tree planting campaigns by the government is a proposed way to increase rainfall in the region. It is estimated that 60 % of rainfall over the evergreen Amazon forest comes from the forest itself through evapotranspiration (TheAmazon.org, 2007; Avissar and Otte, 2007). The government should therefore employ strict measures through policies and laws that control both afforestation and deforestation in order to sustain the water cycle, hence, rainfall in the region. However, this should not be done to a large scale. The researcher suggested that a small-scale afforestation such as combining tree planting and agriculture will have a less consequences as this will improve agricultural yields, provides fuel wood and conserves water and soils for the farmers.

Other management options include:

Rainwater harvesting, which involves the accumulation and deposition of rainwater and runoff for reuse before it reaches the aquifer. The water collected from roof tops or runoff channels is redirected to a deep pit with percolation or large storage tanks. The harvested water can be used for drinking and other purposes like irrigation. Rainwater management, also known as harvesting, is receiving renewed attention as an alternative to or a means of augmenting water sources. Intercepting and collecting rainwater where it falls is a practice that extends back to pre-biblical times (Pereira et al., 2002). It was used 4,000 years ago in Palestine and Greece; in South Asia over the last 8,000 years (Pandey et al., 2003). This method provides an alternative or supplementary water supply during the rainy season and some part of the dry season. It provides water when there is a drought, can help mitigate flooding of low-lying areas, and reduces demand on wells which may enable ground water levels to be sustained.

Improved land management such as conservation tillage, mulching and cover cropping to maintain soil moisture and reduce water loss and better control of grazing is often seen as a beneficial practice in water resource management.

Conservation tillage is any method of soil cultivation that leaves the previous year's crop residue (such as corn stalks or wheat stubble) on fields before and after planting the next crop, to reduce soil erosion and runoff (Unger et al. 1988; Parr et al. 1990). Conservation tillage is especially suitable for erosion-prone cropland as it can reduce soil erosion by as much as 60 – 90 % depending on the method. Pieces of crop residue shield the soil particles from rain and wind until new plants produce a protective canopy over the soil. This method conserved water by reducing evaporation at the soil surface and also improves soil and water quality by adding organic matter as crop residue decomposes; this creates an open soil structure that lets water in more easily, reducing runoff.

The success of this method is however dependent on the control grazing within designated areas of the catchment. A large number of livestock (cows, camels, sheep and goats) roam everywhere within the catchment. These animals eat up everything they come across on their way and usually encroach into farmlands when they run out of food on their route. At the end of any cultivation season for example, farmers will be in haste to harvest and take home their produce (including the residue) for fear of being eaten by the nomadic herders. With this in mind, the success of this method will be very minimal.

Even though in some years the rains are poor within the Ka catchment and the land is not highly threatened by soil erosion, conservation tillage is still useful in reducing surface runoff and conserving soil moisture.

7.4. Conclusion

This research carried out a water balance of the basement complex area of the Sokoto basin, northwest Nigeria with the aim of improving the understanding of the hydrological behaviour of such basement catchment systems. The research used modelling with a variable landscape approach to compute the water balance of the region, taking into consideration the major hydrological processes and their spatial variability on the landscapes over time. A detailed conclusion about different aspects of these processes has been given at the end of individual chapters. The following is however a summary of the main contributions of this research to knowledge.

- The research 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 Sokoto basement complex catchment. They represent the towns, cultivated lands, sealed surfaces, hard rocks, forests and fadama landscapes.
- The research 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 research also developed a new computational model to estimate the water balance for the exposed hard rock areas. The behaviour of these varies between the areas of fractured and non- fractured rocks. While the hydrological processes in the fractured hard rock are dominated by high fissure outflow to the river (about 52 % of annual rainfall due to high fissure inflow and low actual evaporation), the processes in non- fractured hard rocks are mainly dominated by high runoff to the river, fadama and cultivated lands (about 73 % of annual rainfall due to minimal infiltration and low actual evaporation).
- Identifies and models the importance of the interconnectivity of individual landscapes through runoff-/run-on processes to the hydrological behaviour and water balance of the area. The river, fadama and cultivated II & IV landscapes receives additional run-on from other landscapes amounting to about 14 % of annual rainfall. The hydrological processes and human activities in these landscapes are highly dependent on the interconnectivity because it determines for example the likely areas to have good groundwater supplies (where there is

sufficient saprolite/saprock thickness) due to enhanced opportunities for recharge or potentially good cultivated lands with enhanced soil water contents due to the run-on. The fadama landscape plays a vital role in the catchment for food production and as a source of groundwater for domestic use and irrigation in the dry season.

- The hydrological behaviour of fadama and some cultivated lands are demonstrated to be highly influenced by the runoff-run-on interconnectivity. The additional run-on to cultivated lands II & IV for example results in the generation of much higher simulated runoff with about 212 mm/yr, compared to those cultivated lands (sub areas I & III) that do not receive run-on with about 145 mm/yr. The higher soil water contents arising from the run-on also allow modelled higher AET (about 813 mm/yr compared to 686 mm/yr). This is consistent with actual practices where the types of crops grown on these landscapes are mostly high water demand crops such as rice and maize, unlike in cultivated lands without run-on that supports only low water demanding crops such as millet.
- A method to compute the catchment water balance has been developed based on variable landscape approach that recognises the important spatial differences in the hydrological behaviour across the basement complex areas. The dominant hydrological processes are shown to differ between landscapes based on the surface characteristics e.g. AET is the dominant process in the forest landscape taking about 98 % of rainfall on the landscape and representing about 27 % of the overall water loss in the catchment water balance. Runoff however dominates the hydrological processes in the sealed surfaces (52 % of rainfall) and non- fractured rocks (73 % of rainfall); while groundwater outflow dominates the hydrological processes in the fractured hard rocks (52 % of rainfall).
- The research has improved the understanding of the hydrological behaviour of the basement complex region, suggesting that a unified rational approach to water resources planning and development that takes cognizance of actual hydrological behaviours of different landscape units is needed. The improved understanding of the hydrological behaviour of the basement complex areas

should inform 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. This will improve the livelihood of the people in the area through improved access to water during difficult times of the year.

7.5. Further investigation

i. Similar researches using the landscape approach should ensure that actual area sizes for the different landscape units are used due to continuous rapid change in the land use pattern.

ii. The fixed planting date of 3rd July chosen to represent all the years in the 37 year simulation is based on best assumption of rainfall onset in the region. However, this may not be true in real situation due to high variability in rainfall onset and cessation in the region. Future work should consider modifying the method to allow for input of different annual planting dates.

iii. Hargreaves method was used in this research to estimate the ETo due to limited data availability. Future research should consider using the standard FAO 56 Penman-Monteith with more dataset for better evaluation of the water balance in the catchment.

iv. Expansion of the plant parameter database is needed to support a greater range of vegetation scenarios that can be simulated in the model e.g. mixed cropping.

v. The runoff estimation in WaSim model was done using the SCS Curve number method. This method's credibility was questioned by the proponents of physically based models [e.g. Smith (1976); Rallison and Crunshy (1979); Chen (1982)] due of its simplicity and that the method has never been subjected to peer or journal review by anyone outside the SCS. A better method of runoff calculation should be used in the future.

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APPENDICES

APPENDIX A: general questions asked in the short structured interview during fieldwork

1. When does the rain usually start here
2. When does the rain stop
3. What types of crops do you grow
4. When does the planting start
5. When do you first weed your crops
6. When is the second weeding
7. What is the duration to harvest
8. Do you obtain good yields of crops every year
9. What is the duration of moisture holding in the soil after rainfall
10. Do floods occur and when
11. Duration the water stays on the surface after rainfall
12. Where do you think the water runs to?
13. Where are the sources of water supply for domestic and other uses during rainy
14. Where are the sources of water supply for domestic and other uses during dry season
15. Do you have any spring?
16. How long do the springs run within a year?
17. What is the typical depth of hand dug wells and boreholes in your area
18. Why do you think the depth of wells stop at that point
19. Do the wells supply water throughout the year

APPENDIX B: River stages at Gusau and Fokku with rainfall from Gusau station for the hydrological years 1976/77 and 1978/79

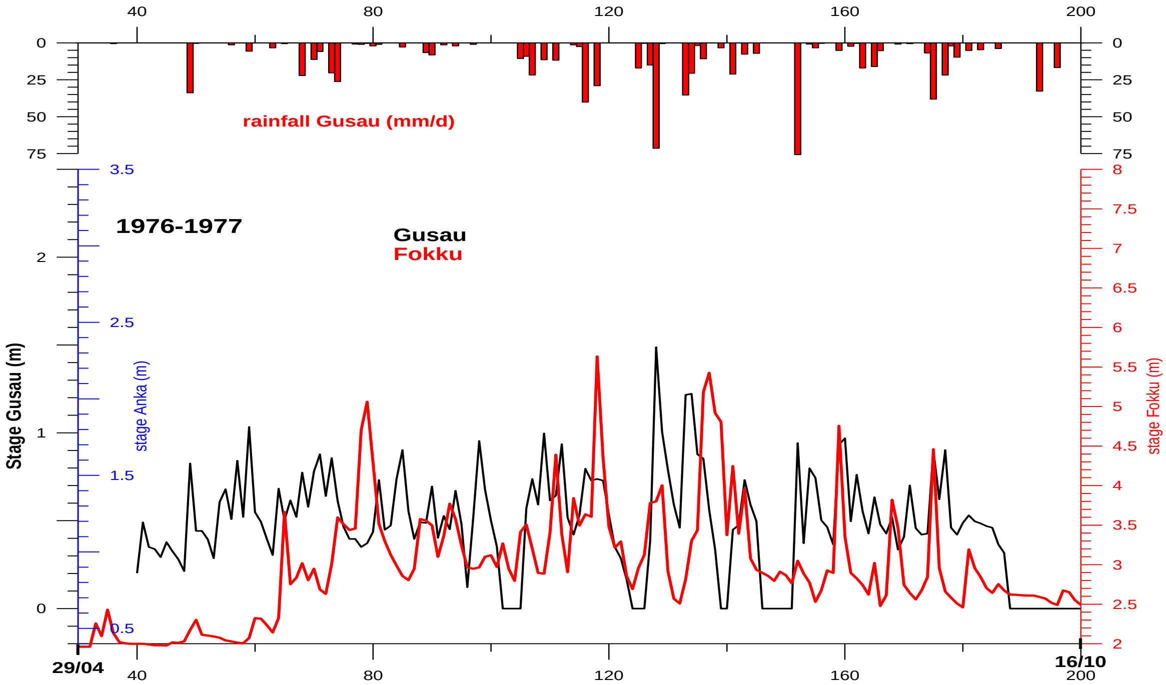

Figure B1: River stages at Gusau and Fokku with rainfall from Gusau station for the hydrological year 1976/77

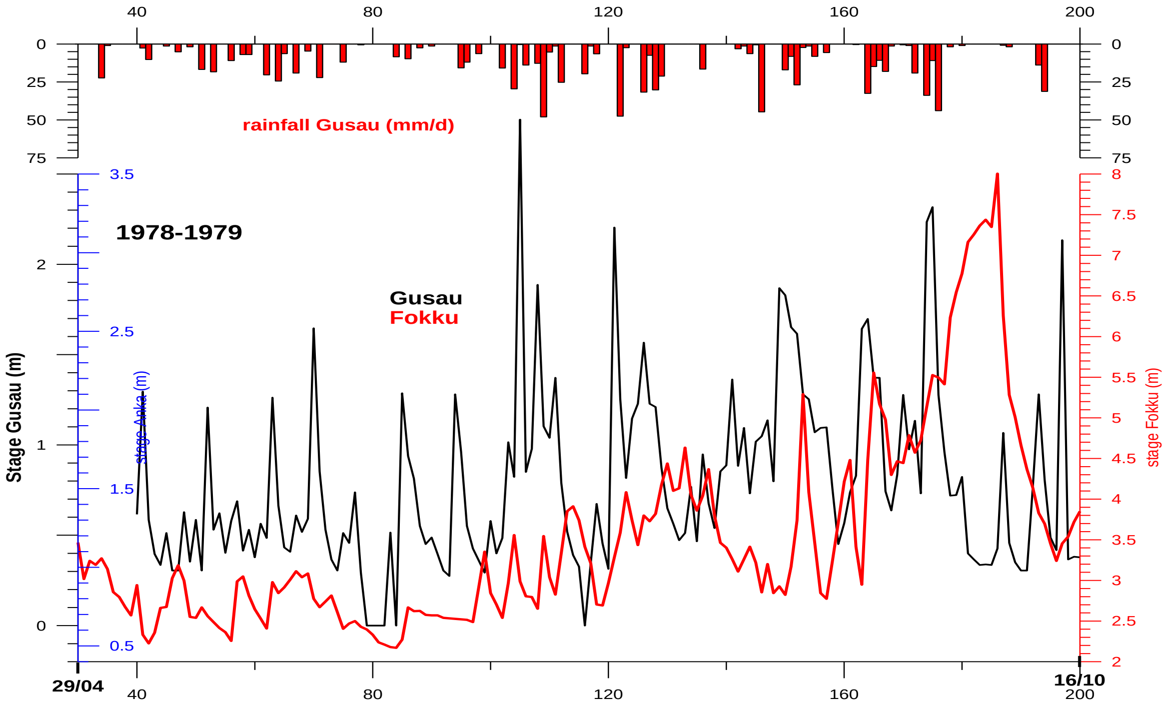

Figure B2: River stages at Gusau and Fokku with rainfall from Gusau station for the hydrological year 1978/79

APPENDIX C: Run-on weighting from hard rock to river, fadama and cultivated lands

The percentage flow contribution from hard rock to the cultivated lands is illustrated on the diagram in **Error! Reference source not found.** and estimated as follows:

Total Hard rock (HR) landscape area = 25 % distributed as shown in **Error! Reference ource not found.**. In the diagram, only hard rock II with PLA = 10 % contributes flow to cultivated areas (Cult) II and IV in addition to the fadama and river.

For HR II, total RF = 0.0375 + 0.0626 + 0.45 + 0.45

Of the outflow from hard rock II, 9/10 goes to cultivated landscapes of which half goes to Cult II and half goes to Cult IV.

So the RF = 4.5/10 = 0.45 of HR II outflow to Cult II and RF= 4.5/10 = 0.45 of HR II outflow to Cult IV. The AC = 10/5 = 2

RunF = 2.0 x 0.45 = 0.9

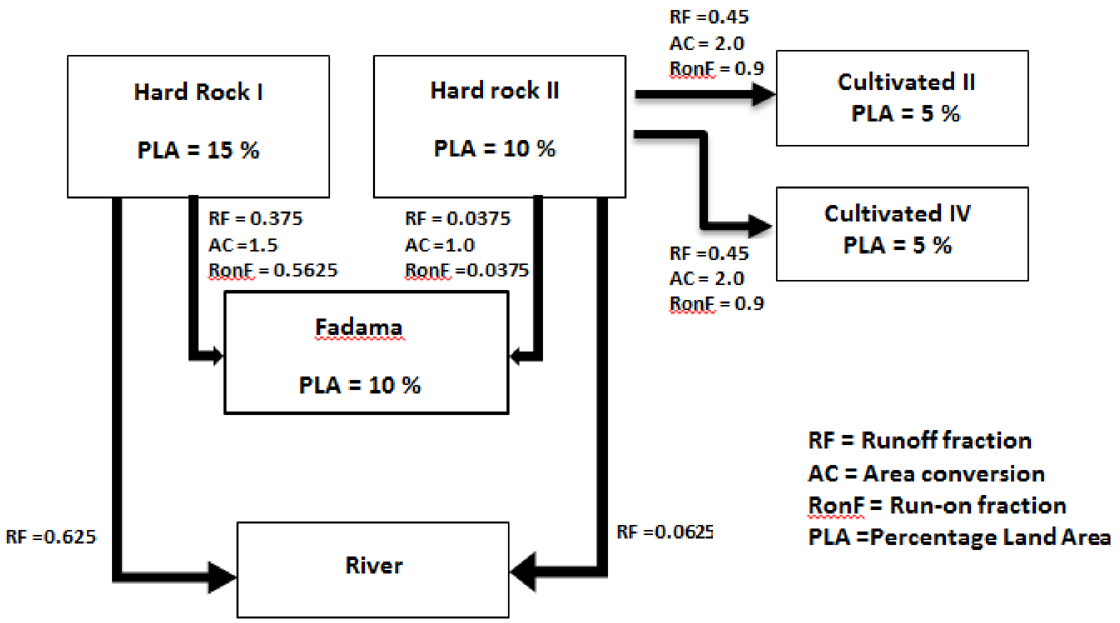

Figure 7.1: Area weighted run-on calculation from Hard rock Landscapes

Using the 12.57 mm runoff, the run-on to cultivated lands II & IV is calculated as follows:

Run-on to cultivated lands = 12.57 x 0.9 = 11.3 mm/d

The remaining 1/10 outflow from HR II goes to river and fadama, with 5/8 to the river and 3/8 to the fadama.

The distribution factor of HR II to the river is 0.0626 and to the fadama is 0.0375

The area conversion for the fadama = 10/10 = 1

Run-on factor for the fadama = 1 x (0.0375) = 0.0375

Run-on to the fadama = 12.57 x 0.0375 = 0.5 mm/d

Area conversion of the river is unity,

So the run-on weighing factor for the river = 1 x (0.0625) = 0.0625

Run-on to the river = 12.57 x 0.0625 = 0.8 mm/d

For the calculation of run-on weighting from HR I to the river and fadama, similar procedures such as that described in HR II are followed. The flow from HR I only goes to the river and fadama, with 5/8 to the river and 3/8 to the fadama respectively. The area conversion is obtained by dividing the area of HR I by the area of fadama;

AC = 15/10 = 1.5

Run-on weighting factor = 1.5 x (3/8) = 0.5625

For the river, the weighting factor = 1 x (5/8) = 0.625

Again using the 12.57 mm runoff as an example,

Run-on to the fadama = 12.57 x 0.5625 = 7 mm/d

Run-on to the river = 12.57 x 0.625 = 7.9 mm/d