UNIVERSITE D'ABOMEY - CALAVI (UAC)

INSTITUT NATIONAL DE L'EAU

Federal Ministry of Education and Research

WASCAL

West African Science Service Center on Climate Change and Adapted Land Use

Registered under N°: ……./UAC/VR-AARU/SA

A DISSERTATION

Submitted

In partial fulfillment of the requirements for the degree of

DOCTOR of Philosophy (PhD) of the University of Abomey-Calavi (Benin Republic)

In the framework of the

Graduate Research Program on Climate Change and Water Resources (GRP-CCWR)

By

AZUKA, Chukwuebuka Vincent

Public defense on: 12/15/2016

RAINFALL-RUNOFF PROCESSES AND SPATIAL VARIABILITY OF SOIL PROPERTIES OF THE KOUPENDRI CATCHMENT IN NORTH-WEST BENIN, WEST AFRICA UNDER DIFFERENT LAND USE/LAND COVER.

======

Supervisors:

IGUE, A. M.**,** Full Prof., National Institute of Agricultural Research, Benin.
Bernd Diekkrüger, Full Prof., Institute of Geography, University of Bonn, Germany.

JURY

Prof. Dr. Ir. Euloge K. Agbossou, University of Abomey-Calavi, Benin **President**
Prof. A.M. Igue, National Institute of Agricultural Research, Benin. **Supervisor**
Prof. Abel Afouda, University of Abomey-Calavi, Benin. **Rapporteur**
Prof. Kwasi Preko, Kwame Nkrumah University of Science and Technology, Ghana **Rapporteur**
Associate Prof. Julien Adounkpe, University of Abomey-Calavi, Benin. **Examiner**

Dedication

This work is dedicated first and foremost to the almighty God for giving me strength and wisdom to carry out and completed this research. To my late father and the entire family members especially my beloved wife-Ugochinyere, I salute your courage for believing so much in me, and unflinchingly supported me throughout this program.

Acknowledgement

This PhD work is realized in the framework of the West African Science Service Center on Climate Change and AAdapted Land use (WASCAL) and funded by the German Ministry of Education and Research (BMBF) in collaboration with the Benin Ministry of High Education and Scientific Research (MESRS)).

My special thanks goes to my supervisors Prof. A.M. Igué and Prof. B. Diekkrüger their painstaken efforts during this research work. Prof. A.M. Igué supported me greatly and even accompanied me to the field during the field soil survey. Prof. B. Diekkrüger took interest in this work and showed his readiness each time I approached him to discuss with me some of the problems and challenges that I faced and proffering possible solutions to them.

I will also like to thank the Hydrology research group (HRG) especially Gero Steup, Yira Yacouba, Aymar Bossa and Felix Opt for their efforts during the installation of climate, gauge and soil moisture stations in Koupendri catchment where this research was carried out.

I will not fail to mention the Dassari Basin coordinator Adolphe Avocanh for providing me with wonderful logistics during my field work, and my field assistants; Denis, Prudentio and Alaza who helped during data collection especially during my research trip to University of Bonn, Germany.

A lot of people also contributed to seeing that this research work was a success. These include Dr. Ozias Hounkpatin, Dr. Djafarou, Dr. Moris, and my colleagues especially Dr. Ganiyu Oyerinde, Dr. Jean Hounkpe, Dr. Felicien Badou, Dr. Biao Eliezar and Dr. Garba Charlene. Dr. Lawin was willing to discuss my research work and also gave me tailor-made advise on how to improve the work.

Special mention to the wonderful time I had with friends and colleagues from the WASCAL Climate Change and water resources GRP and the entire WASCAL staff at Universite D'Abomey-calavi. Special thanks to Prof. Abel Afouda, Dr. Julien Adounkpe, Emelda, and Salem for the good time we had in Abomey-Calavi. Indeed, it was a great experience! Thank you for making my stay those days filled with precious memories.

I am grateful to the University of Nigeria, Nsukka for giving me a good platform and also granting me a study leave in order to participate in this program.

I will not conclude if I do not mention my amiable wife, my mother and my wonderful siblings who held on with me and endured my absence. I enjoyed your wonderful support.

Abstract

Soil is an important input data in most hydrological modeling. A detailed (1:25000) soil survey and soil classification was done using SOTER (SOil and TERrain) approach. Data on both morphological (color, structure, mottles e.t.c), physical (texture, bulk density (BD) and saturated hydraulic conductivity (Ksat)), and chemical properties (soil organic carbon (SOC), cation exchange capacity (CEC), total nitrogen (TN), available phosphorus (Avail.P), carbon-nitrogen ratio (C:N) e.t.c) were obtained. 180 surface soil (0-20 cm) samples were collected in a grid resolution of 25 m x 25 m and supplemented with additional 116 samples at 5 m x 5 m resolution within the grid across three land use types (maize-sorghum cropland (MS), rice field and fallow-shrub-grassland (FSG)) to evaluate spatial variability of soil properties. These samples were analyzed using standard laboratory procedures. Further data analysis using simple statistical and geostatistical tools and Pearsons's correlation analysis were performed. The soil map of the catchment showed five distinct soil types, belonging to three major soil orders namely: Ultisols, Inceptisols and Alfisols (USDA), and four reference soil groups: Plinthosols, Cambisols, Luvisols and Gleysols (WRB). More than 55 % of the soils were mainly Plinthosols, highly degraded, acidic in nature and low in nutrient with low soil water retention capacity. The variability was high for Ksat, moderate for SOC, Avail.P and C:N, but low for TN, BD. SOC showed the strongest spatial dependence (0-5.3%) across the three land use. The spatial dependence, pattern and distribution of the soil properties were influenced by land use and soil management practices but independent of individual property or geology. Six microplots (1m x 1m) for measuring surface runoff were installed on each of the two slope positions and each of the two land use types. Moreso, infiltration runs, soil samples and soil moisture measurements were done in triplicates. The suitability of a conceptual model (NRCS-CN) to capture plot-scale rainfall-runoff processes was tested. To understand rainfall-runoff processes at the catchment scale, WaSiM model was calibrated and validated using the most sensitive and the optimized soil, land use and unsaturated zone parameters. Surface runoff coefficient for the microplots and the catchment were computed and compared. Soil hydrologic properties (infiltration rate, soil moisture, surface runoff and saturated hydraulic conductivity) were influenced by land use and slope position though little disparity exists between the laboratory and the in situ determined values. Both total and event-based plot scale surface runoff were high and significantly ($p < 0.05$) influenced by the land use. Runoff coefficient at plot scale (0.3-0.9 %) compared to the catchment scale (0-0.6 %) revealed strong scale issues. NRCS-CN simulation captured the dynamics of the plot-scale rainfall-runoff processes (R^2= 0.84 -0.97; ME= 0.56-0.91) with slight over-and-underestimation of peak and low flows. The model WaSiM was successfully calibrated (NSE=0.61, R2=0.61, RMSE= 0.63) with acceptable uncertainty range or value (P-factor = 94%; r-factor = 0.93), and also validated (NSE=0.68, R2=0.78, RMSE= 0.57) for the Koupendri catchment. The result was satisfactory and showed strong agreement between the modeled and the observed data. Direct flow was the dominant runoff (more than 85 % of the total runoff) component in the catchment. The water balance reflected the hydro-climatic condition of the catchment with real evapotranspiration ranging between 68 % and 75 % of the total annual rainfall.

Keywords: Soil classification, geostatistics, microplot, hydrological properties, rainfall-runoff.

Résumé

Le sol est une donnée d'entrée importante dans la plupart des modèles hydrologiques. Une enquête détaillée sur les sols (1: 25 000) et la classification des sols ont été effectuées à l'aide de l'approche SOTER (sol et TERrain). Des données sur les propriétés morphologique (couleur, structure, présence de tâches indicatrice de réaction oxydoréduction etc.), physique (texture, densité apparente (DA) et conductivité hydraulique à saturation (Ksat)), et chimique (teneur en carbone organique (SOC), capacité d'échange cationique (CEC), etc.) on été collectées. 180 échantillons de sol on été prélevés (0-20 cm) à l'intérieur des mailles de 25m x 25m et complété avec 116 par un échantillonnage à une échelle plus fine (5m x 5m) sur trois types d'occupation de terre (champs de mais-sorgho (MS), rizières, et jachères-prairies-formations arbustives (FSG)) afin d'évaluer la variabilite spatiale des propriétés du sol. Ces échantillons ont été analysés au laboratoire suivant les procédures conventionnelles. Le traitement des données a été fait à partir d'outils statistiques standards, de méthodes géostatistiques et de la corrélation de Pearson. La carte de sol du bassin montre cinq différents types de sols appartenant à trois principaux ordres: Ultisols, Inceptisols and Alfisols (USDA) et quatre groupes de sol: Plinthosols, Cambisols, Luvisols et Geysols (WRB). Plus de 65% des sols sont Plinthosols, profondément dégradés, acides avec de faibles teneurs en nutriments et en capacité de rétention en eau. La variabilite est grande pour le Ksat, moyenne pour le SOC, le phosphore disponible et le rapport carbone/azote, et faible pour l'azote totale et la DA. Le SOC est associé à la plus grande dépendance spatiale en fonction du type d'occupation de terre. La dépendance spatiale et la distribution des propriétés de sol sont influencés par les pratiques de gestion du sol mais indépendants des propriétés du sol elles-mêmes ou de la géologie.Six micro-parcelles (1m x 1m) de mesure du ruissellement de surface ont été installés sur chacune des deux positions de pente et sur chacun des deux types d'utilisation des terres. Aussi, les essais d'infiltration, les échantillons de sol et les mesures d'humidité du sol ont été effectués en trois exemplaires. L'adéquation d'un modèle conceptuel (NRCS-CN) pour la simulation de l'impact de la position des pentes et du type d'occupations des terres sur la relation pluie-débit à l'échelle de la parcelle a été testée. Afin de comprendre cette relation a l'échelle du bassin, le modèle WaSiM a été calibré et validé avec des paramètres de sol, du type d'occupation des terres et de la zone non-saturée Les écoulements de surface à l'échelle de la parcelle et à l'échelle du bassin ont été comparés. Bien qu'une petite disparité existe entre les données du terrain et celles du laboratoire, il a été constaté que les propriétés hydrologiques du sol (taux d'infiltration, humidité du sol, écoulement superficiel et conductivité hydraulique saturée) sont influencées par le type d'occupations des terres et par la position des pentes. A l'échelle de la parcelle, l'écoulement de surface total et événementiel est important et significativement ($p<0.05$) influencé par le type d'occupation des terres. L'écoulement de surface à l'échelle de la parcelle (0.3-0.9%) et à l'échelle du bassin (0-0.4 %) soulève la problématique liée à l'échelle spatiale considérée pour analyser les processus hydrologiques. Le modèle NRCS-CN reproduit très bien (R^2=0.84 -0.97; ME=0.56-0.91) la dynamique de la relation pluie-débit à l'échelle de la parcelle mais surestime et sous-estime quelques peu les pics et des étiages. Le model WaSiM a été calibré (NSE=0.61, R2=0.61, RMSE= 0.63) et validé (NSE=0.68, R2=0.78, RMSE= 0.57) avec succès pour le bassin du Koupendri. Les incertitudes ont été évaluées avec un p-factor de 94% et un r-factor de 0.93 indiquant un intervalle acceptable d'incertitude. Les résultats montrent qu'il y a une bonne superposition entre les courbes des débits simules et des débits observes même si le model sous-estime quelque fois les picsL'écoulement de surface est la principale composante du débit (plus de 85% de l'écoulement

total) indiquant un dépassement de la capacité d’infiltration du sol ou un écoulement Hortonien comme le mécanisme de production du débit dans le bassin

Table of contents

List of Figures

List of Tables

List of Plates

List of Abbreviations

AFES	A Sound Reference Base for Soils
ANOVA	Analysis of Variance
CEC	Cation Exchange Capacity [cmol/kg]
CPCS	Commission de Pédologie et de Cartographie des Sols
DEM	Digital Elevation Model
ETR	Actual or Real Evapotranspiration
ETpot	Potential Evapotranspiration
FAO	Food and Agriculture Organization of the United Nations
GLOWA	Globaler Wandel des Wasserkreislaufs
IMPETUS	Integrative management project for an efficient and sustainable use of freshwater resources in West Africa
INRAB	National Institute of Agricultural Research, Benin (Institut National des Recherches Agricoles du Bénin)
ISRIC	International Soil Reference and Information Centre
IUSS	International Union of Soil Science
Ksat	Saturated hydraulic conductivity.
LAI	Leaf Area Index
LSSEE	Laboratoire des Sciences de Sols, Eaux et Environnement (Laboratory of Soil Sciences, Water and Environment)
ME	Model efficiency
RCBD	Randomized Complete Block Design
NCS-CN	National Conservation Service-Curve Number
NRCS-CN	Natural Resources Conservation Service-Curve Number
ORSTOM	Office de la Recherché Scientifique et Technique d'Outre-Mer
SOC	Soil Organic Carbon
SOTER	SOil and TERrain
SWAT	Soil and Water Assessment Tool
UNESCO	United Nations Education Scientific and Cultural Organization
UNDP	United Nations Development Programme
UNEP	United Nations Environmental Programme
USDA	United State Department of Agriculture
WASCAL	West African Science Service Center on Climate and Adapted Land use
WaSiM	Water Balance Simulation model
WRB	World Reference Base for Soil Resources
95%PU	95 percent prediction uncertainties

Chapter 1

General Introduction

One serious challenge confronting hydrologist and water managers around the world has been how to sustainably manage and protect catchment resources and the environment (Jones *et al*., 2001; Yasin and Clemente, 2014). Such decisions on sustainable water resources management require sound scientific information on rainfall-runoff processes. A rainfall-runoff process which relates the amount of discharge produced by a catchment in response to rainfall and catchment characteristics play significant roles in the hydrological cycle. Rainfall-runoff process is influenced by the increasing climate (rainfall) variability and fluctuations in West Africa where a strong decrease (-25%) in rainfall has been reported (Bonell, 2004). Consequently, this has resulted to reduced discharge and water shortages for domestic and agricultural purposes and also, poses a serious threat to sustainable development (Speth et al., (2010)). River discharge is affected by several drivers such as land use changes, water withdrawals and climate variations (Roudier *et al*., 2014). Global hydrological cycle and ecosystem functions are dependent on the complex interactions between soil, vegetation, and the atmosphere (Miller *et al*., 2007).

Recently, concerns about soil data availability for hydrological modeling have risen due to the impact of global warming on water resources. Soil properties and their spatial distribution influences most land surface processes and patterns of hydrological processes (Grayson and Blöschl, 2001) such as runoff generation, groundwater recharge, and infiltration and water retention characteristics. Thus, characterizing the soils will enhance our understanding of the complex land surface-atmosphere interactions especially the hydrological processes (Anguela *et al*., 2008). The classification and characterization of soils are done through soil survey involving examination and description of the soil in the field. While a detailed soil survey gives the inventory of the soils found in an area, their distribution and variability are expressed and quantified using both classical and geostatistical tools. These geostatistical tools e.g kriging and co-kriging has been a powerful tool for assessing soil spatial variability. Recently, this tool has received widespread utilization by soil scientists and agricultural engineers (Webster and Oliver, 2007; Iqbal et al., 2005).

In West Africa, high impact of climate and land use change on hydrological processes has been reported (Kasei, 2010, Giertz *et al.*, 2010; Götzinger, 2007, Jung, 2006, Busche *et al.*, 2005). Hydrologists always place high consideration on the hydrological consequences of land use change, from both monitoring and modeling perspectives (Bosch and Hewlett, 1982; Liu, *et al*., 2012; Mendoza *et al*., 2010; Niehoff, 2002; Nejadhashemi *et al*., 2011). This is mainly because of their influence on the water resources availability and on the different hydrological components and processes like interception, infiltration, albedo and evaporation (Scanlon et al., 2007; Rientjes et al., 2011) resulting to increased runoff generation and stream flow regime. Bonell (2004) reported decreased infiltrability and increased runoff coefficients due to the destruction of the top soil layers caused by forest clearance and increased agricultural activities in sahelo-sudanian areas. Also, increased Hortonian runoff caused by the modification of soil properties and infiltration capacity as a result of deforestation has been observed (Leblanc *et al*., 2008). Thus, there is need to understand land use and land cover effects on soil (hydraulic) properties and their variability, and catchment hydrology for its sustainable management, conservation of ecosystem services and reduction of negative downstream impacts.

1.1 Context and problem statement

Most hydrological and land use change studies employ multi-modeling approach and only vary the spatial distribution of the vegetation cover on basin or in-land valley hydrology (Cornelissen et al., 2013; Fohrer *et al*., 2002). However, the key variable such as soil (hydrological) properties that drive hydrological processes are sometimes not measured and this limits the applicability of such models. The reason is well known and mostly associated with the limited time and high cost of field measurements and obtaining soil data. Until now, there is no detailed soil data for hydrological modeling in Koupendri catchment. The only available soil map was produced by ORSTOM (UNEP-GEF Volta Project, 2008) at scales (1:200.000, 1:250.000 and 1:500.000) considered too coarse to capture detail soil distribution needed for understanding the hydrological processes of this small catchment (11.8 km^2). In other to increase our knowledge and reliability of conclusions drawn from most hydrological modeling, investigating the hydrological processes from the local or point to the catchment scale may reveal some important facts. Such studies required detailed investigation and acquisition of soil data at the local scale. This has not been considered in the previous studies. Therefore, this study tends to bridge this gap and generate data on soil hydrologic properties required for modeling the catchment hydrological processes.

1.2 Literature review

1.2.1: Importance of soil properties and their variability in hydrological modeling

Hydrological modeling and sound decisions on soil and water resources management require soil data as inputs. The catchment soil properties influences the spatial patterns of water flow paths and storage (e.g. Grayson and Blöschl, 2001; Uhlenbrook et al., 2004; Weiler and Naef, 2003). Thus, the knowledge of the physical and hydrological properties of soils is a necessary for rainfall-runoff modeling and hydrological studies (Albertson and Kiely, 2001; Herbst *et al.,* 2006a). Soils exhibit vertical and horizontal variability linked to topography or relief, geology and climatic characteristics that led to its formation. This in turn determines different management areas, use and productivity of soils especially for precision agriculture and natural resource management (Mello *et al.,* 2006; Wang et al., 2009). Nearly all distributed hydrological models require input of spatially resolved soil properties. Modeling the hydrological processes and land use change is highly dependent on the accuracy and the understanding of the soil data. Accurate data on soil properties and understanding of its heterogeneity for hydrological modeling can be generated through detailed soil survey and described using appropriate soil classification system and/or taxonomy. The available soil maps for the catchment were those produced by the ORSTOM at the scale of 1:200.000, 1:250.000 and 1:500.000. Also, the recent SOTER map of Benin at a scale of 1:200.000 (Igue, 2000; Weller, 2002) covered only the south and central part of Benin while the Northern part is yet to be completed. Besides not covering the study area, these two soil maps were produced on scales considered too coarse and difficult to capture the heterogeneity of soil properties at local/catchment scale. It is worthy to note that in view of the high cost of soil survey, soil descriptions should be made as detailed and comprehensive as possible so that the information can serve multiple purposes (FAO, 2006). This alone underscores the relevance of this study aimed at overcoming the above limitation or challenge of the past soil surveys.

1.2.2 Land use/land cover and soil hydrological properties

Land cover is defined as the biophysical state of the earth’s surface and immediate subsurface including the type of vegetation (forest, cropland, pastures e.t.c.) that covers the land surface, wetlands, soils, biodiversity, surfaces, and groundwater, as well as human structures, such as buildings, roads or pavement (Di Gregorio and Jansen, 2000; Turner *et al*., 1990). Land use involves both the manner in which the biophysical attributes of the land are used or manipulated by humans and the intent underlying such manipulation i.e. the purpose or function for which land is used by the population (Cihlar and Jansen, 2001; Turner *et al*., 1990). In other words, land use describes the human activities that are directly related to land, making use of its resources or having an impact on them. It has been widely recognized that the vegetation plays an important role in the modulation of the earth's climate and hydrological system (Dale, 1997). The hydrological processes of catchments are strongly regulated by the vegetation and land use or land cover (Gao *et al.,* 2009). Vegetation cover is an important variable in the hydrological cycle as it is the medium through which rainfall must pass to reach the soil and begin the journey back to the sea. The need for new agricultural land was a strong argument for the extensive clearing of natural vegetation (Ungaro *et al*., 2004). Also, the need to provide food, water, fiber, and shelter to more than six billion people drives worldwide changes to forests, farmlands e.t.c (Foley, 2005). It has been reported that the existing high rate of deforestation and degradation of vegetative cover may have a serious effect on soil and water resources (UNEP, 2003). The recurrent droughts, severe soil erosion, sedimentation of reservoirs and water bodies, soil quality deterioration, surface- and ground-water resource reduction and biodiversity loss are some of the problems related to deforestation and vegetation clearance (Asefa *et al.,* 2003; Lemenih *et al.,* 2005). Land cover plays a key role in controlling the hydrologic response of watersheds in a number of important ways (Schilling et al., 2008; Mao and Cherkauer 2009; Elfert and Bormann, 2010; and Ghaffari *et al.,* 2010). Changes in land cover can lead to significant changes in leaf area index, evapotranspiration (Mao and Cherkauer, 2009), soil moisture content and infiltration capacity (Fu *et al.,* 2000; Costa *et al.,* 2003), surface and subsurface flow regimes including base flow contributions to streams (Tu, 2009) and recharge, surface roughness (Feddema *et al.,* 2005), runoff (Burch *et al.,* 1987) as well as soil erosion through complex interactions among vegetation, soils, geology, terrain and climate processes. Evapotranspiration decrease in catchments caused by deforestation results in intensified runoff in a short timescale (Eamus *et al.,* 2006). Also, degradation of vegetation cover will lead to serious reductions in humidity, soil moisture and retentiveness and groundwater recharge. Ultimately, deforestation, especially in the low-medium precipitation and high temperature regions, leads to destabilization of the water cycle, increased incidents of droughts and floods, and in a long-term perspective to desertification and decrease of water yield (Harper *et al.,* 2008).

Soil physical and hydrological properties are related to vegetation type, and vegetation conversion can alter these properties. Shukla (2003) reported that changes in land use could affect the physical, chemical and biological characteristics of the soil. Land use type influences the infiltration capacity which has a direct influence on surface runoff and on hydrological regime of rivers, and lower catchment areas. Yimer *et al.,* 2008 reported a decline in infiltration capacity and soil moisture content after conversion of forest to cultivation and grazing land. Upon conversion of natural lands to cultivated fields, water retention capacity is strongly influenced (Schwartz *et al*., 2000; Bormann and Klaassen, 2008; Zhou *et al*., 2008). The knowledge of water retention capacity and land use effects on this property is important for efficient soil and water management. Soil water retention characteristics is affected by soil organic matter (SOM) content and porosity, which are significantly influenced by land use type (Zhou *et al*., 2008). Ndiaye *et al.*, (2007) has shown that improper soil management decreases the soil macroporosity in the long-term affecting the soil moisture (θs). Agricultural land use reduces the secondary pore system significantly, resulting in increased surface runoff (Germer *et al.,* 2010).

1.2.3: Soil survey and classification

Soil exist as a mixture of individual separates such as gravel, sand, silt, clay or organic matter in varying proportions which influences their characteristics or behaviour. Soil survey involves making inventory of the various kinds of soil that occur on a given landscape or region. Thus, it helps to gain the knowledge of the spatial arrangement and distribution of the kinds of soils that occur on the landscape which are important for land use planning and management (FAO, 2006). Boundaries are drawn around different kinds of soil to produce a soil map of the landscape/region. Although, soils within a boundary cannot be homogenous and pure, the purity of a mapped soil increases with the intensity (or detail) of the survey. In a soil survey, a detailed description is kept of each kind of soil that is mapped. Naturally, soils are organized into layers called horizons which differ from each other above or below it. Each horizon is designated by its depth, colour, particle size distribution, structure, consistency, pore size distribution, quantity of roots and other features. The organization of our knowledge about soils to predict their behavior and performance is termed soil classification. This enables us to organize our knowledge about soils and simplify our decision making with regard to management and use of different soils. The exchange of soil information found in different areas was made possible by the different soil classification systems developed by scientists for grouping soils with similar properties into one class. Dokuchaev, a Russian geologist initiated the scientific classification of soils by relating soil characteristics to soil formation (genetic principle). Other classification systems that evolved afterwards depend on this zonality concept. This concept was later found inadequate for soil description and a new concept, US soil Taxonomy was developed (Soil Survey Staff, 1975; Buol et al., 2003). Other commonly used soil classification schemes include; the FAO classification (FAO, 1974; 1986), the world reference base (WRB) for soil resources (IUSS Working Group WRB, 2006, 2014) and the French (ORSTOM) classification mostly used by the Francophone countries of West Africa (CPCS, 1967).

1.2.4 Soil classification systems

Numerous soil classification systems have evolved for classification of soils. A few of such classification systems are considered and reviewed below;

The U.S. soil taxonomy

This has been described as the best and most comprehensive soil classification of the world. It gained international recognition at the world congress of soil science in 2014 (IUSS Working Group, 2006, 2014). It focuses on quantitatively measured soil properties instead of on soil-forming processes or factors. The U.S. Soil Taxonomy is broadly sub-divided into six levels; orders, suborders, great groups, sub-groups, families and series (Soil Survey Staff, 1999). Table 1 indicates the general structure of Soil Taxonomy with its six Categories – Orders to Series (Pavel et al., 2009). The Order may be defined as soils having properties or conditions resulting from, or reflecting, major soil-forming processes that are sufficiently stable in a pedologic sense (Arnold and Eswaran, 2003). The Suborder category may be defined as soils within an Order class having additional properties or conditions that have major controls, or reflect such controls, on the current set of soil-forming processes. At this level, more dynamic features are selected as evidence of influence on pedogenesis (Pavel et al., 2009). The Great Groups are soils within a Suborder having additional properties that constitute subordinate or additional controls, or reflect such controls on the current set of soil-forming processes. Consequently, classes of Suborders provide additional information useful for interpreting soil behaviour in various landscape settings. The Subgroups are more complicated as they are soils within a Great Group having additional properties resulting from a blending or overlapping of sets of processes in space and time that cause one kind of soil to develop from, or towards another kind of soil. These include; classes of intergrades with linkages to other Great Groups, Suborders, or Orders and, extragrades, having sets of processes or conditions that had not been recognized as diagnostic for any class at a higher level, including nonsoil features. Families are soils within a Subgroup having properties that often are indicative of the potential for further pedogenic development. Such properties are often chemical and physical characteristics with less capacity to change due to use and management e.g. soil textures, mineralogy, soil moisture and temperature regime variability and clay activity e.t.c.

Details of soil series classification are not shown in the primary structure of Soil Taxonomy or its Keys as they pertain to many properties not applied in higher level classes, such as horizon thickness, colours, structural units, in-place biological features, and other information about the parent materials present in the family class. The placement into most taxa is made based on the presence of certain diagnostic horizons, materials and properties in a soil profile defined and determined quantitatively through both analytical and field observations. The use of quantitative criteria allows even a non-specialist to name a soil, if necessary information on the profile is available. A peculiarity of the US Soil Taxonomy is that it is climate oriented and thus requires measured or estimated information on water and temperature regimes of soils. The USDA soil classification system, soil taxonomy, can be said to be a multi-categoric based on soil profile properties, with a genetic bias. Each category is an aggregate of taxa defined at about the same level of abstraction with the smallest number of classes in the highest category and the largest number in the lowest category. For detailed work, the family and series categories are most appropriate since both are distinguished on the basis of properties selected to make taxa more homogenous for practical uses of soils (Pavel et al., 2009).

The FAO/UNESCO system

This system was mainly tool for preparing small-scale soil map of the world and not a comprehensive system of soil classification. Like most soil classification systems, it was developed to serve as basis for making comparisons between various systems but not to replace national classification system (FAO, 1974). It was originally a soil legend correlating the variety of soil surveys throughout the world to a common soil map of the world. The initial legend has 106 units classified into 26 groupings while the revised legend has 28 major soil groupings subdivided at the second level into 153 soil units (FAO, 1974; 1988). The soil units correspond roughly to great groups from the USDA Soil Taxonomy, while larger main grouping are similar to the USDA soil suborder. The soil map of Africa published by FAO in 1986 show that all African soils were grouped into 10 soil associations with Yermosols, Xerosols and Luvisols occupying about one-third of Africa's land area.

Table 1.1: The structure of the US soil taxonomy

Level	Taxon name	Taxon characteristics	Borders between classes	Diagnostics	Terminology
0	Soils	Kingdom			
1	Order	Collective	Formal	Chemico-morphological and regimes	Artificial
2	Suborder	Collective	Formal	Regimes & morphological	Artificial
3	Great group	Generic 1	Formal	Chemico-morphological	Artificial
4	Subgroup	Specific Varietal	Formal	Chemico-morphological	Artificial
5	Family	Specific Varietal	Formal	Chemico-mineralogical	Mixed
6	Series	Generic 2	Formal	Chemico-morphological	Traditional

Pavel *et al*., (2009).

The French system (ORSTOM/INRA)

This system of classification is a natural, hierarchical system that is based on principle of soil evolution and the degree of evolution of soil profile as a whole. In this system, the object of soil investigation – soil mantles (Couverture Pédologique) are defined as real natural three-dimensional bodies while the soil section (solum) is a conceptual two-dimensional cut of soil mantle (Pavel et al., 2009). The idea of a soil reference is the basic one in French classification, and serves as an archetype of certain soil. The four main levels or hierarchies recognized by the French classification system are classes, subclasses, groups and subgroups. The classes and subclasses were mainly collective levels. The classes partly reflected the stage of soil evolution, and partly general trends of soil-forming processes. The subclasses were grouped by various criteria, commonly by climatic conditions of soil formation. The level of groups was generic, though some groups were more specific particularly about soil structure. This system was later modified and adapted for use in the tropical regions by the French pedologists ORSTOM (Office de la Recherché Scientifique et Technique d'Outre-Mer) (Segalen et al., 1979) now Institut français de recherche scientifique pour le développement en coopération. However, a new French soil classification created by the French association for soil investigation (AFES) and declared non-hierarchical was published in 1990 under the name Référentiel Pédologique (Pavel et al., 2009). This was later reworked and printed in 1993 to suit the classification of the soils of Europe while the latest version suitable for the classification of the soils of the world over was published in 1995 (AFES, 1998). This new classification system proposes the use of qualifiers which allows naming soils in a more precise manner (Pavel *et al*., 2009). This to a great extent makes the structure of the French classification system look very similar to that of WRB (IUSS Working Group WRB, 2014; 2014). Although the Référentiel Pédologique was declared not to be a hierarchical taxanomy (AFES, 1998), the system still put emphasis on climatic zonation rather than lithogenic influences.

The world reference base for soil resources (WRB)

This was developed under the auspices of the International Union of Soil Science, by building on the foundations of the FAO legend. The aim is to harmonize soil classification systems and establish a standard for summarizing and correlating the wealth of soil resources of different countries (IUSS working Group, 2006). Though a comprehensive classification system, it was not intended to replace national soil classification systems but to accommodates them and serves as a basis for communication at international level (IUSS Working Group, 2006; 2014). The legend of FAO-UNESCO Soil Map of the World strongly influenced the structure of WRB (FAO, 1974, FAO, 1988; 1991). It serves both as a correlating, communication, inventory and monitoring tools for the world's soil resources. One major and most important recent change in the WRB is that the sequences of qualifier, including the rules for its usage are now suitable for classifying soils and creating map legends (IUSS Working Group, 2014).

The soil classification is based on measurable and observable soil features or properties in the field such as diagnostic horizons; diagnostic properties and diagnostic materials. These features must account for their relationship with soil forming processes and thus contribute to a better characterization of soils.

Objective criteria derived from both field inspections and laboratory results of the soil are integrated and used for systematic classification of different soil types into a Reference Group with specific characteristics denoted through the use of prefixes and suffixes. Thus, it involves a two-phase soil classification system of soil made up 32 Major Soil Groups or Reference Soil Groups (RSGs) and over 120 well defined qualifiers for specific soil characteristics or classification. The structure of WRB list the possible principal and supplementary qualifiers for each RSG from which the second level of the classification is constructed. Unlike the supplementary qualifiers, the principal qualifiers are given in a priority sequence. The underlying principles governing the WRB class differentiation are:

At the *first level* (RSGs), class differentiation are done based on soil characteristic features mainly according to characteristic soil features produced by the dominant identifier, except where *special soil parent materials* are of overriding importance.

At the *second level* (RSGs with qualifiers); soils are differentiated according to soil features resulting from any secondary soil-forming process that has significantly affected the primary characteristics. In many cases, soil characteristics that have a significant effect on land use are taken into account.

1.2.5 Hydrological models and modeling in West Africa

Hydrological models especially the rainfall-runoff models have proven to be a vital tool for improved decision making in hydrology and provide solutions to many practical problems such as flood forecasting and protection, and water management. West Africa is faced with severe or acute water resources and management problem due to its severe rainfall or climate variability characterized by large inter-annual fluctuations. Such large fluctuations in the precipitation amount cause large inter-annual variability, reduction of discharge quantities and water availability. Consequently, this results to increased demands on the scarce water resources. Decisions aimed at solving this perennial problem required an understanding of the hydrological processes. This is achieved most times through the use of improved hydrological models (Beven, 2001). Such quest for hydrological models is primarily driven by the limitation of hydrological measurements since models provide a means of extrapolating known measurements in both space and time to areas where data is not available in order to assess the likely impact of future hydrological change (Beven, 2001). This is true for most tropical West African catchment and especially Benin. A good number of hydrological or rainfall-runoff modeling efforts have been initiated in West Africa recently in an attempt to find solution to water scarcity problems. In Benin, these efforts had concentrated in the Ouémé catchment in central Benin (e.g., Götzinger, 2007) and its sub-catchment including the Donga Catchment (Séguis *et al*., 2011; Le Lay *et al*., 2008; Varado *et al*., 2006), Terou catchment (Cornelissen *et al*., 2013; Giertz *et al*., 2010; Hiepe and Diekkrüger, 2007; Sintondji, 2005; Busche *et al*., 2005; Bormann and Diekkrüger, 2004) and the Aguima Catchment (Bormann *et al*., 2005; Giertz *et al*., 2005). In these studies, different hydrological models ranging from simple lumped, conceptual to distributed physically based models has been applied for different purposes. Some of these models or their combinations investigated the effect of climate and land use change on rainfall-runoff or hydrological processes (e.g. Cornelissen et al., 2013; Kasei, 2010; Giertz *et al*., 2010; Hiepe and Diekkrüger, 2007; Sintondji, 2005; Bormann and Diekkrüger, 2003; Giertz and Diekkrüger, 2003; Legesse et al., 2003). Although, the ability of these models to properly account for the effect of climate and land use change on hydrological processes were highlighted in these studies, the need for more data especially field spatial data on soils and soil hydrologic properties which is not sufficiently available limit their application. This was also buttressed by Andersen et al. (2001) who noted that non-availability of field data was a problem for detailed analysis or evaluation of runoff generation processes using a physically-based distributed model MIKESHE at a regional scale for the Senegal River Basin (375,000 km^2) in West Africa.

At the local, catchment and regional scale, a good number of models have been successfully applied in Benin (Bormann *et al*., 2005; Giertz *et al*., 2005; Giertz 2004; Cornelissen et al., 2013). Recent multi-modeling impact studies of a tropical catchment in Benin identified poor representation of the catchment's soil characteristics and flow processes as the major weakness of all hydrological models considered (Cornelissen *et al*. 2013).

Models such as WaSiM, SWAT e.t.c. which simulate the soil-vegetation-atmospheric interactions (SVAT), may be more suited for understanding the hydrological processess influenced by land management and spatial variability of soil hydraulic properties in complex catchments. However, model such as TOPMODEL, which bases its distributed predictions on an analysis of topography, might be more suited to assessing the loss of nutrients from grassland as demonstrated by Scanlon *et al.*, (2004). It is obvious that the applicability and predictive ability of different model types depends on the data requirements of the user, data availability and cost of data acquisition. If a detailed database is available, the predictive capacity of process based models is much higher than that of a conceptual model. But if data are scarce and uncertain, then a simple, conceptual model can lead to better results due to increased robustness with regard to data errors and data gaps (Grayson and Blöschl, 2001). In this study, I intend to embark on detailed data (soil data, hydro-meteorological measurements e.t.c) acquisition. Therefore, WaSiM –a distributed and mainly physically based model was used not only because of its widespread adaptability in tropical environments but also, its predictive accuracy with reduced uncertainty.

1.2.6 Runoff generation processes and mechanisms

Runoff is defined as the amount of precipitation or portion of precipitation which travels or makes its way towards the nearest stream channels, lakes or oceans as surface/overland flow or subsurface flow (interflow, base flow) as shown below (Fig. 1.1). This is usually measured at the outlets or stream channels in catchment observation. Runoff occurs when the demands of evaporation, interception, infiltration and surface retention have been met or satisfied by precipitation. However, the process of transformation of rainfall into runoff over a catchment is very complex. Runoff generation controls the amount of water that gets into the stream and flows outwards through the catchment outlet during and immediately after the storm. Runoff generation varies temporally and spatially due to the interplay of wetting and drying phases. Runoff can be generated both by an Infiltration excess, partial area infiltration excess or saturation excess overland flow mechanisms, and more recently as a subsurface storm flow or perched subsurface storm flow mechanism (Beven, 2001). Each of these mechanisms (Fig. 1.2) has a different response to rainfall or snowmelt in the volume of runoff produced, the peak discharge rate, and the timing of contributions to streamflow in the channel. The relative importance of each process is affected by climate, geology, topography, soil characteristics, vegetation and land use. The mechanism of runoff generation includes;

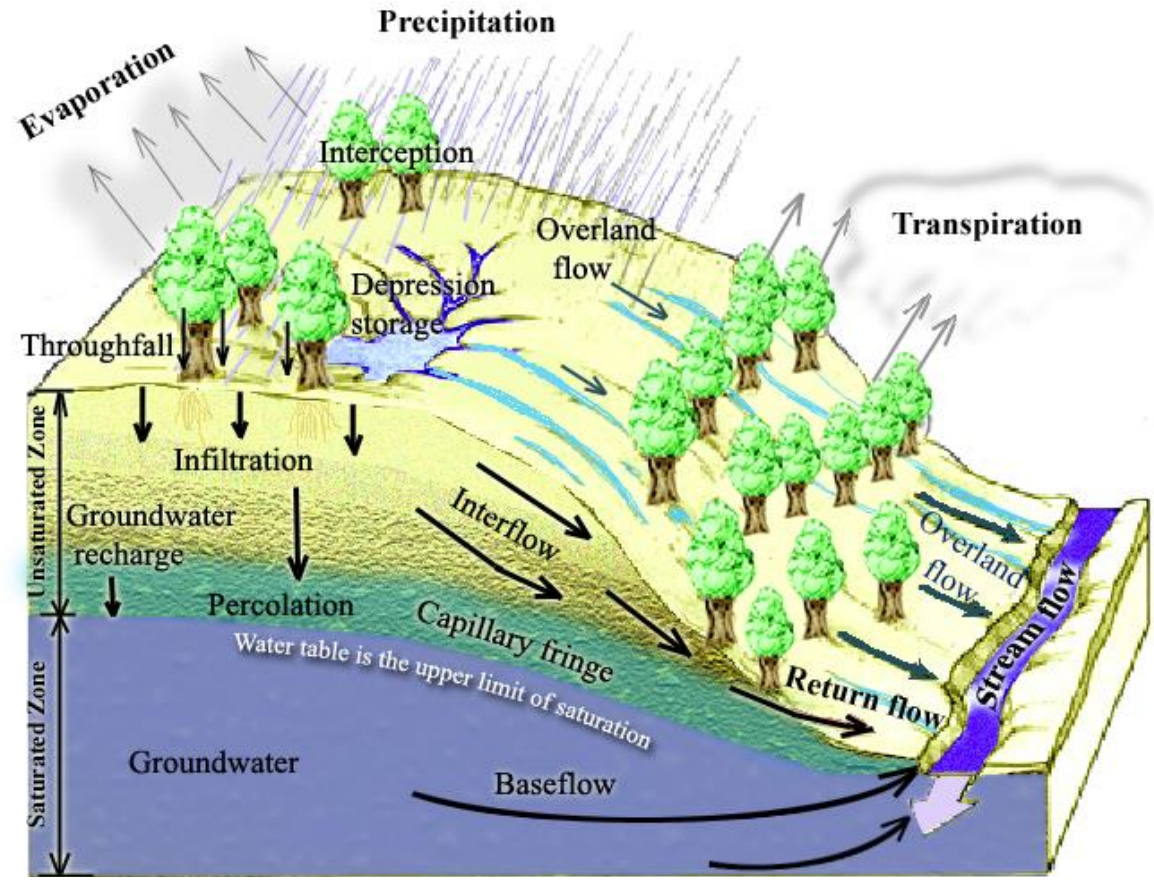


Figure1.1: Physical Processes involved in Runoff Generation (Tarboton, D.G., 2003)

Infiltration excess overland flow: Infiltration excess occurs when the rainfall comes at a rate higher than the rate at which the otherwise unsaturated soil can absorb water. It also starts or occurs in areas where the soil permeabilities are lowest and gradually expand to areas with higher permeabilities since infiltration capacity tends to decrease with increase wetting (Beven, 2012). This is also known as hortonian overland flow because it was discovered by Robert E. Horton (Horton, 1933) who is a famous American hydrologist. Infiltration excess runoff generation occurs when the rate of input of precipitation exceeds the infiltration capacity of soils or where the rainfall intensity is higher than the infiltration capacity of the soil (Fig 1.2a). In other words,. Bare soil areas will be particularly vulnerable to such infiltration excess runoff generation since the energy of the raindrops can rearrange the soil particles at the surface and form a surface crust, effectively sealing the larger pores (Beven, 2012).

Partial area infiltration excess overland flow: This was proposed when information on infiltration capacities of the soils and rainfall rates could not support prediction of runoff production in many catchments under the assumption that infiltration excess surface runoff was produced everywhere on the hillslopes. Betson (1964) suggested or proposed that more usually; only part of a catchment would produce runoff in any particular storm. And that since infiltration capacities tend to decrease with increasing soil moisture, the downslope flow of water on hillslopes tends to result in wetter soils at the base of hillslopes, the area of surface runoff would tend to start close to the channel and expand upslope. This partial area model (Fig 1.2b) is allowed for a generalization of the Horton conceptualization (Beven, 2012). It is now realized that the variation in overland flow velocities and the heterogeneities of soil characteristics and infiltration rates are important in controlling partial area responses.

Saturation excess overland flow: This occurs when the soil is saturated and cannot take up further water or filled with water from a subsoil restriction, such as shallow bedrock (Dunne, 1978; Ward and Robinson, 2000). This was discovered by the studies of Dunne & Black (1970) working in Vermont. They observed that surface runoff produced on soils with high surface infiltration capacities, resulted from a saturation excess mechanism (Fig.1.2c)). This type of response had been previously suggested by Cappus (1960) who was working in France. According to Beven (2006; 2012), such response occurs in valley bottom areas or areas of saturated soil, particularly headwater hollows where there is convergence of flow and a gradual decline in slope towards the stream. It may also occur on areas of thin soils, where the antecedent soil moisture deficit and storage capacity/volume is limited or smallest, or in low permeability and low slope areas, which will tend to stay wet during recession periods. They tend to be dynamic, *i.e.*, they grow during a rainfall event, and are therefore often referred to as variable (dynamic) contributing or source areas (Beven, 2000).

The subsurface storm flow: This occurs in areas where responses are controlled by subsurface flow. This was found to occur in some catchment with relatively deep soil and high soil infiltration capacities but have its responses dominated by subsurface stormflow (Hursh and Brater, 1941; Hewlett and Hibbert, 1967; Dunne and Black, 1970; Hewlett, 1974; Anderson and Burt, 1978). In humid tropics, it occurs in steep terrain with conductive soils but under extreme conditions of high rainfall and antecedent soil moisture in drier climates which lead to formation of transient water tables that induces lateral flow to the channel (Anderson and Burt, 1990b; Wilcox *et al.*, 1997).

For these soils, surface runoff is limited mainly to the channels, so the storm runoff production must be controlled by subsurface responses (Fig.1.2 (d)).

Perched subsurface storm flow: This occurs in catchment or areas with well-developed soil cover but impermeable subsurface layers and thus has its response dominated by throughflow (Weyman, 1970). Through flow or lateral flow through the soil zone, occurs as shallow perched saturated flow in cases where the lateral hydraulic conductivity is higher than the vertical one and a sufficiently high slope is present (Wagener et al., 2004). This permeability break within the soil perhaps associated with horizon boundary might lead to the generation of a perched water table and even to saturation at the surface of a soil that may be unsaturated at depth (Weyman, 1970; Beven, 2012) (Fig.1.2 (e)). He noted that the “quick response” of stream discharge to rainfall is a result of rapid increases in through flow output as saturated conditions extend upslope.

In summary, Fig 1.2 below represents a wide spectrum of possible runoff generation mechanisms or hydrological responses that may occur in different environments or even in different parts of the same catchment at different times due to different antecedent conditions, soil characteristics or rainfall intensities. Attempts have been made to suggest which mechanisms might be dominant in different environments (Dunne, 1978) but there may still be much to learn from direct observations of runoff processes in a catchment of interest (Beven, 2006b; 2012). Traditionally, the use of storm hydrograph has been useful in differentiating between different conceptualizations of catchment response based on the dominance of one set of processes over another.

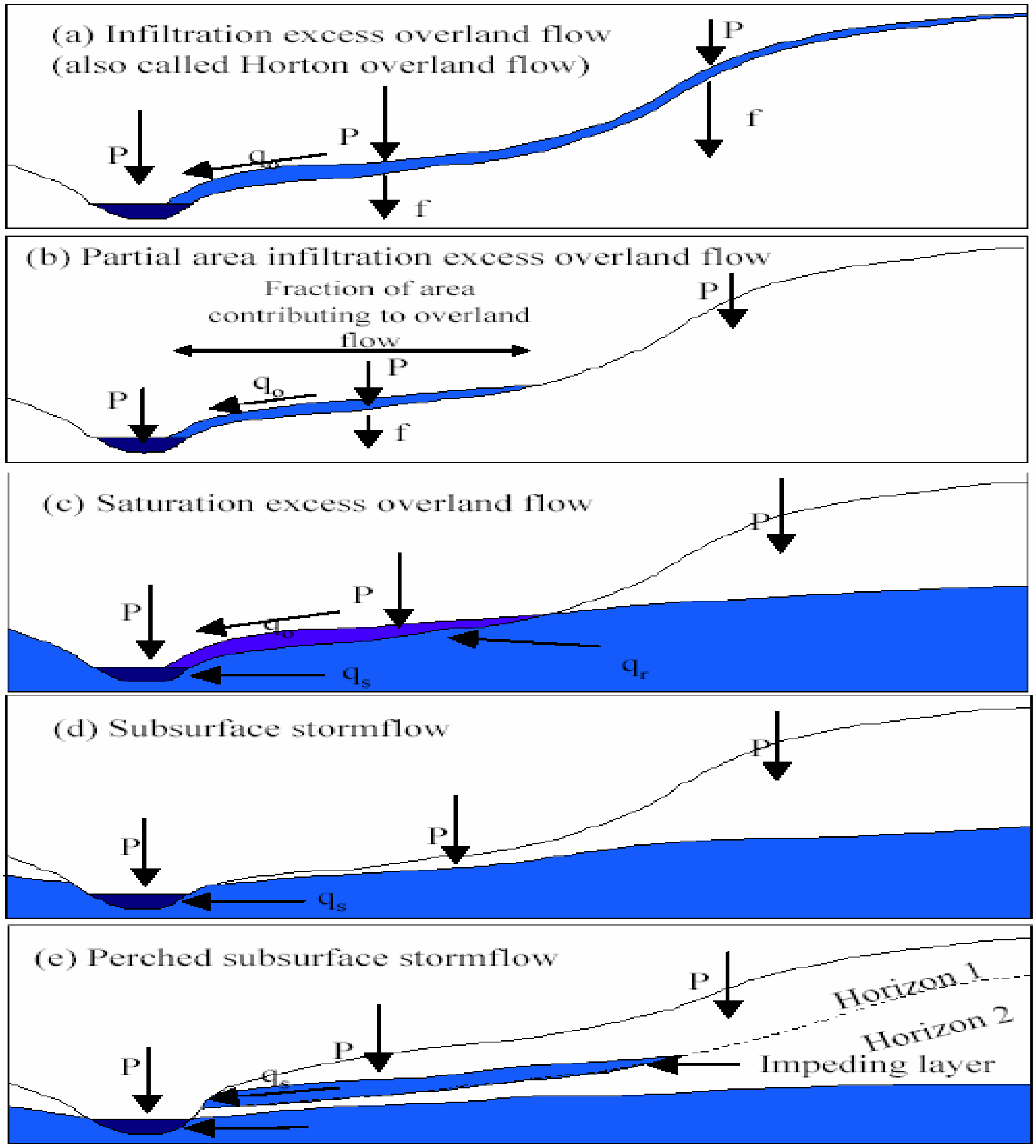


Fig 1.2: Classification of runoff generation mechanisms [following Beven, 2012; 2006b; 2001; 2000]. (a) Infiltration excess overland flow (Horton, 1933); (b) partial area infiltration excess overland flow (Betson, 1964); (c) saturation excess overland flow (Cappus, 1960; Dunne and Black, 1970); (d) subsurface stormflow (Hursh; Hewlett); (e) perched saturation and throughflow (Weyman, 1970). With: P = precipitation, qo = overland flow, qs = subsurface flow, f = infiltration.

1.2.7 Model calibration and validation

Model calibration involves determining the best parameters of the model parameters by comparing the predictions made by the model using a set of assumed conditions with the observed data for similar conditions. The quality of the calibration procedure depends on the quality and quantity of the time-series data used (Wagener et al., 2004). The *quality* of the data is a function of the amount of information and noise present. The quantity depends on the complexity of the model structure and on the quality and characteristics of the data. Short time-series of usually minimum of one complete year for continuous modeling might be sufficient if it is of high quality and has a high degree of hydrologic variability. Most river basins around the world are ungauged including Koupendri catchment. Interestingly, this lack of data often increases with decreasing catchment sizes (Blöschl et al., 2013). However, most distributed hydrological and physically based hydrological models are more robust and do not require extensive hydrological and meteorological data for their calibration (Gayathri et al., 2015). The model has been successfully calibrated using short term time series data (Giertz et al., 2006). Calibrating hydrological models involves mainly three procedures; manual adjustment by trial and error, automatic model calibration, and the combination of both (Refsgaard and Storm, 1996).

Model validation involves running a model using input parameters measured or determined during the calibration process without changing any parameter value for another period. In other words, it is a process of demonstrating that a given site-specific model is capable of making sufficiently accurate simulations though this may vary based on project goals (Refsgaard, 1997).

1.2.8 Model uncertainty analysis

Uncertainty analysis is a very important part of most hydrological or rainfall-runoff modeling process. Uncertainty analysis is important because it affects the output of model predictions especially the discharge or streamflow. Most uncertainties in hydrological modeling process could be due to error in data observation and conditioning, model structure and specification, and unknown initial boundary conditions. Others include; prediction of uncertain future, choice of model and uncertainty estimation methodology, and uncertainties due to model misconception or misrepresentation (Abbaspour, 2008; Pappenberger and Beven, 2006). Although some of these sources and components of uncertainties can be reduced or completely removed, uncertainties caused or introduced by the randomness in the natural processes usually associated with data uncertainty cannot be reduced (Melching *et al.,* 1990; Wagener et al., 2004). This underscores the importance of uncertainty analysis of model predictions.

1.2.9 Model evaluation and efficiency criteria

Model evaluation has been an integral part of most hydrological modeling studies as a way of comparisons between simulated and observed variables especially streamflow. It measures how well a model simulation fits the available observations (Beven, 2001). Although, the most fundamental approach to assessing model performance in terms of behaviours is through visual inspection of the simulated and observed hydrographs (subjective assessment), hydrologists often use efficiency criteria to provide an objective assessment of the closeness of the simulated behaviour to the observed measurements (Krause et al., 2005). The graphical techniques provide mostly a visual comparison of simulated and measured constituent data and a first overview of model performance (ASCE, 1993). These are essential for appropriate model evaluation (Legates and McCabe, 1999). However, the objective assessment generally requires the use of a mathematical estimate of the error between the simulated and observed hydrologic variable(s) i.e. objective or efficiency criteria. Some of the efficiency criteria used for evaluating hydrological models include but not limited to the coefficient of determination (R^2), Nash-Sutcliffe efficiency (NSE), residual or root mean square error (RMSE), RMSE-observation standard deviation ratio (RSR), percent bias (PBias) and Kling-Gupta efficiency (KGE). Details of each of these efficiency criteria can be found in Krause et al. (2005). The choice and use of these efficiency criteria in dependent on the behavior of the observed streamflow hydrograph one intend to investigate. This is because each of these criteria may place different emphasis on different types of simulated and observed streamflow behaviours (Krause et al., 2005). Morias et al., (2007) recommended the use of NSE, PBias, RSR, in addition to the graphical techniques for model evaluation of streamflow, transport of sediments and nutrients. Legates and McCabe (1999) also concluded that a complete assessment of model performance should include one “goodness of- fit” measure (e.g. NSE, R^2) and at least one absolute error measure (e.g., RMSE). Model simulation can be judged as satisfactory if NSE > 0.50 and RSR < 0.70, and if PBias ± 25% for streamflow, PBias ±55% for sediment, and PBIAS ±70% for N and P. This may form the basis or the baseline for the evaluation of most hydrological model simulation including WaSiM**.**

1.3 General Objective

1.3.1 Main Objective

This study aimed to understand the distribution of soils, hydrologic properties, and rainfall-runoff processes from the local (1 m^2) to the catchment scale (11.8 km^2) for adequate utilization of soil and water resources, and ecosystem services across the catchment.

1.3.2 The specific objectives

- To characterize the soil and develop a soil map of the catchment for sustainable management of soil and water resources.
- To evaluate the spatial distribution of soil properties in the catchment under different land use types.
- To assess the impacts of land use and slope positions on soil hydraulic properties in the catchment.
- To evaluate the variability of plot-scale rainfall-runoff processes and its prediction using NRCS-CN approach under different land use and slope positions.
- To evaluate the rainfall-runoff processes of the catchment using WaSiM model.

1.4 Research Questions

- What is the nature and distribution of soils across the Koupendri catchment?
- Can the distribution of soil properties in the watershed be predicted or interpolated?
- How does different land use and slope position influence soil hydraulic properties of the catchment?
- What is the nature of plot-scale surface runoff variability under different land use and slope position in the catchment and can this surface runoff be simulated?
- How accurately can the hydrological processes of the catchment be simulated using model?

1.5 The hypothesis includes;

- The nature and distribution of soils can be obtained through detailed soil survey and classification.
- Spatial variability or distribution of soil properties could be predicted or interpolated using simple statistical and geostatistical tools.

- ❖ Land use and local hillslopes may affect soil hydraulic properties which play key roles in controlling the hydrologic response and processes of a catchment.
- ❖ Surface runoff variability may be understood through experimental study and may be simulated using simple or conceptual models or equations.
- ❖ Hydrological processes are simulated with different accuracies by different models.

1.6 Novelty

Recent hydrological modeling is common in analyzing processes and water availability. Numerous studies have discussed the applicability of models to different situations. In Benin, many of these studies are performed at a range of scales from the local scale (point of few km^2) to the larger catchment scale (about 50,000 km^2). For these studies, different model types are applied and the applicability of these models is studied by using multi-model ensembles. The disadvantage of many of these studies is that they are purely computer based and that there is often a gap between understanding of the processes and the analysis using models. Thus, studies that link local scale field work with hydrological modeling increases the knowledge and the reliability of the conclusions drawn from the results.

1.7 Scope of the thesis

This research is focused on understanding the distribution of soils and soil hydrological properties, and the hydrological processes of the Koupendri catchment. It involves a combination of field and laboratory work as well as hydrological modeling to get a comprehensive picture of the catchment hydrological processes. This serves as a prerequisite to perform land use and climate change studies. The field work involved detailed soil survey and soil classification to generate data on soil distribution within the catchment, spatial soil sampling under different land use, measurement of soil hydrological properties e.g. infiltration, soil moisture, runoff or discharge at local and catchment scale, and hydraulic conductivity. Soil hydrological properties were measured in-situ and in the laboratory and the results were compared. These data on soils and soil hydrological properties in combination with land use and short-time series data of climate and discharge were used for the calibration and validation of the model.

1.8 Expected results and benefits

This research is expected to give detailed and elaborate information on the distribution soils, their characteristics and spatial variation within the catchment for sustainable management of soil and water resources. The soil data provided by this study is useful for hydrological modeling, land use and climate change studies. Influence of land use and slope position on key soil hydrological properties, and point scale or local scale hydrological processes is also provided. These are useful information needed not only for future studies in the catchment but also for validation of some models to enhance reliable prediction of potential hydrological consequences such as erosion, flood, and drought e.t.c in the catchment. Information on soil moisture dynamics provided in this study is also valuable for many applications such as; hydrological modeling, weather forecasting, flood early warning, drought monitoring, agriculture, and climate change studies.The study also provided useful results on point/local-to-catchment scale hydrological processes which enhances our knowledge and understanding of hydrological processes and for future climate and land use change studies.

1.9 Thesis structure

The thesis is made up of eight chapters. The first chapter introduced or highlighted the concept of rainfall-runoff modeling including the key roles played by soil, and sustainable water resources management issues reported within the region in various studies. The issues of soil spatial distribution, soil survey methods, hydrological processes and modeling were also reviewed. Also included in chapter one is the objectives and research questions that this research seeks to answer, the hypothesis, novelty and scope of the thesis. The study area is presented in chapter two while chapter three highlights the data, materials and methods used. The results of the soil survey and soil classification of the Koupendri catchment were presented and discussed in Chapter 4. Chapter 5 focused on the results of the spatial variability of some soil properties using simple statistical and geostatistical tools. The results of the influence of land use and slope position on soil hydraulic properties were presented and discussed in chapter 6. Local or point scale hydrological processes on two slope positions and land use types in the Koupendri catchment north-west of Benin: Observation and modeling using NRCS-CN approach was presented and discussed in Chapter 7. The distributed and physically based WaSiM model (Schulla, 2007; 2012) was calibrated and validated for the catchment and its suitability evaluated in Chapter 8. Chapter 9 gave the general conclusions and perspectives.

CHAPTER 2

Description of the study area

2.1 Location

The study was conducted on 11.8 km^2 area of Koupendri catchment - a part of Volta basin located north-west of Benin (Fig. 2.1). The catchment is located on latitude 1° 08'40’’ to 1°11'0'' N and longitudes 10°44'30'' to 10°46'50''E and has a relatively flat physiography with a mean slope of 0.4 %, and height above sea level of 220 m.

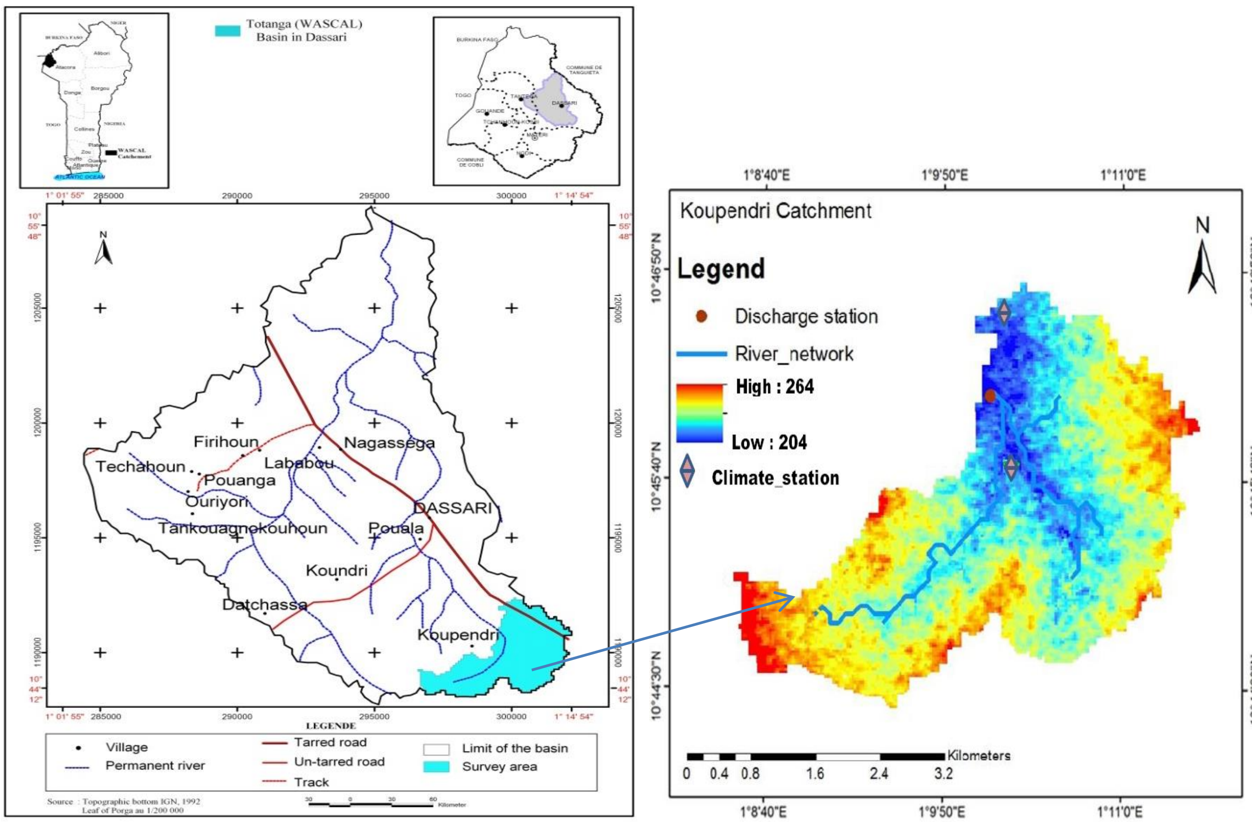


Figure 2.1: Location of Koupendri catchment in Benin**.**

2.2 Geology and Geomorphology

The geology of north-west Benin is made up of the Precambrian superior Proterozoic consisting of metamorphic/crystalline rocks e.g. siltstones, sandstones gneisses, including less abundant mica schists, quartzites and amphibolites (Faure and Volkoff, 1996; 1998; Wright and Burgess 1992). In other words, it encompasses a set of geological substratum made up of more recent metamorphic/crystalline and sedimentary formations. The relief consists of two morphological units differentiated by their altitude. The first morphological unit is oriented north-north-east and south-south-west of the department of Atacora. It has an altitude varying between 400 and 640 meters, or even more. The second morphological unit is oriented south-south-east and north-north-west. The relief is generally low and has an altitude that varies between 150 and 300 meters (LSSEE, 2003). Koupendri catchment is located within the second morphological unit and can be best described as an undulating pediplain relief overlying a Precambrian basement of sedimentary origin and made up of acid metamorphic rocks such as Schist. It is part of the protected area (National Park and Hunting Area of Pendjari) located mostly on a floodplain.

2.3 Climate

The climate is within the continental dry northern zone (Faure and Volkoff, 1998), mainly dry sudanian or semi-arid. It has a unimodal rainfall distribution or pattern with distinct wet (rainy) and dry seasons. The rainy season lasts from May to mid-October while the dry season lasts for six months, from November to April. Annual rainfall varies between 900 and 1200 mm, with a yearly mean of 950 mm. During the rainy season, temperature varies between 25 and 30° C, with a relative humidity that can reach up to 97 percent in August. However, during the dry season, the temperature reaches a maximum of between 39 and 42. The relative humidity is between 25 and 55 percent (Barry et al. 2005).

2.4 Vegetation and land use

The catchment is located within the Northern (dry) sudanian or semi-arid region according to the vegetation zone classification of Benin by Wezel and Böcker (2000). The Sudanian vegetation is dominated by tree/shrub savannah or open savanna i.e. trees interspersed with grasses (Saidou et al., 2004) of low density composed of *Combretum spp* and *Acacia gourmaensis Crossopteryx febrifuga* (Idieti, 2012). Other grasses (Andropogon gayanus, Impérata cylyndrica, Pennisetum and hydrophilic grass e.t.c) and shrub trees (Cajanus cajan, Acacia papaya, Guiera senegalensis, Terminalia glanscena, Gardenia ternifolia and Acacia maerostachia e.t.c) including sparsely dispersed plantation trees (Eucalyptus camaldulensis, Tectona grandis (teak) and Anacardium occidentale (cashew tree) e.t.c) can be found. The major land use is agriculture which focuses on grain crops such as maize, sorghum, rice etc., tuber crops such as yam, oil and cash crops such as cotton, and pastoralism (Forkuor et al., 2014).

2.5 Soils

The dominant soils of Koupendri catchment are mostly plinthosols with many gravels and plinthites, and shallow depth (Azuka et al., 2015). The soils are slightly acidic, with sandy to loamy topsoil and increasing clayey subsoil (Gaiser et al., 2010; Azuka et al., 2015). Only a small amount of the land is suitable for agriculture, livestock, and for dwellings due to poor nutrient status of the soil including limited availability of water. Moreso, poor soil moisture and soil fertility was identified as major ecological constraints in the area (Challinor et al., 2007; Sanchez, 2002).

2.6 Hydrology

Koupendri catchment is one of the sub-catchments of Dassari catchment that drains into the Penjari River. Hydrologically, Koupendri catchment behavior is ephemeral or seasonal and dries out during the dry season. It drains over a few kilometers with a water level ranging between 10-20 m and depth to groundwater of less than 45 m. Due to its characteristic undulating pediplain and almost flat relief, runoff generation is assumed to be mainly dominated by the Hortonian overland flow that originated as a result of infiltration excess overland flow.

2.7 Demography, environmental, social and economic activities

The population of the Koupendri catchment is made up of peasant farmers and herdsmen mostly migrant from neighbouring Bukina-faso and Niger. The population is less than 60 persons/km^2 and made up of different ethnic groups such as Dendi, Djerma, Hausa, Yoruba, Fons, Yom e.t.c. Their religious practices are mostly traditional religion with few Islam, Catholicism and Pentecostal (Protestants) adherents. Agricultural activities occupy more than 90 % of the economy of the study area. Despite the ecological constraints in the area, agricultural activities are rapidly expanding due to population growth, migration and accessibility. Thus, there is increase in the demand of arable lands and reduction in fallow periods. This brings competition over this finite resources resulting to over-exploitation and further land resources degradation which hinders the economic development in the region.

CHAPTER 3

Data, materials and methods

Introduction

Modeling the hydrological processes from point to larger scales require input of large amount of observed data in time and space. Basically, WaSiM model requires two types of data sets for hydrological simulation (Table 3.1); spatially distributed data (DEM, basin characteristics, soil and land use data) and hydro-meteorological data (temperature, rainfall, humidity, wind speed, global ra diation, and discharge). The materials and methodologies employed in this research work were also highlighted. Detailed soil survey and soil classification for the study location was carried out using SOTER approach while the spatial variabilities of soil properties under different land use was evaluated using geostatistical tool. To understand the hydrological processes at local or point scale, soil hydrologic properties including surface runoff were evaluated under two slope positions and two land use types. At the catchment scale, WaSiM model was calibrated and validated to help understand the hydrological processes.

Table 3.1: Data requirement and sources for hydrological modeling

Data	Source
Climate (Precipitation, temperature, humidity e.t.c)	WASCAL climate station (Hydrology Research group)
Discharge	WASCAL (Hydrology Research group)
Elevation (DEM 30 m x 30 m resolution)	WASCAL (Hydrology Research group)
Soil	Detailed soil survey (1:25000)
Land use/cover map (30 m x 30 m resolution)	Chabi et al., 2016.

3.1 Data

3.1.1 Soil data

The soil data used in this study was obtained through a detailed (scale 1:25,000) soil survey and mapping of Koupendri catchment soil using Soil and TERrain (SOTER) digital database approach (van Engelen and Ting-tiang, 1995). Soil moisture data was also obtained from the soil moisture or soil water station installed on a hillslope of Koupendri catchment at Wanteou by the Hydrology Research Group (HRG) supported under the framework of WASCAL.

3.1.2 Land use data

One of the most important factors that affect water balance or streamflow components in a catchment is land use or land cover. According to IPCC (2010), land cover is the actual manifestation of land use (i.e., forest, grassland, crop land). As part of the of the West African Science Service Centre on Climate Change and Adapted Land use (WASCAL) campaign, a land use map of Dassari catchment (Fig 3.1) was produced at a scale of 30 m resolution by one of the PhD students in 2013 (Chabi et al., 2016). The land-use/land-cover map used in this study was extracted from this land use map for Koupendri catchment using ArcGIS 10.1. The map was georeferenced with ground truth data and the original legend was modified to make it necessary to be used by WaSiM for modeling the hydrological processes of the catchment. With this modification of legends, six land-use/land-cover classes were identified in the study area (Table 3.2). The dominant class being is tree savannah (savanna woodland, agroforestry and plantations), shrub savanna (shrub savanna), grassland (savanna grassland), water (riparian forest/woodland), cropland (cropland and fallow), and urban (settlement and bare land).

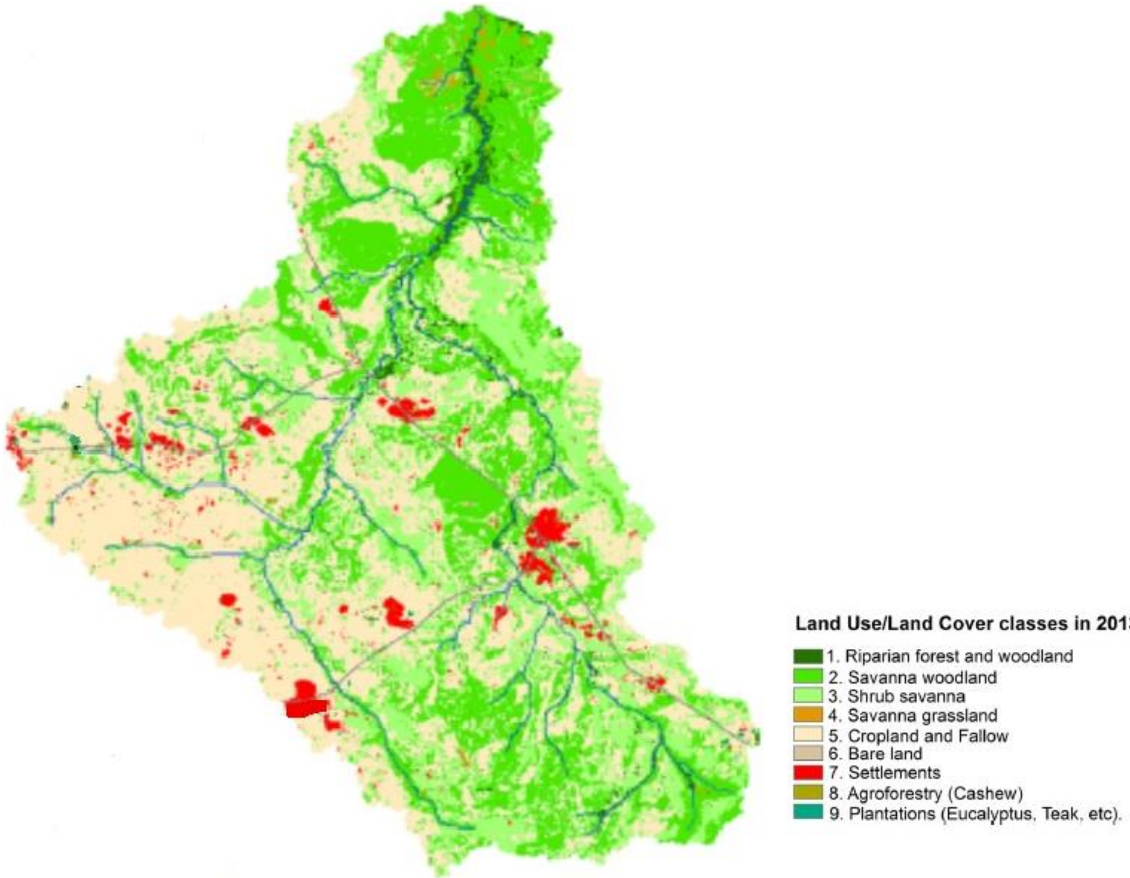


Figure 3.1: Land use/land cover map of Dassari Catchment, north-west Benin (Chabi et al., 2016).

Table 3.2: Land use Land cover distribution for Koupendri catchment.

Land Use/Cover	Area (Km^2)	Count	Percentage (%)
Forest-tree savanna	4.59	5,100	38.85
Shrub-savanna	4.10	4,558	34.72
Grassland	0.045	50	0.38
Urban	0.044	49	0.37
Cropland	2.76	3,059	23.35
Water	0.259	307	2.34

3.1.3 Climate and discharge data

Most gauging networks in Benin are concentrated in large river basins e.g Ouemé and its tributaries. Little or no attention is paid to small catchments considering the high cost of procuring and installing hydrometric equipments. The climate and discharge station in Koupendri catchment were installed, monitored and maintained by the Hydrology Research Group (HRG) supported under the framework of WASCAL. The climate and discharge stations were installed in 2013. Information obtained from the climate station include; temperature, rainfall, humidity, wind speed and global radiation. Discharge measurements at Koupendri catchment outlet was made every year during the rainy seasons to establish rating curves used to convert measured water levels to continuous discharge. At the local scale, runoff or discharge was measured after each rain event from six microplots each installed on two slope positions and two land use types.

3.2 Materials and Methods

3.2.1 Soil survey and classification

Field observations were made using toposequence method with clinometer during reconnaissance survey of Koupendri catchment. Transects were positioned at an interval of 250 m both along tracks or roads across the catchment. With the help of the global positioning system (GPS), about 200 observations points by auger drillings at 250 m interval and ten (10) profile pits were done in the catchment (Fig. 3.2). The soil mapping of the location was carried out using Soil and Terrain (SOTER) approach (Igué, 2000; Weller, 2002) with the idea that land in which terrain and soil occur incorporates processes and systems of interrelationships between physical and biological phenomena evolving through time. Soil profile description was made based on the guidelines for soil profile description (FAO, 1991; 2006). The profiles were sampled for determination of both physical and chemical properties of the soil. The results of the soil analysis were used for the classification and characterization of the soil.

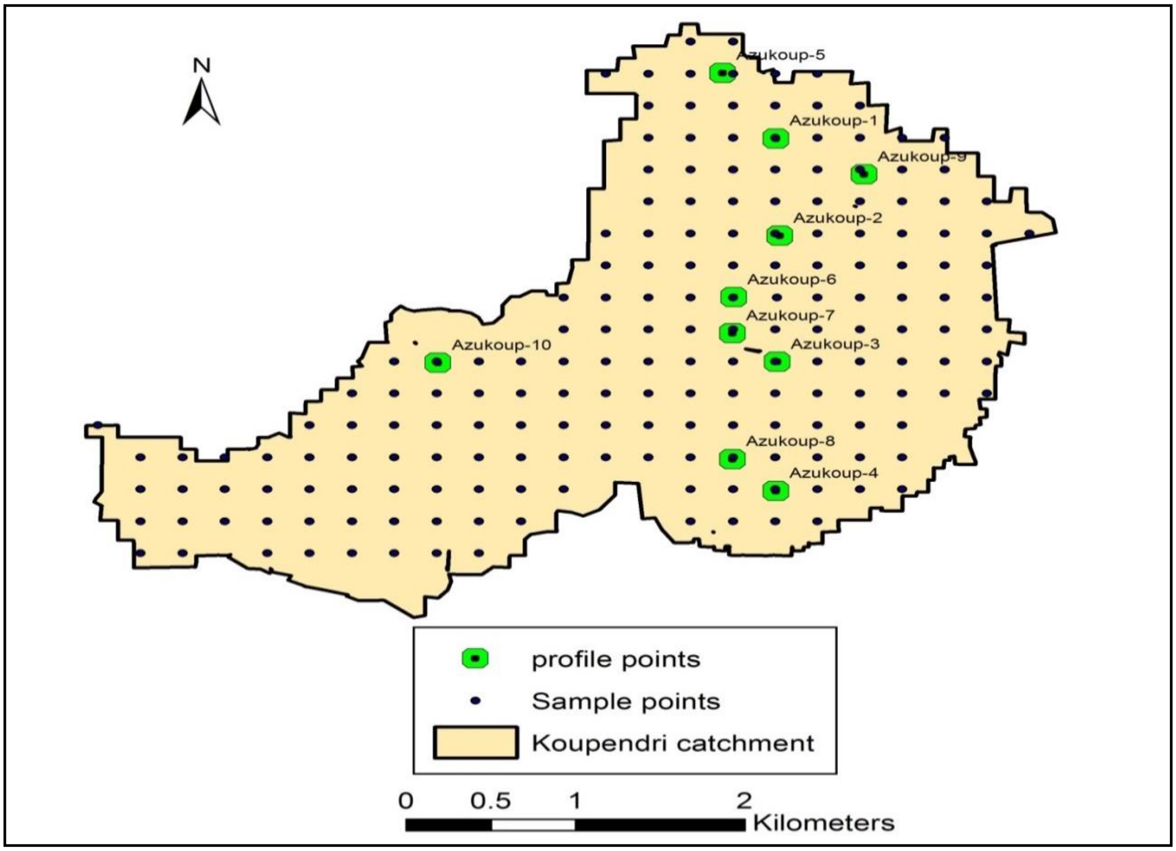


Figure 3.2: Map of the Koupendri catchment showing auger sampling and profile points

3.2.1.1 SOTER approach

This approach uses the methodology of mapping land characteristics based on the idea that land (in which terrain and soil occur) incorporates processes and systems of interrelationships between physical and biological phenomena evolving through time. In other words, the SOTER (SOil and TERrain) procedure proposes a data structure for land description which offers a more heterogeneous view on the structure of land (Weller, 2002). It went further to view land as being made up of natural entities consisting of combinations of terrain and soil individuals. SOTER is a hierarchical system in which the higher level of classification is based on morpho-metric land form criteria and altitude levels. The concept identifies areas of terrain (land units) with distinctive, often repetitive pattern of geomorphic or geological elements (land form, lithology, surface form, slope and parent material) together with a corresponding soil pattern (Shield and Coote, 1988; Brabant, 1992; and SOTER, 1995). Tracts of land distinguished in this manner are named SOTER units with each representing a unique combination of terrain and soil characteristics. Thus, it is based on the principle of the soil-landscape paradigm with land form and geology as structuring elements and soil as inventory of attribute. Separation of units is made if it can be mapped at the given scale, and then digitized. The elements belonging to the units are stored in two different data bases; the geometry in GIS (geographic information system) and attribute information in a RDMS (relational database management system). The attribute information on the elements belonging to the units are stored in a database on three main levels: Terrain unit with patterns of land form such as elevation, major land form and general lithology; Terrain components containing data for slope, surface form and groundwater; soil components containing soils' information and soil profile description (Igue, 2000; Weller, 2002). The soil component is not described by a single reference profile but by a set of soil profiles for each soil type that can contain a fixed/same number of soil descriptions /information in each horizon of the profile (Weller, 2002; Weller and Stahr, 1995).

The SOTER mapping approach resembles physiographic soil mapping in many respects. However, its main difference lies in the stronger emphasis SOTER puts on the terrain-soil relationship when compared to what is commonly done in traditional soil mapping. This is true particularly at smaller mapping scales. At the same time SOTER adheres to rigorous data entry formats necessary for the construction of universal terrain and soil database.

3.2.1.2 Choice of soil classification system

Prior to commencement of any soil survey and soil mapping, a reference system had to be selected and adopted for soil classification. In 1973, a group of West African soil scientists at an FAO-sponsored correlation meeting in Ghana recommended the adoption of the FAO/Unesco soil legend for West African countries (Okoye, 1995). In this study, the FAO/Unesco soil legend and the French classification were used for the soil map of the koupendri catchment. The soil map of the sub-basin was produced at the scale of 1:25,000. The description, classification and characterization of the soil were done based on the Guidelines for Soil Description (FAO, 2006), Field Book for Describing and Sampling Soils (Schoeneberger *et al*., 2002), Keys to Soil Taxonomy (Soil Survey Staff, 2010) and the third edition of the World Reference Base for Soil

Resources (IUSS Working Group WRB, 2014), and correlated with the FAO/UNESCO legend and French classification system (CPCS, 1967).

3.2.2 Spatial sampling for geostatistics

Soils properties are spatially dependent and thus require appropriate sampling design to capture such spatial variability. Systematic or random sampling scheme is judged more appropriate than random sampling and has been widely used on spatial variability studies (McBratney and Webster, 1983). Unlike random sampling scheme, grid sampling scheme minimizes generation of very close points that limit accurate assessment of spatial variability (Weindorf and Zhu, 2010). Sampling in a regular grid pattern also provided more accurate results and a good choice of lag distance when determining the semi-variogram compared to random pattern (ESRI, 2010; Wang and Qi (1998). Thus, a systematic sampling scheme in a regular grid size was used in this study. Surface soil samples were collected from 0-20 cm depth using the systematic sampling approach in a regular grid size/pattern at 25 m interval in three selected land use within the catchment for analysis. The selected land use includes; Maize-sorghum cropland, Rice field and a fallow shrub land (Fig. 3.3). In each of the selected land use, a maximum of 60 points were sampled at 25 m interval, and additional 40 points sampled at 5 m interval within the initial sampling points. This was done to avoid missing the short-range variation crucial for estimating the most important part of the variogram (Oliver and Webster, 2014). To ensure true representation of the site or location, all samplings were made in triplicates within 0.5 m radius at each sampling points and mixed together to give one sample. About 291 disturbed and undisturbed soil samples were collected across the three selected land use for describing the spatio-temporal variation in the soil properties in the catchment.

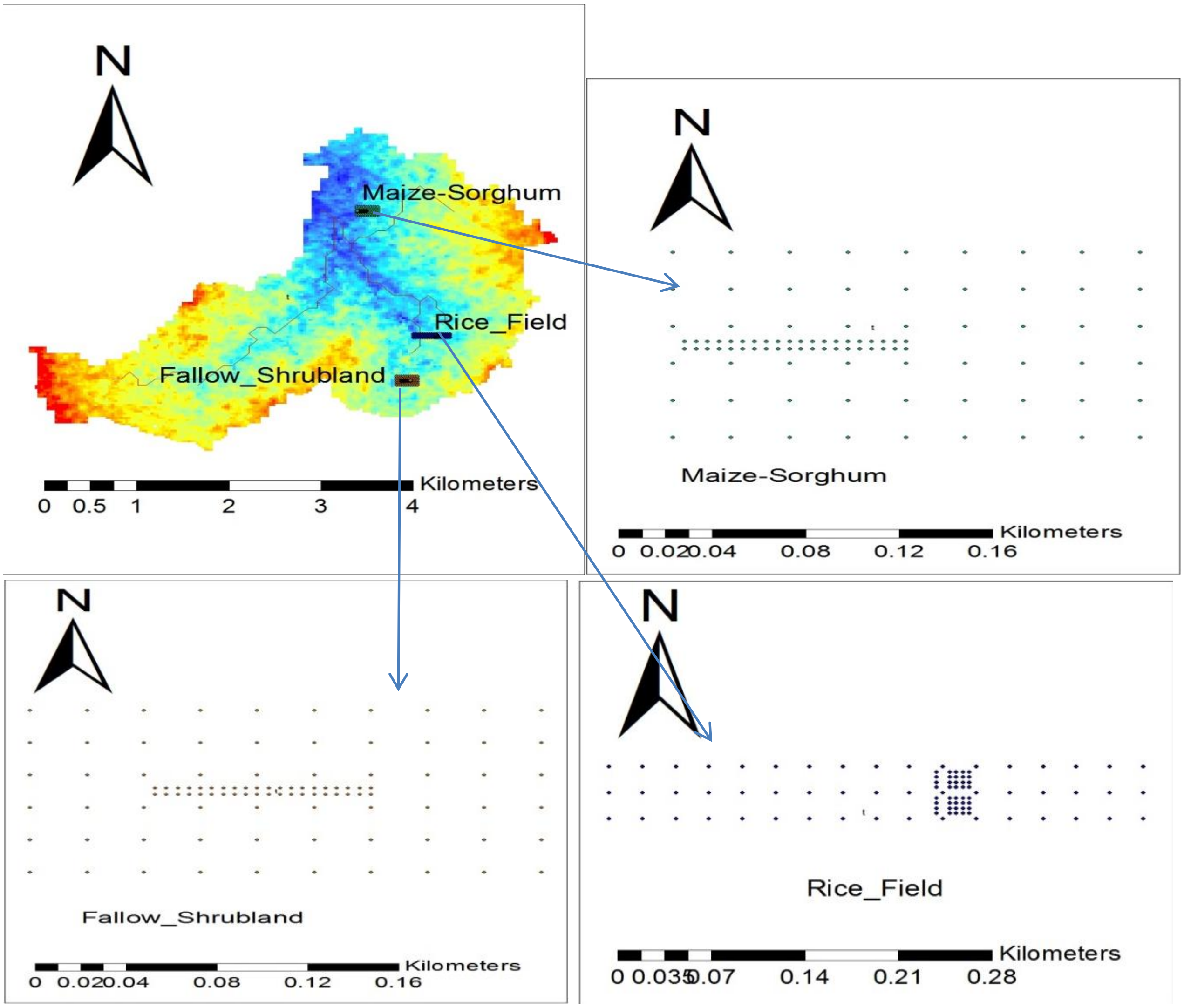


Fig 3.3: Sampling pattern for geostatistical study.

3.2.3 Laboratory analysis/methods

Soil samples collected for soil classification during soil survey and for geostatistical analysis were analyzed using standard laboratory procedures. The particle size distribution of the < 2 mm size fraction of soil samples were determined using the hydrometer method described by Gee and Or (2002). Bulk density was determined by core method as described by Blake and Hartge, (1986), and Anderson and Ingram (1993). Soil organic carbon (SOC) was determined on the air dried, 2 mm sieved samples according to the Nelson and Summer (1982) method. The organic matter content (OM) was obtained by multiplying values of organic carbon by a factor of 1.724. The pH value was determined potentiometrically using a pH meter in a soil: liquid ratio of 1:2.5 suspensions of soil in 0.1N KCl and distilled water (McLean, 1982). Saturated hydraulic conductivity (K_{sat}) was measured using the constant head permeameter method. Darcy's equation, as outlined by Young (2001) was used for the computation of K_{sat}

$$K_{sat} = QL/(A\ T\ \Delta H) \quad (1)$$

Where Q = steady state volume of outflow from the entire soil column (cm^3), L is the length of soil column (cm), A is the interior cross-sectional area of the soil column (cm^2), ΔH is the change in hydraulic head or the head pressure difference causing the flow (cm), T is the time of flow (sec).

Soil water retention characteristics (field capacity (0.33 bars) and wilting point (15 bars)) were determined using pressure plate extractors or apparatus (Van Reeuwijk, 2006), then Available Water Capacity (AWC) was computed from FC and PWP.

$$AWC = FC - PWP \quad (2)$$

Total nitrogen (N) was determined by Kjeldahl method (Bremner, 1996). Available phosphorus (P) was determined using Bray II method (Bray and Kurtz, 1945). Cation exchange capacity (CEC) was determine using the method described by Lavkulich (1981) or the $BaCl_2$ compulsive exchange method by Gillman and Sumpter (1986). Exchangeable Cations (Na, K, Ca, and Mg) were extracted using ammonium acetate (NH_4OAc). The cations were read on Flame Photometer (K, Na, and Ca) and Atomic Absorption Spectrophotometer (AAS) (Mg) respectively. Soil color was determined using Munsell colour charts (Munsell Colour Company, 2000). Soil depth was determined by measuring the thickness of each soil horizon using a ruler/tape graduated in centimeters. Total porosity (%) (Assumed particle density p_s = 2.65 kg m^{-3}), base saturation (BS), exchangeable sodium percentage (ESP) and CEC of clay were computed, using their respective equation as follows:

$$TP = \left(1 - \frac{ps}{pb}\right) x\ 100 \quad (3)$$

$$BS = \frac{Ca + Mg + K + Na}{CEC} x\ 100 \quad (4)$$

$$ESP = \frac{Exchangeable\ Na}{CEC}\ x\ 100 \tag{5}$$

3.2.4 Descriptive and geostatistical analysis

Exploratory data analysis was done to get rid of outliers. Descriptive statistics or simple statistical analysis was performed. The analysis of Pearson's r correlation matrix was done using Stata software (version 13.1) to ascertain the relationships that exist between pairs of the variable i.e. the soil properties. Besides the exploratory analysis done to get rid of the outliers, the normality of the data sets was analyzed using skewness, kurtosis and Shapiro-Wilk test (Shapiro and Wilk, 1965). Non-normality data sets distribution has been reported to influence the outcome or results of geostatistical analysis (Kerry and Oliver, 2007). Some of the data that exhibited non-normal distribution were transformed using a univariate normality or transformation approach such as ladder of powers (Table 3.3) by Hamilton (1990) before geostatistical analysis. Logarithm, square root, inverse and power function transformations were performed to satisfy the normality requirement of geostatistical analysis.

Table 3.3: Nonlinear transformation for changing distributional shapes

Power	Transformation	Name	Effects	Inverse function
3	X^3	Cube	Reduction extreme negative skewness	$(X^*)^{1/3}$
2	X^2	Square	Reduce negative skewness	$(X^*)^{1/2}$
1	$X^1=X$	Raw	None	X^*
-0.5	$X^{1/2}$	Square root	Reduces mild positive skewness	$(X^*)^2$
-1	$Log_{10}(X)$	Log	Reduces positive skewness	10^{X*}
-1.5	$(X^{-1/2})= -1/SQRT(X)$	Negative reciprocal root	Reduces extreme positive skewness	$(-X^*)^{-2}$
-2	$-(X^{-1})=-1/X$	Negative reciprocal	Reduces very extreme positive skewness	$(-X^*)^{-1}$

X^*: transformed variable; Source: Hamilton (1990).

Trend analysis was also carried out to check and correct the global trend in the data. The characterization of the spatial pattern or structure of spatially dependent soil properties was done using geostatistical tools. A semi-variogram was used to quantify the spatial patterns of regionalized variable. This helps us to derive important input parameters for kriging interpolation. The semivariogram is derived as follows;

$$\gamma(\mathrm{h}) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [z\,(x_i) - z(x_i + h)]^2 \tag{6}$$

$z(x_i)$= measured sample at point x_i, $z(x_i+h)$= measured sample at point x_i+h, and $N(h)$ = the number of pairs separated by lag interval or distance *h* (Grego *et al.*, 2006; Wang, 1999; Zhao *et al.*, 2010). The fitting of the semivariogram models to the data was done after checking for anisotropy. Thereafter, several semivariogram or variogram models were fitted to the data. The semi-variogram was fitted or modeled with spherical, exponential, or Gaussian model (equation 7-9) respectively.

$$\gamma(h) = \begin{cases} C_0 + C_1 \left[\frac{3}{2}\left(\frac{h}{a}\right) - \frac{1}{2}\left(\frac{h}{a}\right)^3\right] & for\ h \leq a \\ C_0 + C_1 & for\ h > a \end{cases} \tag{7}$$

$$\gamma(h) = \begin{cases} C_0 + C_1 \left(1 - e^{-h/a}\right) & for\ h \leq a \\ C_0 + C_1 & for\ h > a \end{cases} \tag{8}$$

$$\gamma(h) = C_0 + C_1\left(1 - exp(h^2/a^2)\right) \tag{9}$$

The fitted models provided the input parameters for kriging such as nugget effect (C_0), partial sill or structural variance C_1, total variance or sill (C_0 +C_1, i.e. the total variance and the range or correlation length (a). A continuous map of the interpolation or prediction was done or created using the weighted interpolation method (ordinary kriging). For the transformed data, the mapping of the interpolated data points was done after converting the transformed data points back to their original values. All geostatistical analysis and mappings were done using the geostatistical analyst extension of the ARCGIS software (version 10.2; ESRI, 2010).

The degree of spatial dependence (GD) was also calculated as:

$$GD = \frac{c_o}{c_o + c_1}\ x\ 100 \tag{10}$$

Where GD ≤ 25 % = strong spatial dependence, 25 % < GD ≤ 75 % = moderate spatial dependence and GD > 75 %. = weak spatial dependence. The proportion of this spatial structure determines the ratio of the random factors inducing the spatial variability (cambardella *et al.*, 1994).

3.2.5 Hydrological properties of the hillslope soil under different land use and slope position

3.2.5.1 In situ measurement of soil hydraulic properties using Hood infiltrometer

In situ measurement of infiltration characteristics was done using Hood infiltrometer (Fig. 3.4) (UGT, Müncheberg, Germany), as described by Punzel and Schwärzel, (2007). It consists of three main components e.g the hood and the Mariotte water supply with a bubble tower placed inside its water reservoir, and a U-tube manometer. The principle involved placing the circular hood connected to a Mariotte device within a retaining ring, on the soil surface after cutting down to approximately 0.5 cm (5 mm) or removing the litter layer or vegetation cover. No special preparation of the soil surface, driven of rings into the soil surface or need for use of sand or a special contact layer is required. The gap between the retaining ring and the hood was only filled with moist sand to seal the edge and to prevent the water from leaking out of the side. The bubble tower has an adjustable pipe that controls the suction, thereby allowing air entry at varying distances below the water table of the tower. This way, constant head is established with a positive pressure potential compensated by adjusting to zero total head. Then, the infiltration characteristics were recorded by reading the falling water level directly from the reservoir until steady-state flow, which is reached, when the infiltration rate remains the same for three consecutive time intervals (Punzel and Schwärzel, 2004, 2007; Wooding, 1968). This was repeatedly done for pressure level (tension) from zero up to the air entry or bubbling pressure. Bubbling pressure is the pressure head at which the soils start to drain (Mohamed and Sharma, 2004). The infiltration measurement was replicated thrice in each of the selected land use and slope positions. Soil core samples were also collected before and after each infiltration for determination of initial and final soil moisture content. The soil samples were weighed before and after oven drying in the oven at a temperature of 105^{0}C for gravimetric soil moisture determination;

$$\text{Soil moisture } (\theta_g) = \left(\frac{moist_{soil} - Oven\ dry_{soil}}{Oven\ dry_{soil}}\right) \tag{11}$$

The soil moisture obtained here is gravimetric soil moisture in grams. To convert to volumetric moisture, we multiplied the gravimetric moisture content with the soil bulk density.

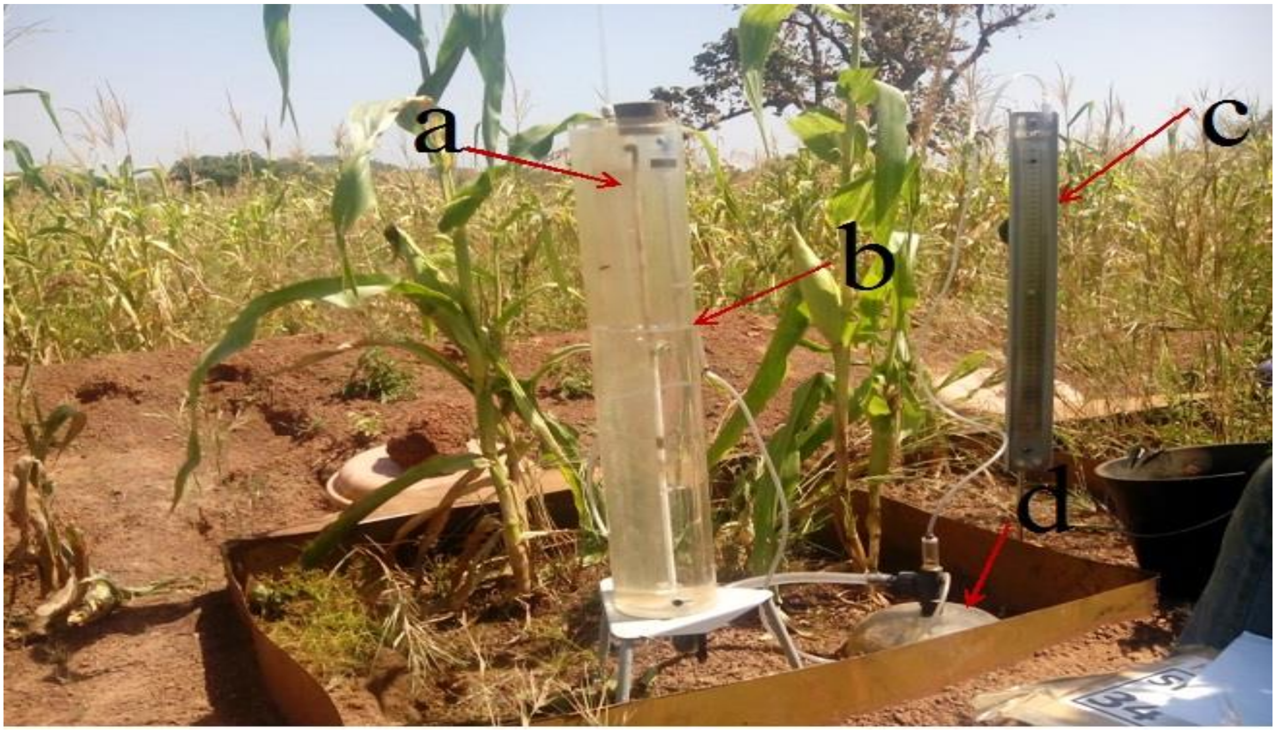


Figure 3.4: Set-up of hood infiltrometer during the field measurement in Koupendri catchment, a = bubble tower, b = water level reservoir, c = u-tube manometer, d = constant water level hood.

3.2.5.2 Underlying theoretical principles and data analysis

Hydraulic conductivity (unsaturated) k_u (LT^{-1}) as a function of water tension h in soils or other open-pored materials near saturation can be described according to Gardner (1958):

$$k_u = k_f . e^{(\alpha . h)} \tag{12}$$

k_f – field saturated hydraulic conductivity (LT^{-1})

h – Hydraulic pressure head (L) - positive in overpressure range.

α= inverse capillary length scale (L^{-1})

Such approach allows an analytical solution for a large number of two- and three dimensional flow processes. It is the regular basis for the interpretation of test results with the infiltrometer systems common so far.

According to Wooding (1968), the following applies to the steady-state infiltration Q from a circular infiltration area (radius a) into the infinite soil:

$$Q = \pi . r^2 . k_u . (1 + \frac{4}{\pi . r . \alpha .}) \quad (13)$$

Q= steady-state infiltration rate (LT^{-1}), r = radius of the disc (L), K_u = unsaturated hydraulic conductivity (LT^{-1}). For experimental determination of k_f and α above, the infiltration test can be run with different water tensions (hydraulic pressure heads) or the infiltration gets fed from source areas with different radii for equal water tensions (Wang, Yates et al. 1998). However, infiltration from different source areas makes sense only in largely homogeneous soils.

For the infiltration test at different water tensions up to the bubble point of the soil, the chosen water tensions (h_1, h_2) applies according to equations (12), (13):

$$\frac{Q_1}{\pi . r^2} = k_f . e^{(\alpha . h_1)} . (1 + \frac{4}{\pi . r . \alpha}) \quad (14)$$

$$\frac{Q_2}{\pi . r^2} = k_f . e^{(\alpha . h_2)} . (1 + \frac{4}{\pi . r . \alpha}) \quad (15)$$

By way of division we get:

$$\alpha = \frac{In\left(\frac{Q_1}{Q_2}\right)}{(h_1 - h_2)} \qquad (h_1, h_2 \neq 0) \quad (16).$$

3.2.5.3 Laboratory determination of saturated hydraulic conductivity

Soil core samples of dimensions 8.0 cm x 7.5 cm were collected in triplicates on each of the two slope positions under the two selected land use types. The samples were taken to the laboratory and saturated for at least 24 hours depending on the soil type before the analysis. Saturated hydraulic conductivity (Ksat) was determined by the constant head method using Eijkelkamp laboratory permeameter. It operates on the basis or the principle of difference in water pressure on both ends of a saturated soil sample and the resulting flow of water is measured for hydraulic conductivity determination. Darcy's equation for analysis of constant head method, as described or outlined by Young (2001) was used for the computation of Ksat

$$K_{sat} = \frac{VL}{(A \; T \; \Delta H)} \quad (17).$$

Where V = steady state volume of outflow from the entire soil column (cm^3), L is the length of soil column (cm), A is the interior cross-sectional area of the soil column (cm^2), ΔH is the change in hydraulic head or the head pressure difference causing the flow (cm), T is the time of flow (sec). The saturated weight of the core samples were taken before the analysis and weighed again after oven drying in the oven at a temperature of 105°C. The result obtained was used to calculate the bulk density and porosity. Bulk density was determined by core method as described by Blake and Hartge, (1986), and Anderson and Ingram (1993) while total porosity (%) (Assumed particle density p_s = 2.65 kg m^{-3}) was computed from bulk density (B_d), using the equation below:

$$TP = \left(1 - \frac{ps}{pb}\right) x\ 100 \tag{18}$$

3.2.5.4 Measurement of soil moisture and soil water retention characteristics

Soil moisture and water retention characteristics was monitored from 2014-2015 under each of the two selected land use or land cover types at the soil-moisture station at Wanteou using three Hydra sonde moisture probes and three pF-meter probes (Figure 3.5) . During this period, rainfall was also measured using the tipping bucket raingauge installed at the location. The soil properties in each of the two selected land use were determined. The selected land use or land cover types are; Maize-Beans cropland + tillage (TMB) and Fallow Shrub-grassland (FSG). These soil moisture sensors were installed at one soil horizon each due to the shallow depth of soils (0-20 cm) of the location at the middle or center slope of each land use or land cover during the period of the study. The soil moisture sensor made up of a special sensor inside the ceramic membrane balances/equilibrates with the soil tension and measure continuously the water content which is adapted to hydraulic potential. The soil moisture was measured a 5 minutes timescale and was converted and compared at 30-minutes and daily timescales.

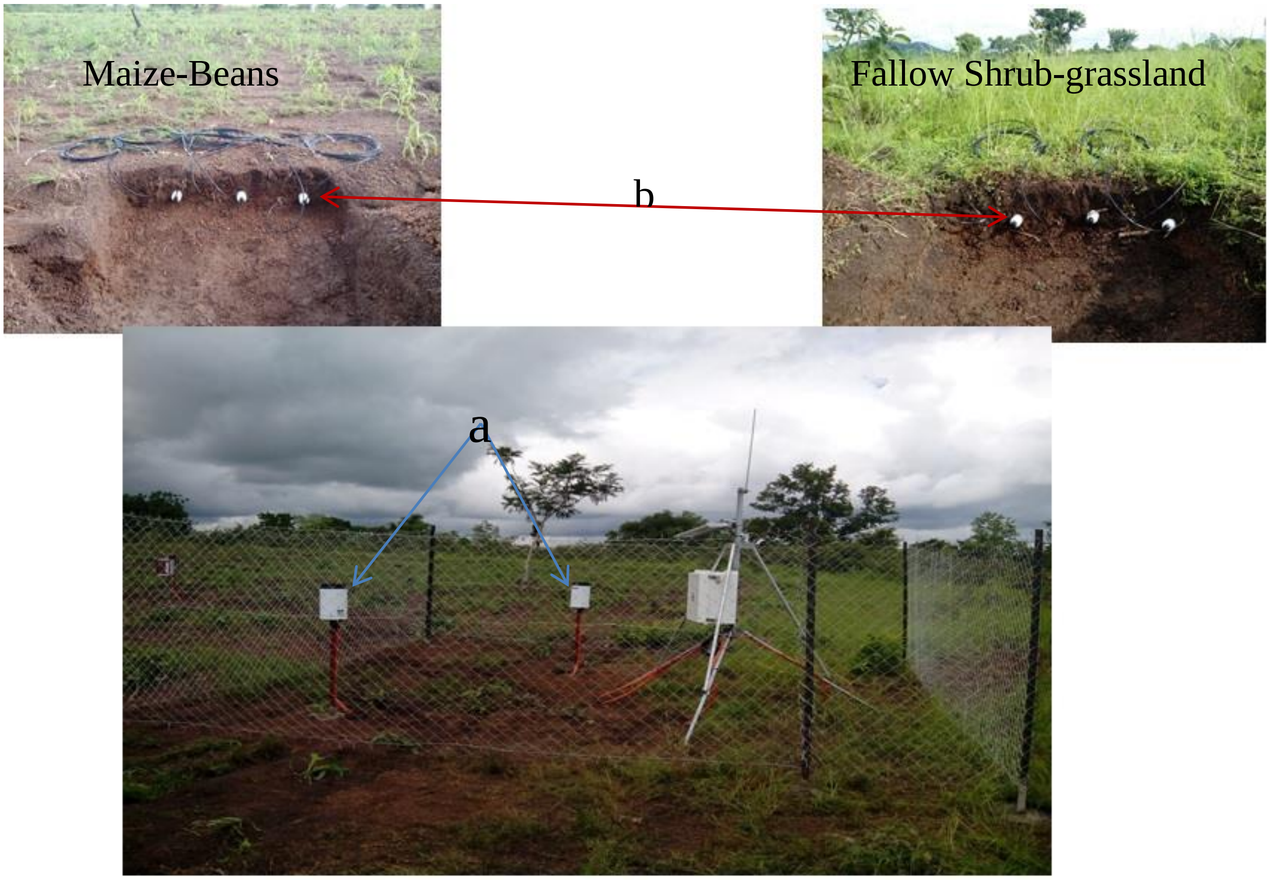


Figure 3.5: Installation of soil moisture sensors and raingauge at the soil-moisture station at Wanteou in Koupendri catchment; (a) Tipping bucket raingauge (b) soil moisture sensors.

3.2.6 Local scale hydrological processes under different land use and slope positions

3.2.6.1 Design of microplots and installation process

Two slope positions; 2.3 % and 5.8 %, and two land use types; tilled-maize-beans intercrop (TMB) and fallow shrub-grass land (FSG) were used for the study. To capture the variability in surface runoff processes in the catchment, six sets of microplots (1 m x 1m) were installed on each of the two selected land use types and two slope positions respectively for surface runoff measurement (Figure 3.6). A total of twenty-four microplots were installed. The site selection was based on a reconnaissance survey considering slope positions and major land use of the catchment. The six sets of the micro plots measuring 1 m x 1 m were installed at 0.5 m interval to capture the influence of soil spatial variability on rainfall-runoff response (surface runoff) monitoring. One way of achieving this is by installing all six plots in each slope position at the same topographic level or position. The microplots are constructed using corrugated metal sheets which were driven

20 cm into the soil with a protrusion 20cm above the soil. Each of the microplots was fitted with a plastic bucket as a collector (Figure 3.7) at its outlet for collecting surface runoff. After each rain event, the total amount of surface runoff in each collector was measured with a graduated cylinder and recorded. This was done from 2014 (September-November) to 2015 (July-October). Also within this period, discharge was measured at the outlet of the entire catchment.

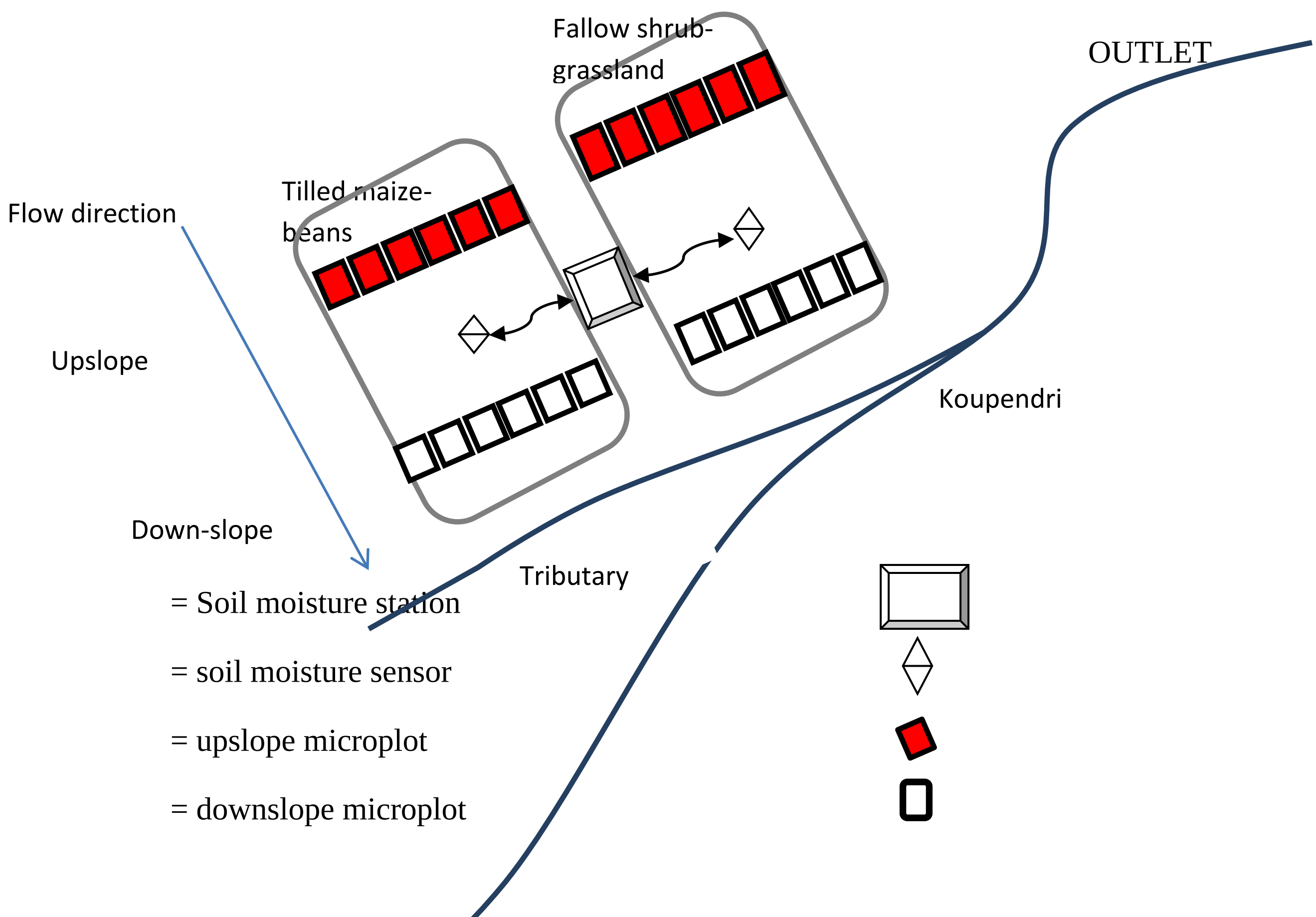


Figure 3.6: Experimental set-up of micro plots at the upslope and downslope of the catchment

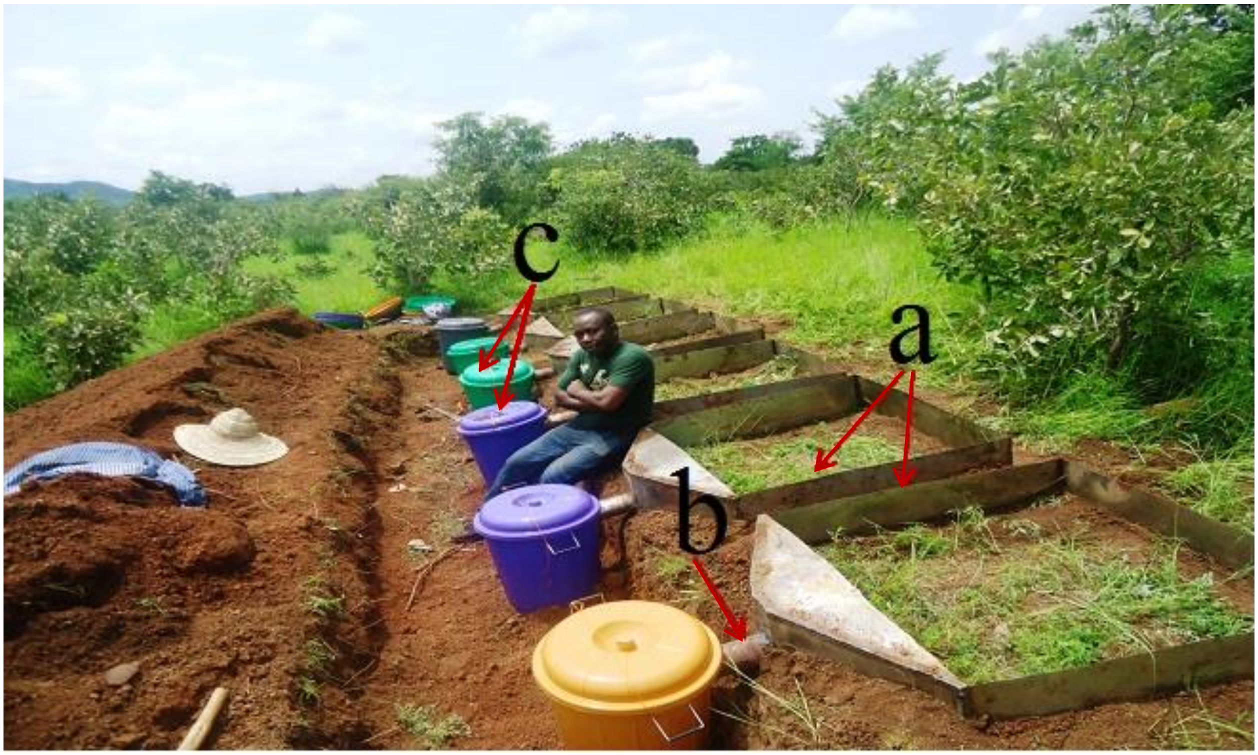


Figure 3.7: Installation of the microplots at the selected site/location, a = microplots, b = outlet, c = collectors (plastic buckets).

3.2.6.2 Computation of surface runoff coefficients at plot and catchment scale

Surface runoff coefficient for some selected rain event considered in 2014 was calculated for the catchment and for the microplots using the relationship (eqn. 19) below;

$$c = \frac{Runoff/discharge(mm)}{Rainfall\ (mm)} \tag{19}$$

Where c = runoff coefficient

3.2.6.3 Determination of Hydrology of Soil Types

The determination of hydrology of soil types was done using information on soil properties and infiltration characteristics of the location. Since the texture of the soil types (Plinthosols) at each slope position and land use types are mostly sandy loam (Table 3.4), the hydrologic of soil groups were determined using infiltration table according to Mishra and Singh (2003). The infiltration rate was obtained from infiltration measurement using a Hood infiltrometer. The measurements were made in triplicates on each slope position and land use type. The average of the three minimum infiltration rates obtained were used to determine the hydrology of soil types for each slope position and land use type (Table 3.4).

Table 3.4: Soil texture and hydrology of soil types for the experimental location.

LandUse/Slope Position.	Sand %	Silt %	Clay %	Texture	Infiltration (cm/day)	Hydrologic Soil group
TMB-Upslope	60	28	12	SL	102.8	A
TMB-Downslope	59	30	11	SL	50.6	A
FSG-Upslope	66	26	8	SL	227.3	A
FSG-Downslope	63	27	10	SL	202.2	A

TMB = tilled maize-beans crop land, FSG = fallow shrub-grassland, SL = sandy loam

3.2.6.4 Determination of the NRCS-CN

Since the soil type (Plinthosols- mostly Sandy loam) and the hydrological soil group are the same, curve numbers (CN) were assigned to each slope position based on land use or land cover types for hydrology of soil types A using the standard curve number table (Mishra and Singh, 2003). Moreover, it has been reported that land use types explain the differences in runoff CN much better than hydrological soil group (Descheemaeker et al., 2008). A curve number of 57 and 66 were assigned to the FSG and the TMB land use types respectively. The assigned CN-values were used to calculate the potential maximum retention or infiltration (S) as shown below (eqn. 20).

$$S = \frac{1000}{CN} - 10 \qquad (20).$$

The surface runoff (Q) for each rain event (P) was predicted or simulated using the equation below;

$$Q = \frac{(P - Ia)^2}{(P - Ia) + S} \qquad (21).$$

Where P = Daily total rainfall; Q = direct runoff; Ia = initial abstraction (accounts for all loses before runoff begins), and S = potential maximum retention or infiltration.

Through studies of many small agricultural watersheds, Ia was found to be approximated by the following empirical equation below:

$$Ia = \boldsymbol{\lambda} S = 0.2S \ (\boldsymbol{\lambda} = 0.2) \qquad (22).$$

$\boldsymbol{\lambda}$ viewed as a regional parameter dependent on geologic and climatic factors (Bosznay, 1989; Ramasastri and Seth, 1985). $\boldsymbol{\lambda}$ is assumed to be equal to 0.2 for practical applications and this was used in this study;

3.2.6.5 Statistical Analysis

The observed or measured surface runoff for each rainfall events in 2014 were subjected to analysis of variance (ANOVA) in RCBD or two-way ANOVA with blocking using Genstat Discovery Edition 10.3 and the mean effects of the land use and slope positions surface runoff was compared using the Fischer's least significant difference (F-$LSD_{0.05}$) as described by Obi (2002). Surface runoff variability was evaluated using the coefficient of variation. The model efficiency (ME) coefficient and root mean square error (RMSE) which were analyzed using the Nash and Sutcliffe model efficiency, and the coefficient of determination (R^2-values) were used to evaluate the predictive accuracy of the NRCS-CN equation (Van Rompaey *et al.*, 2001).

$$ME = 1 - \frac{\sum(Q_{obs} - Q_{pred})^2}{\sum(Q_{obs} - Q_{mean})^2} \qquad (23).$$

where ME is the model efficiency, Q_{obs} is the observed runoff value, Q_{pred} is the predicted runoff value, Q_{mean} is the mean of observed runoff value. Values for ME range from ∞ to 1. The closer ME approximates 1, the better the model prediction.

$$RMSE = \frac{\sqrt{\frac{1}{n}\sum_{i=1}^{n}(Q_{obs} - Q_{pred})^2}}{\frac{1}{n}\sum_{i=1}^{n} Q_{mean}} \qquad (24).$$

Where RMSE is the root mean square error as an error-measure. The closer RMSE approximates to zero, the better the model prediction.

3.2.7 Hydrological modeling of Koupendri catchment

3.2.7.1. Modeling approach: WaSiM.

To model and understand the hydrological processes of the Koupendri catchment, WaSiM model was chosen because it is a basin scale water balance simulation model. Also, it is a deterministic, spatially distributed and physically based hydrological model that describe relevant and core hydrological processes. The hydrological processes described include; unsaturated flow, saturated flow, transport, surface energy balances and stream flow generation or routing. It captures spatial variability of the catchment characteristics using spatially distributed data or boundary conditions such as vegetation, land use and soil properties, rainfall, topography, and climate among others.The model spatial resolution is usually given in a regular grid, which can vary in size from meters to kilometers. Previous applications have demonstrated its capability of simulating successfully different hydrological processes across various ranges of scales (Schulla, 2007). The temporal resolution can range from minutes to days, depending among others on the time resolution of the meteorological data. The highest resolution in time, however, for modeling the hydrological processes is one minute. Due to the physical basis of many of its components, the model can be applied to various basins in a wide range of environmental conditions and scales all over the world (Schulla, 2007). However, because it incorporates both physical and conceptual approaches to describe relevant hydrological processes, some of the parameters (e.g., Ksat, LAI, discharge e.t.c) can be measured while others must be identified by calibration (Seibert, 2000; Beven, 2001; Montanari and Toth, 2007; Singh, 2010). It is recommended to use at least some observed runoff data for the model calibration. The observed discharge was measured at the outlet of Koupendri catchment.

3.2.7.2 Model structure

WaSiM is partly based on physical methods, such as the evapotranspiration model after Penman-Monteith, but also uses conceptual approaches. The main processes of water flux, storage, and the phase transition of water are simulated by physically-based simplified process descriptions (Schulla, 1997). Catchment area was divided into grid cells in order to simulate the catchment water balance. For each grid cell, WaSiM carries out the spatial interpolation of the meteorological input data obtained from the meteorological station. This station can be situated either inside or outside the catchment area. The sub-model that adjusts radiation and temperature modifies their values according to the exposition and the topographic shading of the grid cells (Schulla, 1997).

The spatial interpolation of the meteorological input data is then followed by the simulation of the main hydrological processes such as evapotranspiration, interception, infiltration, and the separation of the discharge into direct flow, interflow, and baseflow. For each grid cell, WaSiM generates the sums as outputs with average, maximum or minimum values of any output data for any time period. This output information reveals spatial variations. Postprocessing includes the visualization and interpretation of the output data. During postprocessing, the water balance of a catchment area is checked and model parameters are calibrated and validated in order to improve the simulation results. The catchment water balance simulated by WaSiM, includes the components of surface runoff, interflow, baseflow, groundwater flow and channel flow, and the storage of water such as interception, snow accumulation, depression storage, and storage of water in the unsaturated and saturated soil (Figure 3.8). In this study, groundwater flow and snow accumulation were not considered part of the catchment water balance considering the catchment size and location.

Table 3.5: Components of WaSiM model

Components	Function
Interception	Storage approach; function LAI
Potential Evapotranspiration	Separate calculation of evaporation from vegetated soils considering all soil layers
Soil module	Richards equation
Infiltration	Based on Peschke (1977) and Green and Ampt (1911)
Overland flow	Horton overland flow
Percolation	Function based on soil saturation and saturated conductivity
Interflow	Storage approach: comparing maximum and actual rate
Baseflow	Linear storage approach
routing	Kinematic wave approach considering retention and translation

- Detail description of each component is found in Schulla (2007, 2012).

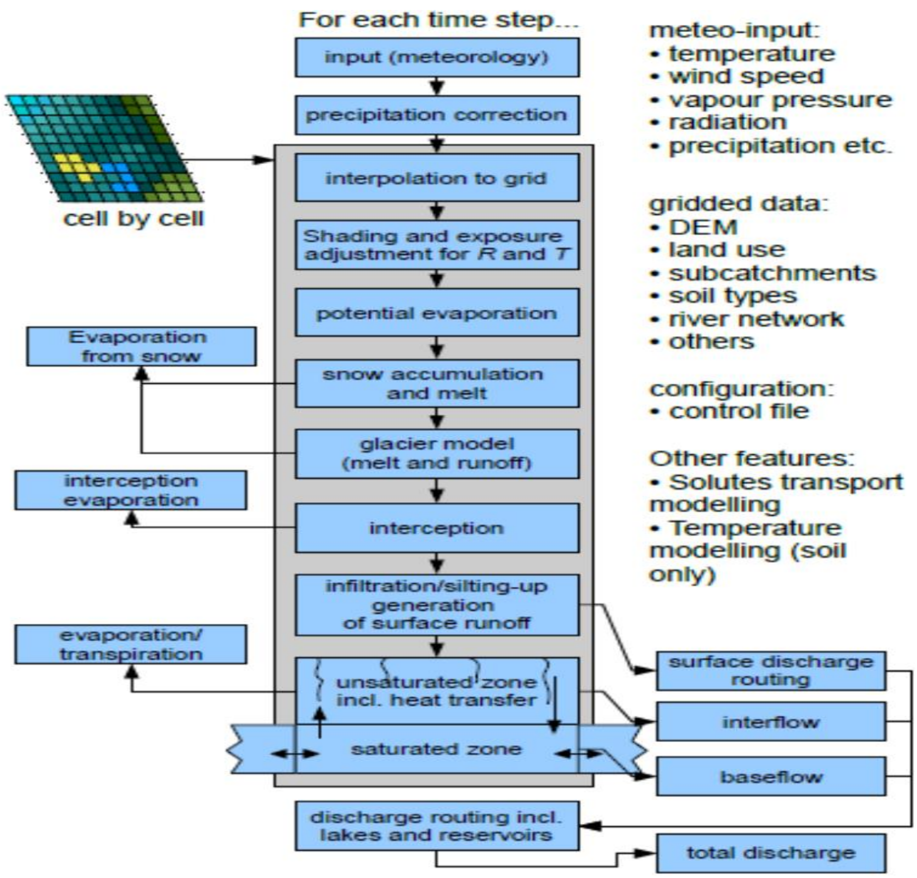


Fig. 3.8: Structure of the WaSiM model (Schulla, 2012)

3.2.7.3 Data processing

The spatially distributed data (DEM, basin characteristics, soil and land use data) and hydro-meteorological data (temperature, rainfall, humidity, wind speed, global radiation, and discharge data were processed using WaSiM pre and post processing software or tools (Arc-GIS, TANALYS). Since the choice of a suitable grid size depends on the given size of the catchment area under investigation, we chose DEM of 30 m resolution for our catchment (11.8 km^2) considering the WaSiM authors' recommendation of 10 m grids size for areas smaller than 1 km^2 and 5 km^2 grid size for areas bigger than 10,000 km^2 (Schulla and Jasper, 1999). Based on the DEM, some information on basin characteristics (slope, flow direction, flow accumulation, exposition and catchment boundaries or flow time etc) were obtained using TANALYS (Fig. 3.9). The spatial interpolation of the sparse meteorological input data (from one station) to the model grid resolution was carried out using Thiessen Polygons interpolation method. Land use and soil data were prepared in the WaSiM format using DEM and Arc-GIS 10.1. The soil map (1:25000) was resampled with the DEM (30 x 30m resolution) using the Arc-GIS software or tools (ESRI, 2010).

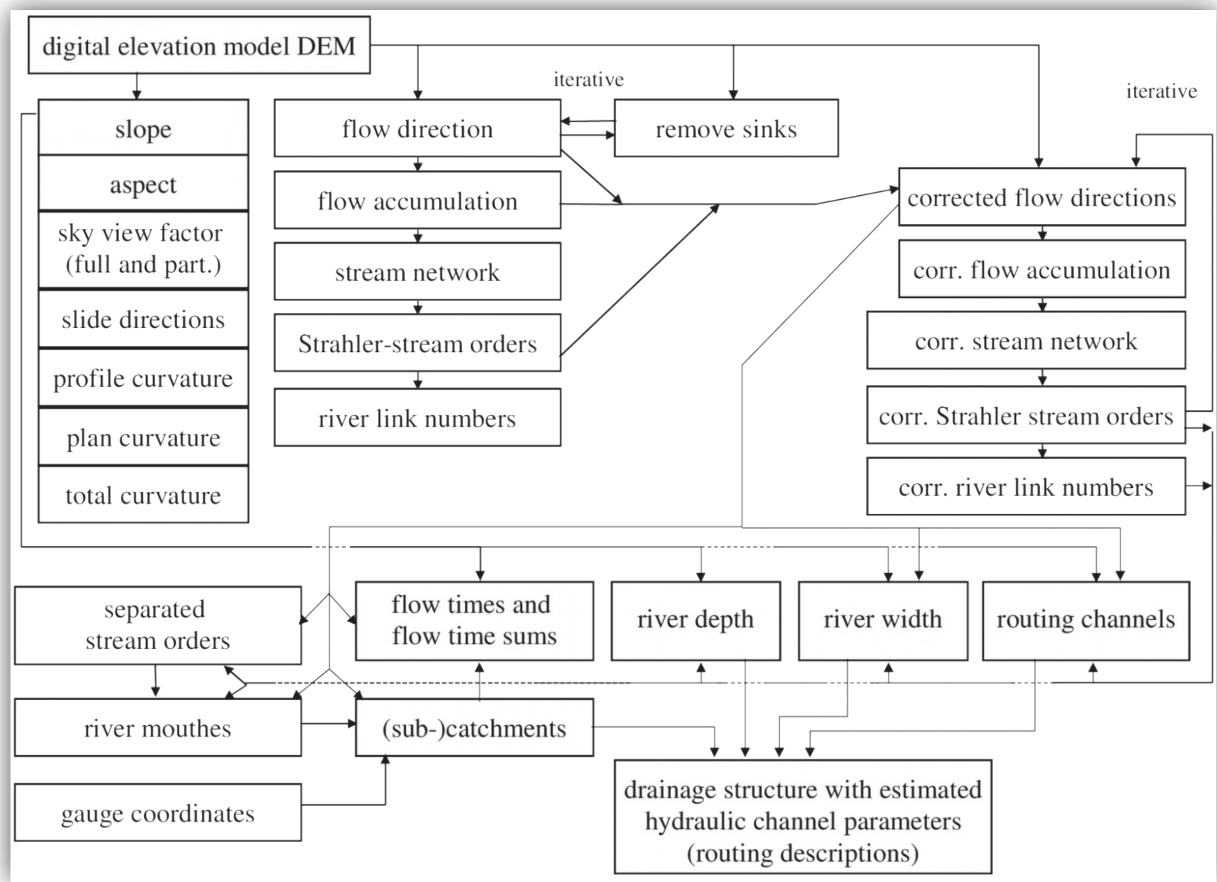


Figure 3.9: Topographic analysis of a digital elevation model by TANALYS *(Schulla, 2012)*

Soil parameterization

The parameterization of the soil types in a distributed way requires soil type grids. The soil type grid was parameterized with a soil type table that describes each grid cell with a parameter data set according to the grid classification. Based on the detailed soil map of the catchment, the catchment was discretized into five different soil types with their respective properties. The parameterization of the soil type with different number of horizons was done using multiple soil horizon method as presented in Table 3.6. Each soil horizon consisting of different number of layers of various thicknesses has different hydraulic properties for simulating soil water dynamics. These include; the saturated hydraulic conductivity which was obtained directly from laboratory or field measurements (Azuka et al., 2015) and, the van Genuchten parameters obtained from the available soil data using the pedotransfer function of Rawls and Brakensiek (1982). The van Genuchten parameters describing the soil water retention function of the horizon and the thickness of the horizons are also shown in Table 3.6.

Table 3.6: Parameterization of the soil hydraulic properties

Soil type	Horizon no.	Texture [-]	Θ_s $[cm^3/cm^3]$	Θ_r $[cm^3/cm^3]$	α $[m^{-1}]$	n [-]	Ksat $[ms^{-1}]$	K_{rec} [-]	d_z [m]	l_v [-]
1	1	L	0.236	0.054	4.4	1.39	1.03E-3	7.9	0.12	1
	2	L	0.231	0.076	2.9	1.34	1.75E-3	8.1	0.35	9
	1	SL	0.244	0.048	4.7	1.42	2.35E-4	7.5	0.10	1
2	2	CL	0.297	0.093	1.2	1.21	5.55E-4	8.4	0.12	2
	3	C	0.246	0.081	0.5	1.07	1.44E-5	8.6	0.43	7
	1	SiL	0.220	0.055	5.5	1.37	6.91E-4	7.5	0.17	1
3	2	SiCL	0.287	0.099	2.2	1.25	1.95E-4	7.8	0.13	2
	3	CL	0.235	0.095	1.7	1.18	5.71E-4	8.7	0.40	7
	1	L	0.232	0.048	4.8	1.42	7.16E-4	6.7	0.12	1
4	2	SiL	0.235	0.05	3.6	1.40	1.64E-4	7.5	0.12	2
	3	L	0.243	0.047	3.3	1.41	5.85E-5	7.8	0.13	2
	4	CL	0.188	0.089	1.1	1.23	2.73E-5	8.1	0.56	5
	1	SiL	0.273	0.068	6.8	1.34	8.12E-4	7.3	0.14	1
5	2	SiL	0.218	0.075	0.6	1.26	1.08E-5	7.7	0.13	2
	3	CL	0.284	0.081	0.5	1.17	2.69E-5	8.5	0.25	2
	4	CL	0.179	0.078	0.4	1.12	2.92E-5	8.6	0.45	5

L= loam, SL= sandy loam, CL= clay loam, SiL= silty loam, SiCL= silty clay loam, C= clay, Θ_s= Saturated water content, Θ_r= Residual water content, α= Van Genuchten parameter, n=Van Genuchten parameter, Ksat = Saturated hydraulic conductivity, K_{rec}= Ksat – recession with depth, d_z = Layer thickness, l_v=Number of soil layers.

Land use parameterization

A multiple landuse approach describing each land use class was used to parameterize the landuse types. All the parameters of each land use types (i.e.height of vegetation, interception capacity evapotranspiration resistance, aerodynamic resistance, leaf area index, root depth, root distribution and albedo) were all taken from literatures (Bronstert et al., 2001; Cornelissen et al., 2013; Güntner, 2002; Hagemann, 2002; Kasei, 2010, Martin, 2005 and Steyaert and Knox 2008).

3.2.7.4 Sensitivity Analysis

Sensitivity analysis is the process of determining the rate of change in model output with respect to changes in model input parameters (Moriasi *et al*., 2007). In other words, sensitivity analysis tells us how a certain change in an input affects the output of a model. Thus, it is a necessary process to identify key parameters and parameter precision required for model calibration (Ma *et al*., 2000).

In this study, more than 500 multiple simulations from WaSiM model output using the initial boundary conditions data sets were used to perform sensitivity analysis for soil, land use and unsaturated zone model parameters. Simlab- a program designed for Monte Carlo based uncertainty analysis was used to generate sample distributions from input factors or parameters using Latin hypercube sampling scheme (Satelli et al., 2004). The ensemble of random variables or loops generated from Simlab was fed into the WaSiM model for execution. The output files from the model execution were fed to the Matlab which executes automatically, the results of the initial calibration process providing information on the runoff components (direct, base and interflow), ETpot, ETact, Storage and the efficiency criteria. This information was extracted from the Matlab, and in combination with the sample distributions or ensemble of random variables generated with the Simlab was used for sensitivity analysis with R-software. The sensitivity analysis focused mainly on the unsaturated zone parameters, saturated hydraulic conductivity (Ks) of the different soil types, surface resistant of crop (RSC) and surface resistant for soil evaporation (RSE). The sensitivity analysis was evaluated at four threshold of sensitivity indices (0.01 (lowest limit), 0.195, 0.25 and 0.295 (upper limit)) using partial correlation coefficient (PCC). These indices represent the levels, magnitude and degree of sensitivity of the runoff components, ETpot, ETact, unsaturated zone parameters, storage and the efficiency criteria to each parameter. The most sensitive parameters were assumed to be at the upper limit. After several runs with the initial boundary condition data sets or parameters, the sensitivity plots generated helped to ascertain or identify the most sensitive parameters.

3.2.7.5 Calibration and validation of WaSiM

In this study, a combination of both automatic and trial by error methods were used for the model calibration processes. The most sensitive parameters obtained during the sensitivity analysis were adjusted during the automatic calibration process and repeatedly ran several times with different combinations of model parameter until the best model fit (observed vs simulated streamflow) judged by the model efficiency criteria was obtained. For the current work, due to non-availability of long-term historical data or gauging station in the catchment prior to the commencement of this research, 2014 was considered as the calibration year. Due to same reason of non-availability or scarcity of data, the model was validated for the year 2015. The validation of the model was done using similar data obtained from the calibration process.

3.2.7.6 Model uncertainty analysis

The uncertainty estimation methodology or algorithm (SUFI-2) of Abbaspour et al. (2007) was utilized for optimizing the parameters and analyzing their uncertainties. This uncertainty analysis methodology follow a sequence of steps involving progressive reduction of the initial or large model parameters uncertainties until a certain calibration threshold or requirements based on the prediction uncertainty is reached (Abbaspour et al., 2004). In this algorithm, all uncertainties (parameter, model, input, etc.) are mapped onto the parameter ranges, which are calibrated to bracket most of the measured data in the 95% prediction uncertainty (95%PU) known as the P-factor (Abbaspour *et al*., 2007). The 95%PU is usually calculated at the 2.5% and 97.5% levels of the cumulative distribution of the output variables obtained through Latin hypercube sampling, excluding 5% of the very bad simulations. The very bad simulations often result from very bad parameter combination. This index has been judged to provide a good measure of assessing the model's ability to capture uncertainties (Arnold et al., 2012; Bossa, 2012).

The strength of the uncertainty analysis can be measured using the R-factor. R-factor is the ratio of average distance between 2.5 and 97.5 percentiles of the cumulative distribution of the simulated variable and the standard deviation of the corresponding measured variable calculated as shown below (Eqn. 25). Good model simulation tends to bracket most of the measured data with the smallest possible uncertainty band.

$$R - factor = \frac{1}{k\sigma_x}\sum_{i=1}^{k}(X_u - X_L)_l \qquad (25)$$

Where k is the number of observed data points, σ_X is the standard deviation of the measured variable X, while X_U and X_L are respectively the 2.5th and 97.5th percentiles of the cumulative distribution of every simulated point.

Theoretically, the value for P-factor ranges between 0 and 1, while that of R-factor ranges between 0 and infinity. A P-factor of one and an R-factor of zero is a simulation that exactly corresponds to the measured data. The degree to which the factors are different from these numbers can be used to judge the strength of the calibration. A larger P-factor can be achieved at the expense of a larger R-factor.

3.2.7.7 Water balance quantification or assessment

The water balance of Koupendri catchment was calculated to determine the role of various hydrological components in the water budget of the catchment. Based on mass conservation or continuity equation, the catchment water balance which is the sum of discharge or runoff (Q), Real or actual evapotranspiration (ETR), groundwater recharge (GWR) and the change in water stored in the saturated and unsaturated zones (ΔS) must equal rainfall (R):

$$R = Q + ETR + GWR + \Delta S \tag{26}$$

However, since groundwater flow or recharge is negligible at the scale of this study considering the catchment size, the water balance for Koupendri catchment was calculated thus;

$$R = Q + ETR + \Delta S \tag{27}$$

Chapter 4

Soil survey and soil classification of the Koupendri catchment north-west of Benin, West Africa.

Introduction

Soil is a basic natural resource with widespread utilization ranging from agriculture, forestry, and other engineering and environmental purposes such as hydrological modeling. The importance of soil data for sound environmental and natural resource management has been reported (e.g., McKenzie *et al*., 2000). Besides being a storage reservoir and source of water supply, soil protects groundwater supplies by buffering and transforming pollutants. It is said that many of the current environmental, social, economic, geologic, and human health issues such as heavy metal poison can be better addressed if soils are considered important and paid due attention (e.g., Howitt *et al*., 2009; Brevik, 2013; McBratney *et al*., 2014 cited in Brevik *et al*., 2014). Recently, there is an increasing global demand for soil data and information for environmental monitoring due to global warming impact on water resources. An understanding of nature, properties, dynamics, distributions and functions of the soil as part of landscapes and ecosystem is paramount especially to prevent its continuous degradation and ensure its continuous and sustainable utilization. In land evaluation, wise decisions on land use and effective management of soils for improved agronomic productivity require an understanding of soil distribution and patterns (McBratney *et al*., 2000). This important data most times is non-existent and sometimes available at a small scale too coarse and difficult to use for accurate modeling of hydrological processes. This is particularly true for most West African catchments including Koupendri catchment in north western Benin, where the impact of climate change is expected to be pronounced. For instance, the existing data on soil types and supporting maps for the catchment were those produced by the erstwhile ORSTOM at the scale of 1:200.000, 1:250.000 and 1:500.000 and date back to the colonial period.

Reliable soil data is a prerequisite for hydrological and environmental modeling, as well as for the design of appropriate land-use systems and soil management practices. This will help to arrest further degradation and rehabilitate the potentials of degraded soils, as well as for a better understanding of the environment (FAO, 2006). Such reliable soil information is obtained through examination and description of the soil in the field. Most soil surveys result in the preparation of a soil map alongside a soil or scientific report which gives the inventory of the soils found in the area, their geographic distribution, physical and chemical characteristics, and climate and land use together with interpretations comparing different land use.

Thorough soil description serves as the basis for soil classification and site evaluation as well as for interpretations on the genesis and environmental functions of the soil (FAO, 2006). Thus, the aim of this study is to make a detailed soil survey of the Koupendri catchment aimed at providing basic soil data appropriate for hydrological modeling, and for making recommendations and decisions on the present and future use of the land for planners, agronomists, and other engineering uses/purposes. This study tends to characterize and classify the soils of Koupendri catchment, and develop a detailed soil map for hydrological modeling and making recommendation for sustainable management of soil and water resources.

4.1 Soil map of the Koupendri catchment

The soil map of the Koupendri catchment was produced using both field observable features and analytical results based on SOTER approach. SOTER approach was originally designed for small scale mapping at 1: 1,000,000 considering terrain-soil attribute relationships. However, at larger scales of 1:100,000 and beyond, only the soil attributes are retained with little or no terrain attributes. The soil attributes obtained from about 200 auger drilling points spaced at 250 m intervals were projected on the map of the catchment. Soils with similar attributes based on field observable features and analytical results were grouped together and mapped using expert knowledge. The soil map of this study was produced at the scale of 1:25,000 showing mainly the soil attributes using the FAO/Unesco soil map legend. The soil map showed that Plinthosols are the dominant soil type in the catchment. Plinthosols which are characteristic of strongly weathered soils (FAO, 1988) consist more than 55% of the catchment soils compared to other soil types; Gleysols, Luvisols and Cambisols (Fig. 4.1).

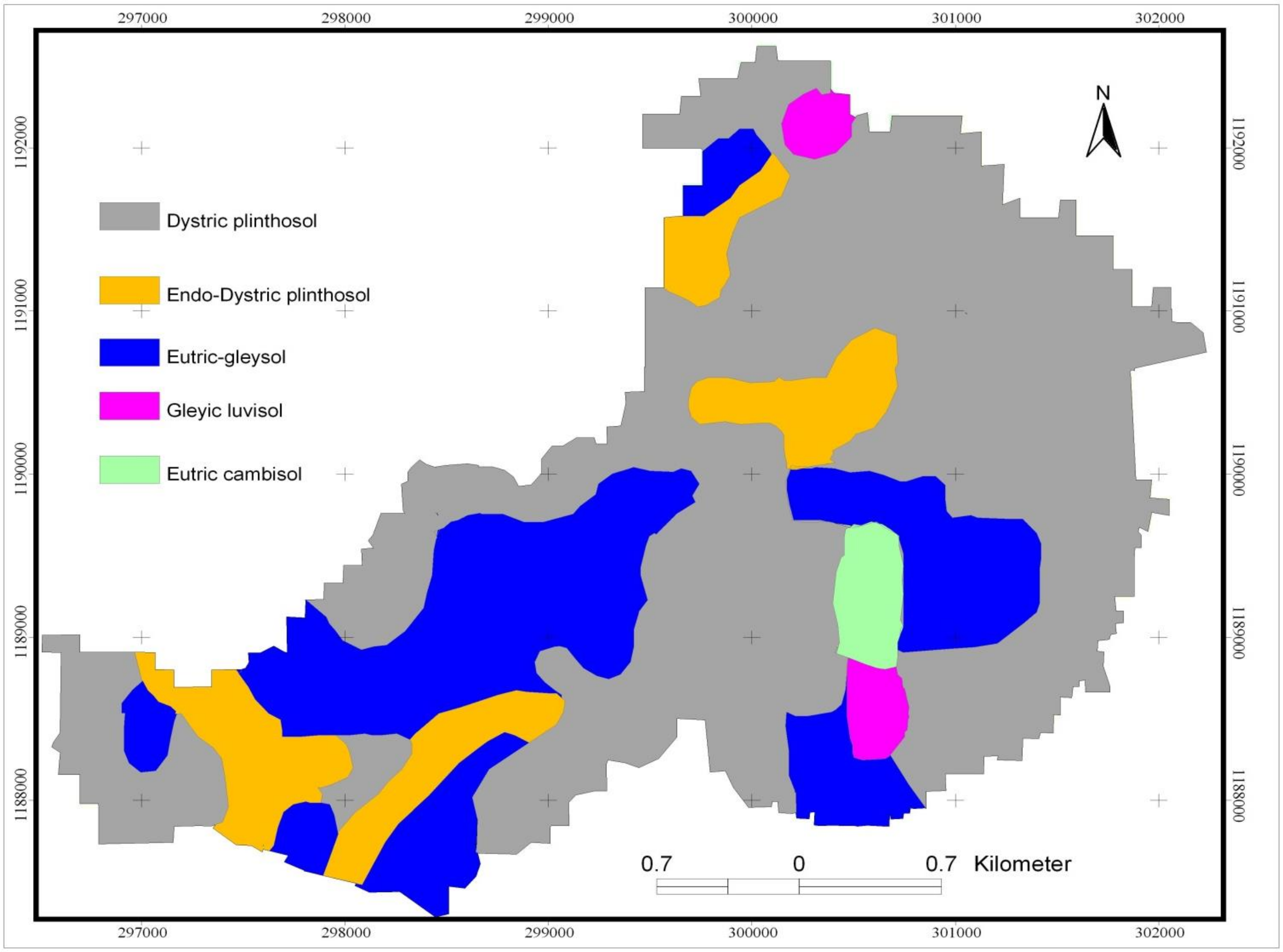


Figure 4.1: Distribution of soils in the Koupendri catchment at a scale of 1:25000

4.2 Soil description and characteristics of the Koupendri catchment

The soil colour (moist, dry) *value and chroma* varied with depth ranging from dark brown 10 YR mostly at the A-horizon to reddish brown 7 YR and yellow 2 YR at the sub-surface horizon except at few horizon (AZUKOUP-4 and AZUKOUP-5) with uniform reddish brown 7 YR throughout the horizons (Table 4.1). The increase in soil color from dark brown 10 YR to reddish brown 7 YR could be attributed to the oxidation of iron oxides responsible for the reddish colour in subsoil horizons (Buol *et al*., 2003) and to a lesser extent, the decrease in SOC with depth. The poor variability in the soil colour *hue*, *value and chroma* is an indication of the presence of soil moisture caused by a high water table due to a shallow aquifer. The presence of mottles in some subsoil layers confirms that the soils have moderate to poor drainage conditions. The soil structure of the surface horizons of the soil profiles were mostly massive and compact with varying size of weak peds except at AZUKOUP-3 that has cubic and platy structure at the surface (Table 4.1). The subsurface horizons were massive and compact with few exception having either platy, prismatic, angular blocky or blocky structure. The consistence (dry) of both surface and subsurface horizons ranged from friable through hard to very hard. The gravel content of the soils increases with depth and ranges from 10 % to more than 60%.

Table 4.1: Koupendri catchment soil morphological characteristics and soil description.

Horizon	Depth (cm)	Color Moist	Color Dry	Structure	HB	Cons.	CF (%)	BA
AZUKOUP-1								
Ap_c	0-20	10YR5/3	10YR7/2	MC	Dis	F	20	high
Bt_{nc}	20-30	7.5YR4/6	7.5YR5/6	MC	Dis	vh	60	low
AZUKOUP-2								
A_c	0-15	10YR4/2	10YR5/2	MC	Dis	F	10	low
Bt_{nc1}	15-47	7.5YR5/3	7.5YR5/6	BL/AB	Gr	F	15	low
Bt_{nc2}	47-80	7.5YR8/2	7.5YR8/6	MC	Dis	F	10	low
AZUKOUP-3								
A_{gh}	0-12	10YR3/2	10YR7/1	Cu/Pl	Gr	Vh	-	high
Bt_{gn}	12-30	7.5YR3/2	7.5YR8/1	Pri/Pl	Dis	Vh/C	-	medium
Bt_{gcn}	30-60	10YR4/3	10YR7/2	M/Pl/C	Gr	Vh	15	low
Bt_{gc2n}	60-100	2.5Y7/2	2.5Y6/2	M/Pl/C	Gr	Vh	15	low
AZUKOUP-4								
A	0-12	7.5YR3/2	7.5 YR7/1	M/C	Dis	Vh	-	high
AB_g	12-35	7.5YR4/2	7.5YR6/2	M/C	Dis	Vh	-	low
Bt_g	35-58	10YR4/3	10YR8/1	AB/C	Dis	Vh	-	low
Bt_{gc}	58-120	2.5Y4/4	2.5Y7/6	BL/C	Dis	Vh	10	low
AZUKOUP-5								
A	0-20	7.5YR5/3	7.5 YR7/2	M/C	Dis	F	-	high
Bt_{ng}	20-56	10YR5/3	10YR7/6	AB	Gr	F	-	low
BC_{ng}	56-100	10YR4/2	7.5YR8/1	AB	Gr	F	-	medium
AZUKOUP-6								
A_{gn}	0-20	7.5YR3/2	7.5 YR7/1	M/C	Dis	F	-	high
Bt_{ng}	20-32	7.5YR7/1	7.5YR8/2	M/C	Dis	S	-	low
Bt_{ngc}	32-55	7.5YR7/1	7.5YR8/1	M/C	Gr	S	30	low
AZUKOUP-7								
A_{gc}	0-17	7.5YR4/2	7.5 YR7/1	AB	Gr	F	5	high
Bt_{gc1}	17-42	7.5YR5/2	7.5YR6/1	AB	Gr	F	10	medium
Bt_{gc2}	42-100	7.5YR5/1	7.5YR6/1	M/C	Gr	S	15	low
AZUKOUP-8								
A_c	0-12	10YR4/2	10YR5/2	AB	Dis	F	20	medium
Bt_c	12-40	7.5YR4/6	7.5YR58	M/C	Dis	Vh	50	low
AZUKOUP-9								
A_c	0-20	7.5YR3/2	7.5YR7/1	M/C	Dis	F	40	high
Bt_c	20-52	7.5YR5/6	7.5YR7/8	M/C	Dis	Vh	60	low
AZUKOUP-10								
A_c	0-15	10YR5/3	10YR7/2	M/C	Dis	F	45	high
Bt_{c1}	15-32	10YR3/3	10YR5/2	AB	Dis	F	50	medium
Bt_{c2}	32-60	2.5YR4/4	2.5YR6/1	AB	Dis	S	60	low

A= A-horizon, c=concretions or nodules, B= B-horizon, h=accumulation of organic matter, V= occurrence of plinthite, Vm= Hardened plinthite (hardpan, iron stone, petroferric or skeletic), g= stagnic conditions, t=illuvial accumulation of silicate clay, n=pedogenetic accumulation of exchangeable Na, p = ploughing, HB = horizon boundary, cons. = consistence, CF = coarse fraction, BA = biologic activity, M/C = massive/compact, BL = blocky,

AB = angular blocky, Pl = platy, Gr = gradual, Dis = distinct, F = friable, Vh = very hard, S = sticky, Cu = cubic, Pri = prismatic.

4.3 Soil textural characteristics

The clay content increased with increasing depth throughout the profiles except at AZUKOUP-4 and AZUKOUP-5 where it is irregular resulting to abrupt textural change (Table 4.2). The sand content decreased with increasing depth throughout the profiles while the silt content was irregular with increasing depth. The topsoils were mostly sandy loam with few silty loam and loam.

The silt/clay ratio and the degree of degradation they reflect are shown in Table 4.2. Generally, the silt/clay ratio decreased with depth throughout the profiles contrary to variation in clay contents. The highest value (6.1) was obtained in the A-horizon of AZUKOUP-4 while the least value (0.5) was obtained at the B-horizon of AZUKOUP-6 and AZUKOUP_10 respectively.

The gravel content of the soils increases with depth in most horizons with mixture of increase and decrease in gravel contents in few horizons (Table 4.2). The gravel content ranges from 9 % in the A-horizon (A_{gn}) of AZUKOUP-6 to more than 65% in the B-horizon (Bt_{c1}) of AZUKOUP-10.

4.4 Soil hydraulic/hydrological properties

The saturated hydraulic conductivity (Ksat), bulk density (BD), porosity (P) and soil water characteristics results for the profiles studied were shown in Table 4.3. The Ksat value was lowest (1.68 cm/d) in a clay loam B-horizon (Bt_{gc2n}) of AZUKOUP-3, and highest (395 cm/d) in a sandy clay loam B-horizon (Bt_{c1}) of AZUKOUP-10. The bulk density was relatively high while the porosity was moderate to low throughout the profiles studied (Table 4.3). The bulk densities range from 1.42 kgm^{-3} at the B-horizon of AZUKOUP-7 to 1.88 Kgm^{-3} at the B-horizon of AZUKOUP-3. Bulk density increases with depth in some profiles and vice versa in other profiles**.** The high bulk density (1.42-1.88 Kgm^{-3}) above the optimal value of 1.40 Kgm^{-3} and the moderate to low porosity (< 50%) below the ideal value (>50%) for healthy root growth in most horizons of the profiles studied could be attributed to soil compaction caused by continuous and intensive pastoral activities and cultivation for many years, poor soil structure (less inter-ped spaces), low soil OM and to a lesser extent the texture especially the silt content as seen in AZUKOUP-3 profile.

The soil water content at field capacity (FC; 0.33 bars) and at Permanent Wilting Point (PWP; 15 bars) had shown a slight variation among the studied profiles (Table 4.3). The highest FC (38.28)

Table 4.2: Soil textural properties of Koupendri soils

Horizon	Depth (cm)	Fine S (%)	Coarse S (%)	Total S (%)	Silt (%)	Clay (%)	Gravel (%)	TC	Silt/Clay
AZUKOUP-1									
Ap_c	0-20	32.00	20.00	52	40	8	30.79	SL	5.0
Bt_{nc}	20-30	22.73	25.43	48	35	17	64.07	L	2.1
AZUKOUP-2									
A_c	0-15	27.70	29.30	57	34	9	14.42	SL	3.8
Bt_{nc1}	15-47	19.02	17.98	37	36	27	17.25	L	1.3
Bt_{nc2}	47-80	19.53	11.87	31	42	27	15.2	L	1.6
AZUKOUP-3									
A_{gh}	0-12	14.94	9.36	24	59	17	10.2	SiL	3.5
Bt_{gn}	12-30	12.65	8.15	20	57	23	15.04	SiL	2.5
Bt_{gcn}	30-60	11.97	10.73	22	47	31	12.61	CL	1.5
Bt_{gc2n}	60-100	7.08	17.88	24	39	37	22 .88	CL	1.1
AZUKOUP-4									
A	0-12	20.45	22.55	43	49	8	10.84	L	6.1
AB_g	12-35	21.00	20.00	*41*	50	9	10.94	SiL	5.6
Bt_g	35-58	21.96	18.04	40	42	8	16.93	L	5.3
Bt_{gc}	58-120	16.00	18.00	34	38	28	12.62	CL	1.4
AZUKOUP-5									
A	0-20	22.39	33.61	56	36	8	11.21	SL	4.5
Bt_{ng}	20-56	15.93	26.07	42	44	14	11.15	L	3.1
BC_{ng}	56-100	21.69	33.31	55	36	9	10.51	SL	4
AZUKOUP-6									
A_{gn}	0-20	25.22	26.78	52	41	7	9.16	SL	5.9
Bt_{ng}	20-32	12.08	16.00	28	41	31	16.79	CL	1.3
Bt_{ngc}	32-55	4.57	11.43	16	29	55	35.91	C	0.5
AZUKOUP-7									
A_{gc}	0-17	12.90	13.10	26	62	12	12.58	SiL	5.2
Bt_{gc1}	17-42	6.08	11.08	17	51	32	16.03	SiCL	1.6
Bt_{gc2}	42-100	5.92	16.08	23	41	36	22.75	CL	1.1
AZUKOUP-8									
A_c	0-12	22.65	21.35	44	46	10	10.19	L	4.6
Bt_c	12-40	15.00	20.00	35	47	18	22.86	L	2.6
AZUKOUP-9									
A_c	0-20	14.59	50.41	65	27	8	53.34	SL	3.4
Bt_c	20-52	13.00	36.00	49	31	20	55.12	L	1.6
AZUKOUP-10									
A_c	0-15	24.00	35.00	59	26	15	52.93	SL	1.7
Bt_{c1}	15-32	12.79	32.21	45	24	31	64.94	SCL	0.8
Bt_{c2}	32-60	6.19	16.81	23	26	51	58.08	C	0.5

L= Loam, SiL= Silty Loam, SL= Sandy Loam, SCL= Sandy Clay Loam, SiCL= Silty Clay Loam, CL= Clay Loam, C= Clay, S= sand, TC= textural class, S = sand.

Table 4.3: Soil physical/ hydraulic properties of the Koupendri catchment

Horizon	Depth (cm)	BD (gcm^{-3})	Ksat (cmd^{-1})	Por (%)	pF 2.5	pF 4.2	AWC
AZUKOUP-1							
Ap_c	0-20	1.50	27.71	43.27	21.46	11.38	10.1
Bt_{nc}	20-30	1.70	26.16	35.85	17.66	9.36	8.3
AZUKOUP-2							
A_c	0-15	1.57	46.93	40.71	22.45	11.85	10.6
Bt_{nc1}	15-47	1.56	26.11	41.27	28.36	15.03	13.3
Bt_{nc2}	47-80	1.58	6.63	40.52	31.91	16.91	15.0
AZUKOUP-3							
A_{gh}	0-12	1.74	22.94	34.33	20.11	10.33	9.78
Bt_{gn}	12-30	1.86	5.97	29.81	19.07	10.09	8.98
Bt_{gcn}	30-60	1.87	2.32	29.43	20.32	10.76	9.56
Bt_{gc2n}	60-100	1.88	1.68	29.06	21.45	11.47	9.98
AZUKOUP-4							
A	0-12	1.63	20.01	38.58	11.03	5.85	5.18
AB_g	12-35	1.54	15.78	41.46	18.53	9.82	8.71
Bt_g	35-58	1.57	8.4	40.59	17.43	9.05	8.38
Bt_{gc}	58-120	1.78	7.16	32.73	20.53	10.88	9.65
AZUKOUP-5							
A	0-20	1.62	60.25	39.00	21.42	11.36	10.07
Bt_{ng}	20-56	1.73	70.96	44.01	16.73	8.87	7.86
BC_{ng}	56-100	1.69	21.57	36.69	15.22	8.065	7.16
AZUKOUP-6							
A_{gn}	0-20	1.57	11.18	40.81	17.70	9.38	8.32
Bt_{ng}	20-32	1.68	5.97	36.77	30.41	16.12	14.29
Bt_{ngc}	32-55	1.59	21.4	39.94	28.44	15.08	13.37
AZUKOUP-7							
A_{gc}	0-17	1.56	20.55	41.07	21.05	11.11	9.94
Bt_{gc1}	17-42	1.42	39.83	46.34	31.73	16.43	15.3
Bt_{gc2}	42-100	1.64	18.29	38.09	38.28	20.23	18.05
AZUKOUP-8							
A_c	0-12	1.49	89.21	43.76	13.44	7.05	6.39
Bt_c	12-40	1.54	151.5	41.91	20.05	10.77	9.28
AZUKOUP-9							
A_c	0-20	1.78	48.79	32.76	11.98	6.35	5.63
Bt_c	20-52	1.80	293.5	31.94	16.18	8.58	7.60
AZUKOUP-10							
A_c	0-15	1.64	190.8	38.01	20.32	10.77	9.55
Bt_{c1}	15-32	1.81	395.6	31.58	19.04	10.10	8.94
Bt_{c2}	32-60	1.86	365.6	29.85	19.71	10.45	9.26

BD= bulk density, AWC= available water capacity, por= porosity, Ksat = saturated hydraulic conductivity, pF 2.5= water content atfield capacity, pF 4.2 = water content at wilting point and PWP (20.23) were recorded for the sub-surface horizon ($Btgc_2$) of AZUKOUP-7. This could be caused by high water table and to a lesser extent due to clay or silt content.

4.5 Soil chemical properties of Koupendri catchment

Soil pH

The soils pH varies from moderately acidic (5.2) in the B-horizon (Bt_{nc1}) of AZUKOUP-2 to slightly alkaline (7.6-9) in the B-horizon (Bt_{gc2n}) of the same profile (Table 4.4). Also shown in Table 4.4 is change in pH i.e. ΔpH (pH_{H2O} –pH_{KCl}) which were positive for all profiles and horizons studied. The values of ΔpH range from 1.1 in the A-horizon (Ap_c) of AZUKOUP-1 to 2.1 in the B-horizons (Bt_{gn} and Bt_{gcn}) of AZUKOUP-3.

Total nitrogen (N), available phosphorus (P) and soil organic carbon (SOC)

The total N ranged from 0.02 in the B-horizon (Bt_{gc}) of AZUKOUP-4 to 0.08 in the A-horizon (A_{gh}) of AZUKOUP-3 (Table 4.4). The SOC decreases with increasing depth in each profile and ranged from 0.048 in the B-horizon (Bt_c) of AZUKOUP-9 to 2.02 in the A-horizon (A_{gh}) of AZUKOUP-3. The available P ranges from 1 mg/Kg in most sub-surface horizons of the soil profiles to 6 mg/Kg in the surface or A-horizon (A_{gn}) of AZUKOUP-6.

The C:N ratio for the profiles and their horizons varied from a narrow range of 4.2 in the B-horizon (Bt_{ngc}) of AZUKOUP-6 to the wider range of 24.02 in the A-horizon (A_{gh}) of AZUKOUP-3 (Table 4.4). Generally, the C:N ratio shows a decreasing trend with increasing depth throughout the profiles and their horizons (Table 4.4).

Base saturation and cation exchange capacity

Generally, the base saturation (BS) was low to moderate (20-60%) for most soil profiles studied with few exceptions (Table 4.4). The exchangeable calcium (Ca) throughout the profiles ranged from very low (<2%) to moderately few (2-5%) in some horizons. The exchangeable Mg is low throughout the profiles except in some horizons where it is moderately high**.** The exchangeable K was also very low in most profiles and their horizons, although moderate to very high values were also recorded in few horizons. The exchangeable sodium (Na) was low throughout the profiles ranging from 0.281 in the A-horizon (A_{gn}) of AZUKOUP-6 to 0.545 in the B-horizon (Bt_{c2}) of AZUKOUP-10. The trend or abundance in decreasing order is $Ca^{++} > Mg^{++} > Na^{+} > K^{+}$ except at AZUKOUP-4.

Table 4.4: Some chemical properties of Koupendri soils

Horizon Name	Depth (cm)	pH (H_2O)	pH (KCl)	ΔpH	Total N	Organic C	C:N	Avail. P	Exchangeable Cations: Ca	Mg	K	Na	CEC	BS (%)	ESP (%)
					-------(%)------		--mg Kg^{-1}-------------------		Cmol Kg^{-1}-----------------						
AZUKOUP-1															
Ap$_{c}$	0-20	5.8	4.7	1.1	0.05	0.66	13.1	2	2.32	0.85	0.20	0.28	8.00	46	3.53
Bt$_{nc}$	20-30	5.9	4.4	1.5	0.05	0.49	10.8	2	1.54	1.22	0.18	0.31	7.36	44	4.17
AZUKOUP-2															
A$_{c}$	0-15	5.8	4.4	1.4	0.05	0.46	9.22	4	1.26	0.51	0.11	0.31	7.52	29	4.11
Bt$_{nc1}$	15-47	5.2	3.9	1.3	0.05	0.35	7.82	5	0.69	0.28	0.07	0.32	6.88	20	4.61
Bt$_{nc2}$	47-80	5.3	4.0	1.3	0.04	0.20	4.83	2	0.97	0.40	0.11	0.44	8.08	24	5.41
AZUKOUP-3															
A$_{gh}$	0-12	6.0	4.6	1.4	0.08	2.02	24.02	2	6.06	4.11	0.23	0.56	16.08	68	3.46
Bt$_{gn}$	12-30	7.0	4.9	2.1	0.06	0.54	9.07	1	4.43	2.72	0.09	1.21	14.4	59	8.39
Bt$_{gcn}$	30-60	6.8	4.7	2.1	0.06	0.46	7.81	1	4.38	2.05	0.13	2.24	17.52	50	12.8
Bt$_{gc2n}$	60-100	9.0	7.4	1.6	0.02	0.20	10.1	2	9.69	15.88	0.11	3.95	22.88	100	17.3
AZUKOUP-4															
A	0-12	6.6	5.4	1.2	0.06	0.66	11.79	1	2.48	2.87	0.14	0.31	7.84	74	3.93
AB$_{g}$	12-35	6.5	5.0	1.5	0.04	0.24	6.67	1	1.57	3.80	0.08	0.32	10.00	58	3.24
Bt$_{g}$	35-58	6.7	4.9	1.8	0.04	0.21	5.92	1	1.61	6.40	0.07	0.32	12.48	67	2.56
Bt$_{gc}$	58-120	7.6	6.0	1.6	0.02	0.20	11.65	1	2.15	14.35	0.10	0.49	19.28	89	2.55
AZUKOUP-5															
A	0-20	6.1	4.9	1.2	0.05	0.43	8.96	2	1.72	0.68	0.10	0.32	4.72	60	6.69
Bt$_{ng}$	20-56	5.6	4.0	1.6	0.04	0.17	4.07	2	1.46	0.63	0.11	0.44	6.00	44	7.30
BC$_{ng}$	56-100	5.8	4.2	1.6	0.03	0.22	6.97	1	0.75	0.44	0.076	0.29	6.08	26	4.80
AZUKOUP-6															
A$_{gn}$	0-20	5.4	4.1	1.3	0.05	0.73	14.66	6	0.72	0.21	0.09	0.28	8.24	16	3.41
Bt$_{ng}$	20-32	5.5	4.1	1.4	0.05	0.31	6.35	2	1.56	1.14	0.15	0.37	7.44	43	5.01
Bt$_{ngc}$	32-55	5.6	4.1	1.5	0.06	0.25	4.2	2	3.84	3.03	0.26	0.36	14.48	52	2.47
AZUKOUP-7															
A$_{gc}$	0-17	5.6	4.0	1.6	0.06	0.71	12.02	2	1.89	0.64	0.17	0.37	5.76	53	6.41
Bt$_{gc1}$	17-42	5.6	4.1	1.5	0.03	0.43	12.62	1	4.46	2.67	0.30	0.35	12.48	62	2.83
Bt$_{gc2}$	42-100	5.9	4.0	1.9	0.05	0.35	7.02	1	6.18	2.07	0.25	0.42	20.0	45	2.08
AZUKOUP-8															
A$_{c}$	0-12	6.0	4.8	1.2	0.08	1.27	16.71	3	2.71	1.08	0.22	0.32	7.84	55	4.09
Bt$_{c}$	12-40	5.5	4.1	1.4	0.05	0.63	12.6	2	1.11	0.46	0.22	0.32	9.76	22	3.26
AZUKOUP-9															
A$_{c}$	0-20	6.4	5.0	1.4	0.91	0.07	13.57	3	1.99	0.68	0.26	0.32	7.6	43	4.17
Bt$_{c}$	20-52	5.4	4.2	1.2	0.64	0.05	13.38	3	0.82	0.57	0.17	0.30	7.12	26	4.24
AZUKOUP-10															
A$_{c}$	0-15	6.8	5.3	1.5	0.10	1.22	12.81	3	4.48	2.43	0.52	0.33	10.8	72	3.05
Bt$_{c1}$	15-32	6.4	4.8	1.6	0.08	0.87	11.31	1	6.53	4.66	0.31	0.37	16.88	70	2.18
Bt$_{c2}$	32-60	8.0	6.8	1.2	0.06	0.31	5.27	3	9.29	11.24	0.44	0.55	28.56	100	1.91

N=nitrogen, C= carbon, C:N= carbon-nitrogen ratio, Avail.P = available phosphorus, Ca= calcium, Mg= magnesium, K= potassium, Na= sodium, CEC= cation exchange capacity, BS= base saturation, ESP= exchangeable sodium percentage, H2O= water, KCl = potassium chloride.

The exchangeable sodium percentage (ESP) was low throughout the horizons except at the B-horizon (Bt_{gc2n}) of AZUKOUP-3 where it is 17.3, a value that is above the critical level (> 15%) that causes deterioration of soil structure and Na toxicity (Landon, 1991). Since the BS indicates the degree of leaching of basic cations, most of the soil profiles studied was moderately (43-46%) to highly leached (16-29%) except AZUKOUP-3, AZUKOUP-4, AZUKOUP-7 and AZUKOUP-10 with higher BS values. The A-horizons of AZUKOUP-5 and AZUKOUP-8 also show some signs of weak/low leaching. The CEC across the landscapes and profiles ranged from 4.72-28.56 $Cmolkg^{-1}$ (Table 4.4). The lowest values for the CEC were recorded at AZUKOUP-5 with a range of 4.72-6.08 $Cmolkg^{-1}$ and the highest values at AZUKOUP-10 with a range of 10.8-28.56 $Cmolkg^{-1}$. The CEC of soil profiles followed the trend exhibited by the exchangeable basic cations especially exchangeable Ca^{++} reflecting that these basic cations are the main ion contributors in the exchange complexes.

4.6 Soil classification of Koupendri catchment

Soil classification of Koupendri catchment was done following World Reference Base for Soil Resources [WRB] (IUSS Working Group, 2006; 2014) and Soil Taxonomy (Soil Survey Staff, 2010) classification schemes, and then correlated with the FAO-UNESCO legend and French Classification schemes (Table 4.5). The table showed seven (7) soil types at sub-group level classification for Soil Taxonomy and 10 soil types for WRB correlated to five (5) soil types for both the FAO-UNESCO legend and the French classification schemes.

4.7 Discussions

The soils show indication of poor structure or structural deterioration caused by prolonged and intensive cultivation, and compaction through trampling by human and animals that destroy or fragments soil aggregates. The soils were less deep with mainly Ap and Bt horizons while C horizon was virtually absent. This confirmed why cash crops and plantation agriculture could not thrive in the catchment. The soils were mostly gravelly ranging between 10% and above 60%. Such soils with gravel contents above 60% are termed gravelly soils (Buol et al; 2003), and affect the physical and hydraulic properties of soil (Brakensiek and Rawls, 1994; Sauer and Logsdon, 2002). The combination of the soil structure and the gravel content also influenced the drainage of the catchment which ranged from good through normal to imperfect or very poor drainage. The clay increase in most B-horizons especially the kandic horizons confirmed previous reports from other studies. It has been reported that clay increase in most kandic horizons is as a result of clay migration-accumulation or illuviation, clay destruction, selective erosion, sedimentation or lithological discontinuity (FAO, 1988; Lal, 1976; Van Wambeke, 1989; Driesen and Dudal, 1991).

Table 4.5: Soil classification and correlation for Koupendri soils.

Soil Profile Identity	Soil Classification System		Correlating System	
	USDA Soil Taxonomy.	World Reference Base for soil Resources (WRB).	FAO/UNESCO Legend.	French System.
AZUKOUP-1	*Typic plinthustults*	*Albic Petric Plinthosols* (Lixic, Dystric)	*Dystric Plinthosols*	*Sols ferrugineux tropicaux peu profonds lessivés concrétionné*
AZUKOUP-8		*Albic-Petric Plinthosols* (Loamic, Epi-Dystric)		
AZUKOUP-9		*Albic Pisoplinthic Plinthosols* (Dystric)		
AZUKOUP-2	*Plinthic-Kandiustults*	*Albic-Petric Plinthosols* (Hyper-Dystric, Loamic)	*Endo-dystric Plinthosols*	*Sols ferrugineux tropicaux moyennement profonds lessivés peu concrétionnés*
AZUKOUP-6		*Albi-Petric Plinthosols* (EndoClayic, Epi-Dystric)		
AZUKOUP-3	*Aquic Haplustepts*	*Eutric Vertic Gleyic Cambisols* (Petrocalcic, Takyric)	*Eutric Cambisol*	*Sols bruns eutrophes tropicaux*
AZUKOUP-4	*Aquic kandiustalfs*	*Albic Gleyic Anthraquic Abruptic Luvisols* (Hyper-Eutric)	Gleyic Luvisol	*Sols ferrugineux tropicaux lessivés profonds hydromorphes*
AZUKOUP-5	*Typic kandiustalfs*	*Albic Gleyic Abruptic Luvisols* (Hyper-dystric, Profondic)		
AZUKOUP-7	*Aquic kandiustalfs*	*Epi-Eutric Gleysols* (EndoSiltic, Vertic)	*Eutric Gleysols*	*Sols hydromorphes à pseudogley*
AZUKOUP-10	*Typic Plinthustalfs*	*Eutric Pisoplinthic Gleysols* (Endoclayic, vertic)		

The fact that clay minerals are unstable and break down under intense chemical weathering especially in humid and sub-humid climates further buttressed the claim. This was also reported in Alemayehu *et al*., (2014) for some Ethiopian soils. This also applied to the Argic B-horizon which is similar to kandic horizons since part of the pedon may meet the requirements of both horizons when considered at the same classification level (Ngongo and Langohr, 1992).

The decrease in silt/clay ratio with depth can be attributed to massive destruction of clay, selective erosion, and to a lesser extent illuviation of clay from the surface (Ap) horizon to the sub-surface (Bt) horizon. The decrease in silt/clay ratio with depth is in agreement with reports from some studies of Nigerian soils (Ezeabasili, 2014; Chukwu, 2013; Lal; 2000) and Benin soils (Igué, 2000). Lal (2000) reported that the silt/clay ratio of most tropical soils decline with depth and widely ranged from soil to soil even within the same toposequence. However, a contrary result of an increasing silt/clay ratio with depth was reported for lowland soils in southwestern Ethiopia (Alemayehu *et al*., 2014). The silt/clay ratio is an index of weathering (Van Wambeke, 1959), and one of the most important criteria for the definition of the ferralic horizon. According to FAO (1988), the silt/clay ratio for a ferralic horizon should be less than or equal to 0.2. This underscores the absence of a ferralic horizon and Ferralsols in all the studied profiles. High silt/clay ratios observed in most horizons alongside resistant skeletal composition of the parent material reflect that the soil is less weathered and thus, at less advanced stage of development.

The decreasing Ksat with increasing depth observed has also been reported in some tropical studies (Ziegler *et al.,* 2004; Zimmermann & Elsenbeer, 2008; Zimmermann *et al.,* 2006). Such decrease could result to saturation excess overland flow during high-intensity rainfall events (Germer *et al.,* 2010; Godsey *et al.,* 2004). The low values of Ksat at some soil depth can lead to formation of an impeding layer and consequently lead to perched water tables, diminished groundwater recharge and the development of interflow. This is because, Ksat represent the capacity of the soil to drain or transmit water (Klute and Dirksen, 1986) and governs vertical percolation of water within the soil profile. The high bulk densities obtained agrees with that obtained for similar soils in Terou-Igbomakoro catchment, central Benin (Junge, 2004; Sintondji, 2005). Such high bulk density may present serious challenge to agronomic and hydrological processes. The available water holding capacity (AWHC) showed a closer relationship with silt content than with clay or SOC contents.

The acidic nature of the soils could be attributed to the parent material which is acid metamorphic schists. However, as an indication of soil acidification, soil pH is dependent not only on the nature of the parent material but also on the level of soil leaching in the environment. This may suggest why some of the soils were moderately alkaline. Based on the soil pH rating of Jones (2003), the pH_{H2O} throughout the profiles fall within moderately acidic to moderately alkaline.

According to Soil Survey Staff (2006, 2010), ΔpH can be positive, zero or negative depending on the net surface charge at the time of sampling. The positive ΔpH which indicates presence of negatively charged colloids lends credence to the translocation of clay from the uppermost or surface horizon and its accumulation in the B-(illuvial) horizon through illuviation processes.

Generally, available P shows a decreasing trend with increasing depth for all the profiles. The slightly higher values of SOC and total N observed in the A-horizon of AZUKOUP-3 could be due to waterlogging of the location which slowed down the turn-over of the surface organic material while that of available P could be due to use of phosphate fertilizer for cultivation at the site of the profile pit (AZUKOUP-6). Similar decrease in SOC with increasing depth for each profile has been reported (Alemayehu *et al*., 2014; Campos, 2002; Agyare, 2004). There was no clear direct association of total N and SOC with increasing depth of the profiles as reported by Alemeyehu *et al*., (2014) for some Ethiopian soils. However, the very low contents of total N, SOC, and available P may be attributed to intensive and prolonged cultivation, and the frequent annual bush burning and crop residues (a common land clearing practice for cultivation) at the end of the year or more explicitly during the dry season. This frequent bush burning practices, coupled with high temperature accelerates the rapid turn-over of organic materials in the catchment. This was also affirmed by Yilma (2006) who reported that burning of biomass in prevailing-slash-and burn systems and high temperatures lead to a rapid decomposition of organic matter and consequently, poor SOC. Studies in Ethiopia (Habtamu *et al*., 2009; Alemayehu *et al*., 2014), west Africa (Lal *et al*., 2003; Yilma, 2006) and other parts of the world had reported significant reduction in SOC and Total N caused by burning and removal of crop residue. Low fertility is linked with low CEC and low reserves of N and P-availability. The very low contents of available P suggest that it is a serious limiting nutrient for crop production in the catchment despite that moderately acidic to slightly alkaline soils (5.5-9.0) favour P- availability. This confirms the report that P is considered the main limiting nutrient for crop production in drier savanna (Sanchez 1976, Kowal and Kassam 1978).

The C:N ratio was low throughout the horizons and fall below the optimal range (10-12:1) acceptable for arable soils (Havlin *et al*., 1999). This could be attributed to high oxidation and loss of organic matter as evidenced by the poor or very low SOC in the two profiles. The C:N ratio is important because the availability of nitrogen (N) for plant growth is dependent on the ratio. High

C:N > 30:1 implies N immobilization due to decomposition of organic residue by microbes while C:N < 20:1 implies limited immobilization and release of N into the soil environment for plant uptake (Jones, 2003).

The analytical result of the base saturation (BS) and cation exchange capacity (CEC) revealed that exchangeable Ca and Mg were dominant cations at the exchange complex accounting for more than 80% of exchangeable bases and between 50-65% of total cations of the exchange site. Both BS and CEC were low to moderate and could be due to the predominance of Kaolinite clay minerals and also, poor recycling and depletion of basic cations, OM and clay contents due to erosional processes and inappropriate management (incessant bush burning) of residues but to a lesser extent, soil reaction or pH. Similar reports were made for sub-humid catchment in central Benin (Igué, 2000; IMPETUS, 2003).

4.8 Partial summary and conclusion

Soil survey and classification for Koupendri catchment in north western Benin, West Africa provided soil information for hydrological modeling, future agronomic decisions, soil and water management, engineering and other socio-economic purposes. A detailed soil survey was carried out using SOTER approach. Soil samples collected during the soil survey were analyzed using standard laboratory procedures. The analytical results and the field observable features were used for classifying the soils. Field observable features show that the catchment has a relatively flat physiography with height above sea level ranging from 215-224 m above sea level, and gently slopy (0-6 %). The soil pH ranges from slightly acidic to relatively alkaline with poor fertility status evidenced by poor SOC, total N, C:N ratio, low CEC, exchangeable cations, less weathered soil with textural characteristics that is prone to crusting, compaction and hinders root growth. The study also confirms that P-availability is the major agronomic constraints in drier savanna regions. The permeability and the available water capacity of the soil were very low, presenting a serious soil water management problem for both agronomic and hydrological purposes. The soil map of the catchment produced at a scale of 1: 25000 using FAO/UNESCO legends showed five distinct soil types. The classification of the soils reveals seven soil types at sub-group level of classification belonging to three major orders: Ultisols, Inceptisols and Alfisols (USDA). The WRB gave ten distinct soil types belonging to four major or reference soil groups. These were correlated as Plinthosols, Cambisols, Luvisols and Gleysols for FAO-UNESCO legend; and *Sols* *ferrugineux tropicaux peu profonds lessivés concrétionnés, Sols hydromorphes à pseudogley, Sols tropicaux moyennement profonds lessivés peu concrétionnés, Sols bruns eutrophes tropicaux* and *Sols ferrugineux tropicaux lessivés profonds hydromorphes* for French classification system. The WRB gave a more detailed, concise and better soil classification that correlates better with FAO/UNESCO legend and French classification scheme than USDA Soil Taxonomy. Soil fertility or nutrient assessment for the catchment will provide information for improved soil nutrient management. Also, land cover and residue management with appropriate tillage and conservation practices is paramount for improved soil productivity and hydrological processes of the catchment.

CHAPTER 5

Spatial variability of soil properties under different land use in the Koupendri catchment, north-west of Benin.

Introduction

Soils is heterogeneous, diverse and dynamic in nature but are characterized by high spatial variability ranging from point scale to global scale. Such variability in both natural and managed ecosystems has been a major driver of physical, hydrological and, biological processes (Kumar and Ramadevi, 2006). In nature, complex pedological processes, their use and management drive soil variability at various spatial and temporal scales (Rodenburg *et al*., 2003; Viera and Gonzalez, 2003). Generally, soil properties exhibit high heterogeneity at different spatial scales but can vary substantially under different land use (Nadrowski et al., 2010). Data availability on soil spatial variability is high for temperate soils compared to tropical soils of the savanna region in West Africa. Idowu *et al*., 2003 reported that the West African savanna is one region with limited data on soil spatial variability across different land uses of the soil resources. Until now, little or no studies have been done on this subject especially in Benin in order to bridge this gap.

The spatial distribution of soil properties at different sampling scales has been widely evaluated using geostatistical tools (Paz-González et al., 2000). The approach is based on the theory of regionalized variables of Matheron (1971) that take into consideration the spatial variability of a variable e.g soil property as a random function represented by a stochastic model (McBratney et al., 2000). Geostatistics is based on the assumption of spatial dependence. Kriging, spline and inverse distance weighting (IDW) are three geostatistical tools that are used for making statistical inference for unknown data prediction from the known data (Coyne and Thompson, 2006) especially soils sampled in grid-like pattern. However, compared to other interpolation methods, kriging minimizes unbiased estimation variance and provide the error term or variance for the prediction from known variogram and thus has become the most preferred and optimal interpolator (Kalivas et al., 2002; Oliver, 2010). The ability of Kriging to predict optimally, values at unknown location with minimum variance and without bias has also boosted its popularity (Oliver and Webster, 2014). Oliver and Webster (2014) also reported that kriging is now applied with increased sophistication in many discipline like petroleum engineering, mining and geology, meteorology, hydrology and soil science. Kriging interpolation and prediction maps serves as veritable tools for understanding the variability of soil properties in a given location. This tool may be implemented at different scales in relation to specific data, depending on the resolution desired in the study (Webster and Oliver, 2007). The objective of this chapter is to evaluate and characterize the structure of spatial variability of some soil properties of koupendri catchment under different land use/ land cover.

5.1 Descriptive statistics for the evaluated soil properties under different land use.

The basic and classical descriptive statistics of the soil parameters evaluated or assessed are shown below (Table 5.1). The average values of Ksat (103.3±50.42 cm/d), BD (1.77±0.135 g/cm^3), SOC (1.25±0.271 %), TN (0.106±0.017 %), Avail.P (4.14±1.14ppm) and C:N (11.91±2.29) were highest under the maize-sorghum land use and lowest under the rice field land use. However, porosity, TN, Avail.P and C:N were lowest under the fallow shrub-grassland land use. Similarly, the mean values of TN, Avail.P and C:N decreased as follows; maize-sorghum > rice field > fallow shrub-grassland (FSG), while that of Ksat, BD and SOC follow the order; maize-sorghum>fallow shrub-grassland >rice field. The use of NPK fertilizers increased the TN and Avail.P levels in the maize-sorghum and rice field land use types respectively compared to the FSG. Wang *et al*., (2009) made similar findings for a small watershed on a loess plateau in China under different land use. However, tillage and soil management practices such as manure addition, plant and organic matter residue, incessant bush burning and intensive grazing influenced most of the soil properties under different land use. Saturated hydraulic conductivity is one soil property adjudged to be a sensitive indicator of soil disturbance (Ziegler *et al.*, 2004; Zimmermann *et al*., 2006) mainly land use and soil tillage practices.

Yilma (2006) also observed poor SOC as a result of biomass burning in prevailing-slash-and burn systems. The index of overall variation (CV) is also shown in Table 4.2. The results showed that the variability of BD, porosity, SOC, TN, Avail. P and C:N were mostly low (7 %) with a few moderate (39 %) variability under the different land use types while that of Ksat was mostly high (48-75 %). This clearly showed that Ksat which is an important hydraulic property influencing flow and transport process is a highly varied property irrespective of land use. Agyare (2004) also reported high CV of more than 100 % for Ksat in the Volta basin. Bulk density has the lowest CV (7-8.6 %) across the three land use types which fall within the range observed by Warrick and Nielsen (1980). Similar low CV for BD was reported by Agyare (2004) for the Volta basin. Several other researchers (e.g Wang *et al.,* 2009; Wei *et al.,* 2008; Chen *et al.*, 2006 and Liu *et al.*,

2006) have reported moderate variability of TN and Avail.P. The variability of the selected soil properties were higher in the fallow shrub-grassland land use compared to the other land use types. This clearly showed that apart from variability caused by geology, climate and vegetation type, land use and soil management practices such as tillage, fertilizer application etc. also influences the spatial structure and variation of these soil properties. It has been reported that addition of NPK fertilizers influence and reduces the variability of C:N (Zhang *et al.*, 2015).

SOC, TN and C:N, BD and porosity are highly skewed and showed non-normal distribution as shown by the normality test of skewness and kurtosis under the maize-sorghum land use while Avail.P and SOC were under the cultivated rice field. None of the evaluated soil properties was normally distributed under the fallow-grassland land use while Ksat was the only soil property that is not normally distributed across all the three land use types evaluated. The principal reason for some soil properties not having normal distributions may be related to soil management practices and temporal effect of tillage practices (Cambardella et al., 1994; Tesfahunegn *et al.*, 2011). Zimmermann (2007) reported that agricultural activities may promote spatial Ksat patterns that are completely random, with strong and extensive autocorrelations. In other words, disturbances affect the Ksat spatial structure, in particular the correlation length, in the topsoil. Other authors have reported that some soil properties (e.g. SOC, TN, Avail.P) did not fulfil the normality requirement and transformed them before further analysis (Ferreira *et al*., 2015; Wang *et al.*, 2009).

Table 5.1: Summary statistics for the soil properties under different land use at the catchment

Land use	Soil property	No.	Min.	Max.	Mean	S.D.	C.V.	Skew	T.skew	Kurt	T.Kurt	Dist.
MS	SOC (%)	100	0.61	1.91	1.25	0.271	21.71	0.170		0.130		N
	Total N	100	0.07	0.15	0.106	0.017	15.94	0.168		-0.138		N
	Avail.P	100	2.38	6.9	4.14	1.14	27.5	0.585	0.0197	-0.607	-0.79	T^p
	C/N	100	6.1	15.93	11.91	2.287	19.2	-0.187		-0.423		N
	Ksat	100	22.43	238.6	103.3	50.42	48.83	0.675	0.152	-0.0724	-0.516	$\sqrt{K}/^{log}$
	Por.	100	22.56	45.28	33.24	5.093	15.32	-0.103		-0.425		N
	BD	100	1.45	2.05	1.77	0.135	7.686	0.103		-0.425		N
Rice Field	SOC	91	0.74	1.05	0.891	0.095	10.6	0.436		-1.1144		N
	Total N	91	0.08	0.097	0.084	0.006	7.021	0.98	0.115	0.252	-0.804	T^p
	Avail.P	91	1.05	4.65	2.644	0.810	30.62	0.235		-0.375		N
	C/N	91	8.23	13.38	10.68	1.332	12.47	0.425	0.0088	-0.692	-0.736	$T^{1/CN}$
	Ksat	91	7.24	46.77	18.69	9.19	49.16	1.221	0.368	0.745	-0.487	T^{log}/T^p
	Por.	91	40	53.96	47.56	4.49	9.89	-0.107	0.067	-1.41	-1.42	T^p
	BD	91	1.22	1.59	1.39	0.119	8.57	0.107	0.010	-1.41	-1.42	T^p
FSG	SOC	100	0.51	1.84	0.987	0.385	38.98	0.872	0.089	-0.52	-0.934	T^p
	Total N	100	0.05	0.109	0.082	0.02	23.78	0.036	-0.0627	-1.439	-1.352	T^p
	Avail.P	100	1.19	4.25	2.332	0.727	31.17	0.588	0.0084	-0.341	-0.900	T^p
	C:N	100	6.16	27.19	12.5	4.327	34.62	1.228	-0.147	1.08	-0.271	$T^{1/\sqrt{CN}}$
	Ksat	100	8.28	137.9	40.8	30.4	74.4	1.491	0.127	1.59	-0.487	T^{log}
	Porosity	100	36.3	50.57	42.12	4.09	8.56	-0.687	0.0917	-0.255	-0.826	T^p
	BD	100	1.31	1.69	1.53	0.108	7.068	-0.687	-0.154	0.255	-0.857	T^P

Ksat= saturated hydraulic conductivity (cm/d), N= nitrogen (%), SOC= soil organic carbon (%), Avail. P= available phosphorus (ppm), C:N= carbon-nitrogen ratio, BD= bulk density (g/cm^3), Min= minimum, Max= maximum, S.D= standard deviation, C.V= coefficient of variation, skew= skewness, T.skew= Transformed skewness coefficient, Kurt= Kurtosis, T.Kurt= transformed Kurtosis, Dist.= distribution type, N= normal distribution, T^p= power transformation, √= square-root transformation.

5.2 Correlation analysis of some soil properties under different land use.

The Pearson (r) correlation matrix for the soil properties evaluated under different land use/cover is shown in Table 5.2. Significant ($P < 0.05$) relationships amongst the evaluated soil properties were shown or highlighted in bold. Across the three land use/cover types, carbon-nitrogen (C:N) ratio shows a significant ($P < 0.05$) negative correlation with nitrogen but a significant ($P < 0.05$) positive correlation with OC content. In other words carbon-nitrogen (C:N) ratio increases with decreasing nitrogen but increases with increasing OC content. This confirms the already known fact that besides the type of organic material involved, the rate of mineralization of organic materials is a function of the content of nitrogen in the soil. The low organic matter content of the soils under the three land use types may be the reason for its non-significant correlation with BD. However, significant ($P < 0.05$) positive correlation of C:N with BD under the fallow and maize-sorghum land use, and significant ($P < 0.05$) negative correlation with Ksat under maize landuse was observed. Ksat was found to have significant ($P < 0.05$) negative correlation with BD under fallow land use only

Table 5.2: Pearson r correlation analysis results for the soil properties under different land use.

	Ksat	BD	OC	TN	C.N	Avail.P
			Fallow land use			
Ksat	1					
BD	**-0.430**	1				
OC	-0.156	**0.270**	1			
TN	**0.236**	-0.152	0.022	1		
C:N	**-0.255**	**0.278**	**0.866**	**-0.448**	1	
Avail.P	0.149	-0.057	**0.233**	**0.339**	0.030	1
			Maize-Beans cropland			
Ksat	1					
BD	0.129	1				
OC	-0.019	0.088	1			
TN	-0.071	-0.186	**0.491**	1		
C:N	0.027	**0.255**	**0.692**	**-0.270**	1	
Avail.P	0.045	**0.210**	**0.431**	0.179	**0.344**	1
			Rice field			
Ksat	1					
BD	0.176	1				
OC	0.094	0.115	1			
TN	-0.177	-0.013	0.020	1		
C:N	0.164	0.118	**0.846**	**-0.512**	1	
Avail.P	-0.095	-0.049	-0.053	-0.024	-0.048	1

In bold, significant values (except diagonal) at p-level of significance =0.050 (two-tailed test)

5.3 Geostatistical analyses results of some selected soil properties under different land use.

The semi-variogram models and some geostatistical parameters of Ksat, BD, SOC, TN, Avail.P and C:N under different land use types in Koupendri catchment are shown in Table 5.3. The semi-variance or variogram of their distribution are shown in Figs. 5.1-5.6. The selection or choice of the best-fit semi-variogram model for accurate interpolation map was facilitated by cross validation. Closer values of the mean standardized error (MSE) to 0, and closer values of the root-mean-square standardized errors (RMSSE) to 1, suggested close relationship of the predicted values to measured values (Wackernagel, 1995). The model (e.g. spherical, exponential or

Gaussian) with the lowest or smallest nugget values, RMSSE and MSE or GD % for the evaluated parameters were selected. Most of the soil properties were best fitted with exponential and spherical models. Similar findings were reported for the Volta basin (Agyare, 2004). The nugget effect C_0 of SOC across the three land use types was lowest implying strong spatial dependence. The high nugget effect of TN under rice field can be attributed to the variation at spatial scales smaller than or not detected at the present sampling scale. However, research has also shown that nugget effect could also be the result of soil and crop management practices e.g fertilizer napplication (Xu ***et al***., 2013). Others researchers (Chien *et al.*, 1997; Han *et al.*, 2010b) reported that the partial sill or structural variance C_1 component of the sill or total variance (C_0+C_1) is the variance caused or contributed by soil parent materials, climate, and terrain characteristics.

The spatial correlation length (range) of SOC (94-286 m), Ksat (69-133 m), C:N (88-168 m), TN (88-180 m), BD (120-198 m) and Avail.P (132- 231 m) was high across the three land use types indicating a longer distance over which these soil properties are closely related. Beyond these ranges, there is no spatial autocorrelation. The nugget ratios GD % or the spatial dependence of each of the parameters differed significantly ($P < 0.05$) across the three land use types (Table 5.3). Most of the soil properties investigated showed strong and moderate spatial dependence except TN and BD that showed the weakest spatial dependence under the fallow shrub-grassland. Wang *et al.*, (2009) also found a very weak spatial dependence (97.9 %) for soil total phosphorus in a shrub land. The higher range or spatial dependency of these soil properties is an indication that the soil disturbance is minimal and so did no affect their spatial structure. Zimmermann (2007) also reported that spatial dependence of Ksat is most pronounced under natural forest and under a regenerating fallow. He noted that agriculture seems to promote spatial Ks patterns that are completely random, but with strong and extensive autocorrelations.

Table 5.3: Soil properties and their model parameters

Land use	Soil properties	Model parameters C_0	C_1	C_0+C_1	R	GD %	Model estimator RMSE	MSE
FSG	SOC^{ε}	0.003	0.176	0.179	157.12	1.62	0.25	0.03
	$SOC^{\$}$	0.009	0.145	0.154	94.08	5.80	0.24	0.03
	TN^{ε}	0	0.003	0.003	10.109	0	0.05	0.02
	$TN^{\$}$	0.003	0.000	0.003	180	86.33	0.06	0.06
	$C:N^{\varepsilon}$	0.365	24.393	24.758	139.95	1.47	3.29	0.04
	$C:N^{\$}$	1.466	20.275	21.742	88.604	6.74	3.21	0.02
	$Avail.P^{\varepsilon}$	0.065	0.026	0.091	187	71.58	0.29	0.03
	$Avail.P^{\$}$	0.068	0.021	0.090	160	76.04	0.29	0.04
	$Ksat^{\varepsilon}$	0	0.324	0.324	83.23	0	0.45	0.03
	$Ksat^{\$}$	0.042	0.268	0.310	69.81	13.61	0.44	0.02
	$BD^{\$}$	0.600	0.185	0.785	120.33	76.41	0.76	0.00
	BD^{ε}	0.563	0.238	0.800	144	70.32	0.76	0.01
MS	$SOC^{\$}$	0.004	0.091	0.095	119.41	4.63	0.19	0.01
	SOC^{ε}	0	0.106	0.106	180	0	0.19	0.01
	$TN^{\$}$	0.000	0.000	0.000	128.10	54.06	0.02	0.00
	$C:N^{\varepsilon}$	2.167	3.691	5.858	108.2	36.99	1.85	0.02
	$C:N^{\$}$	2.629	3.082	5.711	91.956	46.04	1.87	0.01
	$Avail.P^{\varepsilon}$	0.013	0.036	0.049	231	26.52	0.13	0.01
	$Avail.P^{\$}$	0.017	0.032	0.049	198	34.40	0.14	0.01
	$Ksat^{\varepsilon}$	1.360	6.382	7.741	98.64	17.56	2.03	0.00
	$BD^{\$}$	0.010	0.013	0.023	153.33	43.57	0.12	-0.01
	BD^{ε}	0.008	0.015	0.024	198	34.88	0.12	0.01
Rice Field	$SOC^{\$}$	0.004	0.010	0.014	258.36	27.16	0.08	0.00
	SOC^{ε}	0.003	0.010	0.013	286	24.23	0.08	0.00
	$TN^{\$}$	6.39	2.66	9.05	90.48	70.61	0.09	0.00
	$TN^{\$}$	6.5	2.41	8.91	64.47	72.95	0.09	0.01
	$C:N^{\$}$	0.000	0.000	0.000	168	69.28	0.01	0.00
	$Avail.P^{\varepsilon}$	0.300	0.472	0.773	132.12	38.91	0.73	0.01
	$Ksat^{\varepsilon}$	0.008	0.008	0.016	133	51.27	0.12	0.01
	$BD^{\$}$	0.009	0.006	0.016	122.48	59.18	0.11	0.00

$^{\varepsilon}$=exponential, $^{\$}$= spherical F= fallow land, MS=maize-sorghum cropland, SOC = soil organic carbon (%), Ksat= saturated hydraulic conductivity (cm/d), BD= bulk density (Kgm^{-3}), TN = total nitrogen (%), C:N = carbon-nitrogen ratio, Avail. P = available phosphorus (ppm), C_0 = nugget effect, C_1 = structural variance or partial sill, C_0+C_1 = Sill or total variance, GD % = nugget ratio, R= range (m), RMSE = root-mean square standardized error, MSE = mean standardized error.

5.4 Spatial distribution of soil properties under different land use types.

The interpolated maps clearly show the distribution of the soil properties evaluated in Koupendri catchment. The prediction of each soil property at the unsampled location was done using ordinary kriging and the observed semi-variogram of the soil properties in ArcGIS as described by Han *et al.(*2010*b*). The interpolated maps for the spatial distribution of Ksat, BD, SOC, TN, Avail.P and C:N ratio under different land use types are shown below (Fig. 5.1-5.6). The maps showed that land use and soil management practices may have influenced their distribution.

The land use and soil management practices includes; the use of NPK fertilizers and manure for agricultural activities i.e. cultivation of maize, sorghum and rice e.t.c in the catchment. Also, the usual practice of leaving crop residue in the field after harvest and constant bush fires experienced during the dry season especially for the fallow shrub-grassland in the catchment influenced the quantity of these soil properties and their variability or distribution. Similar findings were made by (Tan and Lal, 2005; Wang *et al.*, 2009; Xu and Xu, 2003) across various land use and vegetation types. Others (Williams *et al.*, 2005; Cambardella and Karlen, 1999; Kılıç *et al.*, 2004) reported fertilization and cultivation practices. Wang *et al.,* (2009) who observed moderate variability of TN and total P under different land use types also reported significant change in the spatial patterns of TN and total P under the then land use *changes* in china.

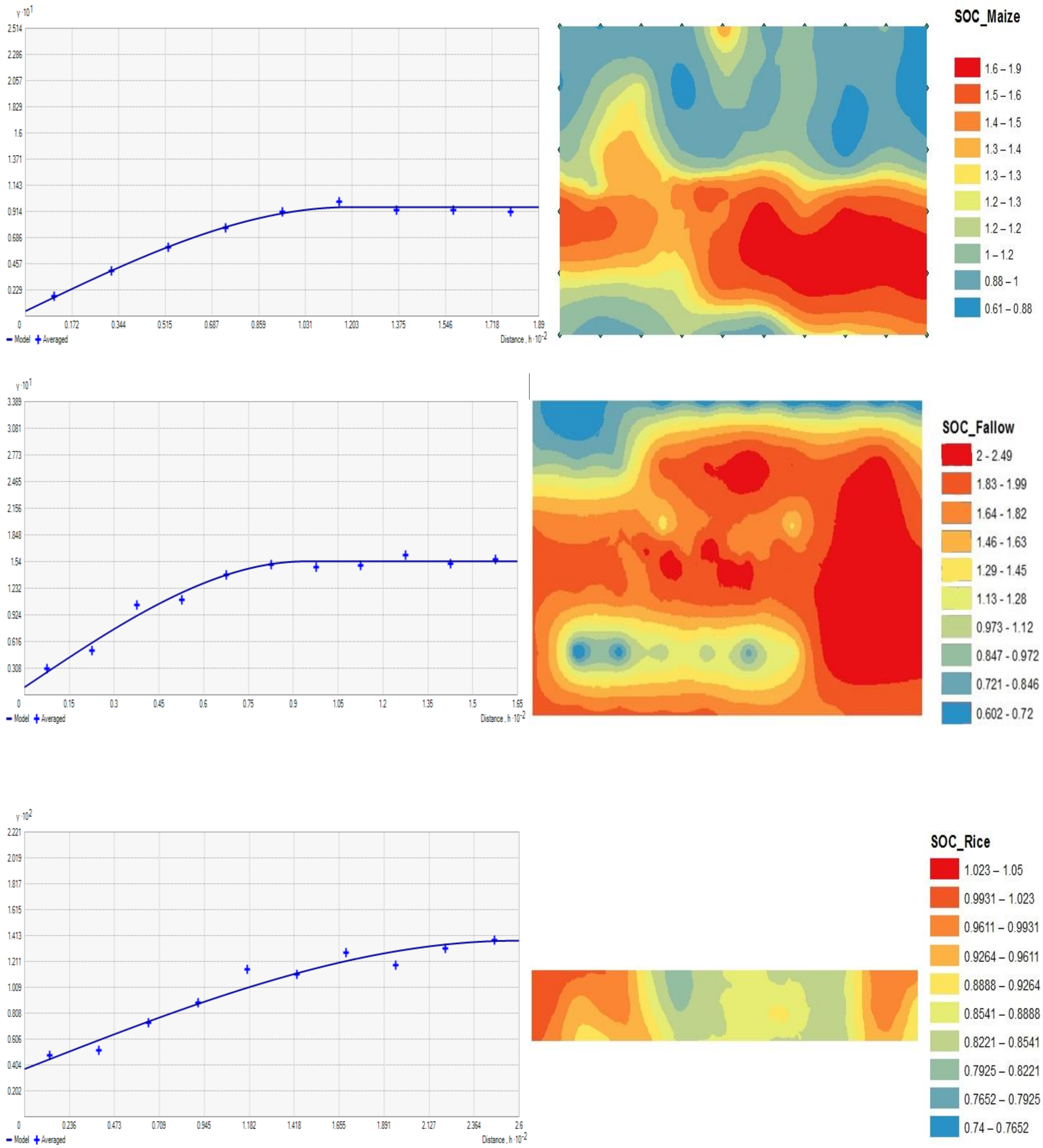


Figure 5.1: Variogram and mapping of soil organic carbon (SOC) under different land use

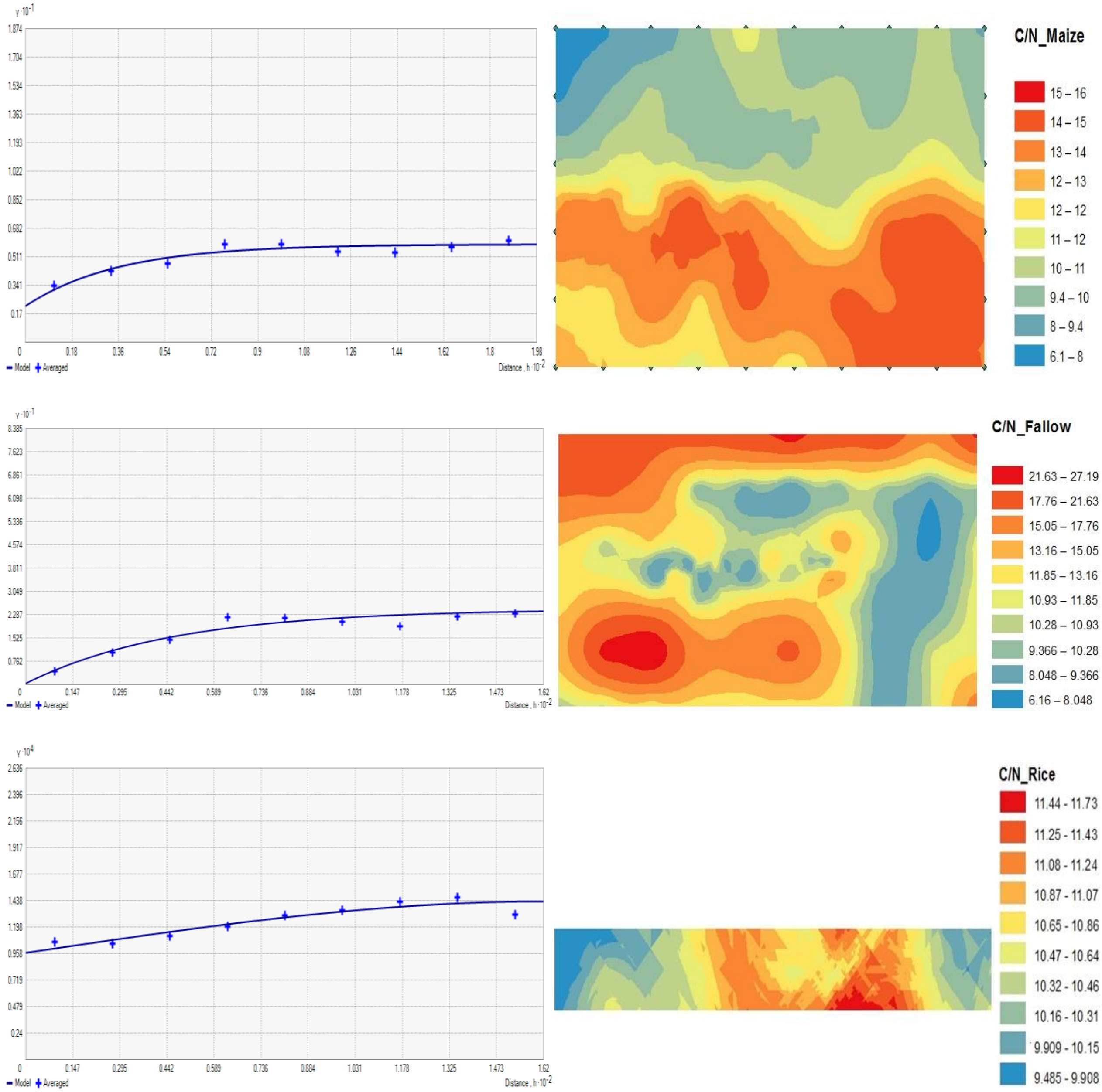


Figure 5.2: Variogram and mapping of carbon-nitrogen ratio (C:N) under different land use

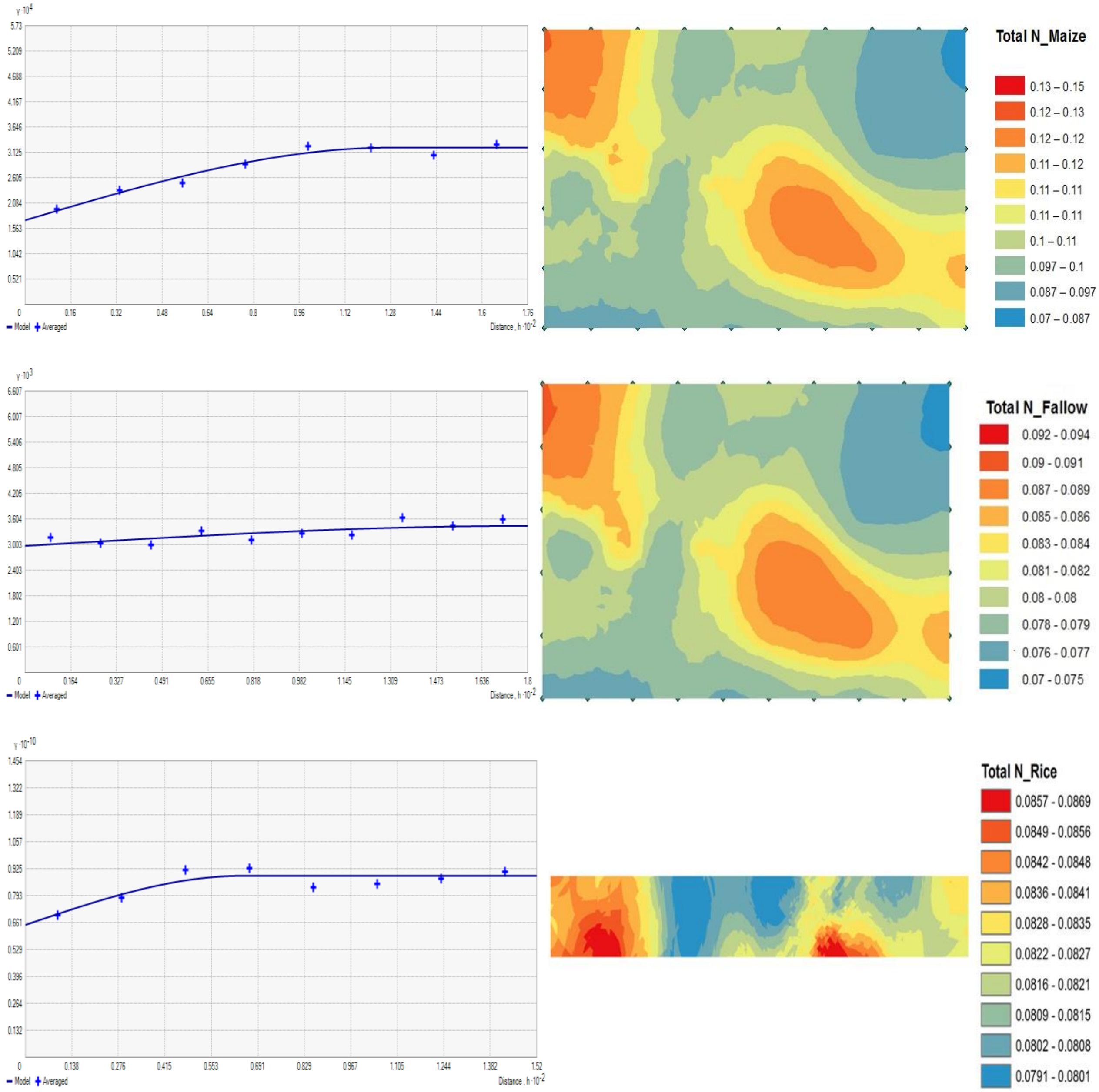


Figure 5.3: Variogram and mapping of total nitrogen (Total N) under different land use.

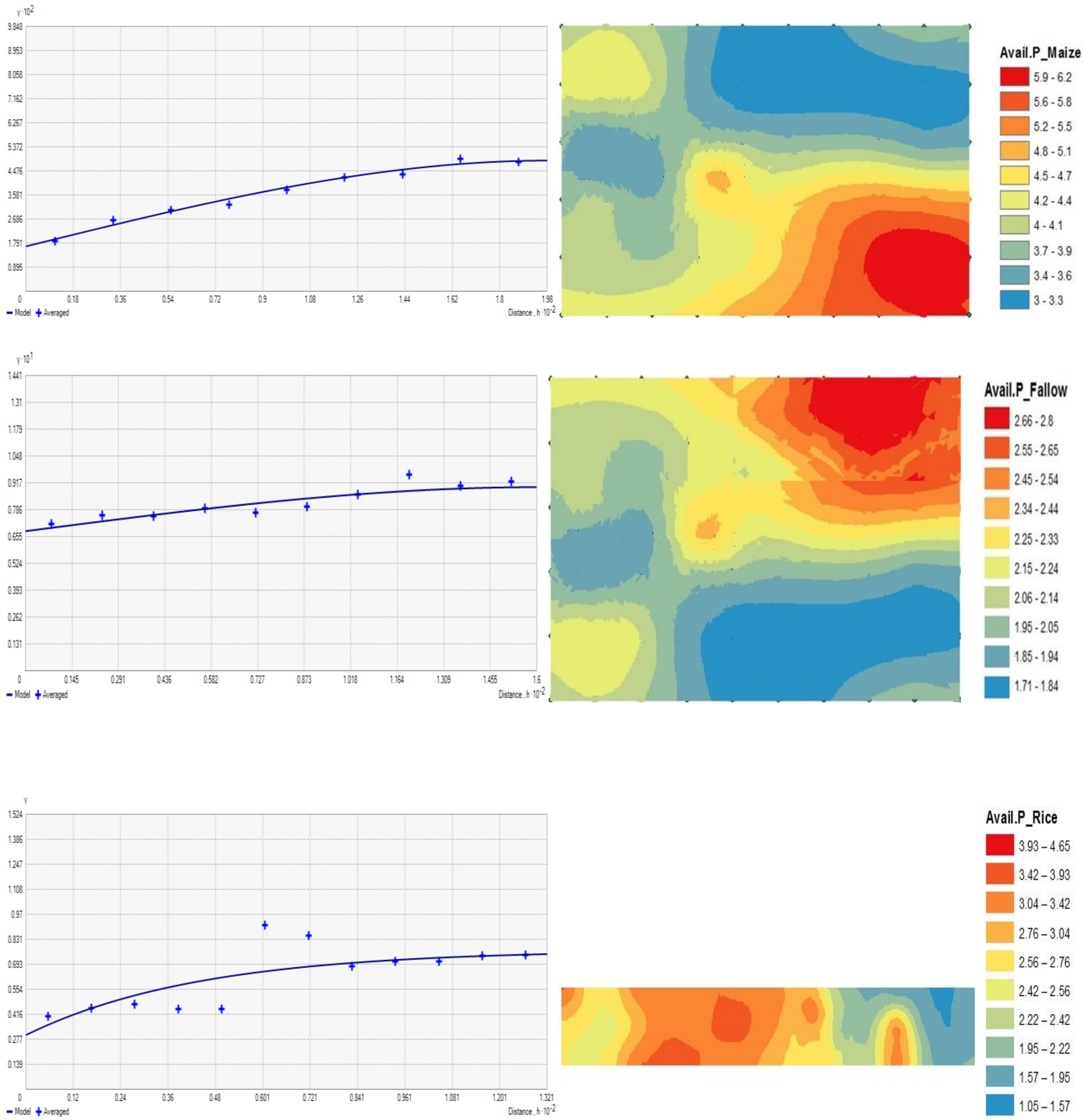


Figure 5.4: Variogram and mapping of available phosphorus (Avail.P) under different land use.

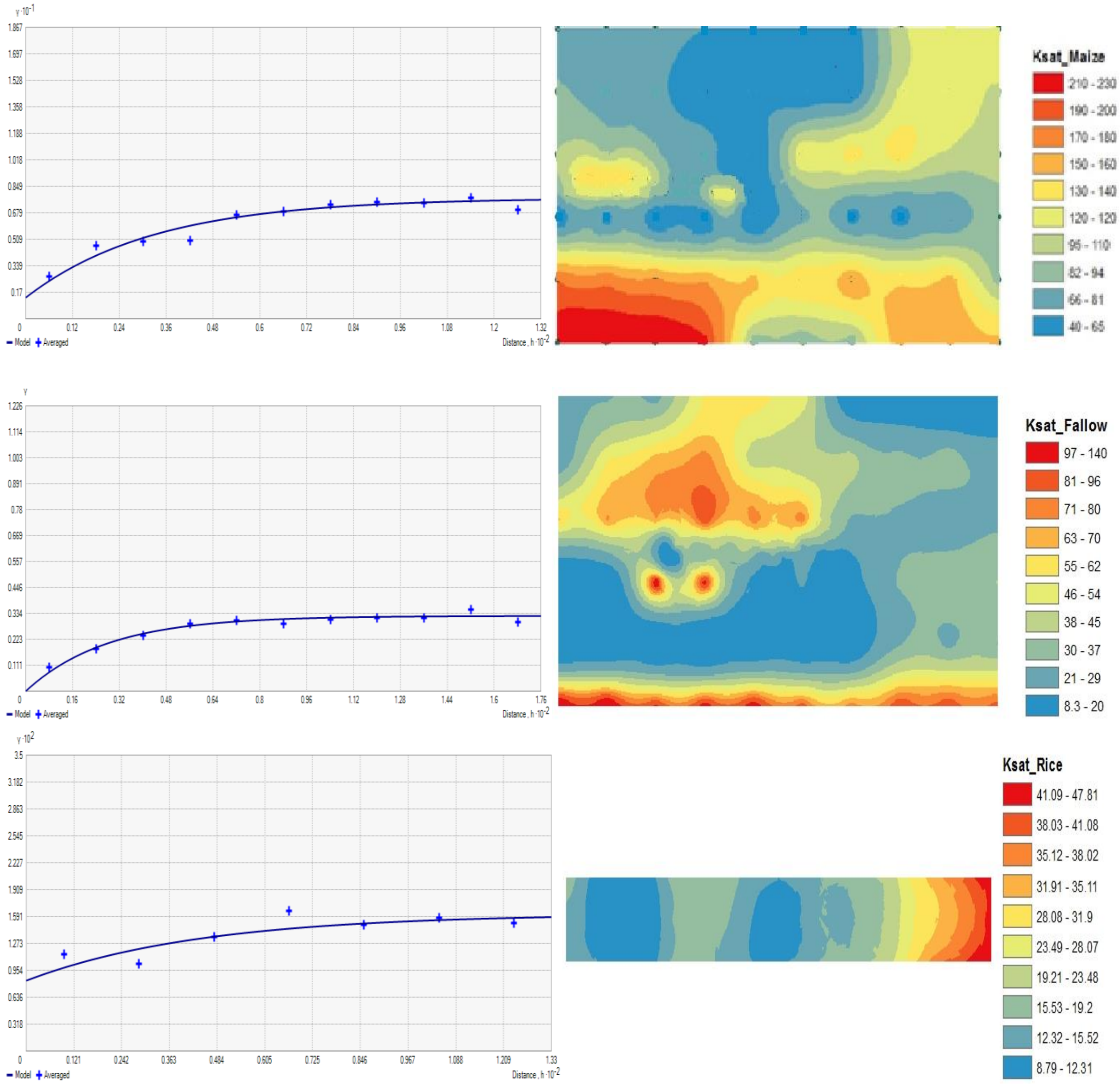


Figure 5.5: Variogram and mapping of saturated hydraulic conductivity under different land use

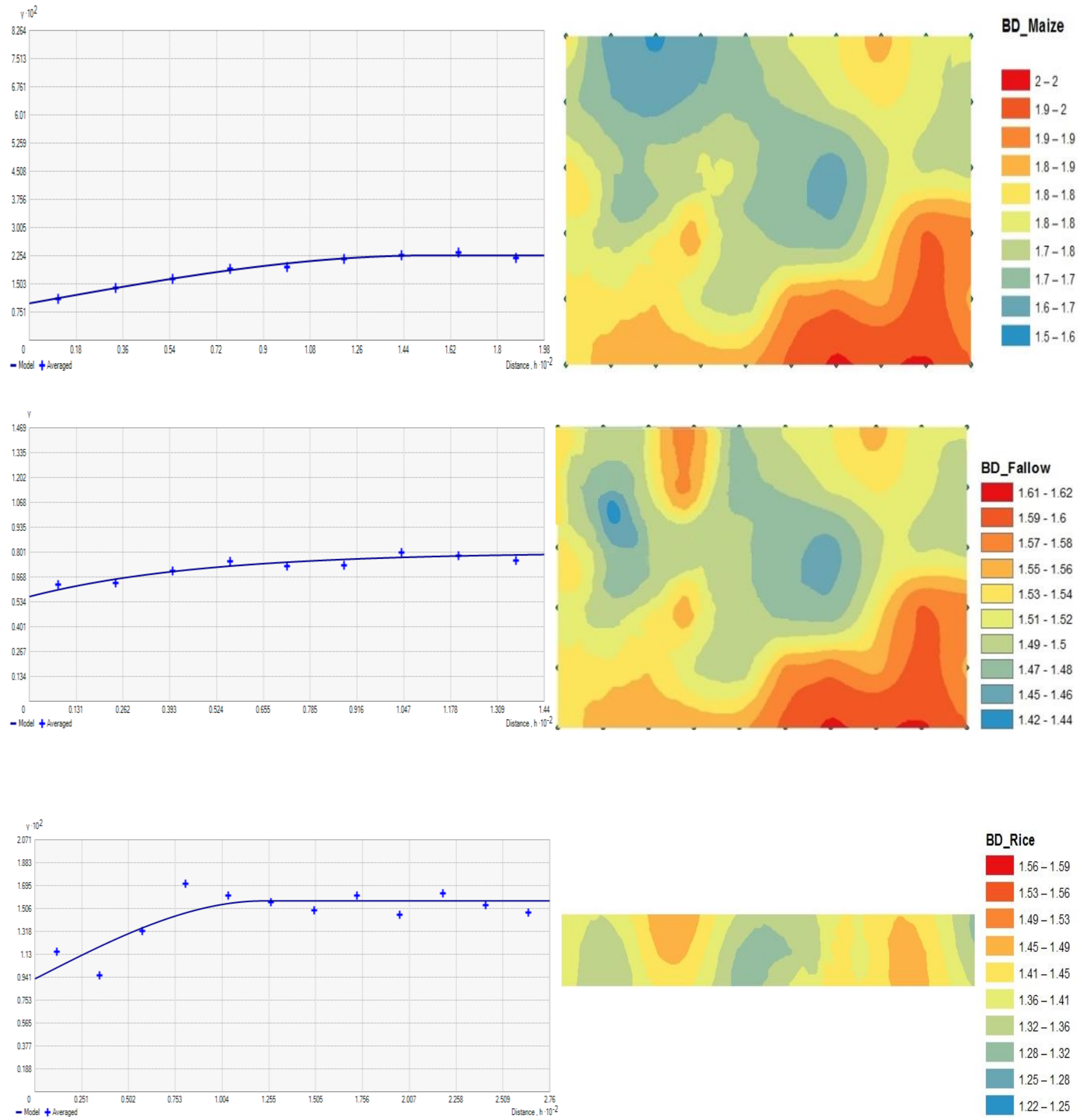


Figure 5.6: Variogram and mapping of bulk density (BD) under different land use.

5.5 Implication of spatial variability of SOC, N, P, C:N, Ksat and BD for land resources management.

Spatial variability of soil properties provides important information not only about their distribution but also their implication for land (soil and water resources) management.The magnitude, spatial scale and general form of the variation of the soil properties evaluated in Koupendri catchment as shown by the C.V. and the variograms reveal that SOC, Ksat, C:N and Avail.P were highly variable and more spatially dependent across the three land use types compared to TN and BD.

The implication is that the spatial structure of these soil properties were captured within the scales used in this study and predictions or interpolations made with these variograms may represent reality in the field. Moreso, there is an indication that the current land use and soil management practices have little or minimal impact on the spatial structure of SOC, Ksat, C:N and avail.P. This is because strongly spatially dependent properties are mainly controlled by intrinsic variation in soil characteristics such as soil texture and mineralogy. However, TN and BD are purely random properties with little variability and weak spatial dependence despite having high autocorrelation length. This implies that the degree to which these variables or soil properties become less similar at increasing distance is less than proportionate the distance between the variables. In other words, the spatial autocorrelation of these soil properties may be revealed at smaller scales other than the one used in this study. Thus, interpolations or predictions made with these variograms may not represent reality in the field. At the scale used in this study, these soil properties are weakly spatially dependent or spatially independent and thus seem to be uniformly distributed under the different land use though with little variation. Other factors such as tillage practices and the application of NPK fertilizers in the cultivated fields may have affected their variability and spatial structure

5.6 Partial summary and conclusions

Sustainable use of soil resources and environmental management, developing effective framework and efficient experimental designs for research approaches require an understanding of soil spatial variability. Soil sampling was carried out across three land use types using systematic sampling approach. The laboratory results were further subjected to simple statistical, correlation and statistical analysis. The results show that the soil properties varied moderately across the various land use evaluated except Ksat that showed high variability under the different land use types. The variability of TN and BD were mostly low across the three land use types. The soil properties exhibit normal and non-normal distribution across the three land use types. The Pearson correlation analysis showed significant relationships amongst the soil properties which may influence their variability. The range values showed considerable variability amongst the measured soil properties though TN and BD are weakly spatially dependent across the land use types. SOC has the strongest spatial dependence among all the soil properties studied and across various land use. Land use and soil management practices such as tillage operations and fertilizer applications are assumed to influence the distribution, spatial structure or patterns of the soil properties The prediction maps provided useful information on the spatial distribution of the soil properties, showing their exact position in the field and thus could serve as an important monitoring and evaluation tool especially for improved agricultural productivity and understanding the catchment hydrological processes.

CHAPTER 6

The effect of land use and slope position on some hydraulic properties of sandy loam hillslope soils of Koupendri catchment, north-west of Benin.

Introduction

The knowledge of soil hydraulic properties is required describe for characterizing the catchments hydrological behaviour. Soil hydraulic parameters such as soil hydraulic conductivity vary significantly in space (Vereecken *et al*., 1997; Warrick and Nielsen, 1980; Zhu and Mohanty, 2002) and influenced some hydrological processes such as runoff generation, groundwater recharge, and infiltration and water retention characteristics. Soil moisture dynamics and water retention capacity is one important hydraulic/hydrologic property that affects flow and transport processes, soil productivity and management. The main objective of soil and water resources management systems is to enhance water infiltration rather than runoff mainly by improving the soils physical and hydro-physical properties (Brady and Weil 1999). This further ensures that crop water requirements for the growth and development of crops which are important functions of root zone soil moisture are met (Grayson and Western, 1998).

Soil hydraulic properties especially infiltration capacity and soil water retention are altered or influenced by land use and vegetation (Zimmermann *et al*., 2006; Price *et al*., 2010). The effect of tropical forest conversion to cattle pastures on surface soil hydraulic properties has been reported (Martínez and Zinck, 2004; Zimmermann *et al*., 2006; Zimmermann and Elsenbeer, 2008). Research has also shown that agricultural land use and improper soil management reduces the macro porosity and secondary pore system significantly, affecting soil moisture content, and consequently result in increased surface runoff (Germer *et al.*, 2010; Ndiaye *et al.*, 2007).

Soil hydraulic properties are measured in-situ or in the laboratory using soil cores. Determination of soil hydraulic properties from laboratory experiments on soil cores has been adjudged to be time consuming and costly (Oliver and Smettem, 2005). This also does not offer accurate representation of the effective soil hydraulic properties that control hydrologic processes at much larger spatial scales (Minasny and McBratney, 2002). For such soils, measured hydraulic properties are usually poor (Reynolds *et al.*, 2000) due to the dissection of the continuous macropores by the core walls (Angulo-Jaramillo *et al.*, 2000).

Among the several methods used for characterization of surface soil hydrologic or hydraulic properties, in situ measurement of infiltration rates has been widespread (Boczko *et al*., 2006).

Compared to other standard tension infiltrometers, hood infiltrometer not only require little transportation effort, with little soil disturbance during soil surface preparation, but also eliminate the effect of contact layer or materials on measured soil hydraulic properties (Reynolds and Zebchuk, 1996). This makes the result more reliable than the results from core methods and other tension or pressure infiltrometers. This chaper therefore aims to assess the effect of land use and slope position on soil hydraulic properties of local hillslope of Koupendri catchment using laboratory and field or in-situ methods.

6.1 Soil textural characteristics at 0-40 cm depth on two slope position and land use types

The soil textural characteristics within the root zone (0-40 cm) of the selected slope positions under different land use types are shown below (Table 6.1). The results show that sand is the dominant particle size (56-62 %), followed by silt (28-31 %) and the least is clay (6-16 %). The soils are mostly sandy loam at all depths although sand, silt and clay decreases with depth. The textural classes were mostly sandy loam. The soils are also have high (52-71 %) gravel contents that increases with depth. This qualifies the soils of the hillslope as gravely sandy loam soil.

Table 6.1: Soil properties at the two slope positions and land use types.

Landuse	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Textural class	O.C. (%)	Gravel (%)
FSG Upslope	0-20	61	31	8	SL	1.84	52.8
FSG Upslope	20-40	56	28	16	SL	1.15	66.5
FSG Downslope	0-15	60	29	10	SL	1.63	70.99
TMB Upslope	0-20	62	32	6	SL	1.33	53.4
TMB Upslope	20-40	59	30	11	SL	1.23	58.9
TMB Downslpe	0-20	61	30	9	SL	1.41	52.82

O.C= organic carbon, FSG=fallow-shrub-grassland, TMB= tilled maize-bean, SL=sandy loam

6.2 Soil hydrological/hydraulic properties of Koupendri catchment hillslope

The hydrological properties of the hillslope soil of Koupendri catchment under two slope positions and land use types are shown in Table 6.2. The results show the soil hydrological properties measured were higher upslopes compared to their downslope counterparts under the selected land use types. Saturated hydraulic conductivity (Ksat) determined in the laboratory was higher (90-156 cm/d) upslope but lower (55-110 cm/d) downslope in both of the two selected land use. This is also similar for the Ksat determined in-situ with higher values (73-247 cm/d) upslope and lower values (32-225 cm/d) downslopes for both selected land use types. Steady state infiltration rate followed similar trend with higher values (112-287 cm/d) upslope and vice versa (60-262 cm/d) for both land use type. Generally, the result shows that Ksat was higher under the FSG on both slope positions compared to the TMB. Similar trend or characteristics was shown by initial and final volumetric soil moisture content and bulk density. However, the soil porosity was higher under the TMB plot compared to the FSG. The gravel content was high downslope of FSG (Table 6.2).

Table 6.2: Mean values of soil hydraulic properties of Koupendri catchment hillslope.

Land Use/Slope Position.	Ksat (cm/day) In-situ	Ksat (cm/day) Lab	Initial θ_v (cm^3/cm^3)	Final θ_v (cm^3/cm^3)	BD (Kgm^{-3})	Porosity[b] (%)	Infiltration (cm/day)
TMB-Upslope	**73.1**	**90.1**	**0.084**	**0.198**	**1.30**	**50.92**	**112.8**
TMB-Downslope	**32.3**	**55.5**	**0.042**	**0.258**	**1.38**	**48.07**	**60.6**
FSG-Upslope	**247.4**	**155.5**	**0.090**	**0.224**	**1.36**	**48.57**	**287.3**
FSG-Downslope	**225.9**	**101.5**	**0.088**	**0.277**	**1.37**	**48.42**	**262.2**

TMB= tilled maize-bean plot, FSG= fallow shrub-grass land, K_{sat} = saturated hydraulic conductivity, θ_v= volumetric moisture content, **BD = bulk density, [b]Estimated from bulk density values, assuming particle density of 2.65 g cm^{-3}.**

6.3 Temporal soil moisture dynamics at two timescales under different land use types

The temporal variability of soil moisture or soil moisture dynamics at 30-minutes and daily timescale for a sandy loam soil under different land use is shown below (Figs. 6.1 and 6.2). The dynamics of soil moisture captured the dynamics of the rainfall characteristics. This is an indication that rainfall dynamics is a major driver of soil moisture dynamics under the two land use types. Generally, soil moisture under FSG land use was higher throughout the period evaluated with daily maximum and minimum values of 0.27cm^3/cm^3 and 0.1 cm^3/cm^3 repectively at daily time scale, and 0.392 cm^3/cm^3 and 0.096 cm^3/cm^3 respectively at 30-minutes timescale. The laboratory measurements (Table 6.2) also confirmed this observation having both initial and final soil moisture contents higher under FSG land use on both slope positions.

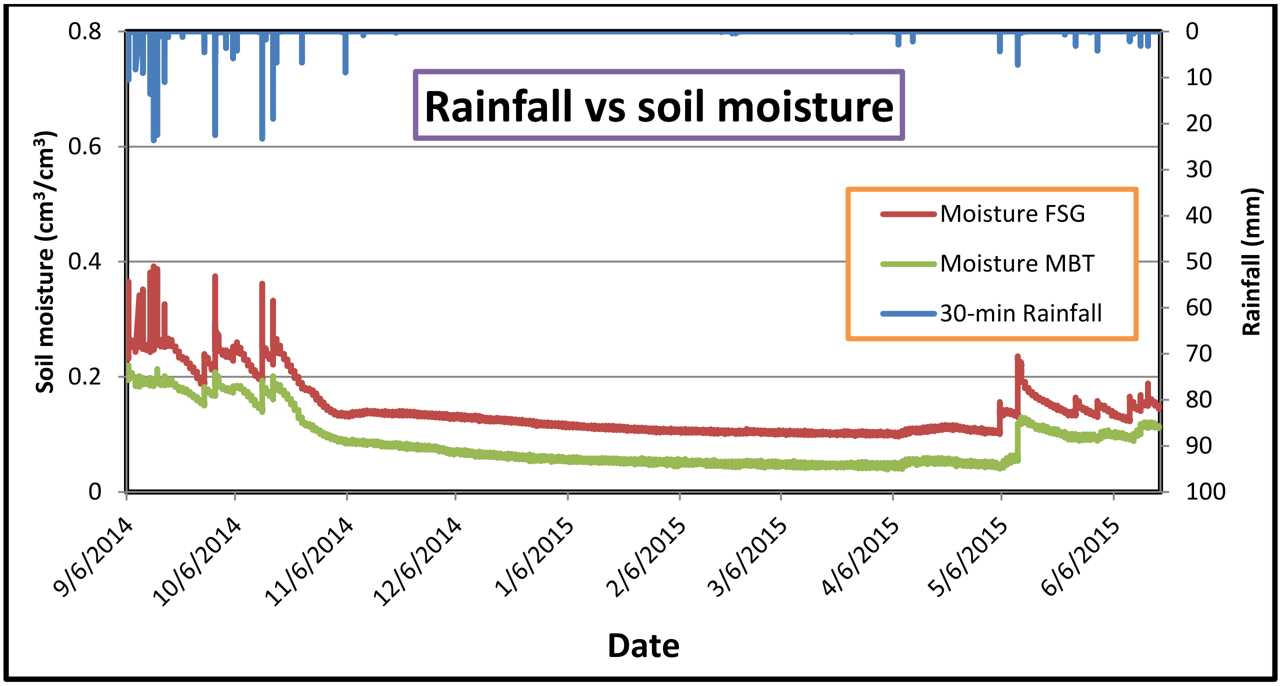


Figure 6.1: Temporal variability of rainfall and soil moisture dynamics under different land use at 30-minutes timescale.

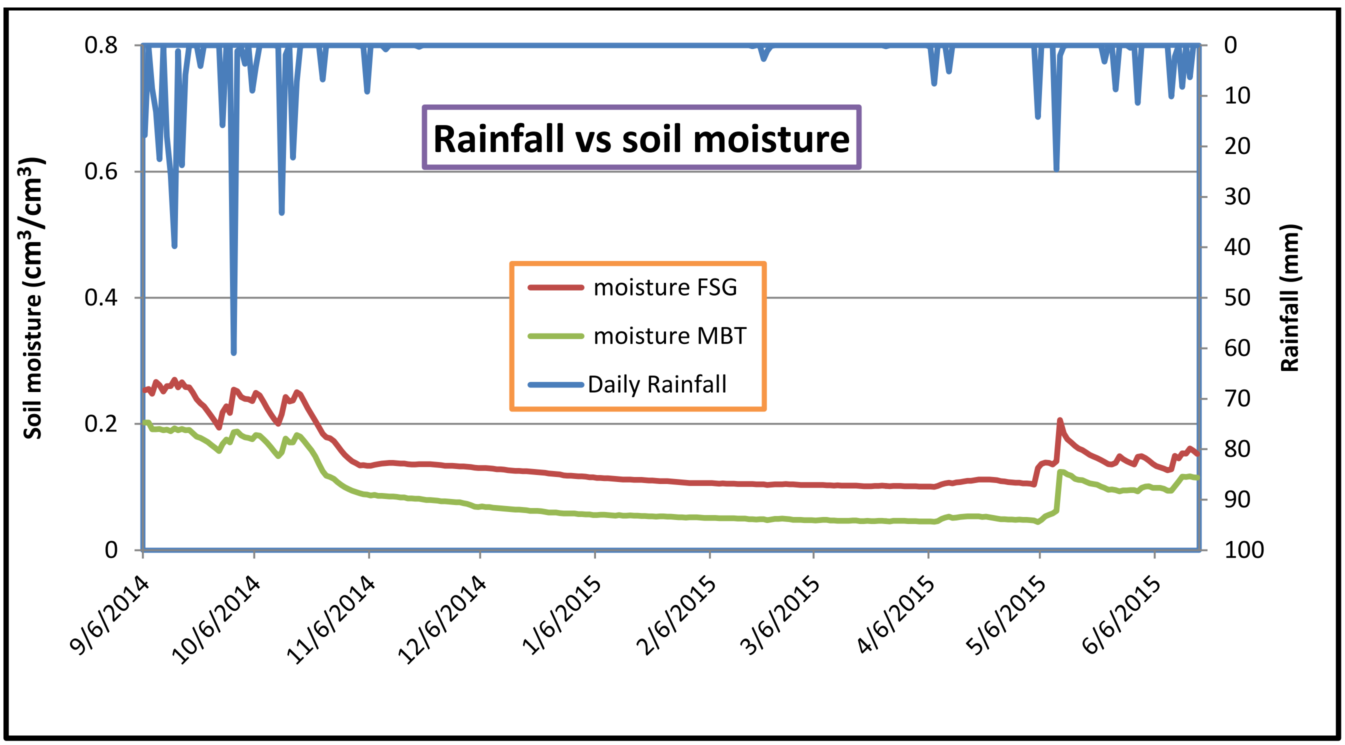


Figure 6.2: Temporal variability of rainfall and soil moisture dynamics under different land use at daily timescale.

6.4 Discussions

The high gravel content of the soils is assumed to have significant influence on soil hydraulic properties and may explain the high value of Ksat obtained downslope of FSG. Water tends to move faster through coarse or large pores than through small pores. Jury et al., (1991) also relates soil saturated hydraulic conductivity as a function of pore size; coarser textured soils have larger pores and higher saturated conductivity than finer textured soils. This may also explain the high steady state infiltration rate recorded in this study. The infiltration rate was observed to be 9-88 % higher upslope compared to the downslope position of the hillslope under the two land use types. Similar report was made by Brown et al. (1988) who observed 50- 100 % higher infiltration rates for a silt loam upstream compared to the downstream furrow.

The result obviously showed a significant effect of land use on the soil hydraulic properties especially soil Ksat. Ksat was adjudged a sensitive indicator of soil disturbance mainly tillage practices and soil management practices (Ziegler *et al.*, 2004; Zimmermann *et al*., 2006). This also supports the findings that tropical forest conversion to pasture have great impact on surface soil hydraulic properties (Martínez and Zinck, 2004; Zimmermann *et al*., 2006; Zimmermann and Elsenbeer, 2008). This is because; soil tillage destroys macropores, its network continuity and prevents formation of larger pores. There is high relationship between soil hydraulic properties and soil structural stability and, also macro porosity. Numerous soil stable macropore structure, connectivity and continuity as result of high biological activity can be linked to the observed high soil hydraulic properties on both slope positions under the FSG compared to TMB. Thus, transport and flow processes (both nutrient and contaminant), water balance and the hydrology of the hillslope is influenced by the effect of soil management and land use on soil hydraulic properties. The differences observed between the Ksat determined in-situ and in the laboratory could be attributed to the differences in coverage or size between the tension disc of the Hood infiltrometer and the core samples. This could also be attributed to the destruction or creation of artificial macropores in core or laboratory determined Ksat resulting to either high or lower values unlike in-situ determination that ensure minimal disturbance of soil macropores. Basile (2003) went further to state or argue that the differences observed between the laboratory and in-situ measured soil hydraulic properties is due to differences in the hysteretic paths taken during wetting procedures. Both in-situ and laboratory determined saturated hydraulic conductivity, initial or antecedent soil moisture contents and steady-state infiltration rates were found to increase upslope.

However, bulk density values and final soil moisture contents of the soils decreased upslope, thus the increased infiltration rate upslopes can be interpreted.

Assuming the maximum daily soil moisture (Fig. 6.2) value represent field capacity, and minimum value represent permanent wilting point, available water capacity (0.16-0.17) of the hillslope soil fall within the range for sandy loam soils (Jensen et al., 1990). Joshi et al., (2011) also confirm that soil textural characteristics have significant effect on soil water holding capacity or retention characteristics and storage. This information is vital for the determination of irrigation water requirements especially for effective daily irrigation scheduling and efficient irrigation management. The low soil moisture storage observed especially in the dry period (October, 2014-April, 2015) may be due to the coarseness of the soil including the gravel contents. This is because coarse textured lose water easily compared to fine textured soils. It has also been reported that at higher soil water potentials, coarse-textured soils are known to lose more water and plants growing on such soils tend to exhaust their water supply faster than plants growing in fine-textured soils (Hultine et al., 2005).

In this study, since the texture (sandy loam) and soil particle size distribution (sand, silt and clay percent) under the two land use types were almost similar (Table 6.1), the differences in the actual soil water or moisture content may not be attributed to soil texture but to the differences in land use or land cover type, and soil management practices. It is well known that tillage operation reduces the amount of residue, enhance rapid breakdown of soil structure or aggregates and organic matter, increases BD, and reduces hydraulic conductivity and infiltration, and consequently the soil-water storage capacity and quantity of soil water conserved in the soil. It was obvious that the soil moisture content was significantly influenced by land use and soil management practices as this remains higher throughout the period evaluated under the FSG compared to TMB. This further confirms the above result of the volumetric soil moisture content obtained under the two land use types.

The results also showed that the temporal dynamics of the soil moisture depicted the precipitation characteristics. The height and pattern of the peak is dependent on rainfall characteristics such as amount, duration and intensity. A high amount of rainfall of low intensity at longer duration leads to high amount of soil moisture compared to a high amount of rainfall of high intensity at short duration. The soil moisture dynamics peaks during rain events and the response was quick but descends slowly during the cessation of rain. The peaks of the soil moisture dynamics were captured better at 30-minutes timescale when compared to daily timescale mainly due to differences in timescale.

6.5 Partial summary and conclusion

This study evaluated the effect of land use and slope positions on soil hydrologic properties on a hillslope of Koupendri catchment. The soil hydraulic or hydrological properties were determined using both in situ and laboratory methods. Also, steady state infiltration rates were measured in-situ under different land use types and slope position. The texture of the soils is sandy loam with the dominance of sand. The results showed that the soil hydraulic properties were influenced by land use and slope positions. Higher values of the soil hydraulic properties were obtained under the FSG and upslopes. The study also revealed widespread disparity between in-situ and laboratory determined soil hydraulic properties especially hydraulic conductivity, and its inter-dependency on soil management practices. Soil moisture content was influenced by land use, soil management practices and rainfall characteristics irrespective of the soil textural and particle size distribution. Soil moisture dynamics is solely driven by the rainfall characteristics. Although soil moisture dynamics was captured better at 30-minutes timescale, soil moisture monitoring at daily timescale provided realistic information necessary for effective daily irrigation scheduling. Although, the determination method or approach has some impact on the measured soil hydraulic properties, the information conveyed were similar in terms of land use and slope position effect on soil hydraulic properties.

CHAPTER 7

Microplot scale rainfall-runoff processes on two slope positions and land use in Koupendri catchment north-west of Benin: observation and modeling using NRCS_CN approach.

Introduction

Rainfall over West Africa is mostly convective in nature, heavy and of short duration (Kasei, 2012) and is characterized by large multiscale variability (e.g. Lebel et al. 2000; Le Barbé et al. 2002). This is of great interest in soil and water resources management due to its significant contribution to surface runoff and soil erosion by water. Surface runoffs are mainly studied on the plot scale using runoff plots of various sizes (FAO, 1991). The importance of plot-scale runoff and soil loss study has been reported, and reliable data from extensive field measurement have played a crucial role in the analysis and prediction of soil erosion and hydrological processes at larger scales (Licznar and Nearing 2003; Zhang et al. 1996; Nearing et al. 1999). This involves scaling up of runoff processes from plots to the entire catchments. This often faces pronounced scale effects as observed in different environments (Blöschl and Sivapalan, 1995). In West Africa, van de Giesen et al. (2000) observed that runoff from small plots is higher than runoff from their corresponding larger plots. Such observed scale effects have been attributed to the spatial variability in rainfall (Gómez et al., 2001; Séguis et al., 2002) and recession infiltration (van de Giesen et al., 2005). Although scale issues has been addressed (van de Giesen et al. 2011; Leys et al. 2010; Cerdana et al. 2004), field measurements from plots of similar dimension often show large spatial and temporal variability. This variability has been attributed partly to the variability in natural conditions, and disturbances caused by tillage and soil management practices including installation of the experimental design. In order to address this consistent and pertinent unresolved issue or challenge, there is need to increase the number of these plots to obtain reliable result. However, these runoff plots are expensive to install, operate and maintain, thus need to be simulated from available rainfall data. One of the simplest or conceptual rainfall-runoff models for correlating rainfall to runoff i.e. predicting runoff from rainfall is the Natural Resources Conservation Service-Curve Number (NRCS-CN) approach formerly known as Soil Conservation Service-Curve Number (SCS-CN) approach (USDA, 1986). As an example, this method has been successfully applied in a plot-scale study in northern steep hillslope of Ethiopia for simulating surface runoff (Descheemaeker et al. 2006, 2008). The main objective of this chapter was to evaluate surface runoff variability and plot scale rainfall-runoff processes using NRCS-CN approach on a hillslope of the Koupendri catchment under different land use and slope positions. The results were compared to surface runoff coefficients obtained at the catchment scale to analyze scale dependency. This is important for sustainable and efficient management of soil and water resources, and for future soil erosion research in the catchment and region.

7.1 Surface runoff under two land use types and two slope positions

The effect of land use and slope position on the observed surface runoff is shown in Table 7.1. The results reveal that land use has significant effect ($p < 0.05$) on the event surface runoff in most of the events studied. However, the reverse was the case for the slope position and their interaction with land use. The surface runoff for the events observed within the study period was lower under the FSG compared to TMB plots on both slope positions throughout the events. The result showed a significant effect ($p < 0.05$) of land use on total surface runoff. On the other hand, the slope position and their interaction with land use have no significant effect ($p <0.05$) on the total runoff measured (Table 7.2). Out of the total rainfall amount of 448.8 mm recorded for the period, a total surface runoff of 339.4 mm was collected under TMB as against 249.2 mm under FSG (Fig 7.1).

Table 7.1: Mean effect of runoff events under different land use and slope positions.

Rainfall (mm)	Slope position	Runoff (mm)	Land use	Runoff (mm)
	Upslope	**4.45**	**FSG**	**4.20**
18.2	**Downslope**	**4.87**	**TMB**	**5.12**
	$LSD_{0.05}$	**NS**	$LSD_{0.05}$	**NS**
	CV (%)	**33.8**	CV (%)	**33.8**
	Upslope	**26.3**	**FSG**	**20.3**
40.5	**Downslope**	**24.0**	**TMB**	**29.9**
	$LSD_{0.05}$	**NS**	$LSD_{0.05}$	**5.81**
	CV (%)	**8.70**	CV (%)	**8.70**
	Upslope	**15.29**	**FSG**	**12.84**
17.68	**Downslope**	**15.12**	**TMB**	**17.58**
	$LSD_{0.05}$	**NS**	$LSD_{0.05}$	**1.72**
	CV (%)	**7.2**	CV (%)	**7.2**
	Upslope	**32.87**	**FSG**	**27.87**
39.8	**Downslope**	**31.67**	**TMB**	**36.66**
	$LSD_{0.05}$	**NS**	$LSD_{0.05}$	**1.574**
	CV (%)	**2.1**	CV (%)	**2.1**
	Upslope	**20.26**	**FSG**	**19.65**
23.75	**Downslope**	**19.98**	**TMB**	**20.59**
	$LSD_{0.05}$	**NS**	$LSD_{0.05}$	**0.736**
	CV (%)	**2.2**	CV (%)	**2.2**
	Upslope	**22.13**	**FSG**	**20.20**
29.55	**Downslope**	**22.51**	**TMB**	**24.40**
	$LSD_{0.05}$	**NS**	$LSD_{0.05}$	**1.89**
	CV (%)	**6.3**	CV (%)	**6.3**
	Upslope	**25.67**	**FSG**	**21.05**
32.2	**Downslope**	**23.20**	**TMB**	**27.82**
	$LSD_{0.05}$	**NS**	$LSD_{0.05}$	**2.563**
	CV (%)	**7.2**	CV (%)	**7.2**
	Upslope	**13.05**	**FSG**	**10.27**
22.5	**Downslope**	**14.20**	**TMB**	**17.20**
	$LSD_{0.05}$	**NS**	$LSD_{0.05}$	**2.245**
	CV (%)	**10.2**	CV (%)	**10.2**
	Upslope	**35.15**	**FSG**	**32.70**
46.8	**Downslope**	**35.43**	**TMB**	**37.88**
	$LSD_{0.05}$	**NS**	$LSD_{0.05}$	**2.11**
	CV (%)	**3.8**	CV (%)	**3.8**

TMB = tilled maize-beans crop land, FSG = fallow shrub-grassland, $LSD_{0.05}$ =least significant difference at 5% probability level, CV %= coefficient of variation, NS =not significant

Table 7.2: Mean effect of the interaction of land use and slope positions on runoff events.

Rainfall (mm)	Land use	Upslope	Downslope
	FSG	4.03	4.37
18.2	TMB	4.87	5.37
	$LSD_{0.05}$	NS	NS
	CV (%)	36.1	36.1
	FSG	20.0	20.7
40.5	TMB	32.6	27.3
	$LSD_{0.05}$	NS	NS
	CV (%)	26.6	26.6
	FSG	13.12	12.57
17.68	TMB	17.47	17.68
	$LSD_{0.05}$	NS	NS
	CV (%)	13	13
	FSG	27.97	27.78
39.8	TMB	37.77	35.55
	$LSD_{0.05}$	NS	NS
	CV (%)	5.6	5.6
	FSG	20.08	19.22
23.75	TMB	20.43	20.75
	$LSD_{0.05}$	NS	NS
	CV (%)	4.2	4.2
	FSG	20.53	19.87
29.55	TMB	23.73	25.15
	$LSD_{0.05}$	NS	NS
	CV (%)	9.7	9.7
	FSG	22.12	19.98
32.2	TMB	29.22	26.42
	$LSD_{0.05}$	NS	NS
	CV (%)	12.1	12.1
	FSG	9.75	10.78
22.5	TMB	16.35	18.05
	$LSD_{0.05}$	NS	NS
	CV (%)	18.8	18.8
	FSG	32.13	33.27
46.8	TMB	38.17	37.58
	$LSD_{0.05}$	NS	NS
	CV (%)	6.9	6.9

TMB = tilled maize-beans crop land, FSG = fallow shrub-grassland, $LSD_{0.05}$ =least significant difference at 5% probability level, CV %= coefficient of variation, NS =not significant

7.2 Surface runoff variability

The variability in the observed surface runoff depth per event under two land use and slope positions respectively were very low (coefficient of variation (CV) <10 %) except for the first rainfall event (CV< 40 %). The CV ranged from 2.1 to 33.8 % under the different land use and slope positions (Table 7.1). The result showed that the variability was higher and ranged between 4-36.1 % as a result of the interaction between land use and slope position, with 5 out of 10 events exceeding a CV of 10 % (Table 7.1). However, the variability was very low and below 10 % when total surface runoff under the two land use and slope positions including their interactions were considered (Table 7.3).

Table 7.3: Mean effect of land use/land cover and slope positions on total surface runoff

TR (mm)	LU	TSR (mm)	SP	TSR (mm)	LU x SP		
					LU	Upslope	Downslope
448.76	TMB	339.40	Upslope	290.20	TMB	332.80	346.00
448.76	FSG	249.15	Downslope	298.35	FSG	247.60	250.70
	$LSD_{0.05}$	21.42	$LSD_{0.05}$	NS	$LSD_{0.05}$	NS	
	CV %	5.4	CV %	5.4	CV %	8.4	

LU = Land use, TMB = tilled maize-beans Crop land, FSG = fallow shrub-grassland, TR = Total rainfall, TSR = Total surface runoff, SP = Slope position, $LSD_{0.05}$ = least significant difference at 5% probability level, CV %= coefficient of variation, NS =not significant.

7.3 Microplot surface runoff modeling or simulation at plot scale

The assigned CN-values of 57 (FSG) and 66 (TMB) could not reproduce the surface runoff observed at the microplot scale. Therefore, the CN-values were calibrated using the observed rainfall-runoff data for the selected land use types. The calibration results for each land use and slope positions gave CN-values of 96 for FSG and 98 for TMB respectively.

The results of the simulated rainfall-runoff depth for the microplots using the calibrated CN-values are shown in Fig 7.1. Based on the model evaluation criteria used (Table 7.4), the results showed a good simulation or prediction using the calibrated curve number values on both slope positions and land use types. In addition, the results showed that the surface runoff depth under the TMB land use was better simulated or predicted on both slope positions as shown by the evaluation criteria; R^2–values (0.94-0.95), ME (0.91-0.92) and RMSE (0.20-0.22) compared to the FSG land use with R^2-values (0.85-0.86), ME (0.71-0.75) and RMSE (0.38-0.39).

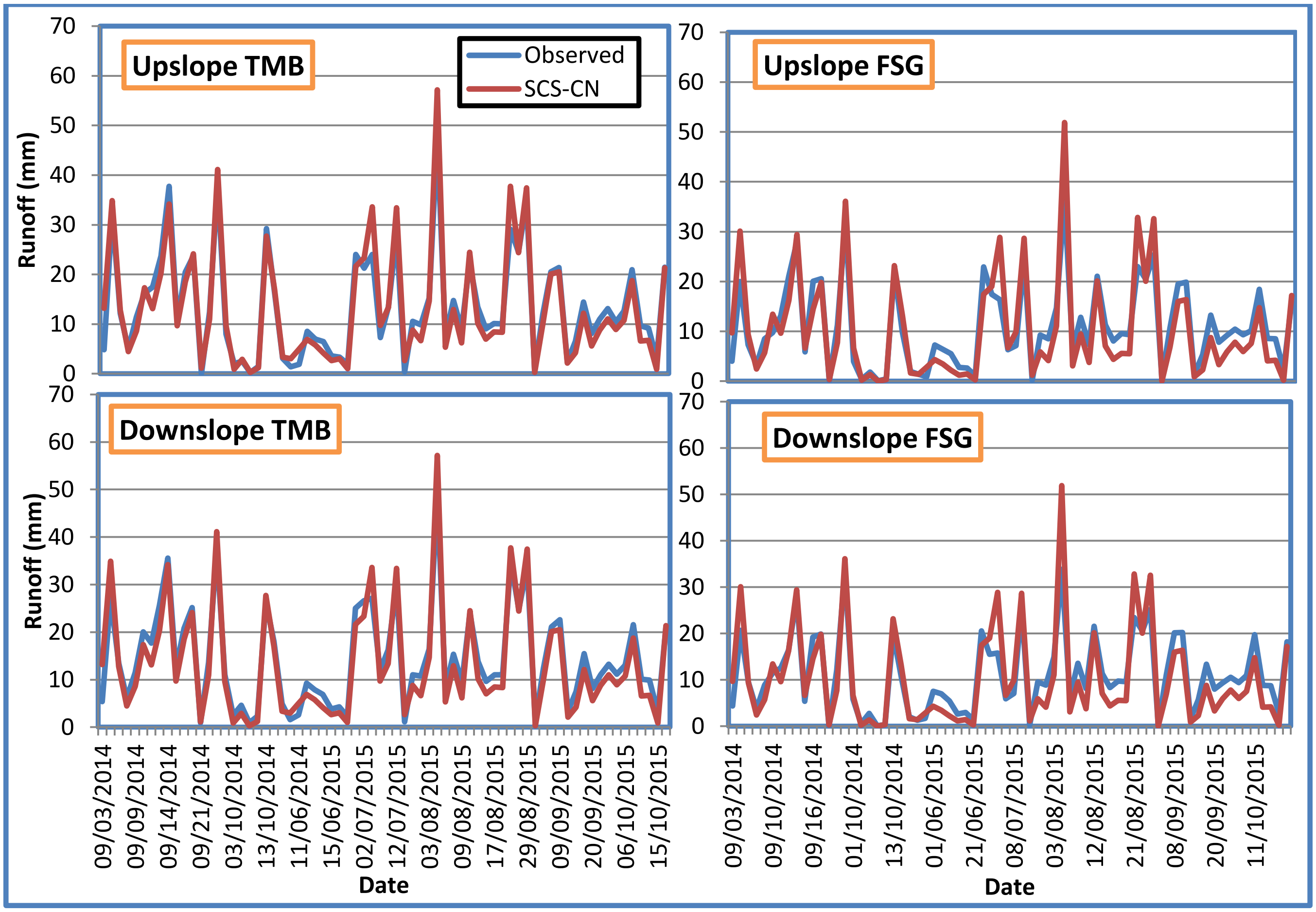


Figure 7.1: Observed and simulated runoff using NRCS-CN method for year 2014 and 2015.

Table 7.4: Evaluation criteria for the observed and NRCS-CN simulated or modeled runoff under different land use and slope positions for two-year (2014-2015) period.

Efficiency Criteria	Upslope TMB	Downslope TMB	Upslope FSG	Downslope FSG
R^2	0.94	0.95	0.86	0.86
ME	0.92	0.91	0.75	0.72
RMSE	0.22	0.21	0.39	0.39

R^2= coefficient of determination, ME= model efficiency, RMSE= root-mean square error, TMB= tilled-maize beans, FSG= fallow-shrub-grassland

7.4 Surface runoff coefficient at plot and catchment scale

The observed surface runoff coefficient at plot and catchment scale did not follow similar trend with the event rainfall recorded at the climate station (Fig.7.2). This could be because surface runoff and runoff coefficient is not only influenced by rainfall amount but also by rainfall intensity which varies within the storm event. The event runoff coefficient was generally high for the microplots reaching a maximum of 0.96 downslope of the hillslope under TMB. The influence of land use on runoff coefficient was more obvious compared to that of slope position. The runoff coefficient was particularly higher downslope in both land use types for the microplots compared to their upslope counterparts. We found lower runoff coefficient for the catchment ranging from 0 to 0.6% compared to the microplots (0.1 to 0.96) under different land use and slope positions throughout the events.

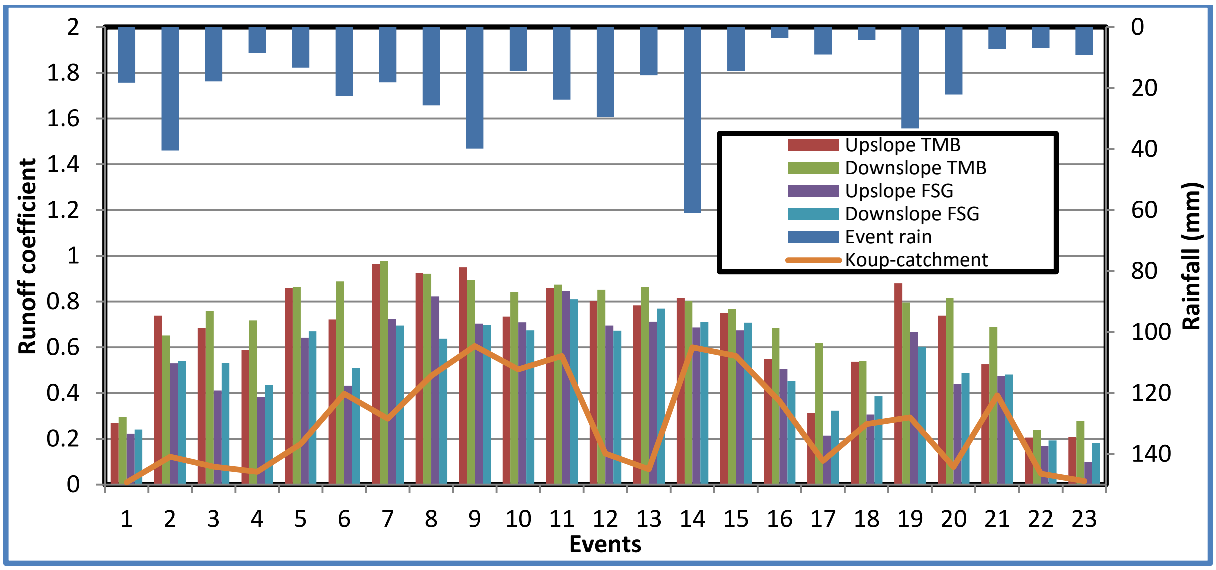


Figure 7.2: Runoff coefficient at the microplot and the catchment scale.

7.5 Discussions

There is a strong influence of land use on surface runoff per event and total surface runoff. Lal (1981) reported that land use type, forest clearing and tillage practices had significant influence on the magnitude of runoff and erosion. The contributions of litter and humus formation, and increased surface roughness to decreased runoff generation have also been reported (Descheemaeker et al., 2006). However, the lower surface runoff under FSG compared to TMB is clearly more of a function of vegetation canopy coverage, land use and soil management practices (Zhou et al. 2006; Huo et al. 1996; Lal, 1981) rather than the key role of litter accumulation and organic matter (Xu, 2005; Pizzaro et al. 2006; Boer and Puigdefábregas 2005). The high surface runoff downslopes especially under the TMB plots can be attributed to poor soil structure and hydraulic properties, and shallow soils (0-15 cm) downslope of the hillslope compared to deeper soils (0-50 cm) upslope. Soil management practices such as tillage leads to breakdown in soil structural aggregates reducing the soil hydraulic functions and flow processes within the microplots. This may explain the differences in the observed total and event surface runoff between the two selected land uses. This result agrees with the findings of Tilahum et al (2013) and Poesen (1984) in most of the events. However, this result contradicts the earlier reports by some researchers (e.g; Chaplot and Le Bissonnais 2000; Sharma et al. 1983; and Djorovi, 1980) that runoff increases with increasing slope steepness in a few events**.** Differences in vegetation coverage which influences rainfall interception, reduces rainfall intensity and hydraulic properties such as antecedent soil moisture, soil porosity, hydraulic conductivity and infiltration (Wang et al., 2013) may have contributed to the disparity in the observed surface runoff depth between the two selected land use types.

The surface runoff variability was very low under the two selected land use and slope positions compared to their interactions depending on the rainfall event. This could be attributed to the homogeneity in the soil hydraulic and other hydrologic properties within each microplots. Though one may not attribute the very low surface runoff variability to the effect of land use or slope position, it is obvious that their interaction influenced surface runoff variability resulting to mostly moderate variability. The implication is that while six microplots may be enough to resolve surface runoff variability and achieve homogeneity under different land use and slope position in Koupendri catchment, more may be needed to resolve variability caused by the interaction of land use and slope positions.

The runoff coefficient for the microplots under two slope positions and land use types were high and varied throughout the period mainly due to temporal variability in rainfall characteristics. Similar high runoff coefficent was reported by Chaplot and Le Bissonnais (2000) on slopes ranging from 2-8 % using plot sizes of 1 m^2 (1m x 1m) and 10 m^2 (2 m x 5 m) respectively. Though Chaplot and Le Bissonnais (2000) attributed the high runoff coefficient to high rainfall intensity and slope steepness, Silva and Oliveira (1999) found that the only independent variable affecting total runoff and runoff coefficient was total rainfall with a significant level close to 100% and R^2 equal to 0.84. Soil crusting and compaction that characterize West African field conditions, often leads to reduction in soil pores and soil water infiltration, and consequently could lead to high surface runoff. Also, land use and soil management through prolonged tillage practices or other agricultural disturbances cause soil structure and organic matter deterioration which promote soil crusting, sealing or compaction. Consequently, subsurface processes are suppressed at the expense of the surface processes leading to increased surface runoff. This apparently may account for the significant difference in the surface runoff depth and runoff coefficient between the two land use in addition to differences in vegetation coverage. Descheemaeker et al. (2006) reported that the total vegetation cover accounted for more than 80 % of the variability in runoff coefficient. Furthermore, the high runoff coefficient observed in the downslope position of mostly the cultivated plot could also be due to the soil moisture state of the soil although this was not investigated in this study. Moreover, Tilahum et al., 2013 attributed the increased runoff coefficient in the downslope compared to its upslope to increased saturation of the watershed at the downslope. In such case, the moisture storage reaches maximum while infiltration capacity is drastically reduced making the saturation overland flow the dominant runoff mechanism.

A comparison of runoff coefficient of the microplots and the catchment showed that the runoff coefficient at the catchment was lower for most of the periods or events considered. This result agrees with the findings in Ajayi et al., (2007) which showed that small plots generally have higher unit runoff discharge compared to larger plots. Van de Giesen et al. (2011) also reported that runoff per metre or unit length of erosion plots and consequently runoff coefficient decreases with increasing length and or size of the plots. This was also confirmed by Stomph et al. (2002) from his laboratory studies which were extrapolated to West African condition. However, linear extrapolation of runoff observed on a small plot usually overestimates actual runoff from larger surfaces, especially for short rainfall events (Van de Giesen et al. 2000, 2005). Similar observations were made by Yair and Raz-Yassif (2004) in a small semi-arid catchments. Thus, the low runoff coefficient at the catchment scale compared to the microplots can be attributed to the issue of scale. The scale effect is produced mostly in the build-up and the infiltration-recession phases (Stomph et al. 2002). This is because water flow on plots with longer slopes or larger surface area has more time to infiltrate due to high surface roughness (Stomph et al. 2002)., heterogeneity of infiltation capacity (Yair and Lavee, 1985) and increased surface retention (Pallis et al., 1997) than on plots with shorter slopes or sizes. While the soils, land use and vegetation coverage of each microplots location may be homogenous, heterogeneity of soils, land use and vegetation coverage across a catchment is common. For instance, the spatial variability of soil hydraulic properties e.g hydraulic conductivity, soil moisture, infiltration e.t.c. within and amongst these various soil types determines and control the flow and transport processes, storage and the discharge measured at the outlet of the catchment. Land use and vegetation covers which regulate the hydrological processes of a catchment (Gao et al., 2009; Gutierrez *et al.*, 1995) also alter the soil hydraulic properties including infiltration capacity, hydraulic conductivity and water retention (Gutierrez et al., 1995). However, it is important to note that scale effects on runoff can also occur along homogeneous hillslopes or landscapes (Stomph et al. 2002).

The simulation using NRCS-CN approach showed closer values of the estimated to the observed under TMB compared to FSG on both slope positions. Tandon and Nimbalkar (2014) also reported closer values of estimated or predicted runoff values to the observed runoff and reiterated the need for a statistical proof that estimated runoff adequately agrees with observations. The various evaluation criteria (RMSE, ME and R^2-values) used confirmed that the model simulation or prediction was good or satisfactory. The good simulation may be due to the fact that the NRCS-CN approach was developed for simulation of runoff depth of small catchment, agricultural or disturbed watersheds. Descheemaeker et al. (2008) developed and evaluated the CN approach for steep hillslopes in northern Ethiopia and found that the CN approach performs much better for plots in less well-restored areas with considerable runoff than well restored areas with less runoff. They also found that land use type was an important explanatory factor for the variation in curve numbers, and possibly the variation in surface runoff. Thus, there is need to develop the CN-values from microplot to catchment scales taking into consideration the site soil properties and land use/land cover.

7.6 Partial summary and Conclusions

The study evaluated the influence of slope positions and land use on surface runoff depth, their variability, and the applicability of NRCS-CN approach for simulating or modeling the observed plot-scale surface runoff. Our results showed that both total and event surface runoff depths were affected by land use. The variability in surface runoff depth does not depend so much on land use and slope positions but their interaction. The runoff coefficient for the microplots was generally high and attributed to shallow soil depth, soil surface characteristics or soil crusting, and poor infiltration characteristics. A comparison of the runoff coefficient at plot and catchment scale revealed strong scale issues influenced by spatio-temporal variability of rainfall characteristis and soil hydraulic properties, land use and vegetation coverage. The six microplots helped to reduce variability and to achieve a clear picture for the measured surface runoff. Though, the NRCS-CN approach was originally developed based on the information obtained from small agricultural land and soil charcteristics in the USA, and mainly used in hydrologic design activities, our simulation results can be considered good. This could be the base for simulation of surface runoff depth in Koupendri catchment. However, this must be used with caution, especially the use of weighted CN value determined from local rainfall and runoff data sets. Efforts must be made to develop CN-values from plot to catchment scale based on the catchment characteristics

CHAPTER 8

Modeling the hydrological processes of Koupendri catchment north-west of Benin.

Introduction

West Africa is faced with severe or acute water resources and management problem due to its severe rainfall or climate variability characterized by large inter-annual fluctuations. Such large fluctuations in the precipitation amount cause large inter-annual variability of discharge quantities. Descroix *et al*., (2009) note that decrease in rainfall in West Africa has led to a greater relative decrease of discharges in Sudanian regions. Sérguis *et al*., (2011) also observed a decreased streamflow or discharge in sudanian region against increased discharge in the sahelian region despite reduced rainfall in the two regions of West Africa. This could be attributed to the differences in the nature of the dominant stream flow generation processes in combination with the land surface characteristics.

Hydrological models have been a veritable tool for understanding the hydrological processes or acquiring precise information on a river basin (Tessema, 2011). A good number of hydrological or rainfall-runoff modeling efforts have been initiated in West Africa recently in an attempt to find solution to water scarcity problems. In Benin, these efforts had concentrated in the Ouémé catchment in central Benin (e.g., Götzinger, 2007) and its sub-catchment including the Donga Catchment (Séguis *et al*., 2011; Le Lay *et al*., 2008; Varado *et al*., 2006), Terou catchment (Cornelissen *et al*., 2013; Giertz *et al*., 2010; Hiepe and Diekkrüger, 2007; Sintondji, 2005; Busche *et al*., 2005; Bormann and Diekkrüger, 2004) and the Aguima Catchment (Bormann *et al*., 2005; Giertz *et al*., 2005). There has not been a hydrological or rainfall-runoff modeling attempt in the Koupendri catchment which is a sub-catchment of Dassari catchment (a part of White Volta catchment in Benin) located in the north-western part of Benin. This region usually has a characteristic drier climatic condition than the Ouémé basin and its sub-catchments. Thus, understanding the underlying mechanism of the catchment hydrological processes through modeling and accurate analysis is important for sustainable management of its soil and water resources. This chapter aims only to evaluate rainfall-runoff processes of Koupendri catchment, in north-west of Benin considering its unique characteristics using WaSiM model.

8.1 Results of the sensitivity analysis of the model parameters.

The results showed that the storage coefficient for baseflow (KK) and the scaling factor for baseflow (Q_{01}) are the most sensitive parameters as expected for base flow (Figure 8.1). However, the most sensitive parameters for direct runoff are KsT_1H_2, KsT_3H_3, KK, Q_{01} and RSC1. The most sensitive parameters for interflow are KsT_1H_1, KsT_1H_2, KsT_3H_1 and KsT_3H_3 while KsT_1H_2, KK, and Q_{01} are the most sensitive parameters for storage. Whereas land use parameters (RSC1, RSC2, RSC3, RSE1, RSE2, and RSE3) were the most sensitive parameters for the potential evapotranspiration (ETpot), the most sensitive parameters for actual or real evapotranspiration (ETR) are KsT_1H_1, KsT_3H_3, KK, Q_{01}, RSC1 and RSC2 (Figure 8.2). The most sensitive parameters for KGE are KD, KK and Q_{01}, while KsT_1H_2, KK and Q_{01} were identified as the most sensitive parameter for NSE. The results show that an increase in KK and Q_{01} increases the baseflow and storage but decreases the direct runoff, actual or real evapotranspiration (ETR), KGE and NSE. In most cases, an increase in Ks results to a corresponding decrease in storage, interflow, ETR, and NSE but an increase in direct runoff. Description for the most sensitive parameters can be found in appendix (IV).

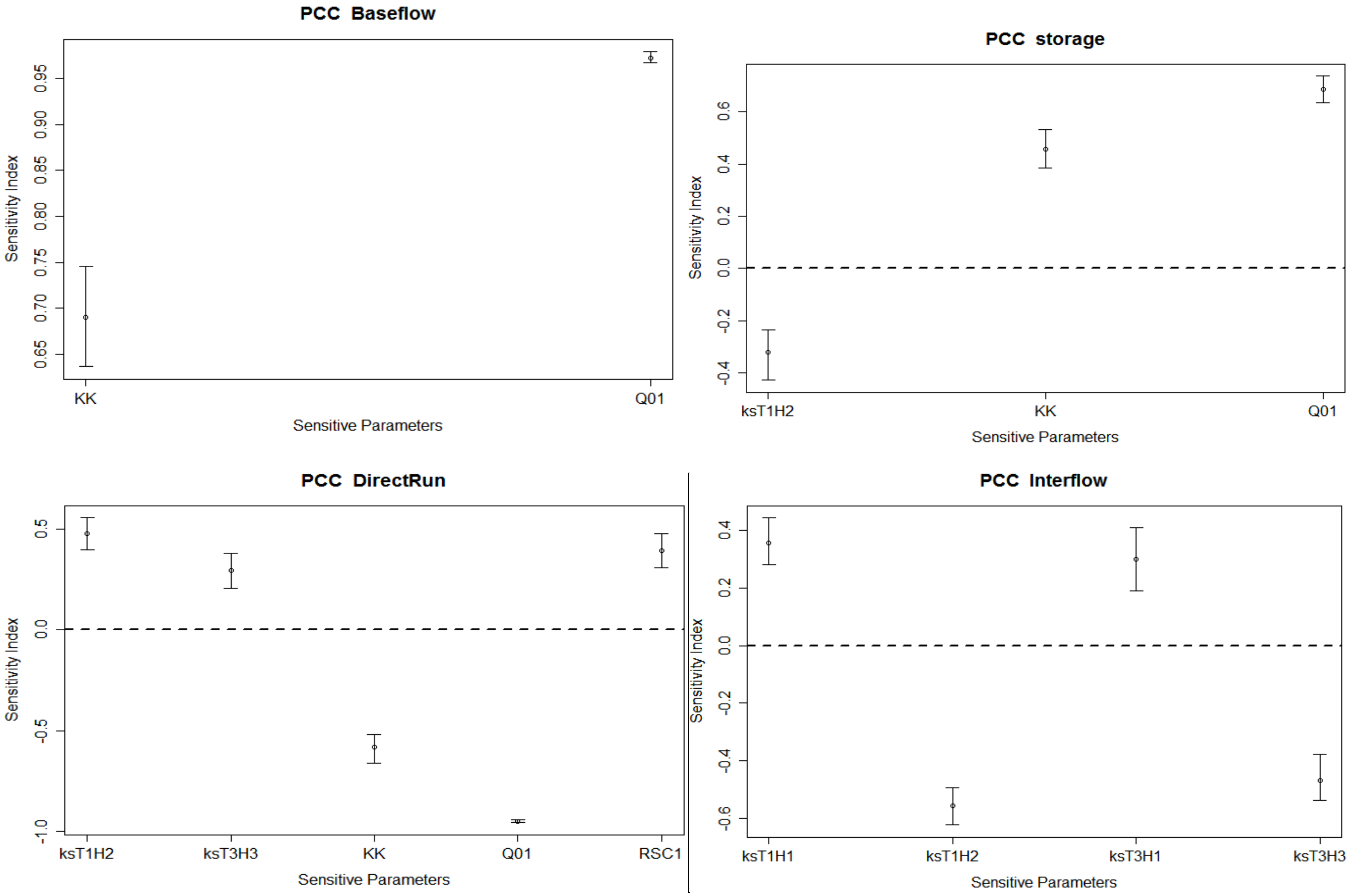


Figure 8.1: Sensitivity analysis results showing the sensitivity indices for the most sensitive parameters for directflow, interflow, baseflow and storage for WaSiM simulation at Koupendri catchment.

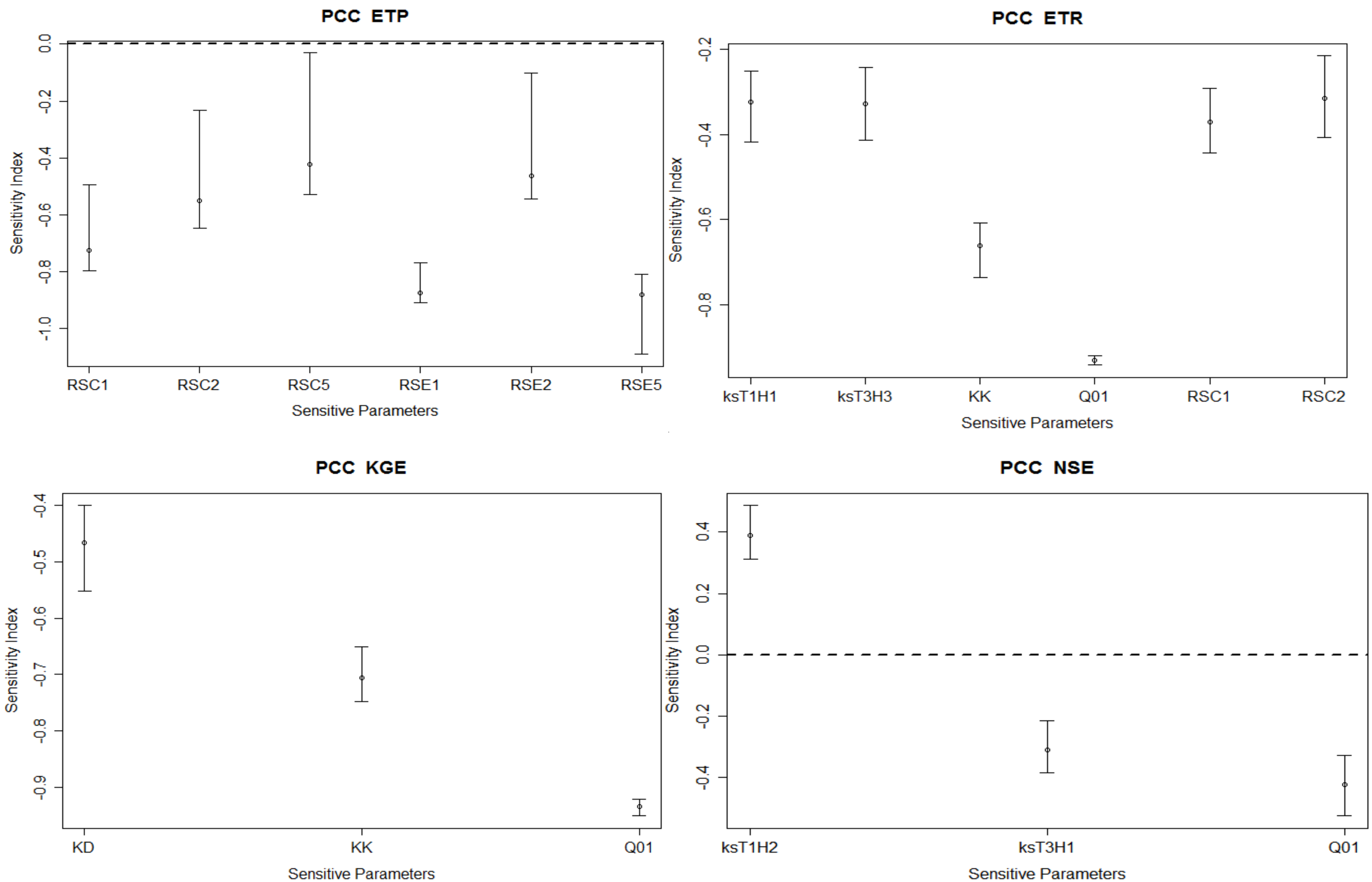


Figure 8.2: Sensitivity analysis results showing the sensitivity indices for the most sensitive parameters for ETpot, ETR, KGE and NSE for WaSiM simulation at Koupendri catchment

8.2 Results WaSim Model calibration and validation

Figure 8.3 provided the plots of the observed versus the simulated daily streamflow series for the catchment as calibrated with WaSiM model. The observed streamflow or runoff dynamics reflected the pattern of the local precipitation. The streamflow dynamics showed that there were a few discharge measurement gaps in the catchment especially at the on-set of rain in 2014. Bossa et al., (2014) noted that gaps in discharge measurement of more than 10 days could occur due to technical problems. Despite this, it can be observed that the model simulations during the calibration captured very well the observed pattern or dynamics, and the magnitude of the hydrograph especially the low flows. In particular, the rising and the recession limbs of the hydrographs were simulated accurately for the catchment. However, the simulation results showed that the model under predicted the peak flows in most of the events.

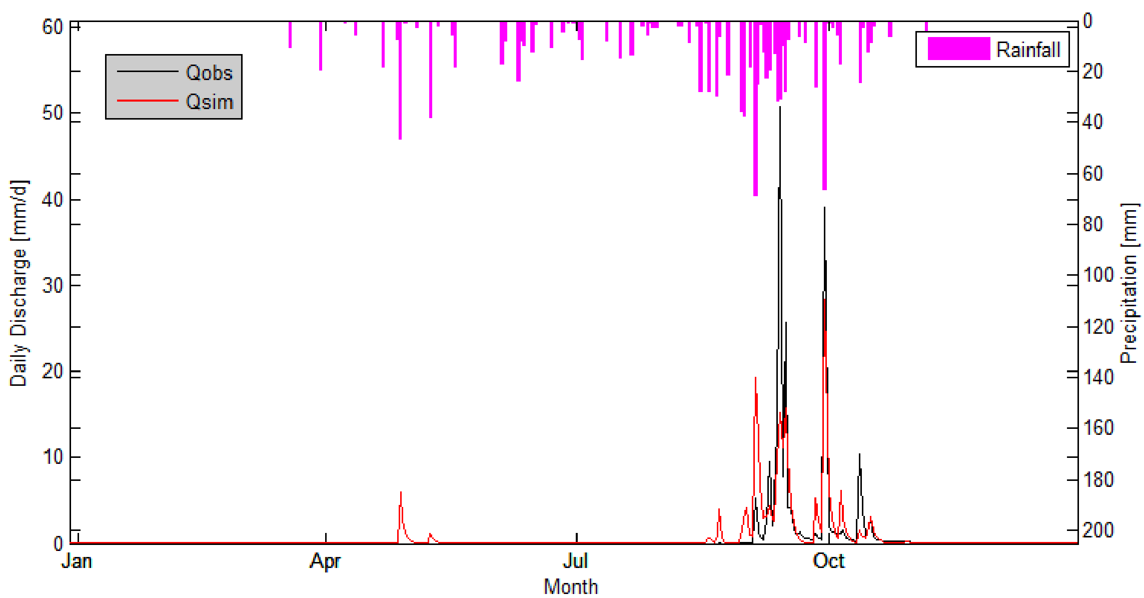


Figure 8.3: Observed vs simulated streamflow or discharge for the calibration year (2014).

The calibrated model was also validated for the year 2015 (Figure 8.4). The streamflow pattern and magnitude of runoff especially the low flows are also well simulated for the validation year. However, the number of peak flows or events under predicted by the model in the validation year was more compared to the calibration year.

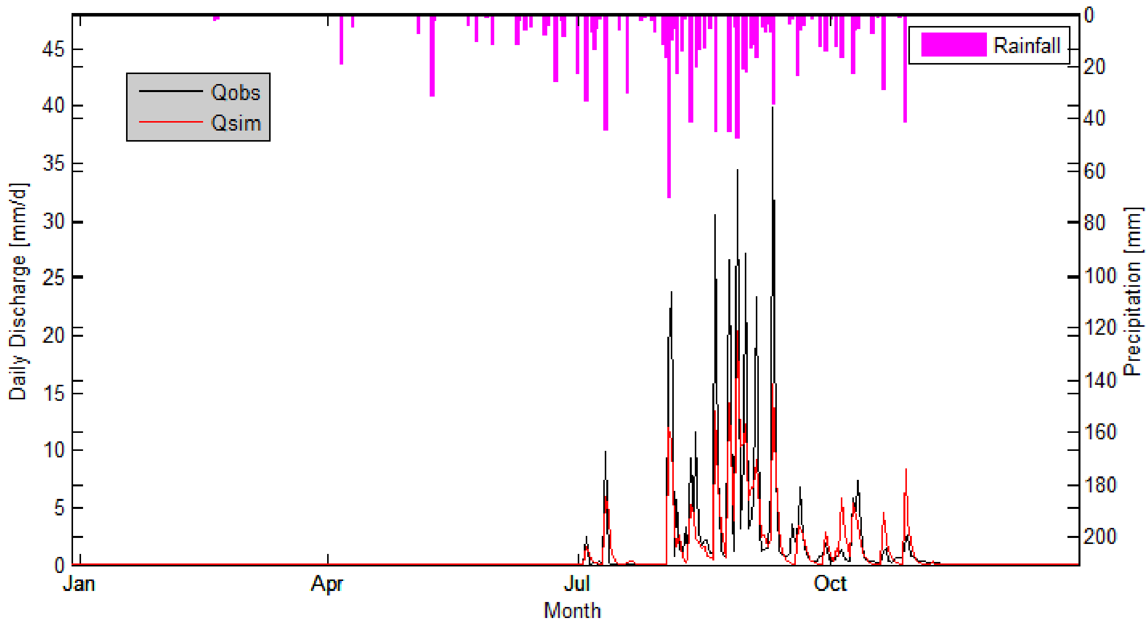


Figure 8.4: Observed vs simulated streamflow or discharge for the validation year (2015).

8.3 Water balance components and model evaluation

The water balance components of the catchment for WaSiM simulation alongside the model performance evaluation criteria during both calibration and validation are shown below (Table 8.1). The results show that the catchment annual rainfall is between the range of 1034-1073 mm with a mean of 1054 mm, and 68-75 % of this annual rainfall is the real evapotranspiration (ETR). The potential evapotranspiration varies from 1971 mm in the calibration year to 2066 mm in the validation year with the highest daily value of 10 mm/d (Figure 8.5). The observed and simulated total discharge or runoff, and their components were lower in the calibration year compared to the validation year despite having almost similar or same annual rainfall total. The hydrograph (Figures 8.6 and 8.7) show that surface or direct runoff is the dominant runoff or discharge component for the Koupendri catchment contributing 87.7 % and 86.6 % of the total runoff or discharge for the calibration and validation year respectively (Table 8.1). The interflow contributed only 9.5 % of the total runoff in the calibration year and 10.8 % in the validation year. Rainfall, evapotranspiration and runoff constitute 98-99 % of the total water balance of the catchment while the variation or changes in the soil moisture storage constitutes only 1-2 %.

The model evaluation measures used revealed accurate or acceptable model prediction of runoff dynamics for the catchment in both calibration and validation years. For the calibration year, the values of NSE, R^2, RMSE, PBias, KGE are 0.61, 0.61, 0.63, -5.3 and 0.61, respectively for daily discharge simulation, and 0.78, 0.68, 0.57, 0.57, 24.2 and 0.49 respectively in the validation year. The results show that NSE and R^2 values were higher in the validation year and vice versa for the other efficiency evaluation criteria used.

Table 8.1: Water balance components and model evaluation criteria

Parameters	Calibration (2014)	Validation (2015)
Rainfall (mm)	1034	1073
ET_{pot} (mm)	1971	2066
ETR (mm)	774	731
ETR (%)	74.8	68
Interception storage (mm)	253.3	234.5
$Runoff_{obs}$ (%)	22.6	39.7
$Runoff_{sim}$ (%)	23.8	30.1
Q_{obs} (mm)	233.8	425.6
Q_{sim} (mm)	246.2	322.5
Q_{dir} (mm)	213.6	281.5
Q_{bas} (mm)	6.3	7.5
Q_{intfl} (mm)	26.2	33.5
$\Delta\theta_s$ (%)	1.4	1.9
Balance (%)	100	100
NSE	0.61	0.68
R^2	0.61	0.79
RMSE	0.63	0.57
RSR	0.63	0.57
PBias	-5.3	24.2
KGE	0.61	0.49

$\Delta\theta_s$= change in soil moisture storage, ETR = real evapotranspiration, ET_{pot} =potential evapotranspiration, Q_{sim}= simulated discharge, Q_{obs}=observed discharge, Q_{dir}= direct/surface runoff, Q_{bas}=base flow, Q_{intfl}=interflow, NSE = Nash-Sutcliffe efficiency, RMSE = root mean square error, R^2 = coefficient of determination, RSR = RMSE-observations standard deviation ratio, PBias = percent bias, KGE = Kling-Gupta efficiency.

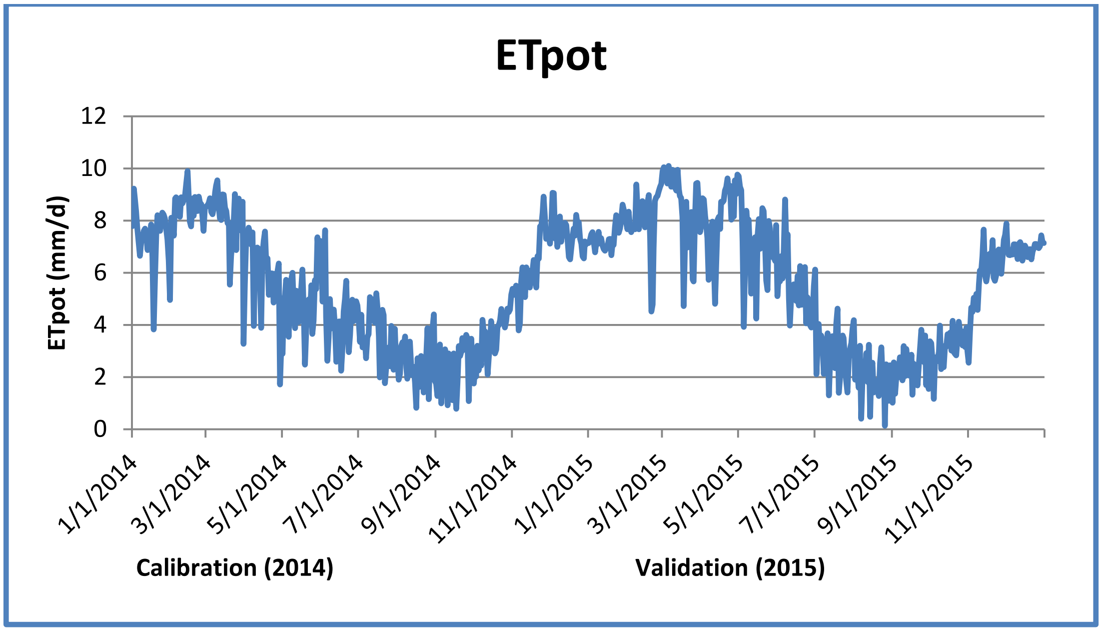


Figure 8.5: Daily ETpot of Koupendri catchment for the calibration and the validation year.

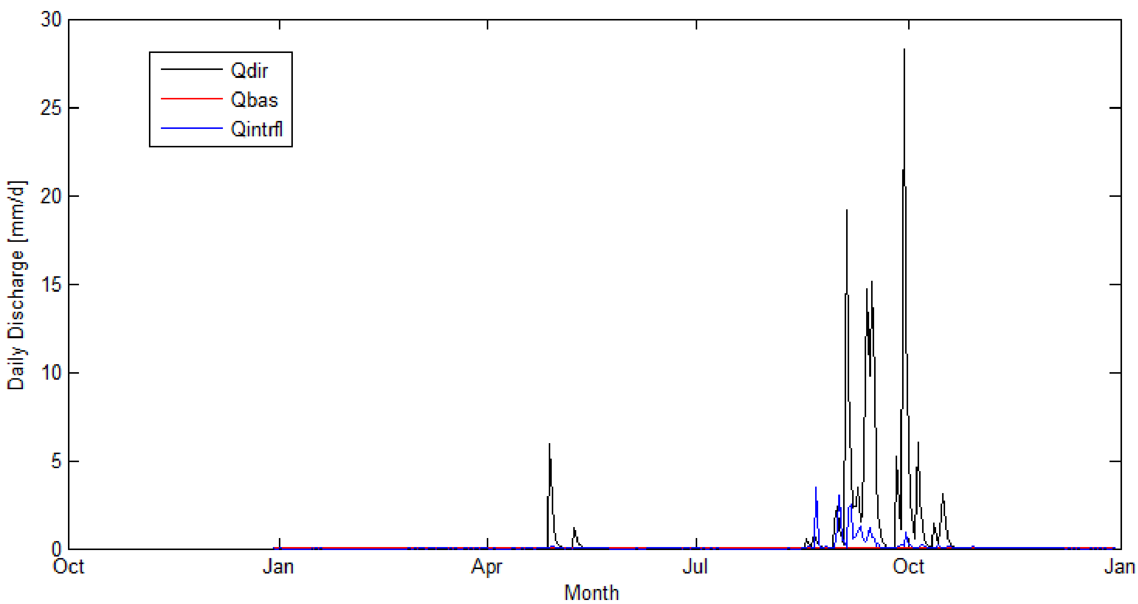


Figure 8.6: Hydrograph showing streamflow or discharge components for the calibration year (2014).

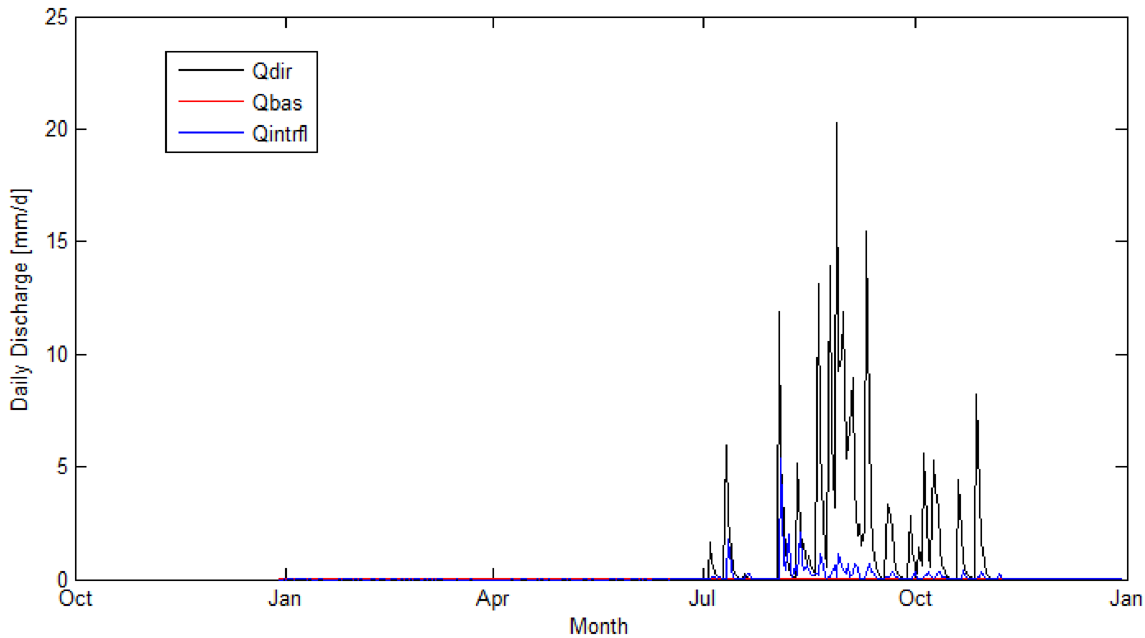


Figure 8.7: Hydrograph showing streamflow or discharge components for the validation year (2015).

8.4 Model Uncertainty

The final optimized uncertainty for discharge through multiple calibration and validation is shown in Table 8.2 while Figure 8.8 presented the final optimized 95% prediction uncertainty (95%PU) band for Koupendri catchment discharge during the calibration year (2014). The P-factor of 94 % and r-factor of 0.93 values were all within the acceptable range or limits for the simulated discharge. This signifies that the model captured or accounted correctly for all the uncertainties in the simulation processes. The result showed that 94 % of the measured discharge was bracketed within the 95 % prediction uncertainty (95%PU) indicating excellent fits. The implication is that the data used were accurately measured and of good quality. Hence, the model was satisfactorily and successfully calibrated for Koupendri catchment since the uncertainty analysis revealed that there were little or no bad simulations during the model calibration process. A model can be considered satisfactorily calibrated if approximately 90% of the measured data are within the 95%PU (Abbaspour et al., 2004).

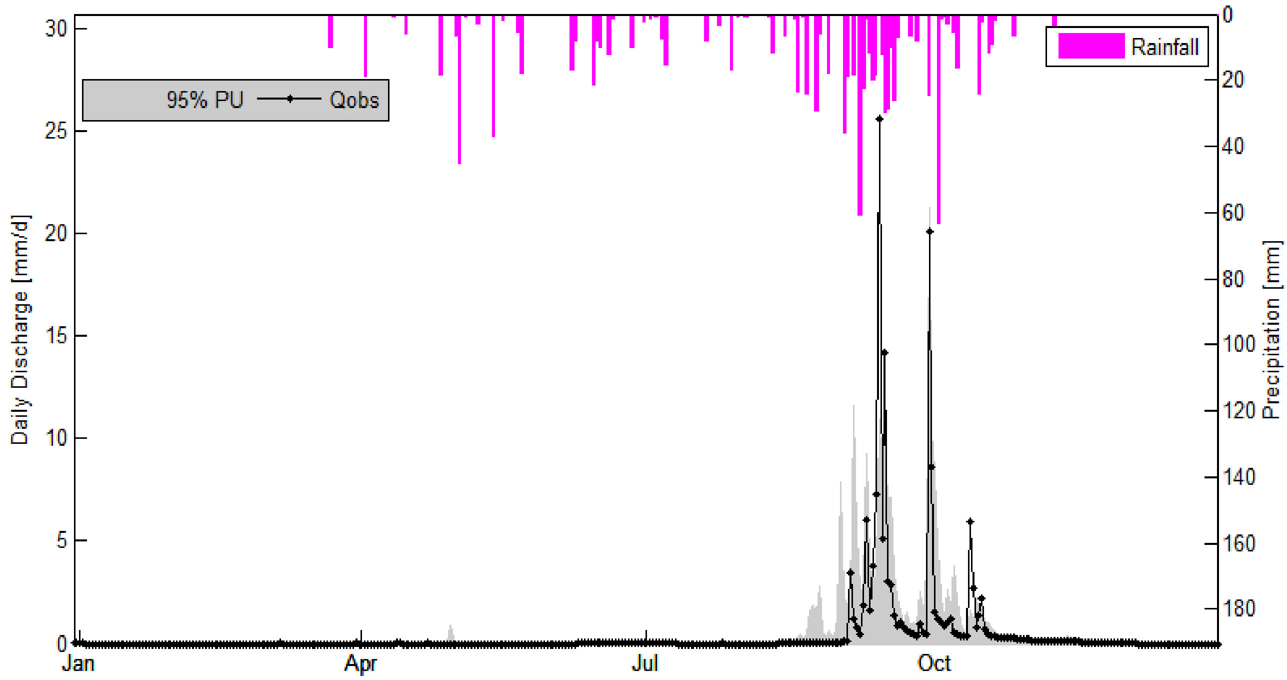


Figure 8.8: Model predictions uncertainty for the Koupendri catchment showing the measured daily discharge enclosed or bracketed by the 95 percent prediction uncertainties (95%PU).

Table 8.2: Uncertainty analysis for discharge simulation in the Koupendri catchment, Benin.

Koupendri catchment	Calibration period	P-factor	R-factor
Discharge	2014	94 (%)	0.93

8.5 Discussions

Although Cullmann et al. (2006) reported that the drainage parameter, dr, is the most suitable parameter for model calibration, this parameter was not found to be a sensitive parameter for Koupendri catchment. However, the baseflow parametes ($Q_{01,}$ KK), surface runoff parameter (KD) and Ksat of different soil types controlled most hydrological processes of Koupendri catchment. The result revealed the inability of the model to capture the peak and low flows during the calibration and validation processes. The shortcoming in the WaSiM simulations or mismatch of peak flows for the catchment supports the findings in the Volta basin using the same model (Kasei, 2010; Martin, 2005). Kasei (2010) attributed this to lateral flows contribution mainly from nearby networks not captured by the drainage density during the model calibration. Also, Martin (2005) attributed it to insufficient rainfall capture or measurement by the existing rain gauges. However, such mismatch in terms of peak flows can also be explained by uncertainties in either rainfall or stream flow observational data or due to errors in modeling extreme precipitation by the model or errors in the rating curve which in most cases does not consider extreme stream flow. According to Wagener *et al*., (2004), studies have suggested poor performance of all models with regards to forecasting under extreme conditions or due to structural and the lack of good quality data. Since we are not dealing with extremes in the present case study, this error is not of much concern. Despite the underestimation or the inability of the model to capture the peak flows, the simulated discharge was close to the reality or observation.

The annual ETR estimated by the model supported the findings of Idieti (2012), Oguntunde et al., (2006) and Ahouansou et al. (2015) that reported the annual ETR in the range of 954.4 mm – 1131m, 690 mm – 1148 mm and 724.86 mm – 1004.55 mm respectively. Similarly, the annual ET_{pot} simulated by the model was different compared to Barry *et al.* (2005) that estimated the annual ET_{pot} to 2540 mm (Pan Evaporation) but similar to Oguntunde *et al*. (2006) that estimated the annual ET_{pot} to 2136 mm (Penman-Monteith method) for the northern part of Volta basin. The result is also within the range of the ET_{pot} from the coast (1800 mm) to the northern (2500 mm) part of the Volta basin (Amisigo, 2005). The maximum daily ETpot reported in this study also supported the findings of Martin (2005) in the Volta basin.

The hydrological budget of the catchment show that about 68-76 % of the total annual rainfall turns into green water (interception and evapotranspiration) and 40 % of this amount is used for primary productivity of natural vegetation and agricultural ecosystems (Willaarts et al. 2012). This rate of green water consumption supports many findings that estimated the ETR at 70-90 % of the total rainfall in the Volta basin (Andreini et al., 2000; Martin, 2005; Kasei, 2010; Ahouansou et al., 2015) which is approximately in the same climatic zone with Koupendri catchment. The high amount of the intercepted water observed (21-25 % of the total annual rainfall) might be explained by the catchment being part of the protected area of Arly and W National Parks where important biomass are conserved. From the land use and land cover map, only about 21 % of the entire catchment has been converted to crop land.

The dominance of surface runoff as the main runoff or streamflow component confirms infiltration excess or Hortonian overland flow as the dominant runoff mechanism in the catchment. Similar reports were made for the Volta basin (Martin, 2005; Ajayi, 2004) and the upper Ouémé basin (Cornelissen et al., 2013) which share similar characteristics with the catchment. However, other studies in the Volta basin (e.g. Kasei, 2010) and the upper Ouémé basin (e.g Giertz et al., 2010) showed that interflow was the dominant streamflow component. The high surface runoff observed in the catchment can be attributed to the shallow depth of the soils which are mainly plinthosols (Azuka et al., 2015) and the rainfall characteristics in the region which are mostly convective with high intensity and of short duration (Kasei, 2012). This could also be linked to the type of model used and the mode or the underlying processes that it uses to simulate different runoff components. A recent multi-model comparative study at upper Ouémé basin showed that SWAT and WaSiM models simulated surface runoff as the dominant runoff component, the UHP model simulated interflow as the dominant runoff component (Cornellissen et al., 2013).

The results of WaSiM calibration and validation for simulating the daily discharge of the Koupendri catchment was satisfactory according to model performance assessment provided by Morias et al., (2007). The uncertainty analysis also revealed that there were little or no bad simulations during the model calibration process. Thus, the model can be adjuged to be satisfactorily and successfully calibrated for Koupendri catchment. A model can be considered satisfactorily calibrated if approximately 90 % of the measured data are within the 95%PU (Abbaspour et al., 2004). In this study, 94 % of the measured data are within the 95%PU. Therefore, the hydrological parameters adopted for the catchments are representative of the catchment characteristics and can adequately mimic the hydrology of the catchment for subsequent climate and land use change studies or analysis.

The model inability to capture the peak flows accurately influenced the model efficiency evaluation used. This resulted to the slight differences in their values. There was more peak flows events underestimated during the validation year compared to the calibration. Consequently, NSE and R^2 were overestimated during the validation period because they are insensitive to model over-and-underestimation. Similarly, the KGE and PBias including the error terms were underestimated because they are highly sensitive to model over-and-underestimation.

8.5 Partial summary and conclusion

In this study, a distributed and mainly physically-based hydrological model WaSiM was applied at Koupendri catchment at 30 m resolution in order to unravel and understand its hydrological processes. In order to parameterize the model, good quality data (land use, soil data, and hydro-meteorological data e.t.c) were gathered and prepared in the format required for running the model using 30 m resolution DEM, Arc GIS and TANALYS. A sensitivity analysis was carried out to determine the most sensitive and important parameters mostly the soil parameters that affect major hydrological processes e.g. runoff generation in the catchment. These parameters were calibrated in the model for simulating the catchment hydrological processes in 2014. The magnitude and strength of the model uncertainty was quantified using P-and-R factors respectively. The model was validated for the year, 2015 using the optimized parameters obtain from the model calibration process in 2014. The model performance was evaluated using different efficiency criteria.

There was satisfactory reproduction of the in situ streamflow measurements by the model with less uncertainty although the peak flows were underestimated, and this is common in most hydrological models. Runoff generation is mainly by infiltration excess or Hortonian overland flow mechanism. There was a good agreement between the simulated and the observed discharge during the calibration and validation period. Therefore, the hydrological parameters adopted for the catchments are representative of those of the catchment and can adequately mimic the hydrology of the catchment.

CHAPTER 9

General conclusion and Perspectives

9.1 General conclusion

One of the main challenges faced by sub-saharan or West Africa is scarcity of field data on soil hydrological properties and hydrological processes required for sustainable management of soil and water resources. The detailed (1:25,000) soil survey and classification for the Koupendri catchment using SOTER approach showed five distinct soil types, belonging to three major soil orders: Ultisols, Inceptisols and Alfisols (USDA), and four reference soil groups: Plinthosols (shallow and deeper Plinthosols), Cambisols, Luvisols and Gleysols (WRB). More than 65 % of the soils were mainly Plinthosols, less deep, highly degraded and acidic in nature, low nutrient and soil water retention capacity. This severely limited crop and plantation agriculture in the catchment.

The saturated hydraulic conductivity (Ksat) was the most varied soil property while SOC have the strongest spatial dependence among all the soil properties studied and across the the three land use type. Significant relationships exist among some of the soil properties across the three land use types. The variograms and the kriging revealed the extent of autocorrelation and variability of these soil properties at a given range and sampling scale. The information provided by the spatial variability of these soil properties could serve as an important monitoring and evaluation tool for soil and water resources management and improved agricultural productivity.

The soil hydraulic properties investigated e.g. Ksat, infiltration rate and soil moisture content were influenced by land use/vegetation cover and slope position. There was disparity in the in-situ and laboratory determined soil hydraulic properties. The dynamics of soil moisture and its temporal variability was driven mainly by rainfall characteristics and influenced by land use types.

The hydrological processes or surface runoff at the point or local scale was high and influenced by land use and slope position. The conceptual model used captured the runoff dynamics at the plot-scale and gave satisfactory results based on the evaluation criteria used. A comparison of the runoff coefficient at plot and catchment scale revealed strong scale issues influenced by spatio-temporal variability of rainfall characteristis and soil hydraulic properties, land use and vegetation coverage.

The hydrological model (WaSiM) was successfully calibrated and validated for the catchment using the most sensitive and optimized parameters of land use, soil and unsaturated zone for better understanding of the catchment hydrological processes. The calibration and validation results were satisfactory based on the model evaluation and efficiency criteria used. Acceptable ranges of uncertainties were obtained for the model simulation. Similar to the plot-scale rainfall-runoff results, the hydrograph revealed high surface runoff at the catchment scale driven mostly by infiltration excess or Hortonian overland flow runoff generation mechanism. The high surface runoff characteristics of the catchment and poor infiltration capacity of the soils resulted to poor soil moisture storage for the soils of the catchment. This raised serious soil and water resources management, and conservation concerns for the catchment.

9.2 Perspectives

This work made significant contribution to hydrological modeling by improving our knowledge on soil and soil hydrological properties including hydrological processes from local to catchment scale. The study unraveled issues that need urgent attention in the catchment for the sustainable management of soil and water resources. The issues highlighted include; soil acidity, poor soil nutrient status, poor soil water holding or retention capacity, soil degradation mostly due to improper and unsustainable soil management practices, and high surface runoff observed at both plot and catchment scale. Future works should focus on soil fertility assessment and evaluation, soil erosion and water quality assessment for sustainable soil and water resources management for the catchment. Also, there is need to quantify the quantity of the catchment available water and investigate the effect of land use change on the hydrological processes of the catchment. This will help to preserve and conserve the soil and water resources and the ecosystem services provided by the catchment.

References

Abbaspour, K. C.; Johnson, A. and van Genuchten, M. T. (2004). Estimating uncertain flow and transport parameters using a sequential uncertainty fitting procedure. *Vadose Zo. J.*, *3*, 1340–1352.

Abbaspour, K. C., Yang, J., Maximov, I., Siber, R., Bogner, K., Mieleitner, J., Zobrist, J. and Srinivasan, R. (2007).Modelling hydrology and water quality in the pre-alpine/alpine Thur watershed using SWAT. *J. Hydrol.*, *333*, 413–430

Abbaspour, K.C. (2008). SWAT Calibration and Uncertainty Programs - A User Manual. Department of Systems Analysis, Integrated Assessment and Modeling (SIAM), Eawag, Swiss Federal Institute of Aquatic Science and Technology, Duebendorf, Switzerland, 95pp. http://www.eawag.ch/ organisation/abteilungen/siam/software/swat/index_EN.

Adewopo, J.B., VanZomeren, C., Bhomia, R.K., Almaraz, M., Bacon. A.R., Eggleston, E., Judy, J.D., Lewis, R.W., Lusk, M., Miller, B., Moorberg, C., Snyder, E.H. and Mary, T. (2013). Top-Ranked Priority Research Questions for Soil Science in the 21st Century. Soil Sci. Soc. Am. J. doi:10.2136/sssaj2013.07.0291, 11 pp.

AFES (1998). *A Sound Reference Base for Soils* (The 'Référentiel Pédologique': text in English), INRA, Paris, 322pp.

Agyare, W. A. (2004). Soil characterization and modeling of spatial distribution of saturated hydraulic conductivity at two sites in the Volta Basin of Ghana. Ecology and Development Series No. 17. 206 pp.

Ahouansou, D.M.M., Agodzo, S.K., Kralisch, S., Sintondji, L.O.C. and Fürst, C. (2015). Analysis of the Hydrological Budget using the J2000 Model in the Pendjari River Basin, West Africa. Journal of Environment and Earth Science, Vol.5, No.19.

Ajayi, A.E., Oguntunde, P.G., Abiodun, B.J. and Horta, I.D. (2007). Influence of spatial structure of soil hydraulic properties on surface runoff processes in West Africa. Journal of Environmental Hydrology, vol.15; 21. 14pp.

Ajayi, A. E. (2004) Surface runoff and infiltration processes in the Volta Basin, West Africa: Observation and modeling, Ecology and Development Series No. 18.

Albertson, J.D. and Kiely, G. (2001). On the structure of soil moisture time series in the context of land surface models. Journal of Hydrology, 243(1-2): 101-119.

Alemayehu, Y., Gebrekidan, H. and Beyene, S. (2014). Pedological characteristics and classification of soils along landscapes at Abobo, southwestern lowlands of Ethiopia. J. Soil Sci. Environ. Manage. Vol. 5(6), pp. 72-82. Doi 10.589/JSSEM13.0432.

Amisigo, B. A. (2005). Modelling riverflow in the Volta Basin of West Africa: A data-driven framework, PhD Thesis Ecology and Development Series No. 34.

Anderson M.G. and Burt T.P. (1978). The role of topography in controlling throughflow generation. *Earth Surfaces Processes and Landforms*, **3**, 331−334.

Anderson M.G. and Burt T.P. (1990a) Process Studies in Hillslope Hydrology, John Wiley and Sons: Chichester, p. 539.

Anderson M.G. and Burt T.P. (1990b). Subsurface runoff. In Process Studies in Hillslope Hydrology, Anderson M.G. and Burt T.P. (Eds.), John Wiley & Sons: New York, pp. 365−400.

Anderson, J.M. and Ingram, J.S.I. (1993). Tropical soils biology and fertility. A handbook of methods, 2nd Ed; CAB International, Wallingford U.K., pp 221

Andersen, J., Refsgaard, J.C. and Jensen, K.H. (2001). Distributed hydrological modelling of the Senegal river basin-model construction and validation. Journal of Hydrology 247, 200−214.

Andreini, M. van de Giesen, N. van Edig, A. Fosu, M. and Andah, W. (2000). Volta Basin Water Balance. ZEF – Discussion Papers on Development Policy, No. 21, ZEF, Bonn

Anguela, P. T., Zribi, M., Hasenauer, S., Habets, F. and Loumagne, C. (2008). Analysis of surface and root-zone soil moisture dynamics with ERS scatterometer and the hydrometeorological model SAFRAN-ISBA-MODCOU at Grand Morin watershed (France) Hydrol. Earth Syst. Sci., 12, 1415–1424.

Angulo-Jaramillo, R., Vandervaere, J.P., Roulier, S., Thony, J.L., Gaudet, J.P. and Vauclin, M. (2000). Field measurement of soil surface hydraulic properties by disc and ring infiltrometers: A review and recent developments. Soil Tillage Res. 55:1–29. doi:10.1016/S0167-1987(00)00098-2.

Arnold, J.G., Srinivasan, R., Muttiah, R.S., and Williams, J.R. (1998). Large area hydrologic modeling and assessment. Part I: Model development. J.Am. water Resour. As. 34(1), 73-89.

Arnold, R. W. and Eswaran, H. (2003). 'Conceptual basis for soil classification: Lessons from the past', in H. Eswaran, T. Rice, R. Ahrens and B. A. Stewart (eds) *Soil Classification: A Global Desk Reference*, CRC Press, Boca Raton, FL, pp. 27–42.

Arnold, J. G., Potter, K.N., King, K.W. and Allen, P. M. (2005). Estimation of soil cracking and the effect on surface runoff in a Texas Blackland Prairie watershed. *Hydrol. Process.* 19(3): 589-603.

Arnold, J, G., Moriasi, D. N., Gassman, P.W., Abbaspour, K. C., White, M. J., Srinivasan, R., Santhi, C., Harmel, D., van Griensven, A., Van Liew, M. W., Kannan, N., and Jha, M. K., (2012). "SWAT: Model use, calibration, and validation". Biological Systems Engineering: Papers and Publications. Paper 406. http://digitalcommons.unl.edu/biosysengfacpub/406.

Asefa, D.T., Oba, G., Weladji, R.B. and Colman, J.E. (2003). An assessment of restoration of biodiversity in degraded high mountain grazing lands in northern Ethiopia. Land Degradation and Development, 14(1):25-38.

Azuka, C.V., Igué, A.M., Diekkrüger, B. and Igwe, C.A. (2015). Soil survey and soil classification of Koupendri Catchment in Benin, West Africa. Afr. J. Agric. Res., Vol.10 (42), pp. 3938-3951. DOI: 10.5897/AJAR2015.9904.

Barry, B., Obuobie, E., Andreini, M., Andah, W. and Pluquet, M. (2005).The Volta River Basin Comprehensive Assessment of Water Management in Agriculture,Comparative study of river basin development and management January, 2005. Draft p. 198.

Basile, A. (2003). Hysteresis in soil water characteristics as a key to interpreting comparisons of laboratory and field measured hydraulic properties. WATER RESOURCES RESEARCH, VOL. 39, NO. 12, 1355, doi:10.1029/2003WR002432.

Beinroth, F. H. and Eswaran, H. (2003) 'Classification of soils in the tropics: A reassessment of Soil Taxonomy', in H. Eswaran, T. Rice, R. Ahrens and B. A. Stewart (eds) *Soil Classification: A Global Desk Reference*, CRC Press, Boca Raton, FL, pp231–244.

Betson, R.P. (1964). What is watershed runoff? Journal of Geophysical Research 69, p.1541-1551.

Beven, K.J. and Kirkby, M.J. (1979). A physically based variable contributing area model of basin hydrology. *Hydrol. Sci. Bull.*, 24 (1), 43-69.

Beven, K.J. (1989). Changing ideas in hydrology: the case of physically-based models. Journal of Hydrology 105: 157-172.

Beven, K.J., Kirkby, M.J., Schoffield, N. and Tagg, A. (1984). Testing a physically-based flood forecasting model (TOPMODEL) for three UK catchments. Journal of Hydrology 69, p. 119-143.

Beven, K. (2001). How far can we go in distributed hydrological modeling? Hydrol. Earth Sys. Sci. 5:1–12.

Beven, K.J. (2000; 2001; 2012) *Rainfall-runoff modelling – the primer*. John Wiley & Sons Ltd, New York.

Blake, G.R. and Hartge, K.H. (1986). Bulk density. p. 363-382. In: Klute, A. (ed.) Methods of soil analysis. Part 1 – Physical and mineralogical methods. 2nd ed. SSSA Book Series No. 5. SSSA and ASA, Madison, W.I.

Bloschl, G. and Sivapalan, M. (1995). Scale issues in hydrological modelling—a review. ¨ Hydrological Processes, 9(3–4): 251–290.

Blöschl, G., Sivapalan, M., Wagener, T., Viglione, A. and Savenije, H.H.G. (2013). Introduction. In: Blöschl, G., Sivapalan, M., Wagener, T. (Eds.), Runoff Prediction in Ungauged Basins: Synthesis across Processes, Places and Scales. Cambridge University Press, pp. 1–10.

Boer, M., and Puigdefábregas, J. (2005). Effects of spatially structured vegetation patterns on hill-slope erosion in a semiarid Mediterranean environment: a simulation study. Earth Surface Processes and Landforms 30, 149–167.

Bonell, M. and Bruijnzeel, L.A. (2005). Forests, water and people in the humid tropics: past, present and future hydrological research for integrated land and water management. Cambridge University Press, Cambridge.

Bormann H. and Diekkrüger, B. (2003): Possibilities and limitations of regional hydrological models applied within an environmental change study in Benin (West Africa), Physics and Chemistry of the Earth 28 (33-36), p. 1323 – 1332.

Bormann, H. and Diekkrüger, B. (2004). A conceptual, regional hydrological model for Benin (West Africa): validation, uncertainty analysis and assessment of applicability for environmental change analyses. Phys. Chem. Earth. 29, 759–786.

Bormann, H., Fass, T., Giertz, S., Junge, B., Diekkrüger, B., Reichert, B. and Skowronek, A. (2005). From local hydrological process analysis to regional hydrological model application in Benin: concept, results and perspectives. Phys. Chem. Earth. 30(6–7), 347–356.

Bormann, H. and Klaassen, K. (2008). Seasonal and land use dependent variability of soil hydraulic and soil hydrological properties of two Northern German soils. Geoderma. 145: 295-302.

Bossa, A.Y. (2012). Multi-scale modeling of sediment and nutrient flow dynamics in the Ouémé catchment (Benin) – towards an assessment of global change effects on soil degradation and water quality.

Bossa, A.Y., Diekkrüger, B. and Agbossou, E.K. (2014). Scenario-Based Impacts of Land Use and Climate Change on Land and Water Degradation from the Meso to Regional Scale. *Water*, *6*, 3152−3181; doi:10.3390/w6103152.

Bosch, J.M. and Hewlett, J.D. (1982). A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. *Journal of Hydrology*, 55: 3-23.

Bosznay, M. (1989). 'Generalization of SCS curve number method,' J. Irrigation and Drainage Engineering, A.S.C.E., 115(1), 139-144

Brabant, P. (1991). Cameroon's Clear Forest Soils: A Study of a Representative Site for Soil Mapping and Land Evaluation. ORSTOM, IRD, Paris, 2 vols., 530 + 278 p.

Brady, N.C. and Weil, R.R. (1999). The nature and property of soils. 13th ed. Prentice Hall. Upper Saddle River, NJ. 881 pp.

Brakensiek, D. L. and Rawls, W. J. (1994). Soil containing rock fragments: effects on infiltration. Catena, 1994, 23: 99–110.

Bray, R.H. and Kurtz. L.T.(1945). Determination of total, organic and available forms of phosphorus in soils. Soil Sci. 59: 30-45.

Bremner, J.M. (1996). Nitrogen – total. In: Bigham J.M. (ed) Methods of soil analysis, part 3, chemical methods. Soil Sci Soc Am Am Soc Agron, SSSA Book, Series no 5, Madison, WI, pp 1085–1121.

Brevik, E. C. (2013). Soils and human health – an overview, in Soils and human health, edited by: Brevik, E. C. and Burgess, L. C., Boca Raton, FL, USA, CRC Press, 29–56.

Brevik, E. C., Cerdá, A., Mataix-Solera, J., Pereg, L., Quinton, J. N., Six, J., and Van Oost, K. 2014): Editorial "The Interdisciplinary Nature of SOIL", SOIL Discuss., 1, 429-462, doi:10.5194/soild-1-429-2014.

Bronstert, A. and Bárdossy, A. (1999). The role of spatial variability of soil moisture for modelling surface runoff generation at the small catchment scale. Hydrol. Earth Sys. Sci. 3:505–516.

Bronstert, A., Fritsch, U. and Katzenmaier, D. (2001). Quantification of the impact of land use and coverage on flood water flow in river areas. Potsdam Institute for Climate Impact Research Potsdam, 243pp. <http://www.umweltdaten.de/publikationen/fpdf-l/3595.pdf>.

Brown, M.J., Kemper, W.D., Trout, T.J. and Humpherys, A.S. (1988). Sediment, erosion and water-intake in furrows. Irrigation Science 9(1), 45- 55.

Busche, H., Hiepe, C. and Diekkrüger, B., 2005. Modelling the effects of land use and climate change on hydrology and soil erosion. In: 3rd International SWAT Conference, pp. 434–443. <http://www.brc.tamus.edu/swat/3rdswatconf/SWAT%20Book%203rd%20Conference.pdf>

Buczko, U. Bens, O. and Hüttl, R.F. (2006). Tillage effects on hydraulic properties and macroporosity in silty and sandy soils. Soil Sci. Soc. Am J., 70:1998-2007.

Buol, S., Hole, F., McCracken, J. and Southard, R. (2003). Soil genesis and classification, 5th ed. Iowa State Press, USA. pp. 126-327.

Burch, G. J., Bath, R. K., Moore, I. D. and O'Loughlin, E. M. (1987). Comparative hydrological behaviour of forested and cleared catchments in Southeastern Australia. /. Hydrol. 90, 19-42.

Cambardella, C.A., Moorman, T.B., Novak, J.M., Parkin, T.B., Karlen, D.L., Turco, R.F. and Konopka, A.E. (1994). Field-scale variability of soil properties in Central Iowa soils. *Soil Science Society of America Journal* **58**, 1501–1511. doi:10.2136/sssaj 1994.0361 599500 5800 0500 33x.

Cambardella, C.A. and Karlen, D.L., (1999). Spatial analysis of soil fertility parameters. Precis. Agr. 1, 5–14.

Campos, A. (2002). Physical and mechanical properties of three tropical forest soils on limestone in Chiapas, Mexico Foresta Veracruzana, vol. 4, núm. 2, pp. 1-9,

Cappus P. (1960). Experimental basin of Alrance - Study of the laws of the flow -Application to the calculation and the forecasting of the flows. La Houille Blanche, A, 493–520.

Cerdana, O., Le Bissonnais, Y., Govers, G., Lecomte, V., van Oost, K., Couturier, A., King, C. and Dubreuil, N. (2004). Scale effect on runoff from experimental plots to catchments in agricultural areas in Normandy. Journal of Hydrology 299, 4–14.

Cihlar, J. and Jansen, L. J. M. (2001). "*From Land Cover To Land-Use: A Methodology for Efficient Land-Use Mapping Over Large Areas"*, The Professional Geographer 53 (2): 275 – 289.

Chabi, A., Lautenbach, S., Orekan, A.O.V., and Kyei-Baffour, N. (2016). Allometric models and aboveground biomass stocks of a West African Sudan Savannah watershed in Benin. *Carbon Balance Manage*, *11:16;* DOI 10.1186/s13021-016-0058-5.

Challinor, A., Wheeler, T., Garforth, C., Craufurd, P., Kassam, A. (2007). Assessing the vulnerability of food crop systems in Africa to climate change. Climatic Change 83(3):381-399.

Chaplot, V.A.M. and Le Bissonnais, Y. (2000). Field measurements of interrill erosion under different slopes and plot sizes: Earth Surf. Process. Landforms 25, 145-153.

Chen, F.S., Zeng, D.H., He, X.Y. (2006). Small-scale spatial variability of soil nutrients and vegetation properties in semi-arid Northern China. Pedosphere 16, 778–787.

Chien, Y.J., Lee, D.Y., Guo, H.Y. and Houng, K.H. (1997). Geostatistical analysis of soil properties of mid-west Taiwan soil. *Soil Science* **162**, 291–298. doi:10.1097/00010694-199704000-00007

Chukwu, G.O. (2013). Soil survey and classification of Ikwuano Abia state Nigeria. J. Environ. Sci.Water Resourc. Vol. 2(5), pp. 150 – 156.

Cornelissen, T., Diekkrüger, B. and Giertz, S. (2013). A comparison of hydrological models for assessing the impact of land use and climate change on discharge in a tropical catchment, Journal of Hydrology doi: http://dx.doi.org/10.1016/j.jhydrol.2013.06.016.

Costa, M.H., Botta, A. and Cardille, J.A. (2003). Effects of large-scale changes in land cover on the discharge of the Tocantins River, Southeastern Amazonia. J. Hydrol. 283, 206–217.

Costa, M.H. (2005). Large-scale hydrological impacts of tropical forest conversion. In: Bonell, M., Bruijnzeel, L.A. (Eds.), Forests, Water and People in the Humid Tropics. Cambridge University Press, Cambridge, pp. 590–597.

Coyne, M.S. and J.A. Thompson. (2006). Fundamental soil science. 403pp Thomson Delmar Learning, Clifton Park, N.Y.

CPCS, (1967). Classification des Sols. Travaux CPCS 1963-1967. ENSA, Grignon. 87 pp.

Cullmann, J., Mishra, V. and Peters, R. (2006). Flow analysis with WaSiM -model parameter sensitivity at different scales Adv. Geosci., 9, 73–77.

Dale, H.V. (1997). The relationship between land-use change and climate change. Ecol. Appl. 7: 753-769.

Descroix, L., Mahé, G., Lebel, T., Favreau, G., Galle, S., Gautier, E., Olivry, J.C., Albergel, J., Amogu, O., Cappelaere, B., Dessouassi, R., Diedhiou, A., Le Breton, E., I. Mamadou, I. and Sighomnou, D. (2009). Spatio-temporal variability of hydrological regimes around the boundaries between Sahelian and Sudanian areas of West Africa: A synthesis. Journal of Hydrology 375, 90–102.

Descheemaeker, K., Poessen, J., Nyssen, J., Raes, D., Haile, M., Muys, B. and Deckers. J. (2006). Runoff on slopes with restoring vegetation: A case study from the Tigray highlands, Ethiopia. Journal of Hydrology 331, 219-241.

Descheemaeker, K., Poessen, J., Borselli, L., Nyssen, J., Raes, D., Haile, M., Muys, B. and Deckers, J. (2008). Runoff curve numbers for steep hillslopes with natural vegetation in semi-arid tropical highlands, northern Ethiopia. Hydrological Processes 22: 4097-4105.

Di Gregorio, A. and Jansen, L. J. M. (2000), "*Land Cover Classification System (LCCS): Classification Concepts and User Manual"*, FAO, Rome (Incl. CD-ROM with application software). [https://www.aginternetwork.net/_base] site visited on 30.10.2013.

Djorovic, M. 1980. `Slope effect on runoff and erosion', in De Boodt, M. and Gabriels, D. (Eds), Assessment of Erosion, 215-225.

Driesen, P. M. and Dudal, R. (1991). The major soils of the world: Lecture notes on their geography, formation, properties and use. Wageningen and Leuven. 310 pp.

Dunne, T. and Black R.D. (1970) Partial area contributions to storm runoff in a small New England watershed. *Water Resources Research*, **6**(5), 1296−1311.

Dunne, T. (1978) Field studies of hillslope flow processes. In *Hillslope Hydrology*, Kirkby M.J. (Ed.), Wiley: Chichester, pp. 227−293.

Eamus, D., Hation, T. and Cook, P. (2006). Vegetation Function, Water and Resource Management. CSIRO Publishing, Melbourne, New South Wales, Australia.

Elfert, S. and Bormann, H. (2010). Simulated impact of past and possible future land use changes on the hydrological response of the Northern German lowland 'Hunte'catchment. J. hydrology, 383 (3-4), 245-255. doi:10.1016/j.jhydrol.2009.12.040.

EMBRAPA – National centre for soil research (2006). Brazilian system of soil classification. Rio de Janeiro: Embrapa Solos. 2.ed. 306p.

ESRI. (2010). Surface creation and analysis. ArcGIS 9.2. The Redlands, CA.

Ezeabasili, A.C.C., Okoro, B.U. and Emengini, E.J. (2014). Relative erodibilities of some soils from Anambra basin. Sky Journal of Soil Science and Environmental Management, Vol. 3(8), pp 83-90.

FAO (1974-88). Soil map of the world. Revised Legend, World Soil resources. Rome.

FAO, (1991). A Manual for the Design and Construction of Water Harvesting Schemes for Plant Production.

FAO (2006). Guidelines for soil description. 4th ed. Viale delle Terme di Caracalla. Rome, Italy.

FAO (2007). World Reference Base for Soil Resources, accessed online on 11th, July 2016. (http://www.fao.org/ag/agl/agll/wrb/doc/wrb2007_c orr.pdf)

Faure, P. and Volkoff, B. (1996). Regional differentiation of soil cover and litho-geomorphology on granite-gneissic base of Benin (West Africa). C.R. Acad. Sci. Paris t. 322, Series IIa, p. 393-400.

Faure, P., Volkoff, B., (1998). Some factors affecting regional differentiation of the soils in the Republic of Benin (West Africa). Catena 32: 281-306.

Feddema, J.J., Oleson, K.W., Bonan, G.B., Mearns, L.O., Buja, L.E., Meehl, G.A. and Washington, W.M. (2005). Atmospheric science: The importance of land-cover change in simulating future climates. Science, 310, 1674-1678.

Feng, P. and Li, J.Z. (2008). Scale effects on runoff generation in meso-scale and large-scale sub-basins in the Luanhe River Basin. Hydrol. Earth Syst. Sci. Discuss., 5, 1511–1531, www.hydrol-earth-syst-sci-discuss.net/5/1511/2008/

Ferreira, V., Panagopoulos, T., Andrade, R., Guerrero, C., and Loures, L. (2015). Spatial variability of soil properties and soil erodibility in the Alqueva reservoir watershed. Solid Earth, 6, 383–392, doi:10.5194/se-6-383-2015.

Foley, J.A., DeFries, R., Asner, G.P., Bradford, C., Bonan, G., Carpenter, S.R., Chapin, F.S., Coe, M.T., Dally, G.C., Gibbs, H.K., Hellowsky, J.H., Holloway, T., Howard, E.A., Kucharlk, C.J., Monfreda, C., Patz, J.A., Prentice, I.C., Ramankutty, N. and Snyder, P.K. (2005). Global consequences of land use: A review. Science, 309 (5734): 570-574. DOI: 10.1126/science.1111772.

Fohrer, N., Moller, D. and Steiner, N. (2002). An interdisciplinary modelling approach to evaluate the effects of land use change. *Phys. Chem. Earth* 27(9-10): 655-662.

Forkuor, G., Conrad, C., Thiel, M., Ullmann, T., and Zoungrana, E. (2014). Integration of Optical and Synthetic Aperture Radar Imagery for Improving Crop Mapping in Northwestern Benin, West Africa. Remote Sensing, 6 (7), 6472–6499.

Fu, B.J., Chen, L.D., Ma, K.M., Zhou H.F. and Wang, J. (2000). The relationships between land use and soil conditions in the hilly area of the Loess Plateau in northern Shannxi, China. Catena 39:69-78.

Gaiser T, Goldbach H, Giertz S, Hiepe C, Klose A (2010). Soils. In: Speth P, Christoph M, Diekkruger B (eds) Impacts of Global Change on the Hydrological Cycle in West and Northwest Africa. Springer, Heidelberg, Germany.

Gao, F., Zhang, Y., Liu, W. (2009). Characteristics of base flow in tropical seasonal rainforest catchments in Xishuangbanna of Yunnan Province, Southwest China. Chinese Journal of Ecology, 28(10):1949-1955.

Gayathri, K.D., Ganasri, B.P. and Dwarakish G.S. (2015). A review on hydrological models. Aquatic Procedia 4:1001-1007.

Gardner, W.R. (1958). Some steady-state solutions of the unsaturated moisture flow equation with applications to evaporation from a water table. Soil Science 85, 228-232.

Gee G.W. and Or, D. (2002). Particle size analysis. In: Dane, J.H., Topp, G.C. (eds). Methods of soil analysis. Part 4. Physical Methods Soil Science Society America Book Series N0. 5 ASA and SSSA, Madison, WI; 255-293.

Germer, S., Neill, C., Krusche, A. V. and Elsenbeer, H. (2010): Influence of land-use change on near-surface hydrological processes: Undisturbed forest to pasture, Journal of Hydrology, 380 (3-4): 473–480.

Ghaffari, G., Keesstra, S., Ghodousi, J. and Ahmadi, H. (2010). SWAT-simulated hydrological impact of land-use change in the Zanjanrood Basin, Northwest Iran. Hydrol. Process., 24(7), 892–903.

Giertz, S., Hiepe, C., Steup, G., Sintondji, L., Diekkrüger, B., (2010). Hydrological processes and soil degradation in Benin. In: Speth, P., Christoph, M., Diekkrüger, B. (Eds.), Impacts of Global Change on the Hydrological Cycle in West and Northwest Africa. Springer, Berlin, pp. 168–197.

Giertz, S., Diekkrüger, B., Steup, G., (2006). Physically-based modeling of hydrological processes in a tropical headwater catchment in Benin (West Africa) - process representation and multi-criteria validation. Hydrol. Earth Syst. Sci., 10, Pages 829-847. Available at: www.hydrol-earth-syst-sci.net/10/829/2006/.

Giertz, S. (2004): Analysis of the hydrological processes in the subhumid tropics of West Africa, with particular reference to land use using the example of the Aguima catchment area in Benin.– Diss. Math.-Naturw. Fak., Univ. Bonn. 249 p. available on: http://hss.ulb.uni-bonn.de/diss_online/math_nat_fak/2004/giertz_simone/giertz.htm

Giertz, S., Junge, B., and Diekkrüger, B (2005). Assessing the effects of land use change on soil physical properties and hydrological processes in the sub-humid tropical environment of West Africa, Phys. Chem. Earth, 30, 485–496.

Giertz, S. and Diekkrüger, B. (2003). Analysis of the hydrological processes in a small headwater catchment in Benin (West Africa). Physics and Chemistry of the Earth 28: 1333–1341.

Gillman, G.P. and Sumpter, E.A. (1986). Modification to the compulsive exchange method for measuring exchange characteristics of soils. Aust. J. Soil Res. 24:61-66.

Gomez, J.A., Nearing. M.A., Giraldcz. J.V. Alberts. E.E. (2001). Analysis of sources of variability of runoff volume in 40 plot experiment using a numerical model. J. Hydrol., 248. 183-197.

Godsey, S., Elsenbeer, H. and Stallard, R. (2004): Overland flow generation in two lithologically distinct rainforest catchments, Journal of Hydrology, 295 (1-4): 276–290.

Govers, G. (2005). Rainfall erosivity and variability in the northern Ethiopian highlands. Journal of Hydrology 311, 172–187.

Götzinger, J., (2007). Distributed Conceptual Hydrological Modeling-Simulation of Climate, Land Use Change Impact and Uncertainty Analysis. Doctoral thesis, University of Stuttgart, Germanyhttp://elib.uni stuttgart.de/opus/volltexte/2007/3349/pdf/Diss_Goetzinger_ub.pdf (consulted on 10.05.2016).

Grayson, R., and G. Blöschl. (2001). Spatial patterns in catchment hydrology: observations and modelling. CUP Archive, August 6.

Grayson, R. B., and Western, A.W. (1998). Towards areal estimation of soil water content from point measurements: Time and space stability of mean response, J. Hydrol., 207, 68– 82.

Grego, C.R., Vieira, S.R., Antinio, A.M. and Rosa, S.C.D. (2006). Geostatistical analysis for soil moisture content under no tillage cropping system. *Scientia Agricola* **63**, 341–350. doi:10.1590/S0103-90162006000400005.

Gupta, H. V., Kling, H., Yilmaz, K.K., and Martinez, G.F. (2009). Decomposition of the mean squared error and NSE performance criteria: Implications for improving hydrological modelling. Journal of Hydrology 377, 80-91.

Gutierrez, J.; Sosebee, R.E.; Spaeth, K.E. (1995). Spatial variation of runoff and erosion under grass and shrub cover on a semiarid rangeland. In: Ward TJ. (Editor), Watershed Management-Planning for the 21st Century, pp. 11–20 American Society of Civil Engineers, San Antonio, TX.

Gülser, C. and Candemir, F. (2008). Prediction of saturated hydraulic conductivity using some moisture constants and soil physical properties. Proceeding of Balwois, Ohrid.

Güntner, A. (2002). Large-Scale Hydrological Modelling in the Semi-Arid North-East of Brazil. Potsdam Institute for Climate Impact Research and University of Potsdam, Germany, 148pp. <http://opus.kobv.de/ubp/volltexte/2005/62/pdf/guentner.pdf>.

Habtamu, K., Husien, O., Haimanote, B., Tegenu, E., Charles, F., Amy, S. and Tammo, S. (2009). The effect of land use on plant nutrient availability and carbon sequestration. pp 208-219. Proc. 10th conf., March 25-27. Addis Ababa. .

Hagemann, S., 2002. An Improved Land Surface Parameter Dataset for Global and Regional Climate Models. Report 336. Max Planck Institute for Meteorology,Hamburg, 28pp. <http://www.mpimet.mpg.de/fileadmin/publikationen/Reports/max_scirep_336.pdf>

Hamilton, L. C. (1990). Modern data analysis. A first course in applied statistics, pp 684

Han, F.P., Hu, W., Zheng, J.Y., Du, F. and Zhang, X.C. (2010*b*). Spatial variability of soil organic carbon in a catchment of the Loess Plateau. *Acta Agriculturae Scandinavica, Section B - Soil & Plant Science* **60**, 136–143. doi:10.1080/09064710902721354.

Harper, D., Zalewski, M. and Pacini, N. (2008). Ecohydrology: Processes, Models and Case Studies, An approach to the sustainable management of water resources. Cromwell Press, Trowbridge, UK.

Havlin, J., Tisdale, .S, Nelson, W. and Beaton, J. (1999). Soil fertility and fertilizers, 6th ed. Macmillan Publishing. USA. pp. 85-196.

Hawkins, R.H. (1993). Asymptotic determination of runoff curve numbers from data. Journal of Irrigation and Drainage Engineering 119: 334–345. DOI: 10Ð1061/(ASCE)0733–9437(1993)119 : 2(334).

Herbst, M., Diekkruger, B. and Vanderborght, J., (2006a). Numerical experiments on the sensitivity of runoff generation to the spatial variation of soil hydraulic properties. Journal of Hydrology, 326(1-4): 43-58.

Hewlett, J. (1974). Comments on letters relating to 'Role of subsurface flow in generating surface runoff. 2. Upstream source areas' by R. Allen Freeze. Water Resources Research 10: 605-607.

Hewlett J.D. and Hibbert A.R. (1967) Factors affecting the response of small watersheds to precipitation in humid areas. In *Forest Hydrology*, Sopper W.E. and Lull H.W. (Eds.), Pergamon Press: New York, pp. 275−291.

Hiepe, C. and Diekkrüger, B. (2007). Modelling soil erosion in a sub-humid tropical environment at the regional scale considering land use and climate change. In: 4th International SWAT Conference, pp. 73–80. <http://www.brc.tamus.edu/ swat/4thswatconf /docs/4th Conf Proceedings.pdf>

Horton R.A. (1933). The role of infiltration in the hydrologic cycle. Transactions-American Geophysical Union, **14**, 446−460

Hou, X., Bai, G., and Cao, Q. (1996). Study on benefits of soil and water conservation of forest and its mechanism in loess hilly region. Research of Soil and Water Conservation, 3 (2), 98–103.

Hultine, K.R., Koepke, D.F., Pockman, W.T., Fravolini, A., Sperry, J.S. and Williams, D.G. (2005). Influence of soil texture on hydraulic properties and water relations of a dominant warm desert phreatophyte. Tree Physiology 26, 313–323.

Hursh C.R. and Brater E.F. (1941). Separating storm-hydrographs from small drainage-areas into surface- and subsurfaceflow. Transactions of the American Geophysical Union, **3**, 863−871.

Idieti, M.E. (2012). Les Hydro-Ecoregions du Basin de la Pendjari au Benin: Analyse des determinants socioeconomiques et environnementaux de la dynamique des ecosystemes naturels. Universite d'Abomey-Calavi.

Idowu, O.J., Aduramigba, V.O. and Ande, E.T. (2003)**.**Variability in surface properties of an Alfisol as function of types of landuse. Comm. Soil Sci. Plant Anal., 34, 3045-3058

Igué, A.M. (2000). The use of a soil and terrain databases for land evaluation procedures-case study of central Benin, PhD university of Hohenheim, Stuttgard, Germany. Thesis, pp. 235

IMPETUS (2003): Final Report, Period 1.5.2000 - 30.4.2003. – 152 p. available on: http://www.uni-koeln.de/globalerwandel/impetus/oeffentliches/EB2003/FinalReport2000_2003.pdf.

Iqbal, J., Thomasson, A., Jenkins, J.N., Owens, P.R. and Whisler, F. D. (2005). Spatial variability analysis of soil physical properties of alluvial soils. Soil Sci. Soc. Am. J. 69(5):1338-1350

IUSS Working Group WRB, (2006). World Reference Base for Soil Resources. World Soil Resources Report No. 103. Food and Agriculture Organization of the United Nations, Rome 128 pp. ISBN-10: 9251055114.

IUSS Working Group WRB. (2014). World Reference Base for Soil Resources 2014. International soil classification system for naming soils and creating legends for soil maps. World Soil Resources Reports No. 106. FAO, Rome.

Jensen, M.E., Burman, R.D. and Allen, R.G. (1990). Evapotranspiration and Irrigation water requirements. ASCE manuals and reports on Engineering practice No. 70. American Society of Civil Engineers, New York, NY.

Joel, A., Messing, I. and Seguel, O. (2002). Measurement of surface water runoff from plots of two different sizes, Hydrol. Process., 16, 1467–1478,

Jones, J. (2003). Agronomic Handbook: management of crops, soils, and their fertility. CRC Press, Boca Raton, Florida, USA. P. 482.

Jones, K.B., Neale, A.C., Nash, M.S., Van Remortel, R.D., Wickham, J.D., Riitters, K.H. and O'Neill, R.V., (2001). Predicting nutrient and sediment loadings to streams from landscape metrics: a multiple watershed study from the United States Mid- Atlantic Region. Landscape Ecol. 16, 301–312.

Joshi, C., Mohanty, B.P., Jacobs, J.M. and Ines, A. V. M. (2011), Spatiotemporal analyses of soil moisture from point to footprint scale in two different hydroclimatic regions, Water Resour. Res., 47, W01508, doi:10.1029/2009WR009002

Junge, B. (2004). The bottoms of the upper Ouémé catchment area in Benin / West Africa. Pedology, classification, use and degradation. PhD thesis, University of Bonn.307 S. available at http://hss.ulb.uni-bonn.de/2004/0401/0401.htm.

Jung, G. (2006). Regional Climate Change and the Impact on Hydrology in the Volta Basin of West Africa. Dissertation Garmisch-Partenkirchen, Germany.

Jury, W.A., Gardner, W.R. and Gardner, W.H. (1991). Soil Physics. John Wiley & Sons. New York.

Kalivas D.P., Triantakonstantis D.P. and Kollias V.J. (2002). Spatial prediction of two soil properties using topographic information. Global Nest: the International Journal, 4: 41–49.

Kasei, R. (2010). Modelling Impacts of Climate Change on Water Resources in the Volta Basin, West Africa. Ecology and Development Series 69. Cuvillier, Göttingen, 195 pp. http://hss.ulb.unibonn.de/2010/1977/1977a.pdf

Kasei, R.A. (2012). Modelling in the Semi Arid Volta Basin of West Africa, Water Resources Management and Modeling, Dr. Purna Nayak (Ed.), ISBN: 978-953-51-0246-5, InTech, Available from:http://www.intechopen.com/books/water-resources-management-and modeling/modelling-in-the-semi-aridvolta- basin-of-west-africa.

Kemper, W.D. and R.C. Rosenau (1986). Size distribution of aggregates. In: methods of soil analysis, A. Klute (Ed.). part I. 2nd Edn, Agron. Monogr. 9 ASA-SSSA, Madison, WI. pp: 425 – 442.

Kerry, R. and Oliver, M.A. (2004). Average variograms to guide soil sampling International Journal of Applied Earth Observation and Geoinformation 5: 307–325. doi:10.1016/j.jag.2004.07.005.

Kerry, R. and Oliver, M. A. (2007). Comparing sampling needs for variograms of soil properties computed by the method of moments and residual maximum likelihood. *Geoderma*, *Pedometrics 2005*, *140*, 383−396.

Kılıç, K., Özgöz, E. and Akbaş, F. (2004). Assessment of spatial variability in penetration resistance as related to some soil physical properties of two fluvents in Turkey. Soil Tillage Res. 76, 1–11.

Kling, H., Fuchs, M. and Paulin, M. (2012). Runoff conditions in the upper Danube basin under an ensemble of climate change scenarios. Journal of Hydrology, Volumes 424-425, Pages 264-277, DOI:10.1016/j.jhydrol.2012.01.011.

Klute, A. and Dirksen, C. (1986). Hydraulic conductivity and diffusivity: Laboratory methods. In: Klute A (ed) Methods of Soil Analysis, Part 1, pp 687-734. Madison, WI: Am. Soc. Agron.

Kowal, J.M. and Kassam, A.H. (1978). Agricultural ecology of savanna: a study of West Africa. Clarendon Press, Oxford, UK. 403 pp.

Krause, P., Boyle, D.P., and Bäsel, F. (2005). Comparison of different efficiency criteria for hydrological model assessment. Advances in Geosciences, 5, 89–97, SRef-ID: 1680-7359/adgeo/2005-5-89.

Kumar, V. and Remadevi (2006). Kriging of Groundwater Levels – A Case Study. JOSH 6, 81-94.

Lal, R. (1976). Soil erosion problems on Alfisols in western Nigeria and their control. Monograph No. 1, IITA; Ibadan, Nigeria. 208pp.

Lal, R. (1981). Deforestation of tropical rainforest and hydrological problems. In: Lal, R., Russell, E.W. (Eds.), Tropical Agricultural Hydrology, pp. 131–140.

Lal, R., Sobecki, T.M., Iivari, T. and Kimble, J.M. (2003). Soil degradation in the United States: extent, severity and trends, pp 3-21. CRC Press LLC, Boca Raton, Florida.

Lal, R. (2000). Physical management of soils of the tropics: Priorities for the 21st Century. Soil Sci., 165: 191-207.

Landon, J. (1991). Booker tropical soil manual: A handbook for soil survey and agricultural land evaluation in the tropics and subtropics. Longman, NY.

Lavkulich, L.M. (1981). Methods Manual, Pedology Laboratory. Department of Soil Science, University of British Columbia, Vancouver, British Columbia, Canada.

Le Barbél, L., T. Lebel, and D. Tapsoba. (2002). Rainfall variability in West Africa during the years. 1950-90. – J. Climate **15**, 187–202.

Lebel, T., F. Delclaux, L. Le Barbél, and J. Polcher. (2000). From GCM scales to hydrological scales: Rainfall variability in West Africa. – Stochastic and Environmental Research and Risk Assessment **14**, 275–295

Leblanc, M. J., Favreau, G., Massuel, S., Tweed, S.O., Loireau, M., Cappelaere, B. (2008). Land clearance and hydrological change in the Sahel: SW Niger. Global and Planetary Change 61: 135–150.

Legates, D. R. and McCabe Jr., G. J. (1999). Evaluating the use of "goodness-of-fit" measures in hydrologic and hydroclimatic model validation, Water Resour. Res., 35, 1, 233–241

Legesse, D., Vallet-Coulomb, C. and Gasse, F. (2003). Hydrological response of a catchment to climate and land use change in Tropical Africa: case study South Central Ethiopia.In: Journal of Hydrology 275, p. 67 – 85.

Le Lay, M., Saulnier, G.M., Galle, S., Séguis, L., Mètadier, M. and Peugeot, C. (2008). Model represenation of the sudanian hydrological processes: application on the Donga catchment (Benin). J. Hydrol. 363 (1–4), 31–41.

Lemenih, M., Karltun, E. and Olsson, M. (2005). Assessing soil chemical and physical property responses to deforestation and subsequent cultivation in smallholders farming system in Ethiopia. Agriculture, Ecosystems & Environment 105(1): 373- 386. DOI:10.1016/j.agee.2004.01.046.

Leys, A., Govers, G., Gillijns, K., Berckmoes, E and Takken, I. (2010). Scale effects on runoff and erosion losses from arable land under conservation and conventional tillage: The role of residue cover. Journal of Hydrology 390, 143–154.

Liu, D.W., Wang, Z.M., Zhang, B., Song, K.S., Li, X.Y., Li, J.P., Li, F. and Duan, H.T. (2006). Spatial distribution of soil organic carbon and analysis of related factors in croplands of the black soil region, Northeast China. *Agriculture, Ecosystems &Environment* **113**, 73–81. doi:10.1016/j.agee.2005.09.006.

Liu, Z., Yao, Z., Huang, H., Wu, S. and Liu, G. (2012). Land Use And Climate Changes And Their Impacts On Runoff In The Yarlung Zangbo River Basin, China Land Degrad. Develop. : DOI: 10.1002/ldr.115, 13pp.

Licznar, P. and M.A. Nearing. (2003). Artificial neural networks of soil erosion and runoff prediction at the plot scale. Catena 51, 89–114.

Ma, L., Ascough II, J.C., Ahuja, L.R., Shaffer, M.J., Hanson, J.D. and Rojas, K.W. (2000). Root zone water quality model sensitivity analysis using Monte Carlo simulation. Trans. ASAE 43(4): 883-895.

Mao, D. and Cherkauer, K.A. (2009). Impacts of land-use change on hydrologic responses in the Great Lakes region. J. hydrology, 374 (1-2), 71-82.

Mahe, G., Paturel, J.E., Servat, E., Conway, D. and Dezetter, A. (2005). The impact of landuse change on soil water holding capacity and river flow modeling in the Nakambe River, Burkina Faso. J. Hydol. 300: 33-43.

Maréchal, D. and Holman, I.P. (2005). Development and application of a soil classification-based conceptual catchment-scale hydrological model. Journal of Hydrology, v312, 277–293. doi:10.1016/j.jhydrol.2005.02.018.

Martin, N. (2005) Development of a water balance for the Atankwidi catchment, West Africa – A case study of groundwater recharge in a semi-arid climate. PhD thesis.

Martinez, L.J., and Zinck, J.A. (2004). Temporal variation of soil compaction and deterioration in soil of soil quality in pasture areas of Columbia Amazonia. Soil and Tillage Research 75, 3 – 18.

Matheron, G. (1971). Regionalized variables theory and its applications. Note book of mathematical morphology Centre, Fasc. 5, EMP. Paris, France, p.212.

McBratney, A.B. and Webster, R. (1983). Optimal interpolation and isarithmic mapping of soil properties: V. Co-regionalization and multiple sampling strategy. Journal of Soil Science 34, 137– 162.

McBratney, A.B., Odeh, I.O.A., Bishop, T.F.A., Dunbar, M.S. and Shatar, T.M. (2000). An overview of pedometric techniques for use in soil survey. Geoderma, 97: 293-327.

McBratney, A., Field, D. J., and Koch, A. (2014). The dimensions of soil security, Geoderma, 213, 30 203–213.

McKenzie, N.J., Jacquie, D.W., Ashton, L.J. and Cresswell, H.P. (2000). Estimation of soil properties using the Atlas of Australian soils, CSIRO Land and Water, Technical Report 11/00 (http://www.clw.csiro.au/publications/technical).

McLean, E.O. (1982). Soil pH and lime requirements. In: methods of Soil Analysis Part II, Page, A.L., R.A. Miller, D.R. Keeney (eds). Chemical and Microbial Properties. American Society of Agron. Madison Wiscosin, U.S.A. pp 199-220.

Melching, C. **S.,** Yen, **B.** C. and Wenzel, H. G., Jr. (1990). A reliability estimation in modeling watershed runoff with uncertainties. ***Water Resour. Rex,*** 26(10), pp 2275-2286.

Mello, G., Bueno, C.R.P. and Pereira, G. T. (2006). Variabilidade espacial das propriedades físicas e químicas do solo em áreas intensamente cultivadas. Revista Brasileira de Engenharia Agrícola e Ambiental 10:294-305.

Mendoza, M.E., Bocco, G., López-Granados, E. and Espinoza, M.B. (2010). Hydrological implications of land use and land cover change: Spatial analytical approach at regional scale in the closed basin of the Cuitzeo Lake, Michoacan, Mexico *Singapore Journal of Tropical Geography* 31: 197–214.

Menz, G., Judex, M., Orekan, V., Kuhn, A., Heldmann, M. and Thamm, H.P. (2010). Land use and land cover modeling in Central Benin. In: Speth, P., Christoph, M., Diekkrüger, B., (Eds.) Impacts of Global Change on the Hydrological Cycle in West and Northwest Africa. Springer, Heidelberg, Germany. Pp 512-534.

Miller, G.R., Baldocchi, D.D., Law, B.E. and Meyers, T. (2007). An analysis of soil moisture dynamics using multi-year data from a network of micrometeorological observation sites. Advances in Water Resources 30: 1065–1081.

Mishra, S.K. and Singh, V.P. (2003). Soil conservation service curve number (SCS-CN) methodology. Kluwer Academic, Dordrecht.

Minasny, B. and George, B.H. (2001). The measurement of soil hydraulic properties in the field. In: Cattle, S.R. and George, B.H. (Eds), Describing, Analysing and Managing Our Soil, First Edition pp. 185-204.

Minasny, B. and McBratney, A.B. (2002) Uncertainty analysis of pedotransfer functions. Eur J Soil Sci 53:417–429.

Minasny, B. and McBratney, A.B. (2007). Estimating the water retention shape parameter from sand and clay content. Soil Sci. Soc. Am. J. 71:1105–1110. doi:10.2136/sssaj2006.0298N

Montanari, A. and Toth, E. (2007). Calibration of hydrological models in the spectral domain: an opportunity for scarcely gauged basins? Water Resources Research, 43(5), 1–10, doi:10.1029/2006WR005184.

Moriasi, D.N., Arnold, J.G., Van Liew, M.W., Bingner, R.L., Harmel, R.D. and Veith, T.L. (2007). Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. Tran. ASABE Vol. 50(3): 885-900.

Munsell colour company (2000). Munsell Soil Color Charts Rewashable Edition (2000), GretagMAcbeth, 617 Little Britain Road, New Winsdor NY12533.

Nadrowski, K., Wirth, C. and Scherer-Lorenzen, M. (2010). Is forest diversity driving ecosystem function and service? Current Opinion in Environmental Sustainability, 2, 75–79.

Ndiaye, B., Molenat, J., Hallaire, V., Hamon, C.G.Y., 2007. "Effects of agricultural practices on hydraulic properties and water movement in soils in Brittany (France)". J. Soil & Tillage Res. 93, 251-263.

Nearing, M.A., Govers, G. and Norton, D.L. (1999). Variability in soil erosion data from replicated plots. Soil science Society of America Journal 63 (6), 1829–1835.

Nejadhashemi, A.P., Wardynski, B.J. and Munoz, J.D. (2011). Evaluating the impacts of land use changes on hydrologic responses in the agricultural regions of Michigan and Wisconsin. Hydrol. Earth Syst. Sci. Discuss., 8, 3421–3468, www.hydrol-earth-syst-sci discuss.net/8/3421/2011/ doi:10.5194/hessd-8-3421-2011.

Nelson, D.W. and Sommers, L.E. (1982). Total carbon, organic carbon and organic matter. In: *Page, A.L, Miller, R.H. and Keeney, D.R. (eds). Methods of soil analysis, part 2*. Am. Soc. Agron, Madison WI, PP. 539-579.

Ngongo, R. and Langohr, L. (1992). Classifying strongly weathered soils from the Zarian basin into the revised international soil classification systems (Soil Taxonomy, 1990; FAO-UNESCO legend, 1988). In PEDOLOGIE: Van Cleemput et al., (eds); XLII-2, p. 99-117.

Niehoff, D., Fritsch, U. and Bronstert, A. (2002). Land-use impacts on storm-runoff generation: scenarios of land-use change and simulation of hydrological response in a meso-scale catchment in SW-Germany. Journal of Hydrology 267, 80-93.

Obi, I.U. (2002). Statistical Methods of Detecting Differences between Means and Research Methodology Issues in Laboratory and Field Experiments (2nd ed.). Enugu: Snaap Press (Nig.) Ltd. 117 pp.

Oguntunde, P.G., Friesen, J., van de Giesen, N. and Savenije, H.H.G. (2006). Hydroclimatology of the Volta River Basin in West Africa: Trends and variability from 1901 to 2002. Phys. Chem. Earth, Parts A/B/C 31, 1180−1188. doi:10.1016/j.pce.2006.02.062.

Okoye, E.O.U (1995). Soil map of Nigeria Project, Federal Department of Agricultural Land Resources, Abuja, Nigeria. In: Soil survey: perspectives and strategies for the 21st century. FAO, Alfred Zinck J. (Eds). Pp 91-95.

Oliver, M.A. (2010). Geostatistical applications for precision agriculture. ISBN 978-90-481-9132-DOI 10.1007/978-90-481-9133-8. Springer Dordrecht Heidelberg London New York. 337 pp.

Oliver, Y.M., and Smettem, K.R.J. (2005). Predicting water balance in a sandy soil: Model sensitivity to the variability of measured saturated and near saturated hydraulic properties. Aust. J. Soil Res. 43:87–96. doi:10.1071/SR03146.

Oliver, M.A. and Webster, R. (2014). A tutorial guide to geostatistics: Computing and modelling variograms and kriging. Catena 113; 56–69.

Olsen, S.R., Cole, C.V., Watanable, F.S. and Dean, L.A. (1954) Estimation of available phosphorus in soils by extraction with sodium bicarbonate. Circ. U.S. Dep. Agric. 939.

Page, T., Haygarth, P.M., Beven, K., Joynes, A., Butler, P., Keeler, C., Freer, J., Owens, P. and Woods, G. (2005). Spatial variability of soil phosphorus in relation to the topographic index and critical source areas: sampling for assessing risk to water quality. Journal of Environmental Quality, 34, 2263–2277.

Palis, R.G.; Rose, C.W.; Saffigna, P.G. (1997). Soil erosion and nutrient loss. IV. Effects of slope length on runoff, sediment yield, and total nitrogen loss from steep slopes in pineapple cultivation. Australian Journal of Soil Research, 35: 907–923.

Pappenberger, F. and Beven, K.J. (2006). Ignorance is bliss: Or seven reasons not to use uncertainty analysis, Water resour. Res., 42, WO5302, doi: 10.1029/2005WR004820.

Pavel, K., Juan-José, I. M., Richard W. A., and Serghei, S. (2009). A handbook of soil terminology, correlation and classification. 1st ED. 449 pp.

Paz Gonzales, A., Vieira, S.R. and Castro, T. (2000). The effect of cultivation on the spatial variability of selected properties of an umbric horizon, Geoderma, 97,273-292.

Pizarro, R., Araya, S., Jordán, C., Farías, C., Flores, J.P. and Bro. P.B. (2006). The effects of changes in vegetative cover on river flows in the Purapel river basin of central Chile. Journal of Hydrology 327, 249–257.

Poesen, J. (1984). `The influence of slope angle on infiltration rate and Hortonian overland flow volume', ZeitschriftfuÈr Geomorphologie, 49, 117-131.

Price, K., Jackson, C. R. and Parker, A. J. (2010). Variation of surficial soil hydraulic properties across land uses in the southern Blue Ridge Mountains, North Carolina, USA, J. Hydrol., 383, 256–268.

Punzel, J. and Schwärzel, K. (2004). Hood infiltrometer – a device for undisturbed field measurements of saturated and near saturated conductivity. Super Soil 2004: 3rd Australian New Zealand Soils Conference, Dec 5–9, University of Sydney, Australia

Punzel, J. and Schwärzel, K. (2007). Hood Infiltrometer – A New Type of Tension Infiltrometer. Soil Sci. Soc. Am. J. 71, 1438-1447.

Ramasastri, K.S. and Seth, S.M. (1985),'Rainfall-runoff relationships,' Rep. RN-20, National Institute of Hydrology, Roorkee-247 667, Uttar Pradesh, India.

Rawls, W. J. and Brakensiek, D.L. (1982). Estimating soil water retention from soil properties. Amer. Soc. of Civil Engin., J. of Irrig. and Drain. 108: 166-171.

Refsgaard, J.C. and Storm, B. (1996). Construction, Calibration and Validation of Hydrological Models.In M. B. Abbott & J.C. Refsgaard (Eds.), Distributed Hydrological Modeling (pp. 41-54). Dordrecht: Kluwer Academic Publishers.

Refsgaard, J. C. (1997). Parameterisation, calibration and validation of distributed hydrological models. *J. Hydrol.*, 198, pp. 69-97.

Reynolds, W.D. and Zebchuck, W.D. (1996). Use of contact material in tension infiltrometer measurements. Soil Technology. 9:141-159.

Reynolds, W. D., Bowman, B.T., Brunke, R.R., Drury, C.F. and Tan, C.S. (2000). Comparison of tension infiltrometer, pressure infiltrometer, and soil core estimates of saturated hydraulic conductivity. Soil Sci. Soc. Am. J. 64:478–484.

Rientjes, T.H.M.; Haile, A.T.; Mannaerts, C.M.M.; Kebede, E. and Habib, E.(2011). Changes in land cover and stream flows in Gilgel Abbay catchment, Upper Blue Nile basin—Ethiopia. Hydrol. Earth Syst. Sci. Discuss., 7, 9567–9598.

Rigon, R., Bertoldi, G. and Over, T.M., (2006). GEOtop: A distributed hydrological model with coupled water and energy budgets. Journal of Hydrometeorology, 7(3): 371-388.

Rodenburg, J., Stein, A., Noordwijk, M. and Ketterings, Q.M. (2003). Spatial variability of soil pH and phosphorus in relation to soil run-off following slash-and-burn land clearing in Sumatra, Indonesia. Soil and Tillage Research 71, 1-14.

Roudier, P., Ducharne, A. and Feyen, L. (2014). Climate change impacts on runoff in West Africa: a review. Hydrol. Earth Syst. Sci., 18, 2789–2801, www.hydrol-earth-syst-sci.net/18/2789/2014/ doi:10.5194/hess-18-2789-2014

Saidou, A., Kuyper, T., Kossou, D., Tossou, R. C. and Richards, P. (2004). Sustainable soilfertility management in Benin: learning from farmers. NJAS , 52 (3/4), 349–369

Sanchez, P.A. (1976). Properties and management of soils in the tropics. John Wiley and Sons. New York, USA. 618 pp.

Sanchez, P. (2002). Soil fertility and hunger in Africa. Science. 295: 2019-2020.

Satelli, A., Tarantola, S., Campolongo, F. and Ratto, M. (2004) Sensitivity Analysis in Practice, a Guide to Assessing Scientific Models. New York: Wiley

Sauer, T. J. and Logsdon, S.D. (2002). Hydraulic and physical properties of stony soils in a small watershed, Soil Sci. Soc. Am. J. 66, 1947-1956..

Scanlon, T.M., Kiely, G. and Xie, Q.S. (2004). A nested catchment approach for defining the hydrological controls on non-point phosphorus transport. Journal of Hydrology, 291(3-4): 218-231.

Scanlon, B., Keese, K., Flint, A., Flint, L., Gaye, C., Edmunds, W. & Simmers, I., (2006). Global synthesis of groundwater recharge in semiarid and arid regions. *Hydrological Processes*, 20(15), p.3335–3370.

Scanlon, B. R., I. Jolly, M. Sophocleous, and L. Zhang (2007). Global impacts of conversions from natural to agricultural ecosystems on water resources: quantity versus quality, Water Resources Research, 43(3), W03437, doi:10.1029/2006WR005486.

Schilling, K. E., Jha, M. K., Zhang, Y. K., Gassman, P. W. and Wolter, C. F. (2008). Impact of land use and land cover change on the water balance of a large agricultural watershed: Historical effects and future directions. Water Resour. Res., 44, 12 pp. doi:10.1029/2007WR006644.

Schoeneberger, P.J., Wysocki, D.A., Benham, E.C. and Broderson, W.D. (2002). Field book for describing and sampling soils, (editors), Version 2.0. Natural Resources Conservation Service, National Soil Survey Center, Lincoln, NE.

Schulla, J. (1997). Flussgebietsmodellierung und Wasserhaushalts-Simulation mit WaSiM-Modellbeschreibung. Eidgenössische technische Hochschule Zürich, Zürich, 189 pp. http://www.wasim.ch/downloads/doku/wasim/schulla_1997.pdf.

Schulla, J. (2007). Model description WaSiM. http://www.wasim.ch/ downloads/ doku/wasim/ wasim_2007_en.pdf

Schulla, J. (2012). Model Description WaSiM (Water Balance Simulation Model). Completely revised version 2012, Hydrology Software Consulting, J. Schulla, Regensdorferstrasse 162. CH 8049, Zürich.

Schulla, J. and Jasper, K. (2007). Model Description WaSiM, ETH Zurich, Zurich, 181, 2007.

Schwartz, R.C., Unger, P.C. and Evett, S.R. (2000). Land use effects on soil hydraulic properties. http://www.cprl.ars.usda.gov/programs/land_use.pdf.

Segalen, P., Fauck, R., Lamouroux, M, Perraud, A., Quantin, P., Roederer, P. and Vieillefon, J. (1979). Projet de Classification des Sols, ORSTOM, Paris, 301pp.

Se´guis, L., Cappelaere, B., Peugeot, C., and Vieux, B. (2002). Impact on Sahelian runoff of stochastic and elevation induced spatial distributions of soil parameters. Hydrol. Process., 16, 312–332.

Séguis, L., Kamagaté, B., Favreau, G., Descloitres, M., Seidel, J.-L., Galle, S., Peugeot, C., Gosset, M., Le Barbè, L., Malinur, F., Vav Exter, S., Arjounin, M., Boubkraoui, S. and Wubda, M. (2011). Origins of streamflow in a crystalline basement catchment in a sub-humid Sudanian zone: the Donga Basin (Benin, West Africa) inter-annual variability of water budget. J. Hydrol. 402 (1–2), 1–13.

Seibert, J. (2000). Multi-criteria calibration of a conceptual runoff model using a genetic algorithm. *Hydrology and Earth System Sciences*, 4 (2), 215–224.

Sharma, K.; Singh, H. and Pareek, O. (1983). ‘Rain water infiltration into a bar loamy sand', Hydrological Sciences Journal, 28, 417-424.

Shapiro, S.S. and Wilk, W.B. (1965). An analysis of variance test for normality (complete examples). Biometrika 52:591-611.

Shields, J.A. and Coote, D.R. (1988). SOTER Procedures manual for small-scale map and database compilation. Working paper and preprint 88/2. ISRIC, Wageningen, 144 ppSharma, K., H. Singh and O. Pareek. (19830. `Rain water infiltration into a bar loamy sand', Hydrological Sciences Journal, 28, 417-424.

Shukla, M.K., Lal, R., Owens, L.B. and Unkefer, P. (2003). Land use and management impacts on structure and infiltration characteristics of soils in the North Appalachian region of Ohio. Soil Science, 168, 167–177.

Silva, C.L. and Oliveira, C.A.S. (1999). Runoff measurement and prediction for a watershed under natural vegetation in central Brazil. R. Bras. Ci. Solo, 23:695-701.

Singh, S.K. (2010). Robust parameter estimation in gauged and ungauged basins. Transactions of the institute of hydraulic engineering, University of Stuttgart, Faculty of Civil Engineering, Stuttgart, Ph.D. dissertation No. 198.

Sintondji, (2005). Modelling the rainfall-runoff process in the Upper Ouém catchment (Terou in Benin Republic) in a context of global change: extrapolation from the local to the regional scale. PhD thesis, University of Bonn, Shaker Verlag, Aachen, 205 S.

Smith, R.E., Corradini, C. and Melone, F. (1999). A conceptual model for infiltration and redistribution in crusted soils. Water Resources Research 35: 1385-1393.

Soil Survey Staff (1975). Soil taxonomy: a basic system of soil classification for making and interpreting soil surveys. USDA-SCS Agric. Handbook 436. US Gov. Print. Office, Washington, D.C.

Soil Survey Staff (2006). Keys to Soil Taxonomy, 10th ed. USDA, NRCS. Washington DC, United States Govt Printing Office. pp. 161-323.

Soil Survey Staff (2010). Keys to Soil Taxonomy, 11th ed. USDA, NRCS. Washington DC, United States Govt Printing Office. pp. 346.

Speth, P., Christoph, M., Diekkrüger, B., (Eds.) 2010. Impacts of Global Change on the Hydrological Cycle in West and Northwest Africa. Springer Publisher. 675 p.ISBN: 978-3-642-12956-8.

Steyaert, L., Knox, R., 2008. Reconstructed historical land cover and biophysical parameters for studies of land-atmosphere interactions within the eastern United States. J. Geophys. Res., 113(D2).

Stomph, T.J., de Ridder, N., Steenhuis, T.S. and Van de Giesen, N.C. (2002). Scale effects of Hortonian overland flow and rainfall-runoff dynamics: laboratory validation of a process-based model. Earth Surf. Proc. Land. 27, 847–855.

Tan, Z. and Lal, R. (2005). Carbon sequestration potential estimates with changes in land use and tillage practice in Ohio, USA. Agric. Ecosyst. Environ. 111, 140–152.

Tandon, P.N. and Nimbalkar, P.T. (2014). Rainfall-runoff relationships using curve number method: a case study. Int. J. Adv. Engg. Res. Studies/IV/I/73-77.

Tarboton, D. G. (2003). Rainfall-runoff processes: A workbook to accompany the Rainfall-Runoff Processes Web module. http://www.engineering.usu.edu/dtarb/rrp.html.

Tessema, S.M. (2011). Hydrological Modeling as a Tool for Sutainable Water Resources Management: A case study of the Awash River Basin. Royal Institute of Technology (KTH).

Tesfahunegn, G. B., Tamene, L., and Vlek, P. L. G. (2011). Catchment scale spatial variability of soil properties and implications on site-specific soil management in northern Ethiopia, Soil Till. Res., 117, 124–139

Tilahun, S., Guzman, C., Zegeye, A., Engda, T., Collick, A.S., Rimmer, A. and Steenhuis, T.S. (2013). An efficient semi-distributed hillslope erosion model for the subhumid Ethiopian Highlands. Hydrol Earth Syst Sci 17:1051–1063.

Tu, J. (2009). Combined impact of climate and land use changes on streamflow and water quality in eastern Massachusetts, USA. J. of Hydrol., 379, 268-283.

Turner, B.L. II, Clark, W.C., Kates, R.W., Richards, J.F., Mathews, J.T., Meyer, W.B. (1990). The Earth as Transformed by Human Action: Global and Regional Changes. In Lambin et al. /Global Environmental Change 11 (2001) 261–269 Biosphere Over the Past 300 Years. Cambridge Univ. Press, Cambridge.

Uhlenbrook, S., Roser, S. and Tilch, N. (2004). Hydrological process representation at the meso-scale: the potential of a distributed, conceptual catchment model. Journal of Hydrology 291, 278–296.

UNEP (2003). Africa environment outlook. http://www.unep.org/aeo/166.htm, 18th June, 2003, date last accessed). pp 1-2.

Ungaro F., Quaglino E., Gallorini D. and Pestarini M. (2004). Physical and hydrological properties of the soils on the three inland valleys of Ghana (Kumassi region) and Burkina Faso (Kompienga region). Research report, Timesis, Italy.

UNEP-GEF Volta Project, (2008). Study on the establishment of a regional system for exchange of data and information on the Volta Basin (Volume 1). *UNEP/GEF/Volta/RR.4/2008.*

USDA, (1986). Urban hydrology for small watersheds. Technical release, no 55 (TR-55). Soil Conservation Service, Washington, DC .

USDA-NRCS. (2004). Part 630: Hydrology. Chapter 10: Estimation of direct runoff from storm rainfall: Hydraulics and hydrology: Technical references. In *NRCS National Engineering Handbook.* Washington, D.C.: USDA National Resources Conservation Service. Available at: www.wcc.nrcs.usda.gov/hydro/ hydro-techref-neh-630.html. Accessed 14 June, 2013.

van de Giesen, N.C., Stomph, T.J., and De Ridder, N. (2000). Scale effects of Hortonian overland flow and rainfall runoff dynamics in a West-African catena landscape. Hydrol. Process. 14, 165–175.

van de Giesen, N.C., Stomph, T.J. and De Ridder, N. (2005). Surface runoff scale effects in West African watersheds: modeling and management options. Agric. Water Manage. 72, 109–130.

van de Giesen, N.C, Stomph, T.J., Ajayi, A.E. and Bagayoko, F. (2011). Scale effects in Hortonian surface runoff on agricultural slopes in West Africa: Field data and models. Agriculture, Ecosystems and Environment 142, 95–101.

van Genuchten, M. TH. (1980). A closed-form equation for predicting the hydraulic cconductivity of unsaturated soils. Soil Science Society of America Journal, 44, 892-898.

van Reeuwijk, L.P. (2006). Procedures for soil analysis, 7th Edition. Technical Report 9. Wageningen, Netherlands: ISRIC-World Soil Information.

van Rompaey, A.,Verstraeten, G., Poesen, J. and Van Oost, K. (2001). Modeling mean annual sediment yield using a distributed approach. Earth Surface Processes and Land Forms 26 (11), 1221-1236.

van Wambeke, A. (1959). The silt / clay ratio, an approximate measure of the alteration stage of the original material of tropical soils. Third conf. International Soil Survey. Dalaba, 1; 161-167.

van Wambeke, A. (1989). Tropical soil and soil classification updates. Advances in Soil Science, New York, 10; 176-193.

Varado, N., Braud, I., Galle, S., Le Lay, M., Séguis, L., Kamagate, B. and Depratere, C. (2006). Multi-criteria assessment of the representative elementary watershed approach on the Donga catchment (Benin) using a downward approach of model complexity. Hydrol. Earth Syst. Sci. 10 (3), 421–442.

Vereecken, H., Kaiser, R., Dust, M and Putz, T. (1997). Evaluations of the multistep outflow method for the determination of unsaturated hydraulic properties of soils, Soil Sci., 162, 618 – 631, doi: 10.1097/00010694- 199709000-00003.

Vieira, S.R. and Paz Gonzalez, A. (2003). Analysis of the spatial variability of crop yield and soil properties in small agricultural plots. Bragantia, Campinas, 62, 127-138.

Wackernagel, H. (1995). Multivariate Geostatistics: An Introduction With Applications, Springer, Berlin.

Wagener, T., Wheater, H.S. and Gupta, H.V. (2004). Rainfall-runoff Modelling in Gauged and Ungauged Catchments, London: Imperial College Press.

Wang, Z.C. 1999. Geostatistics and its application in ecology. (In Chinese.) p. 35–149. Science Press, Beijing.

Wang, C., Zhao, C., Xu, Z., Wang, Y. and Peng, H. (2013). Effect of vegetation on soil water retention and storage in a semi-arid alpine forest catchment. J. Arid Land 5: 207-219. doi:10.1007/s40333-013-0151-5.

Wang, Y., Zhang, X. and Huang, C. (2009). Spatial variability of soil total nitrogen and soil total phosphorus under different land uses in a small watershed on the Loess Plateau, China. Geoderma 150, 141–149. DOI: 10.1016/j.geoderma.2009.01.021.

Wang, X.J., and Qi, F. (1998). The effects of sampling design on spatial structure analysis of contaminated soil, The Sci. Total Environ., 224,29-41.

Ward, R. C. and Robinson, M. (2000). ***Principles of hydrology.*** 4'h ed., McGraw-Hill, London, UK.

Warrick, A.W. and Nielson, D.R. (1980). Spatial variability of soil physical properties in the field. In: Hillel D (ed) Applications of soil physics, pp 319-344. Academic press, New York.

Webster, R. and Oliver, M.A. (2007). Geostatistics for Environmental Scientists, second edition. John Wiley & Sons, Chichester.

Wei, J.B., Xiao, D.N., Zeng, H. and Fu, Y.K. (2008). Spatial variability of soil properties in relation to land use and topography in a typical small watershed of the black soil region, northeastern China. Environ. Geol. 53, 1663–1672.

Weiler, M. and Naef, F. (2003). An experimental tracer study of the role of macropores in infiltration in grassland soils. Hydrol. Process. 17:477-493.

Weindorf, D.C. and Zhu, Y. (2010). Spatial variability of soil properties at Capulin volcano, New Mexico, USA: Implications for sampling strategy, Pedosphere, 20(2), 185-197.

Weller, U. (2002). Land evaluation and land use planning for Southern Benin (West Africa) BENSOTER. Hohenheimer Bodenkundliche Hefte 67. Institut fur Bodenkunde und Standortlehre. University of Hohenheim. Stuttgart. pp. 165.

Weller, U. and Stahr, K. (1995). A site map for South-West - recording of terrain properties and soil parameters. Communication. Dtsch. Floor Cd. Ges. 76. Pp. 1221-1224.

Weyman D. R. (1970). Throughflow on hillslopes and its relation to the stream hydrograph. *Hydrological Sciences Bulletin*, 15:25–33.

Wezel, A. and Bocker, R. (2000). Vegetation of Benin. In: Graef, F., Lawrence, I.M., von Oppen, M. (eds) Adapted Farming in West Africa: Issues, potentials and perspectives, pp. 219-226. Verlag Ulrich E. Grauer, Stuttgart, Germany ISBN 3-86186-315-4.

Willaarts, B., Volk, M. and Aguilera, P.A. (2012). Assessing the ecosystem services supplied by freshwater flows in Mediterranean agroecosystems. Agricultural Water Management 105:21-31. http://dx.doi.org/10.1016/j.agwat.2011.12.019

Wilcox, B.P., Newman, B.D., Bres, D., Davenport, D.W. and Reid, K. (1997) Runoff from a semiarid ponderosa pine hillslope in New Mexico. *Water Resources Research*, **33**, 2301−2314S

Williams, A.G., Ternan, J.L., Fitzjohn, C., de Alba, S. and Perez-Gonzalez, A. (2003). Soil moisture variability and land use in a seasonally arid environment. Hydrological Processes, 17, 225-235.

Williams, C. J.: Characterization of the spatial and temporal controls on soil moisture and streamflow generation in a semiarid headwater catchment, unpublished M.S. Thesis, Boise State Univ., Boise, 2005.

Williams, B., Walker, J., Anderson, J., 2006. Spatial variability of regolith leaching and salinity in relation to whole farm planning. Aust. J. Exp. Agric. 46, 1271–1277

Wilson, G.V. and Luxmoore, R.J. (1998). Infiltration, macroporosity and mesoporosity measurement on two forested watersheds. Soil Science Society of America Journal 52, 329-335.

Wooding, R.A., (1968). Steady infiltration from a shallow circular pond. Water Resour. Res. 4, 1259-1273.

Wright EP, Burgess W (1992) The hydrogeology of crystalline basement in Africa. Geol. Soc. Spec. Pap 66:264.

Xu, J. (2005). Precipitation–vegetation coupling and its influence on erosion on the Loess Plateau, China. Catena 64, 103–116.

Xu,Guo-Ce, Li, Zhan-Bin, Li, Peng, Lu, Ke-Xin and Wang, Yun (2013). Spatial variability of soil organic carbon in a typical watershed in the source area of the middle Dan River, China. *Soil Research*, **51**, 41–49.

Xu, Q.F. and Xu, J.M. (2003). Changes in soil carbon pools induced by substitution of plantation for native forest. Pedosphere 13, 271–278.

Yair, A. and Raz-Yassif, N. (2004). Hydrological processes in a small arid catchment: scale effects of rainfall and slope length. Geomorphology, 61 (1–2), 155–169.

Yair, A. and Lavee, H. (1985). Runoff generation in arid and semi-arid zones. In: Anderson, M.G., Burt, T.P. (Eds.), Hydrological Forecasting. John Wiley and Sons, New York.

Yasin, H.Q. and Clemente, R.S. (2014). Application of SWAT Model for Hydrologic and Water Quality Modeling in Thachin River Basin, Thailand. Arab. J. Sci. Eng. 39, 1671–1684.

Yilma, T. (2006). Modeling farm irrigation decisions under rainfall risk in the White Volta Basin of Ghana. A tool for policy analysis at the farm-household level. Bonn, Göttingen, Germany: University of Göttingen, 2006. p.170.

Yimer, F., Messing, I., Ledin, S. and Abdelkadir, A. (2008). Effects of different land use types on infiltration capacity in a catchment in the highlands of Ethiopia. Soil Use and Management, 24, 344–349 doi: 10.1111/j.1475-2743.2008.00182.x

Youngs, E.G. (2001). Hydraulic conductivity of saturated soils. In; Soil and Environmental Analysis. Smith, K.A. and C.E. Mullins (Eds.). Physical Methods. 2nd Edn. Marcel Decker Inc. NY., pp. 637.

Yu, B., Stott, P., Di, X.Y. and Yu, H.X. (2014). Assessment of land cover changes and their effect on soil organic carbon and soil total nitrogen in Daqing Prefecture, China. Land Degradation and Development 25(6): 520-531 DOI: 10.1002/ldr.2169.

Zhang, X.C., Nearing, M.A., Risse, L.M. and Gregaor, K.C. (1996). Evaluation of WEPP runoff and soil loss predictions using natural runoff plot data. Transaction of the ASAE 39 (3), 855– 863.

Zhang, S.L., Yan, L.L., Sun, Y.K., Huang, J., Mu, L.L. and Huang, Y.Q. (2015). Spatial heterogeneity of soil c:n ratio in a mollisol watershed of northeast china. Land Degradation & Development, doi: 10.1002/ldr.2427.

Zhao, P.P., Shao, M.A. and Wang, T.J. (2010). Spatial distributions of soil surfacelayer saturated hydraulic conductivity and controlling factors on dam farmlands. *Water Resources Management* **24**, 2247–2266. doi:10.1007/s11269-009-9550-y

Zheng, F., He, X., Gao, X., Zhang, C. and Tang, K. (2005). Effects of erosion patterns on nutrient loss following deforestation on the Loess Plateau of China. Agriculture, Ecosystems and Environment 108, 85–97.

Zhu, J. and Mohanty, B.P. (2002). Upscaling of hydraulic properties for steady state evaporation and infiltration. Water Resour. Res. 38:1178. doi:10.1029/2001WR000704.

Zhou, Z., Shangguan, Z. and Zhao, D. (2006). Modeling vegetation coverage and soil erosion in the Loess Plateau Area of China. Ecological Modeling 198, 263–268.

Zhou, X., Lin, H.S., White, E.A. (2008). "Surface soil hydraulic properties in four soil series under different land uses and their temporal changes." Catena. 73, 180-188.

Zimmermann, B. (2007). Spatial and temporal variability of the soil saturated hydraulic conductivity in gradients of disturbance, Doktogrades, der Mathematisch - Naturwissenschaftlichen Fakultät der Universität Potsdam, Postdam. 106.

Zimmermann, B., Elsenbeer, H. and De Moraes, J. M. (2006). The influence of land-use changes on soil hydraulic properties: Implications for runoff generation, Forest Ecol. Manag., 222, 29–38.

Zimmermann, B. and Elsenbeer, H. (2008). Spatial and temporal variability of soil saturated hydraulic conductivity in gradients of disturbance, J. Hydrol., 361, 78–95.

Ziegler, A.D., Giambelluca, T.W., Tran, L.T., Vana, T.T., Nullet, M.A., Fox, J., Tran Duc Vien, Pinthong, J., Maxwell, J.F. and Evett, S. (2004). Hydrological consequences of landscape fragmentation in mountainous northern Vietnam: Evidence of accelerated overland flow generation. J. Hydrol. 287, 124–146.

Appendix

Appendix I: Koupendri Catchment Characteristics and Soil Description

Profile Name	Site Characteristics	Horizon	Depth (cm)	Descriptions
AZUKOUP-1 (x) 300580 (y) 1191445	Dystric plinthosol, peneplain, high slope, 221 m above sea level, cultivated (maize), sudan savanna, Termitarium, Mica schist, no water table and salt, slight/low traces of erosion, Human influence (tillage, pastoral, homes), Drainage (normal) Dry top soil but wet below.	Ap_c albic petroplinthic umbric	0-20	Dark Brown (10YR5/3, moist), Yellowish brown (10YR7/2, dry), sandy loam (clay poor), no mottles, few gravels, massive/compact structure, friable, strongly developed, no cutans, many macro and micro pores, many fine and medium roots, 20 % concretions, high biologic activity, distinct boundary.
		Bt_{nc} Argic Kandic chromic petroplinthic	20-30	Dark Reddish Brown (7.5YR4/6, moist), light brown (7.5YR5/6, dry) loam, no mottles, many gravels, massive/compact structure, very hard, strongly developed no cutans, many macro and micro pores, many fine and medium roots, 60 % concretions, low biologic activity, distinct boundary.
		B_{cv}	>30	Plinthite/Petroferric stones.
AZUKOUP-2 (x) 300580 (y) 1190695	Dystric plinthosol Peneplain, mid-slope, 217 m above sea level, Fallow, sudan savanna, Mica schist, no water table and salt, slight/ low traces of erosion, Human influence (pastoral, bush burning), Drainage (normal) Dry top soil but wet below	A_C albic umbric	0-15	Dark Brown (10YR4/2, moist), Grayish Brown (10YR5/2, dry), sandy loam (clay poor), no mottles, few gravels, massive/compact structure, friable, strongly developed, no cutans, few macro and micro pores, few fine and medium roots, 5-10 % concretions, low biologic activity, distinct boundary.
		Bt_{nc1} Argic Plinthic	15-47	Brown/reddish brown (7.5YR5/3, moist), light Brown (7.5YR5/6, dry) loam, no mottles, few gravels, blocky/angular blocky structure, friable, strongly developed no cutans, many macro and micro pores, many fine and medium roots, 10 % concretions, low biologic activity,

				gradual boundary.
		Bt_{nc2} Argic Plinthic Argillic	47-80	Gray (Grayish yellow) (7.5YR8/2, moist), Yellow (7.5YR8/6, dry), loam, no mottles, few gravels, massive/compact structure, friable, strongly developed no cutans, few macro and micro pores, few fine and medium roots, 10 % concretions, low biologic activity, distinct boundary.
		Bc_{v}	>80	Plinthic/Petroferric stones
AZUKOUP-3 (x) 300580 (y) 1189695	Eutric Cambisol Peneplain, mid-slope, 215 m above sea level, Fallow, sudan savanna, Mica schist, no water table and salt, moderate traces of erosion, Human influence (pastoral, bush burning), Drainage (imperfect) Dry top soil but wet below	A_{gh} Albic Ochric	0-12	Brown/dark brown (10YR3/2, moist), pale Brown/Gray (10YR7/1, dry), silty loam (clay rich), few yellowish mottles, no gravels, cubic /platy structure, very hard, strongly developed, no cutans, few micro pores, few fine roots, no concretions, high biologic activity, gradual boundary.
		Bt_{gn} cambic Argic	12-30	Grayish Brown/Dark brown (7.5YR3/2, moist), Gray /white (7.5YR8/1, dry) silty loam (clay rich), few yellowish brown mottles, no gravels, prismatic/platy structure, very hard/compact, strongly developed no cutans, few macro and micro pores, few fine and medium roots, no concretions, medium biologic activity, distinct boundary.
		Bt_{gc1n} Argic Cambic Natric Vertic Petrocalcic	30-60	Brown/Grayish brown (10YR4/3, moist), Gray/pale brown (10YR7/2, dry) Clay loam, few reddish/yellow mottles, no gravels, massive /platy / compact structure, very hard, strongly developed, no cutans, few macro and micro pores, no roots, 10-15 % concretions, no/low biologic activity, gradual boundary.
		Bt_{gc2n} Argic Natric, vertic Petrocalcic Kandic	60-100	Yellow (2.5Y7/2, moist), lighter yellow (2.5Y6/2, dry) Clay loam, few yellow mottles, no gravels, massive /platy / compact structure, very hard, strongly developed, no cutans, few

				macro and micro pores, no roots, 10-15 % concretions, no/low biologic activity, gradual boundary.
AZUKOUP-4 (x) 300580 (y) 1188695	Gleyic Luvisol Peneplain, high slope, 224 m above sea level, Fallow, sudan savanna, Mica schist, no water table and salt, moderate traces of erosion, Human influence (pastoral, bush burning), Drainage (moderate) Dry top soil but wet below	Ap Albic/ Anthraquic Ochric	0-12	Grayish Brown/dark brown (7.5YR3/2, moist),Gray/ pale brown (7.5 YR7/1, dry), loam, no mottles, no gravels, massive/compact structure, very hard, strongly developed, no cutans, many macro and meso pores, many fine roots, no concretions, high biologic activity, distinct boundary.
		AB_g Albic/ Anthraquic Abrupt textural change	12-35	Dark Brown/Grayish brown (7.5YR4/2, moist), pale brown/ yellowish brown (7.5YR6/2, dry) silty loam (clay poor), few yellowish brown mottles, no gravels, massive/compact structure, very hard/compact, strongly developed, no cutans, many meso and micro pores, many fine and medium roots, no concretions, low biologic activity, distinct boundary.
		Bt_g Argic	35-58	Dark Brown/Grayish brown (10YR4/3, moist), Light Yellow/Gray (10YR8/1, dry) loam, many yellow mottles, no gravels, Angular blocky/compact structure, very hard, strongly developed, no cutans, many micro pores, many fine and medium roots, no concretions, low biologic activity, distinct boundary.
		Bt_{gc} Argic Kandic Gleyic	58-120	Yellow (2.5Y4/4, moist), Dark yellow (2.5Y7/6, dry) Clay loam, no mottles, no gravels, Blocky/ compact structure, very hard, strongly developed, no cutans, few micro pores, few fine roots, 10-15 % concretions of ferromanganate (black),low biologic activity, distinct boundary.
AZUKOUP-5 (x) 300330 (y)	Gleyic Luvisol Peneplain, high slope, 222 m above sea level,	Ap Albic Ochric	0-20	Brown/Dark reddish brown (7.5YR5/3, moist), yellowish/pale brown (7.5 YR7/2, dry), sandy loam (clay poor), no mottles, no gravels,

1191695	Fallow, sudan savanna, Mica schist, no water table and salt, Termitarium, slight/ low traces of erosion, Human influence (pastoral, bush burning), Drainage (Good) Dry top soil but wet below.			massive/compact structure, friable, strongly developed, no cutans, many macro and micro pores, many fine and medium roots, no concretions, high biologic activity, distinct boundary.
		Bt_{ng1} Argic Abrupt textural change Kandic	20-56	Dark Brown(10YR5/3, moist), yellowish brown/Yellow (10YR7/6, dry), loam, few yellowish brown mottles, no gravels, Angular blocky structure, friable, strongly developed, no cutans, many macro and micro pores, many fine and medium roots, no concretions, low biologic activity, gradual boundary.
		Bt_{ng2} Argic	56-100	Dark Brown (10YR4/2, moist), Dark Brown (10YR5/3, dry) Sandy loam (clay poor), reddish mottles, no gravels, Angular blocky structure, friable, strongly developed, no cutans, many micro pores, many fine roots, no concretions, medium biologic activity, gradual boundary.
AZUKOUP-6 (x) 300330 (y) 1190195	Dystric Plinthosol Peneplain, mid-slope, 216 m above sea level, yam cultivation, sudan savanna, Mica schist, no water table and salt, slight/low traces of erosion, Human influence (pastoral, bush burning),Drainage (imperfect) Dry top soil but wet below.	A_{gn} Anthraquic/ Albic Umbric	0-20	Dark reddish Brown/Grayish brown (7.5YR3/2, moist), Gray/ pale brown (7.5 YR7/1, dry), Sandy loam (clay poor), brown/reddish mottles, no gravels, massive/compact structure, friable, strongly developed, no cutans, many macro and micro pores, few fine roots, no concretions, high biologic activity, distinct boundary.
		Bt_{ng} Argic Vertic Plinthic Kandic (stagnatic properties).	20-32	Gray/pale brown (7.5YR7/1, moist), Gray (7.5YR8/2, dry) Clay loam, many yellowish brown mottles, no gravels, massive/compact structure, sticky, strongly developed, no cutans, many macro and micro pores, few fine roots, no concretions, low biologic activity, distinct boundary.
		Bt_{ngc} Argic Vertic Plinthic	32-55	Gray/ Pale Brown(7.5YR7/1, moist), Gray (7.5YR8/1, dry), Clay, many yellow mottles, many gravels, massive/compact structure, sticky,

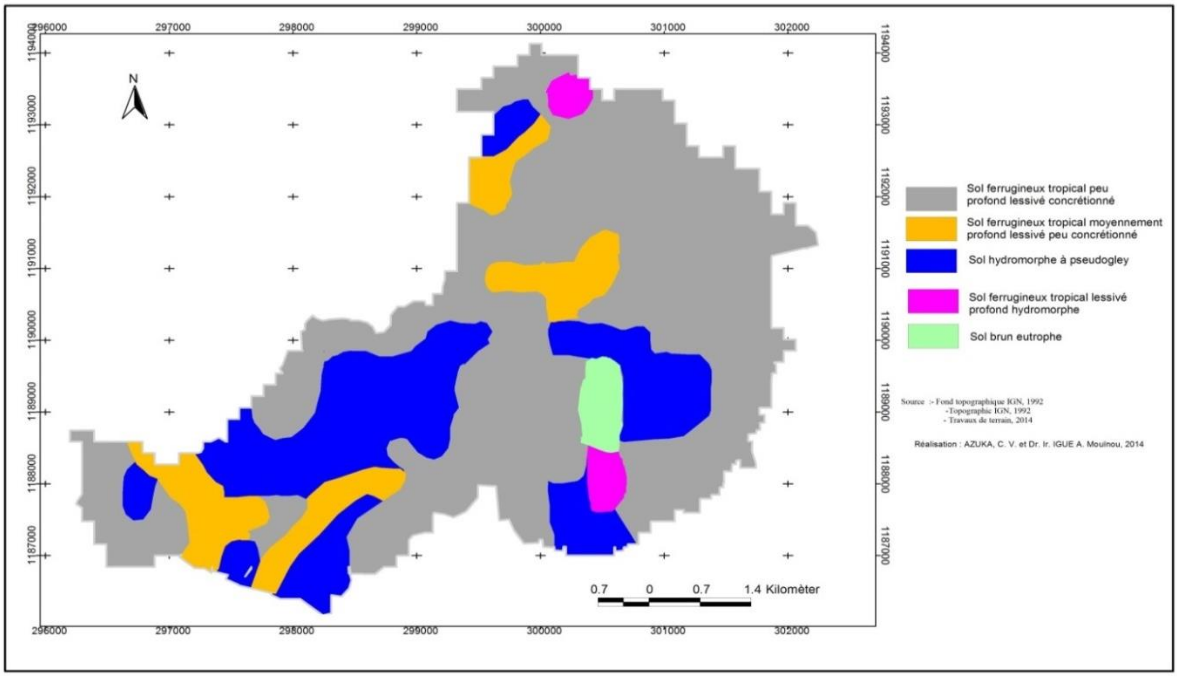
		Kandic (stagnatic properties)		strongly developed, no cutans, many macro and micro pores, few fine roots, 30 % concretions, low biologic activity, gradual boundary.
		B_{cv}	>55	Petroplinthic/Petroferric stones
AZUKOUP-7 (x) 300330 (y) 1189945	Eutric Gleysols Peneplain, mid-slope, 218 m above sea level, Fallow, sudan savanna (Mitragena, Terminalia spp.), Mica schist, no water table and salt, no traces of erosion, Human influence (pastoral, bush burning),Drainage (imperfect) Dry top soil but wet below.	A_{gc} Albic Ochric	0-17	Dark reddish Brown/Grayish brown (7.5YR4/2, moist), Gray/pale brown/yellowish brown (7.5 YR7/1, dry), Silty loam (clay rich), few yellow mottles, no gravels, massive/compact structure, friable, strongly developed, no cutans, many macro and micro pores, many big, medium and fine roots, very few(5 %) concretions, high biologic activity, gradual boundary.
		Bt_{gc1} Argic vertic kandic cambic	17-42	Dark reddish Brown/Grayish brown (7.5YR5/2, moist), Gray/ Pale Brown (7.5YR6/1, dry) Silty Clay loam, many yellow mottles, no gravels, Angular blocky structure, friable, strongly developed, no cutans, many macro and micro pores, many medium and fine roots, few (5-10 %) concretions, medium biologic activity, gradual boundary.
		Bt_{gc2} Argic vertic kandic cambic	42-100	Dark reddish Brown/Grayish brown (7.5YR5/1, moist), Gray/Pale brown (7.5YR6/1, dry), Clay loam, many yellow mottles, no gravels, massive /compact structure, sticky/plastic, strongly developed, no cutans, few macro and many micro pores, few fine roots, 10-15 % concretions, low biologic activity, gradual boundary.
AZUKOUP-8 (x) 300330 (y) 1188945	Dystric Plinthosol Peneplain, High-slope, 222m above sea level, Fallow, sudan savanna (Many Casia spp.), Mica schist, no water table and salt,	Ap_{c} Albic Petroplinthic Umbric/ ochric	0-12	Dark Brown/Grayish brown (10YR4/2, moist), Brown (10YR5/2, dry), Loam, no mottles, few gravels, Angular blocky structure, friable, strongly developed, petroplinthic, no cutans, many macro and micro pores, many fine and medium roots, 20 % concretions, medium biologic activity, distinct boundary.

	slight/low traces of erosion, Human influence (pastoral, bush burning),Drainage (Good) Dry top soil but wet below.	Bt_c/BA_c Argic Petroplinthic Chromic B_{cv}	12-40 >40	Dark reddish brown (7.5YR4/6, moist), yellowish brown (7.5YR5/8, dry) Loam, no mottles, many gravels, massive/compact structure, very hard, strongly developed, petroplinthic, no cutans, many macro and micro pores, many fine and medium roots, 50 % concretions, low biologic activity, distinct boundary. Plinthite/Petroferric stones.
AZUKOUP-9 (x) 301080 (y) 1191195	Dystric Plinthosol Peneplain, High-slope, 220 m above sea level, Fallow, sudan savanna (Many Casia spp.), Mica schist, no water table and salt, slight/low traces of erosion, Human influence (pastoral, bush burning),Drainage (Good) Dry top soil but wet below.	A_c Albic Pisoplinthic Umbric Bt_c Argic Pisoplinthic Chromic B_{cv}	0-20 20-42 >42	Dark reddish Brown/Grayish brown (7.5YR3/2, moist) Gray/Pale brown (7.5YR7/1, dry), Sandy Loam (clay poor), no mottles, many gravels, massive/compact structure, friable, strongly developed, petroplinthic/ fragic, no cutans, many macro and micro pores, many fine and medium roots, 50 % concretions, high biologic activity, distinct boundary. Dark reddish Brown (7.5YR5/6, moist), Yellowish brown (7.5YR7/8, dry) Loam, no mottles, many gravels, massive /compact structure, very hard, strongly developed, petroplinthic, no cutans, many macro and micro pores, many fine and medium roots, 60 % concretions, low biologic activity, distinct boundary. Plinthite/Petroferric stones.
AZUKOUP-10 (x) 298580 (y) 1189695	Eutric Gleysols Peneplain, High-slope, 228 m above sea level, Fallow, sudan savanna (Mitragena, Terminalia spp.), Termiterium, Mica schist, no water table and salt, moderate	A_c Albic Pisoplinthic Ochric Bt_{c1}	0-15 15-32	Dark Brown/reddish brown (10YR5/3, moist), Gray/Pale Brown (10 YR7/2, dry), Sandy loam (clay rich), no mottles, many gravels, massive/compact structure, friable, strongly developed, no cutans, many macro and micro pores, many medium and fine roots, 45 % concretions, high biologic activity, distinct boundary. Dark Brown (10YR3/3, moist), Dark

	traces of erosion, Human influence (pastoral, bush burning),Drainage (good) Dry top soil but wet below.	Argic Pisoplinthic vertic		Brown/Grayish brown (10YR5/2, dry), Sandy Clay loam, no mottles, many gravels, Angular blocky structure, friable, strongly developed, no cutans, many macro and micro pores, few fine roots, 50 % concretions, medium biologic activity, distinct boundary.
		Bt_{c2} Argic Pisoplinthic vertic kandic cambic	32-60	Brown/reddish brown (2.5YR4/4, moist), reddish yellow (2.5YR6/1, dry), Clay, many no mottles, many gravels, Angular blocky structure, sticky, strongly developed, no cutans, many micro pores, no roots, 60 % concretions, low biologic activity, distinct boundary.
		B_{cvm}	>60	Plinthite/Petroferric stones

NB: A= master horizon designated as A-horizon, B= master horizon designated as B-horizon, h=accumulation of organic matter, c=concretions or nodules, V= occurrence of plinthite, V_m= Hardened plinthite (hardpan, iron stone, petroferric or skeletic), g= stagnic conditions, t=illuvial accumulation of silicate clay.

Appendix II: Soil map of Koupendri catchment showing the distribution of soils (FRENCH).



Dystric plinthosol (DP)

These soils are dominant in moist tropical environment especially on gentle but relatively flat topography or slopes (Plate 3.1). They are made up of shallow but degraded soils with imperfect drainage, and are usually found on the lower slopes of undulating landscapes. The soils have high gravel content in the topsoil due to topsoil loss caused by soil erosion and abundant concretions or plinthites in the subsoil. The plithites developed as a result of continual subjection to wetting and drying processes (Embrapa, 2006). The soils are characterized by high erodibility, low soil moisture holding capacity and dries out rapidly in the dry season. The soils are also low in nutrient and thus, are not useful for agricultural activities.

Plate 1: Dystric Plinthosol

Endo-dystric plinthosol (EDP)

These soils are similar to Dystric plinthosol described above but are mainly deeper (40-70 cm) with massive ironpan outcrop at the eroded surface (Plate 3.2). They support only poor pasture for grazing animals but are mostly unsuitable for agricultural productivity except in some areas where the topsoil is fairly deep.

Plate 2: Endo-dystric plinthosol

Eutric gleysol (EG)

This is found mainly in the inland valleys and along river boders or low lying river basins as result of prolonged wetting (Plate 3.3). They are characterized by reddish-brownish, greenish or yellowish mottled colouration, usually porous, sandy or silty textured soils within 50 cm from the soil surface. Although, lighter textured form can be found at about 120 cm or deeper, the soils mostly have poor drainage and also subject to seasonal water logging or flooding. The soils are mostly used for rice, maize and vegetables both in the dry and rainy season mainly due to its high fertility status, organic matter content and water holding capacity.

Plate 3: Eutric gleysol

Cambisol (C)

These are young soils that developed upland mostly on the summit. These soils are rare in the tropics but abundant in temperate regions where low temperature slow down soil formation processes. In the tropics, they are found alongside well developed soils especially in areas of active erosion (FAO, 2007). The soils are shallow with hard iron pan or concretions and mostly not suitable for cultivation but are better left under natural vegetation.

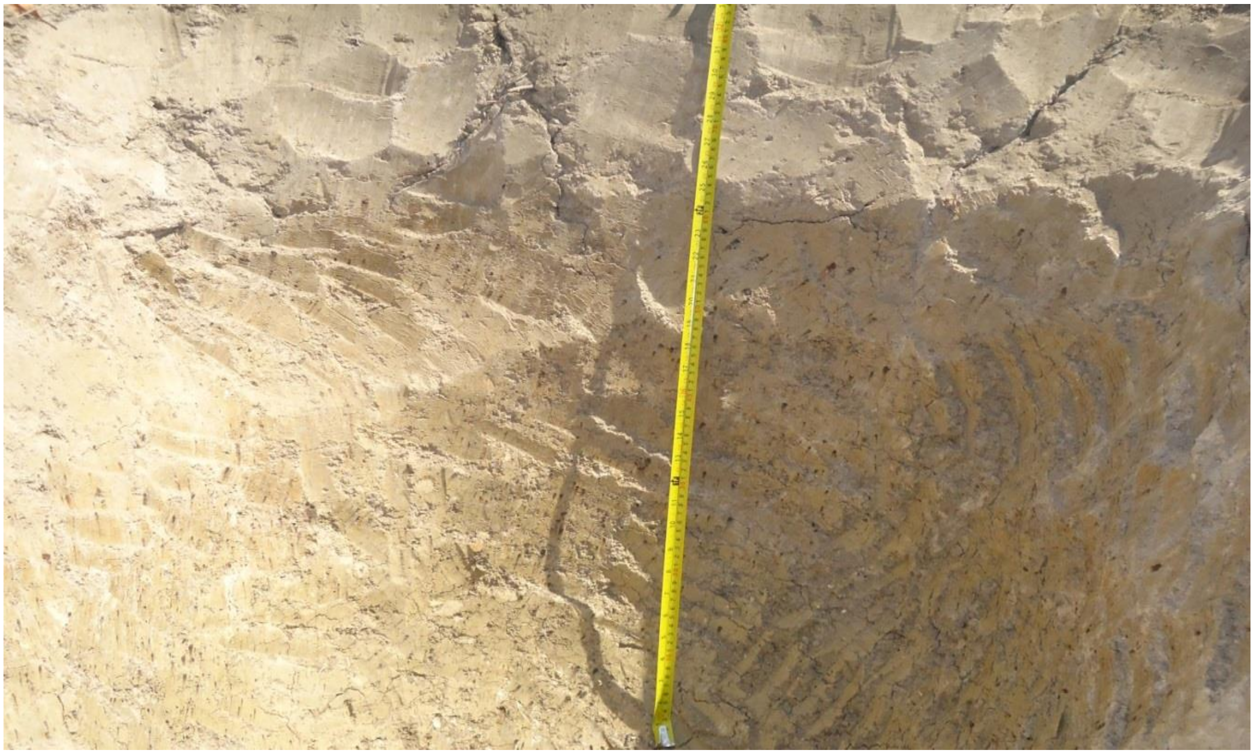


Plate 4: Cambisol

Luvisol (L):

These soils are characterized by marked textural differentiation within the soil profile. The soil texture vary from sandy to loamy soil usually with few ironstone or concretions (petroplinthite) in the top soil overlain by a sandy clay subsoil horizon of tightly packed irregular ironstone gravel and ferruginized sandstone (Plate 3.5). The soils are moderately weathered, porous in nature, well aerated and drained. They are found most suitable for cereal (e.g. maize, millet, sorghum e.t.c) cultivation and occasionally for yam cultivation.

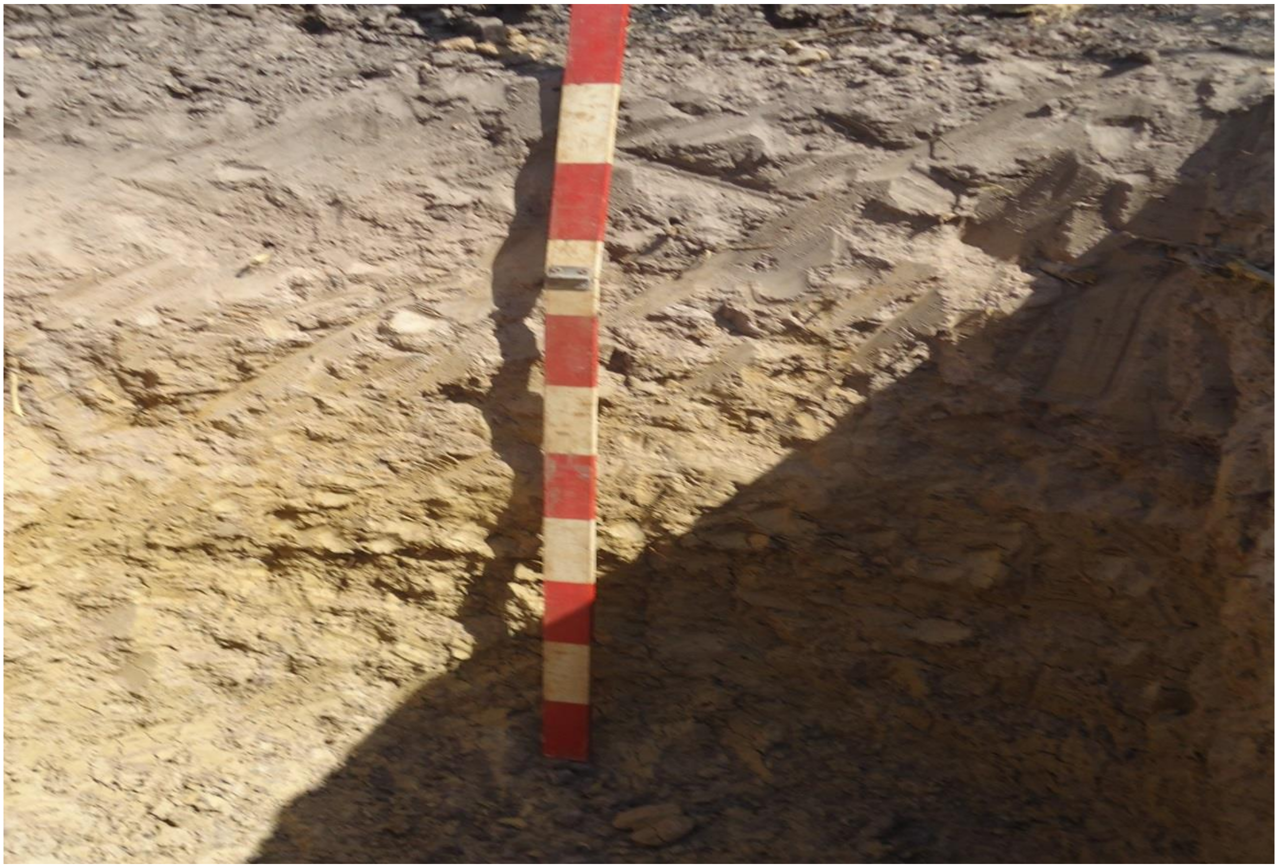


Plate 5: Luvisol

Appendix III: Shapiro-Wilk test analysis across the land use types

Shapiro-Wilk W test for normal data (Maize-sorghum)

Variable	Obs	W	V	z	Prob>z
Ksat	100	0.94815	4.281	3.226	0.00063
BD	100	0.98225	1.466	0.848	0.19823
Po	100	0.97998	1.653	1.115	0.13251
SOC	100	0.97622	1.964	1.497	0.06721
MO	100	0.97624	1.962	1.495	0.06750
N	100	0.98617	1.142	0.294	0.38425
CN	100	0.97999	1.653	1.114	0.13258
Avail.P	100	0.94035	4.925	3.537	0.00020

Based on the results above, all variable having $p > 0.05$ are normally distributed.so only K and Pass are not normally distributed having $p < 0.05$.

Shapiro-Wilk W test for normal data (Rice_Field)

Variable	Obs	W	V	z	Prob>z
K	91	0.85816	10.827	5.257	0.00000
BD	91	0.91694	6.340	4.076	0.00002
Po	91	0.94146	4.469	3.304	0.00048
C	91	0.90253	7.440	4.429	0.00000
MO	91	0.90045	7.599	4.476	0.00000
N	91	0.88545	8.744	4.785	0.00000
CN	91	0.95821	3.190	2.560	0.00523
Avail.P	91	0.97999	1.527	0.935	0.17501

Only Avail.P is normally distributed with $p > 0.05$.

Appendix IV: Description of the most sensitive parameters

Q01	Scaling factor for baseflow
KK	Storage coefficient for baseflow
KD	Storage coefficient for surface runoff
RSC1, RSC2, RSC5	Surface resistance for land use type 1, 2 and 5
RSE1, RSE2, RSE5	Soil evaporation resistance for land use type 1, 2 and 5
KsT_1H_1, KsT_1H_2	Saturated hydraulic conductivity (Ks) of soil type 1 (T_1), first (H_1)and second (H_2) horizon
KsT_3H_1, KsT_3H_3	Saturated hydraulic conductivity (Ks) of soil type 3 (T_3), first (H_1)and third (H_3) horizon.

Azuka, Chukwuebuka Vincent hails from Uruokwe-Egbema Ozubulu in Ekwusigo LGA of Anambra state. He attended the community primary school, Amakwa Ozubulu from 1988-1995 for his primary education. Thereafter, he proceeded to Okongwu Memorial Grammar School Nnewi in Anambra state for his secondary/high school education from 1995-2000. He enrolled to study Soil Science at the University of Nigeria, Nsukka in 2003 and graduated with First Class (4.63/5.00) Honours (B. Agric) Degree in Soil Science in 2008. He worked briefly (October, 2008- February, 2009) as chemistry/physics teacher at Arch Deacon Nwosu Memorial Secondary School, a secondary education setting in Ozubulu, Anambra State. Afterwards, he went for the compulsory one year National Youth Service Corps (NYSC) at the University of Calabar in Cross-River state from 2009-2010. He joined the University of Nigeria, Nsukka as a Graduate Assistant in 2010 and obtained M.Sc Degree in Soil Physics and Conservation in 2013 from the same university. He enrolled in the Doctoral program (Climate change and water resources) of the West African Science Service Centre on Climate Change and Adapted Land Use (WASCAL) sponsored by German Ministry of Science and Education (BMBS) Bonn, and co-hosted by Université D'Abomey calavi, Benin Republic and University of Bonn, Germany. He has successfully defended his thesis "rainfall-runoff processes and spatial variability of soil properties of the Koupendri catchment in north-west Benin, west Africa under different land use/land cover" on the 15th of December, 2016.

Abstract

Soil is an important input data in most hydrological modeling. A detailed (1:25000) soil survey and soil classification was done using SOTER (SOil and TERrain) approach. Data on both morphological (color, structure, mottles e.t.c), physical (texture, bulk density (BD) and saturated hydraulic conductivity (Ksat)), and chemical properties (soil organic carbon (SOC), cation exchange capacity (CEC), total nitrogen (TN), available phosphorus (Avail.P), carbon-nitrogen ratio (C:N) e.t.c) were obtained. 180 surface soil (0-20 cm) samples were collected in a grid resolution of 25 m x 25 m and supplemented with additional 116 samples at 5 m x 5 m resolution within the grid across three land use types (maize-sorghum cropland (MS), rice field and fallow-shrub-grassland (FSG)) to evaluate spatial variability of soil properties. These samples were analyzed using standard laboratory procedures. Further data analysis using simple statistical and geostatistical tools and Pearsons's correlation analysis were performed. The soil map of the catchment showed five distinct soil types, belonging to three major soil orders namely: Ultisols, Inceptisols and Alfisols (USDA), and four reference soil groups: Plinthosols, Cambisols, Luvisols and Gleysols (WRB). More than 55 % of the soils were mainly Plinthosols, highly degraded, acidic in nature and low in nutrient with low soil water retention capacity. The variability was high for Ksat, moderate for SOC, Avail.P and C:N, but low for TN, BD. SOC showed the strongest spatial dependence (0-5.3%) across the three land use. The spatial dependence, pattern and distribution of the soil properties were influenced by land use and soil management practices but independent of individual property or geology. Six microplots (1m x 1m) for measuring surface runoff were installed on each of the two slope positions and each of the two land use types. Moreso, infiltration runs, soil samples and soil moisture measurements were done in triplicates. The suitability of a conceptual model (NRCS-CN) to capture plot-scale rainfall-runoff processes was tested. To understand rainfall-runoff processes at the catchment scale, WaSiM model was calibrated and validated using the most sensitive and the optimized soil, land use and unsaturated zone parameters. Surface runoff coefficient for the microplots and the catchment were computed and compared. Soil hydrologic properties (infiltration rate, soil moisture, surface runoff and saturated hydraulic conductivity) were influenced by land use and slope position though little disparity exists between the laboratory and the in situ determined values. Both total and event-based plot scale surface runoff were high and significantly ($p < 0.05$) influenced by the land use. Runoff coefficient at plot scale (0.3-0.9 %) compared to the catchment scale (0-0.6 %) revealed strong scale issues. NRCS-CN simulation captured the dynamics of the plot-scale rainfall-runoff processes (R^2= 0.84 -0.97; ME= 0.56-0.91) with slight over-and-underestimation of peak and low flows. The model WaSiM was successfully calibrated (NSE=0.61, R2=0.61, RMSE= 0.63) with acceptable uncertainty range or value (P-factor = 94%; r-factor = 0.93), and also validated (NSE=0.68, R2=0.78, RMSE= 0.57) for the Koupendri catchment. The result was satisfactory and showed strong agreement between the modeled and the observed data. Direct flow was the dominant runoff (more than 85 % of the total runoff) component in the catchment. The water balance reflected the hydro-climatic condition of the catchment with real evapotranspiration ranging between 68 % and 75 % of the total annual rainfall.

Keywords: Soil classification, geostatistics, microplot, hydrological properties, rainfall-runoff.