

DISTRIBUTED NUMERICAL MODELLING OF
HYDROLOGICAL-HYDROGEOLOGICAL
PROCESSES IN THE OAKU BASIN



DISTRIBUTED NUMERICAL MODELLING OF
HYDROLOGICAL/HYDROGEOLOGICAL PROCESSES IN
THE DENSU BASIN

BY

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THIS DISSERTATION IS SUBMITTED TO THE UNIVERSITY
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b(t)c



DECLARATION

This is to certify that the content of the PhD dissertation has not been previously submitted to any University or Institute for the award of PhD degree. This dissertation is strictly my work and all published materials in this dissertation have been accordingly referenced to the best of my ability

The research was carried out under the supervision of Professors Bent Hasholt and Bruce Banoeng-Yakubo from the University of Copenhagen and University of Ghana respectively. I have appropriately acknowledged contributions to this research


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DEDICATION

I proudly dedicate this work to All Mighty God and to the Alfa family.



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ABSTRACT: The study was undertaken to develop a Densu basin integrated hydrological model capable of describing the major hydrological processes occurring in the land phase of the hydrological cycle and computation of water balance in the Densu river basin. Inadequate information on the hydrological processes as well as the regional water balance in the basin has adversely affected the sustainable development, assessment and efficient management of the basin's water resources.

A physically based numerical modeling system (MIKE SHE) was applied in an integrated approach. The MIKE SHE model provides a comprehensive framework for studying the interrelationship between upstream and downstream conditions and processes. The saturated and unsaturated zones flows were simulated using a fully implicit finite difference solution technique whereas the governing processes of the evapotranspiration were based on empirically derived equations. A conceptual model was developed using field data followed by model design, calibration and verification.

This study finds that actual evapotranspiration in savannah land cover in the basin ranges between 0.5 mm/day and 4.0 mm/day. In the forest land cover, actual evapotranspiration ranges between 0.4 mm/day and 5 mm/day. Actual evapotranspiration approaches zero during the dry periods in the case of savannah land cover whereas in the Forest land cover the minimum actual evapotranspiration in the dry periods is 0.4 mm/day

Results from the unsaturated zone study indicate that the Togo series soils provide a better medium for direct groundwater recharge with a maximum recharge rate of 0.7m/h and an average rate of about 0.3m/h. The recharge rate in the granite soils is



an order of magnitude lower than that of the Togo series soils but longer recharge duration than in the Togo series soils. The Birimian soils are almost impermeable and therefore the recharge rate is as low as 0.003m/h.

90% of the rainfall in the Densu basin occurs within the duration of 2 to 4 hours. It was observed that the use of daily rainfall as inputs in hydrological models in tropical regions does not represent convective storm events with highly variable precipitation intensities. The use of hourly rainfall data is more appropriate if detailed description of hydrological processes is required. However for the purposes of annual water balance computations, daily rainfall data are equally appropriate.

Simulation of the annual water balance indicate that, 72% of annual rainfall is lost through evapotranspiration, 21% is routed to the Densu river and its tributaries and 8% is groundwater recharge. 0.0009% is base flow and soil moisture deficit amounts to 0.016%.

The application of the MIKE SHE model in the description and characterization of the flow processes in the basin was successful with the only limiting factor being lack of long time series data for model verification.

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CHAPTER ONE

1.0 Structure of dissertation

The dissertation is structured in a form of chapters forming a monograph. The 11 chapters of this dissertation are stand alone chapters but are structured in a framework that follows the general disposition of a standard scientific report/paper as well as the hydrological cycle.

Chapter 1 is basically an introductory chapter that gives the background of the study, description of the problem, Justification of the research and the objective of the research. This chapter also explains the rationale in the choice of the research area as well as identified the relevant related research works that have been undertaken in the research area.

Chapter 2 describes the physical features, climatological conditions, socio-economic profile and the location of the basin. The locations of rainfall and hydrometric stations in the basin are also presented in this chapter. A brief description of the utilization of water resources is also presented in the form of a table in this chapter.

In chapter 3, the methodology applied in the research is presented and also a general perceptual as well as conceptual model of the research area is defined. A general description of the steps in modeling is presented in this chapter. Chapter 3 also presents a description of the data required for the setting-up of the model as well as the description

of the methodology of data collections and both the temporal and spatial resolution of the data collected.

In chapter 4, rainfall analyses in the basin are presented. Rainfall distribution in the research area as well as the partitioning of rainfall into the various components namely, infiltration, Hortonian overland flow and saturated excess flow is investigated and presented in this chapter. This chapter also presents analysis of rainfall duration in the research area.

Chapter 5 presents the estimation of evapotranspiration using the Penman-Monteith method. Chapter 5 also presents MIKE SHE simulated results of actual evapotranspiration, root water uptake and interception storage in the different land use/cover zones in the research area.

Chapter 6 describes overland flow processes and estimation of Hortonian Overland flow as well as overland flow routing.

Chapter 7 describes the unsaturated zone processes and also describes the mathematical principles that govern unsaturated zone flow processes. Variability of unsaturated properties in the research area and how they impact on groundwater recharge is also presented in this chapter. Model results of unsaturated zone water content and rate of water percolation in the different soil types and land use/cover are presented.



Saturated zone processes are described in chapter 8. The mathematical principles governing saturated zone processes and statistical characterization of aquifer properties and model results of groundwater head elevation in the research area are presented in this chapter.

The description of channel flow and brief description of the MIKE 11 model is presented in chapter 9. Models results of river discharges and heads of the Densu River are presented in this chapter.

Chapters 10 and 11 present the water balance analysis and the summary and conclusions of the research findings respectively. The main highlights of the research findings are summarized in chapter 11.

1.1 Introduction

Water is an indispensable natural resource for the survival of mankind all over the world. There is often a general perception that water resources occur in abundance, yet freshwater scarcity remains one of the developmental challenges of our time. The imminent impact of climate change on water resources will even further negate the perception of abundance of water resources especially in the Densu basin and tropical regions in general.

Ghana's fresh water resources are obtained mainly from three river systems namely the Volta, Southwestern and the Coastal river systems, occupying approximately 70%, 22%

and 8% respectively of the total land area of Ghana (Water Research Institute (WRI, 2000). There is also the occurrence of groundwater in three main geological formations namely the basement complex comprising crystalline igneous and metamorphic rocks, the consolidated sedimentary formations underlying the volta basin (including the limestone horizon) and mesozoic and cenozoic sedimentary rocks. Better understanding of the location of the resource and how it moves both on the surface and underground is essential in its evaluation, management and protection.

The Densu River is part of the coastal river system which traverses a highly densely populated part of Ghana and its basin is one of the most exploited in terms of water resources in the country considering its size. The basin is characterized by accelerating surface water quality degradation, and is marked by occasional water shortages (Water Resources Commission (WRC, 2007).

The basement complex comprising crystalline igneous and metamorphic rocks underlying the Densu basin are very important aquifer systems. They occupy a major part of the land area in the basin. A large quantity of the water for domestic, agriculture and industry is abstracted from these aquifer systems (WRI, 2003).

1.2 Statement of the problem

Water resources management studies carried out in recent past, raised concerns about the rapidly increasing demand for both surface and groundwater resources in industries, (particularly mining and hydropower generation), agriculture, domestic consumption and

environmental enhancement. The studies emphasized the need for comprehensive management of the country's water resources so as to meet the ever increasing demands. An action plan was therefore initiated to control and efficiently manage the water resources of the country. This action involved the introduction of Integrated Water Resources Management (IWRM) principles at both basin and national scales in order to achieve efficient management of the resource. Integrated approach to water resources management requires a thorough understanding of the important hydrological processes occurring on the land phase as well as the availability of a great deal of hydrological data and information. Hydrological/hydrogeological research was therefore emphasized as a first step towards efficient management and development of water resources.

The Densu basin, apart from being the source of water resources for the inhabitants in the basin, is also the source of water for the western part of Accra. About 300,000 m³ of water is abstracted from the Weija dam daily for supply to the western part of Accra (WRC, 2007). The demand is expected to increase in the future and that will put a greater amount of stress on the water resources of the basin. The situation will worsen as the population of the basin continues to grow, urbanization and industrialization becomes wide spread and human activities diversified.

Inadequate knowledge of the dynamics of hydrological processes as well as the regional water balance in the basin has adversely affected the sustainable development, assessment and efficient management of the basin's water resources. To effectively manage the resources, it is essential to know how water abstraction affects groundwater

heads and surface water levels and the effects of present and future stresses on the water resources as well as the overall water balance of the basin. A description of the major hydrological processes in the land phase such as groundwater recharge, overland flow generation, root water uptake, canopy storage, evapotranspiration etc is essential in understanding and quantifying the water resources in the basin. The inability to predict the future impact on the resources under different stresses makes it difficult to develop and implement sound management practices.

Another important problem that confronts the basin is the non availability of river flow and groundwater monitoring data. The Hydrological Services Department (HSD) is responsible for measuring river flows in the country but due to financial and logistical constraints, continuous river flow data for one year is barely available. Groundwater level monitoring was recently embarked by the Water Resources Commission under the Integrated Water Resources Management (IWRM) Component which is an integral part of the second phase of the DANIDA supported Water and Sanitation Sector Programme support (WSSPS II). Long time series groundwater monitoring data are therefore not yet available for the characterization of long term patterns of groundwater fluctuations. As a result, characterization of flow processes in the basin cannot easily be done without the use of hydrological models through intensive calibrations.

1.3 Background

The DANIDA/ENRECA hydrogeological project hosted by the Geology Department of the University of Ghana was developed as part of collaboration between the University of

Ghana and the University of Copenhagen, Denmark. The project which started in 1995 is funded by the Danish government through the DANIDA program. The project was developed to address constraints that confront students in the field of research. It was observed that the Department of Geology was not well equipped with the state of the art scientific equipment and relevant techniques to undertake efficient research. The project therefore, established measuring stations in the Densu and the Keta basins to collect hydrological data for research purposes.

The main objective of the DANIDA/ ENRECA project is to enhance research capacities in the field of hydrogeology/hydrology and related fields of studies as well as to make available useful information for research and ultimately to facilitate teaching and research in the Department of Geology of the University of Ghana.

To ensure that the project objective is achieved, a number of scientists from the University of Copenhagen, Denmark have been involved in the supervision of both M.Sc and PhD students. So far over 10 students have obtained PhD and M.Sc degrees under the project.

1.4 Significance of the research

Optimal use of scarce water resources in the Densu basin requires that the resources are viewed in a holistic river catchment perspective. This is because use of water upstream the Densu river system affects the options for other utilizations downstream the river. For example, increase in water supply at Tafo (Upstream) may affect water supply at

Nsawam (downstream). Also land use practices upstream the river system that impact on the water resources will eventually affect water resources downstream the river catchment. Hydrological models provide a means of studying these interrelationships which is essential for better planning and management of the basin's water resources (Sandholt, 2003).

Water resources models are efficient tools that are often used in the assessment of water resources potential and prediction of future circumstances. Their ability to fairly predict the extent of future water resources circumstances and the response of the system to different stresses makes them useful tools for planning, design, implementation and management.

The non availability of a water resources model for the Densu basin limits the understanding of flow processes and characterization of the response pattern of the basin to rainfall. This research seeks to characterize the flow process through the use of a physically based numerical model to enhance understanding of hydrological processes in the basin so as to promote efficient planning and management of the basin water resources to ensure that the growing water needs are properly addressed.

1.5 Selection of research area

The selection of the research area was based on a number of studies undertaken in the country to assess general water resources problems in the basin. One of such studies is the identification, analysis and prioritization of water resources management problems in

the various river basins in Ghana. In 2000, WRC engaged the services of the Water Research Institute of the Council for Scientific and Industrial Research (WRI -CSIR) to undertake the above mentioned study. The study was conducted in all the 16 river basins in Ghana and the report listed the Densu basin as one of the most stressed basins with regards to quality and availability of water resources. Apart from the water shortages and quality issues, other water resources management problems in the basin that were listed in the study report are inadequate reliable information and data, flooding, lack of comprehensive institutional and legal framework and improper land use practices. The findings of the study served as a guide to identify the most stressed basins in the country.

The Densu basin is also known to be one of the most important basins by virtue of its location and dependants and therefore requires considerable attention with regards to water management actions.

The selection procedure also took into consideration the importance and necessity of the site specific research results in the evaluation and management of the basin's water resources and also future planning and developmental activities within the basin.

Another important factor for the selection of the Densu basin for this research is that the DANIDA – ENRECA project has set up a nested catchment in the Pompon sub-catchment within the Densu basin to be used for training and education. The nested catchment has produced adequate reliable data which is useful for model calibration and verification.

1.6 Objectives of the research

This study is designed to develop an integrated water resources model using both a Lump Conceptual Model (NAM) and a deterministic, distributed physically-based numerical modeling system (MIKE SHE) for the description of the major flow processes in the Densu basin. A calibrated runoff and groundwater flow model capable of accounting for and characterizing the hydrological/hydrogeological properties and conditions of the basin is the main objective of the research.

The specific objectives of the research include but not limited to the following:

- To characterize the major flow processes in the basin
- To assess the effect of land use/cover and soil types on groundwater recharge
- To investigate the partitioning and distribution of rainfall in the Densu basin
- To investigate rainfall duration pattern and its implications in hydrological models
- To evaluate the contribution of groundwater to surface water flow during low flow regimes
- To simulate groundwater heads and river discharges/levels
- To evaluate the regional water resources of the basin (water balance)
- To carry out water demand vrs availability assessment

1.7 Literature review

The Water resources Commission has engaged the services of research institutions to carry out some hydrological/hydrogeological works within the basin with the aim of generating specific data which can be used in the basin's water resources management.

Also some research works have been carried out in the basin by other institutions and individuals. Some of the related research works undertaken within the basin include the following:

1.7.1 Groundwater assessment: An element of Integrated Water Resources Management (WRI, 2003)

The main aim of the research was to obtain adequate information on groundwater potential in the Densu basin through a detailed compilation, collation and assessment of groundwater related data and information in the basin. The specific objectives include the following:

- Make a comprehensive inventory of all available hydrogeological data and information, including data on borehole drilling, geological succession, aquifer tests and hydraulic parameters;
- Verify through field visits, the actual locations of boreholes and obtain the coordinates by means of GPS measurements;
- Monitoring of groundwater level fluctuations;
- Assess the hydrogeological conditions in the Densu basin.

The major findings of the research included the characterizations of borehole yields as well as aquifer parameters such as transmissivity, specific capacity and porosity. The research outlined the heterogeneous nature of the aquifer system and recommended a detailed hydrological investigation in the basin so as to enhance the efficient development

of groundwater resources. The Study also recommended an investigation into the interaction between groundwater and the Densu river in order to evaluate the effects of groundwater abstraction on the flow of the Densu River.

1.7.2 Water Balance of the Pompon Sub-catchment within the Densu basin (Tumbulto, 2005)

This research was carried out to improve the knowledge on the elements of water balance in the Pompon sub-catchment of the Densu basin. Measurements carried out in the sub basin included hydro-meteorological measurements for estimating potential and actual evapotranspiration. The main objectives of the research included the following:

- To plan and set up instrumentation of experimental catchment;
- To identify data needs for hydrological modeling;
- To identify the implication for water management in the catchment and beyond;
- To investigate the possible up scaling of results and applicability in neighboring catchments;
- To undertake a routine management of the experimental catchment;
- To provide a thorough description of hydrogeological processes in the catchment;
- To quantify the flows and storages of the catchment;
- To evaluate the water resources in the area;
- To establish a data base for the catchment.

The main findings of the research included the estimation of groundwater recharge, the analysis of rainfall intensities, computation of mean actual evapotranspiration and average soil moisture contents among other parameters estimations. The research recommended among other things, that interaction of groundwater and surface water should be investigated to enhance better management of the Water resources. The research also proposed an upscaling of the Pompom catchment studies to the entire Densu basin.

1.7.3 Identification of major trends in the socio-economic development in the Densu basin of relevance for Integrated Water Resources Management (WRI, 2000)

The main aim of the study is to present updated socio-economic information of relevance for Integrated Water Resources Management. The study also aimed at achieving the following specific objectives:

- Select socio-economic indicators on the Densu basin based on updated data;
- Identify access to and control of water resources of different stakeholders in the Densu basin including the poor and disadvantaged;
- Assess the major trends and dynamics of the socio-economic development in the Densu basin in relation to the water resources;
- Identify the potential conflicts over water resources arising from socio-economic development , their severity and implications;

The outcome of this study stressed the need for institutional collaborations and the need to identify and include stakeholders in water resources management issues. The study also stressed the need to create a buffer zone to protect the Densu River.

1.7.4 Integrated Water Resources Management (IWRM) Plan of the Densu River Basin (WRC, 2007)

The main aim of the Study is to ensure that water resources in the basin are managed properly according to the principles of Integrated Water Resources Management for socio- economic development in the basin and some parts of the city of Accra which depends on the Densu basin for their water resources. Specific objectives of the study include the following:

- Ensure availability of water resources for domestic, industrial and agricultural utilization;
- Ensure good quality of the basin's water resources;
- Ensure sustainable development and utilization of the basin's water resources;
- Promote sound environmental practices in the basin;
- Maintain aquatic ecosystem in the basin;
- Minimize the effects of flood.

1.7.5 Feasibility studies for the construction of the Weija Dam (AESC and Tahal, 1975)

The Architectural and Engineering Services Corporation (AESC) and Tahal (1975) carried out water assessing studies of the Weija dam using a hydrological model. The

studies used synthetic monthly flow data generated using rainfall data in the Nsawam area Evapotranspiration data at Accra. The findings of the study estimated that seepage of the Weija dam amounts to 25.4 mm/month. The water demands at both upstream and downstream were also estimated as well as irrigation water demand. The Study was basically conducted to design the Weija dam as well as decide on the size of the dam.

Another related study was undertaken by Coptran Engineering and Planning Associates applying a seasonal water shed model (SEAMOD) to evaluate seasonal water balance in the Weija area. The study used long term climate data from Accra to simulate seasonal water balance at the reservoir area.

Nii Consult under the UN HABITAT project undertook a study entitled “Densu River Catchment Management Studies in Accra. The study was aimed at identifying training needs and institutional strengthening of stakeholder institutions in the Densu basin.

1.8. Synthesis of literature review

It can be deduced from the list and description of the related studies undertaken in the basin that, there is a knowledge gap in the basin with regards to extensive understanding of hydrological processes in the entire basin. There is also the lack of detailed study towards the computation of a regional water balance for the entire basin. All the studies undertaken in the basin are either limited in area extent (sub-catchment scale) or are directed towards generating specific information in the basin. The interrelationship of hydrological processes in the basin has not been investigated. Also, the relationships



between upstream and downstream processes in the entire basin have not been fully investigated.

CHAPTER TWO

2.0 Research area

2.1 Description of study area

The Densu River basin is located between latitude $5^{\circ}30'N$ - $6^{\circ}17'N$ and longitude $0^{\circ}10'W$ - $0^{\circ}37'W$ in the southern part of Ghana. The basin is bounded to the east and north by the Odaw and Volta basins, respectively. The boundary to the northwest is shared with the Birim basin and to the west with the Ayensu and Okrudu basins

The Densu River is one of the coastal river systems in Ghana with a drainage area of about 2,600 square kilometers. The major tributaries of the Densu River are the Dobro, Pompon, Kuia, Adaiso, and Nsaki rivers (Fig. 2.1) and a set of rivulets which are active only within the rainy seasons.

The river takes its source from the Atewa mountain range and flows down stream in an easterly direction towards Koforidua where it gradually changes its course and flows in a southerly direction into the Weija reservoir (Fig 2.2). The Weija dam was constructed to store water for supply to the Western part of Accra. When the Weija reservoir is full, excess flow discharges into the Densu delta (Sakumo lagoon), which is one of the important RAMSAR sites in Ghana, and finally discharges into the Bay of Guinea. The River has a total length of about 120 km.

The Densu basin occupies a greater part of Eastern Region, some part of Greater Accra Region and a small portion of the Central Region of Ghana. It occupies seven

administrative districts in the Eastern Region namely, Suhum – Kraboa-Coaltar, Manya Krobo, New Juaben, Akwapim North and South, and Akim East and West districts. Insignificant portions of the basin extend to the Kwaebibirem and Fanteakwa districts in the Eastern Region. The basin also occupies a major part of three Districts in the Greater Accra Region, namely, Ga East and West and Accra Metropolitan districts. In the Central Region, it occupies only the Awutu-Efutu-Senya District (Fig. 2.2). About 70% of the basin is located in the Eastern region, 25% and 5% is located in the Greater Accra and Central Regions respectively (estimation of sizes using Arc GIS tools).

The settlement pattern in the Densu basin can generally be described as both rural and urban. The urban settlements are mostly located in the Greater Accra and Eastern Regions. The population density in the basin is one of the highest in the country, with an estimate of about 387 persons per square kilometer, which is about five times bigger than the national average population density of 77 persons per square kilometer (Ghana Population and Housing Census 2000). The population of the basin is about one million people, slightly over one third of the population lives in rural settlement, less than 5000 people in a settlement and the rest are urban settlers, more than 5000 people per settlement according to the Ghana Population and Housing Census 2000.

The Densu basin was originally characterized by moist semi-deciduous forest with rich flora and fauna. This condition has been drastically altered by intense human activities in the basin. The forest lands have been replaced by agricultural lands for the growing of

various types of crops. Urbanization and illegal wood logging have also contributed significantly in the modification of the original environment of the basin.

The basin is characterized by three main vegetation zones which are dictated by the climatic conditions especially the rainfall pattern in the basin. The northern part of the basin where rainfall is highest is marked by deciduous forest made up of tall forest trees. The middle portion of the basin is characterized by a semi deciduous forest with a lush growth of thick and tall trees. The low rainfall within the northern part of the basin gives rise to a savannah and shrub forest vegetation with a few isolated trees. This part of the basin is mainly occupied by thickest of bush and grassland as well as mangrove swamps especially where brackish water prevails.

Protected areas in the basin include two forest reserves in the East Akim District and two small reserves in the Fanteakwa and Yilo Krobo districts. The largest reserve is called the Atewa range forest reserve located at the head waters of the Densu River. The coastal lagoon located down the Weija dam is also an important area that has been classified as a protected zone.

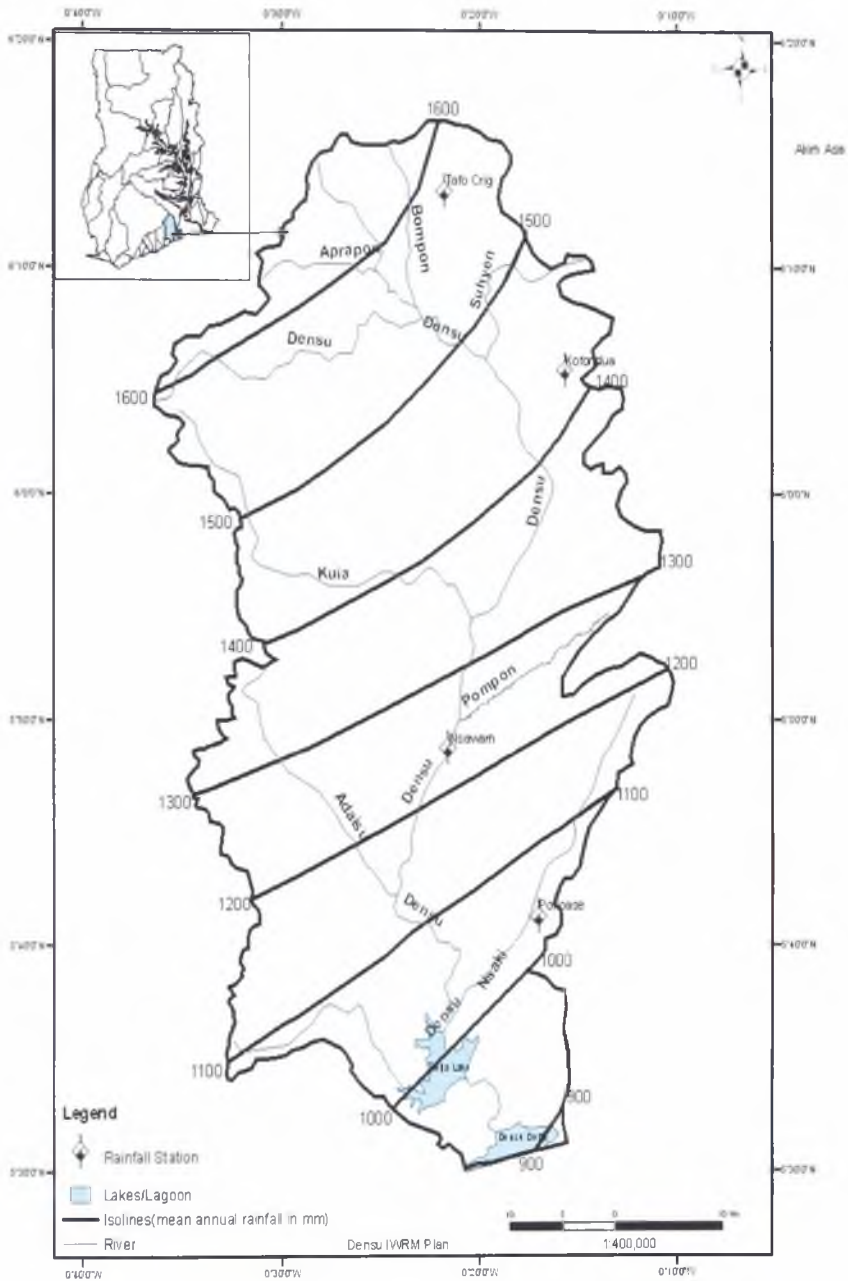


Fig. 2.1 Map of research area showing river network and location of the Densu basin

2.2 Climate and topography of research area

The Densu basin is characterized by high temperatures throughout the year with a mean temperature of about 27 °C. March and April are the hottest months within the basin with an average temperature of about 32 °C. August is the coolest month with a temperature of about 23 °C (Ojo, 1977).

The basin falls under two distinct climatic zones; the dry equatorial climate at the south east coastal plains and the wet semi-equatorial climate farther north from the coast. Both climatic zones are characterized by two rainfall regimes with different intensities (Dickson and Benneh, 1980). The major rainy season extends from March/April to July and attains a peak in June. The second rainfall period is a minor one that occurs between September and November. There is a wide monthly rainfall distribution as well as spatial rainfall variations in the basin (Fig. 2.3).

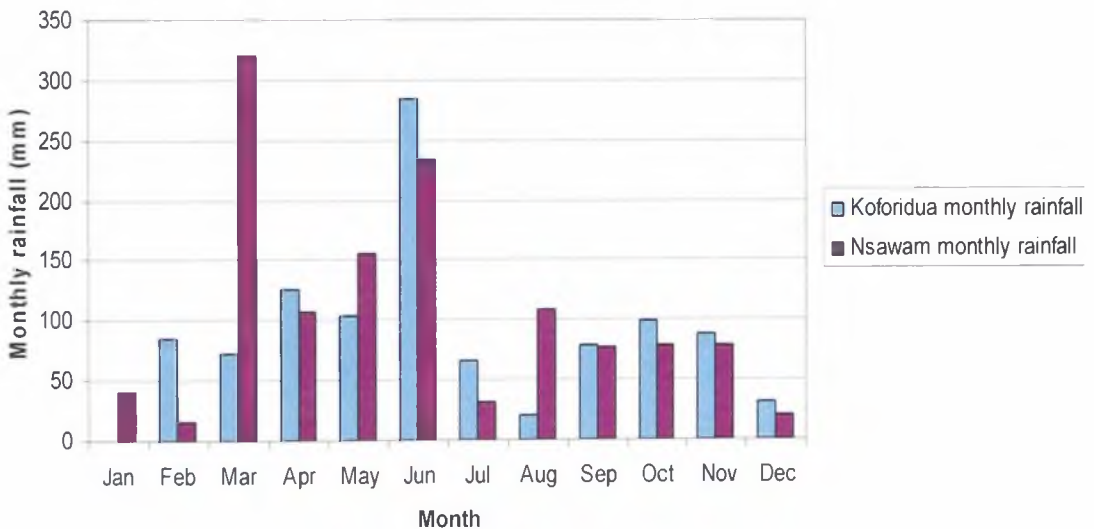


Fig. 2.3 Monthly rainfall distribution at Koforidua and Nsawam (2000)

The annual rainfall in the basin ranges from 1700 mm in the northern portion of the basin to as low as 900 mm in the southern part of the basin near the coast (Fig. 2.1). Generally, it has been observed that the rainfall to the north in the basin is more consistent in terms of pattern and amount than that of the southern part of the basin. Figures 2.4 and 2.5 illustrate the annual variations of rainfall in the southern portion of the basin at Pokuase and the upper midsection of the basin at Koforidua.

The relative air humidity ranges from an average of 50-60% in the driest months to 80-90% in the rainy season. The mean annual potential evapotranspiration varies from 1,700 mm in the southern part of the basin to about 1,500 mm in the northern part of the basin.

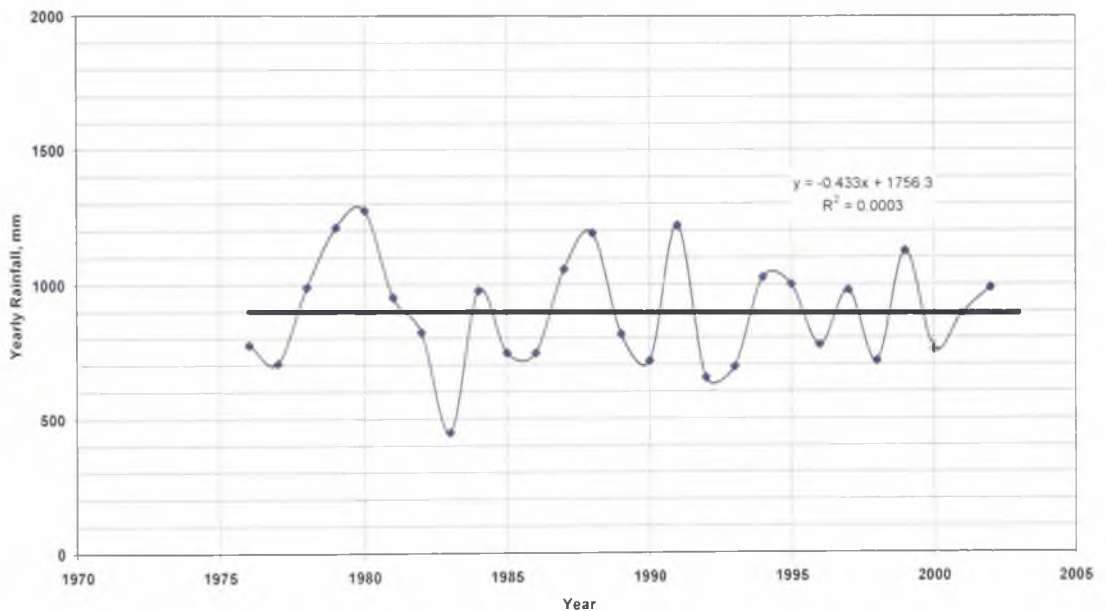


Fig. 2.4 Annual rainfall distribution in Pokuase station (Southern part)

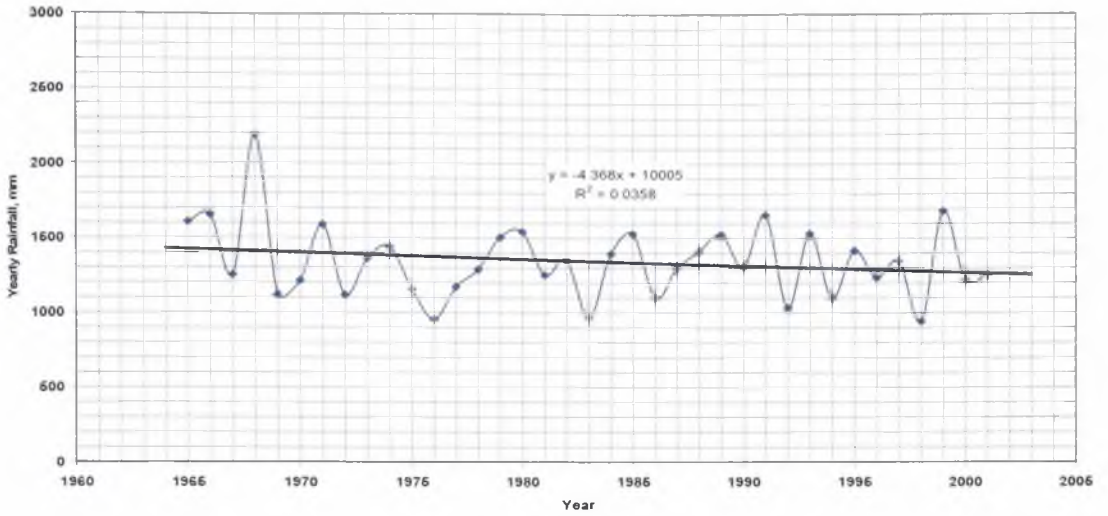


Fig. 2.5 Annual rainfall distribution in Koforidua station (Upper mid section)

The rainfall variations from the upper portion of the basin to the lower part of the basin are demonstrated in the rainfall correlations of neighboring rainfall stations (Figs 2.6 and 2.7).

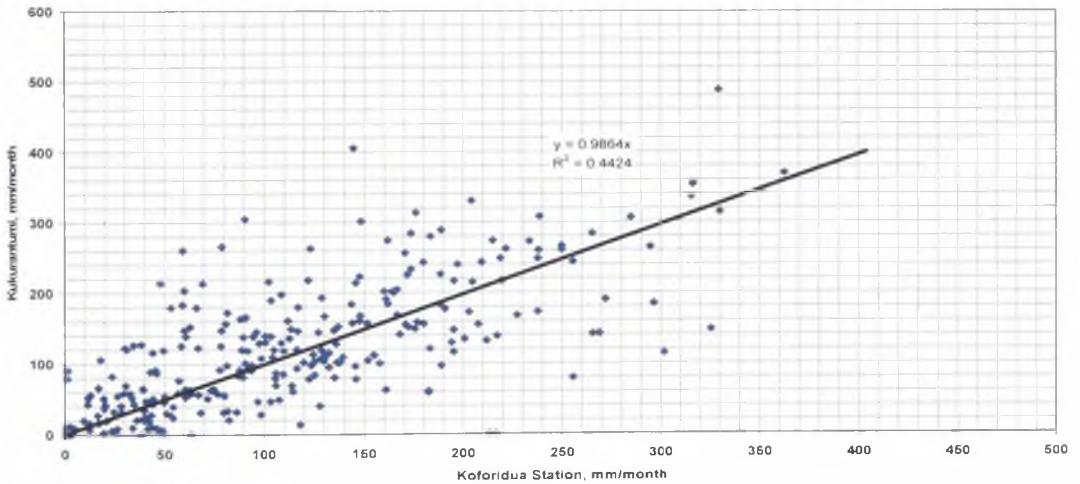


Fig. 2.6 Rainfall correlation: Koforidua/Kukurutumi



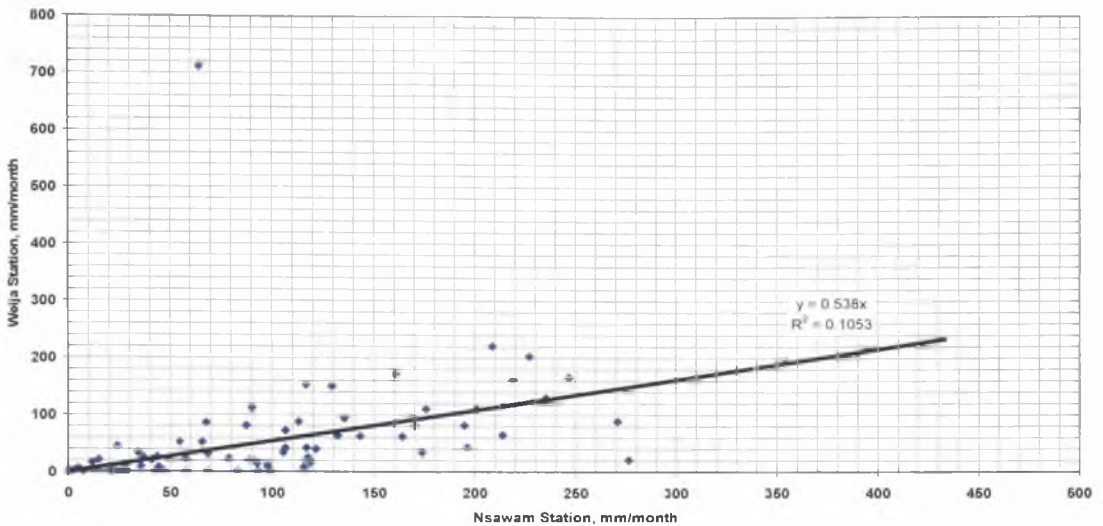


Fig. 2.7 Rainfall correlation: Nsawam/ Weija

The topography of the Basin is diversified. The Basin is characterized by steeply dissected landscapes with hilly and rolling lands to the north, and flat coastal plains to the south with slopes and erosion surfaces that vary from 30% in the upper sections of the basin to less than 2% at the coast (Adu and Asiamah, 1992). The highest portions of the basin have elevations of about 760 m above sea level (Fig.2.8). There are isolated ridges forming characteristic landscape features in some parts of the basin.

The Akwapem mountain ranges to the east forms the steepest parts of the basin. There are also high hills summounded with granite tors in isolated portions around Koforidua, Nsawam and Kukurantumi. South of Nsawam is characterized by the Accra and Cape Coast – Winneba plains which has an average elevation of about 150 m above sea level

(Ojo, 1977). Further downstream to the coast, after Weija, the elevation approaches 50 m above sea level.

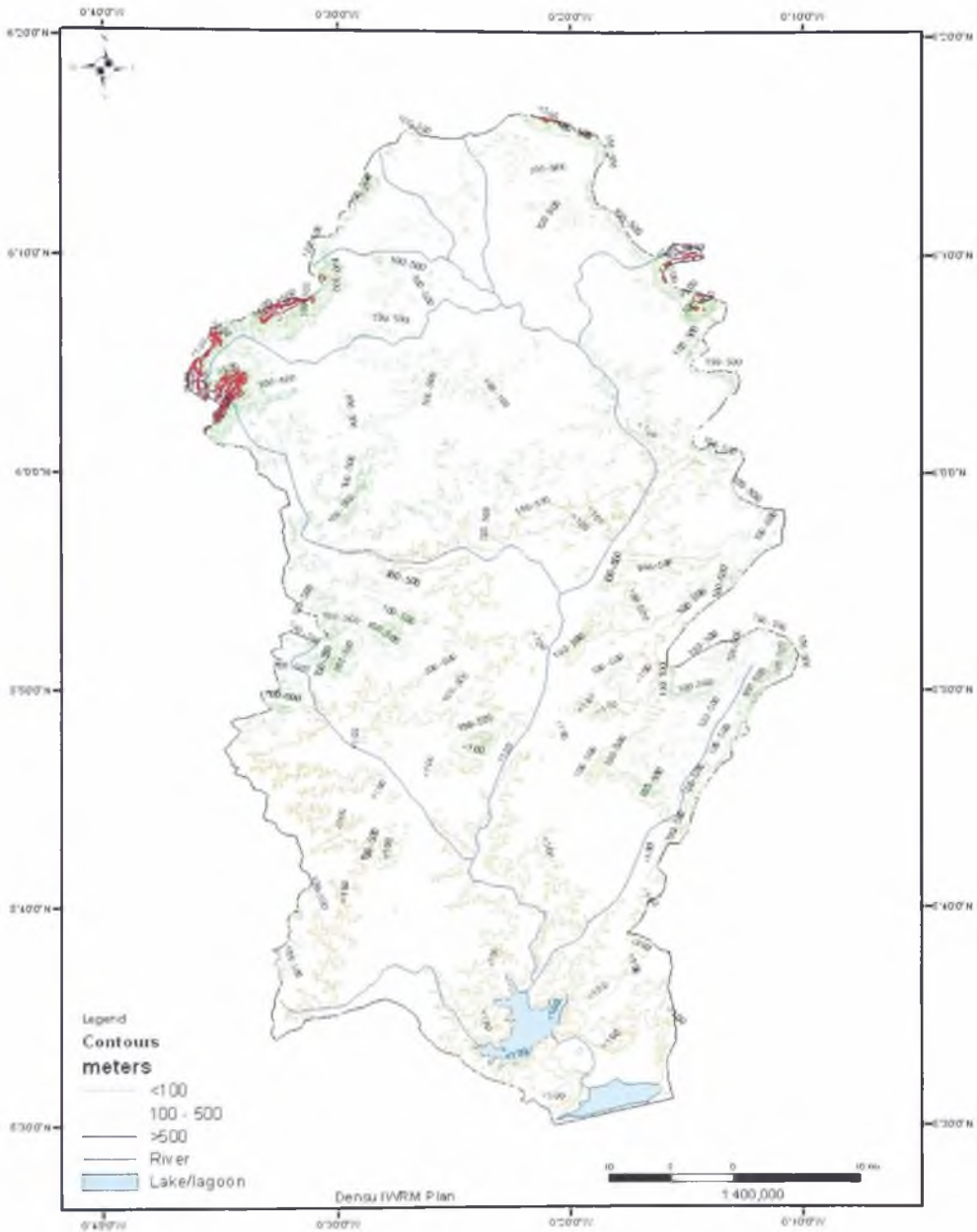


Fig 2.8 Topographic map of the Densu Basin (WRC, 2007)

2.3 Soils of the Densu basin

The major soil types of the Densu basin are Lixisols, Alisols, Leptosols, Acrisols, Luvisols, Fluvisols and solonchaks according to the FAO system of classification as classified in the soils map of the Densu basin by the soil research institute of Ghana (Fig. 2.9).

The fluvisols are alluvial deposits along the river beds. These soils show fluvial properties and they normally form on areas along rivers which are more or less regularly flooded. They contain high rates of weathered minerals.

Acrisols are typical tropical rainforest region or more humid areas of the Savannah soils. They are soils on young landscapes which show clay translocation. The clay accumulation horizon is rubeficated. These soils normally form as a result of the weathering of gneisses or granites by clay mineral formation and translocation on upper parts of slopes. They are usually shallow soils and are susceptible to erosion. Acrisols are located at the north western part of the basin where the Birimian formation made up of gneisses and other rock units of the upper Birimian formation are found. That portion of the basin also has a fairly high elevation. The acrisols have low infiltration capacity. This property of acrisols facilitates run off generation.

The lixisols, luvisols and leptosols groups of soils cover over 90% of the basin where the granitoids and the Togo rocks occur. The leptosols are weakly developed shallow soils which are limited in depth by continuous hard rock or calcareous material (calcium

carbonate equivalent of more than 40%). The lixisols are formed as a result of accumulation of clay and strong weathering and over a slowly permeable horizon. The luvisols are similar to the lixisols except that they have a higher cation exchange capacity than the lixisols.

From the analysis of the well logs, the soils of the basin range from gravels to clay. The soils found on the top of slopes are relatively well drained and are often thinner in thickness than those found in the flat surfaces or depressions. The river valleys are also characterised by relatively poorly drained sands and occasionally clayey sands. The general thickness of the soil in the basin ranges between 2 m and 10 m.

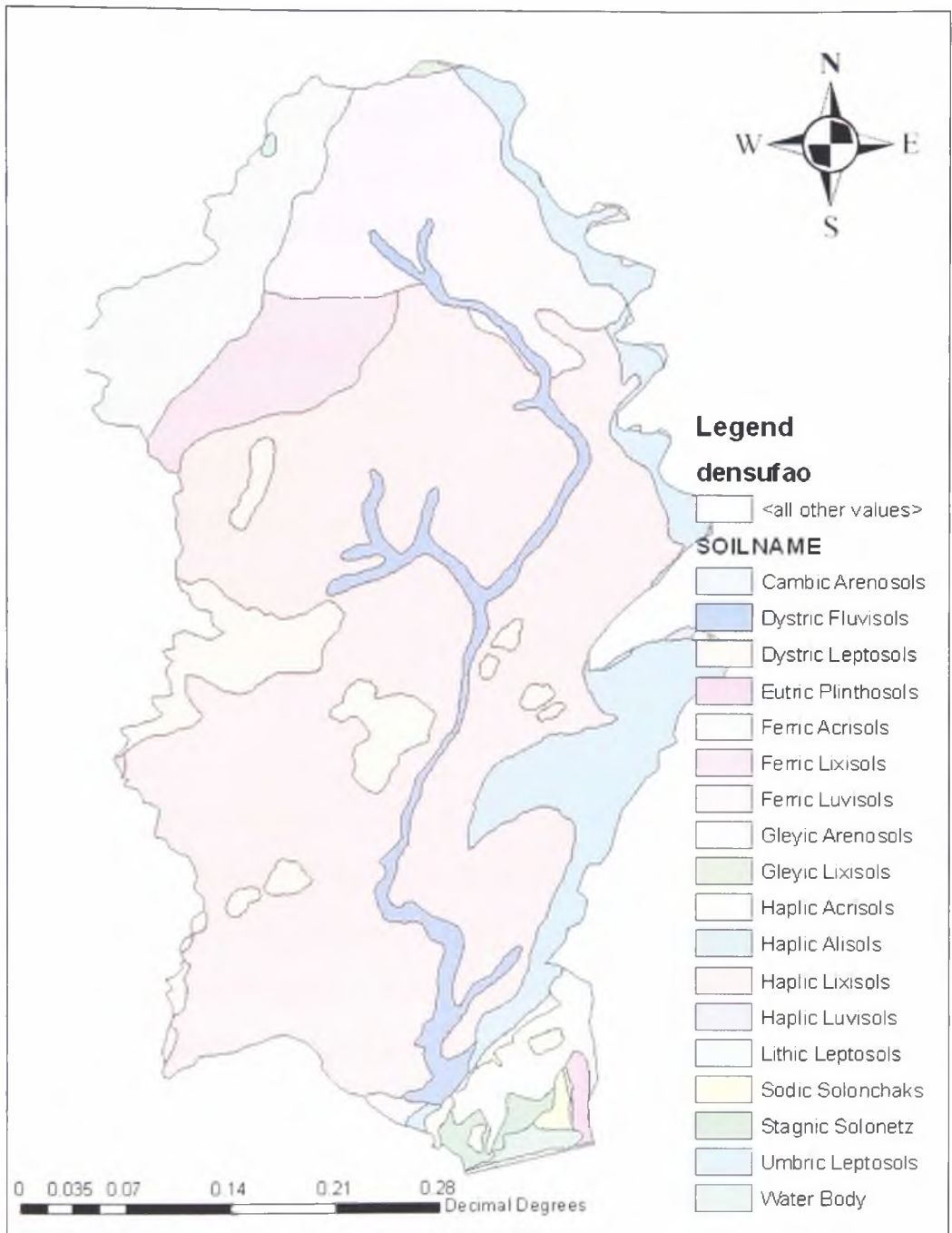


Fig 2.9 Soil map of the Densu Basin (Soil Research Institute of Ghana)

2.4 Geology of the Densu basin

The Densu River basin is composed of crystalline rocks comprising the Upper Birimian system and its associated Precambrian granites and granitoids as well as rocks of the Togo Series which form the Akwapim mountain ranges along the eastern border of the basin bounding the granitoids to the west (Fig.2.10).

The Birimian formation is the oldest rock unit in the study area. It occupies about 4% (based on field estimation) and occurs mainly in the north-western part of the basin. Rocks of the Birimian system that occur in the basin belong to the Upper Birimian formation. The Upper Birimian formation is generally highly foliated, folded, fractured as well as deeply weathered, as a result it has a high degree of secondary porosity. Consequently groundwater occurrence within the Birimian formation is relatively high (WRI, 2003).

The Upper Birimian unconformably overlies the Lower Birimian formation. The rock units that make up this formation include basaltic and andesitic lavas, pyroclastic rocks, hypabyssal intrusives and greywackes. The basic volcanic and pyroclastic rocks have been largely altered to chloritised and epidotised rocks that are some times loosely referred to as greenstones. Generally, rocks of the upper Birimian are intensely folded with dips often steeper than 60° and with general north-south or north-west strikes (Junner, 1940). The rocks of the formation have been highly sheared and usually form high ranges which stand out above the lower relief associated with the Lower Birimian formation (Adu and Asiamah, 1992).

The Birimian formation is intruded by granitoids of uncertain age but which are believed to be post – Birimian and – Pre Takwaian age (Kesse, 1985). These granitoids with their associated gneisses occupy about 90% of the Basin (WRI, 2003). The granites in the basin are classified as the Cape Coast granite complex. Like the upper Birimian formation, the Cape Coast granites are deeply weathered and foliated. There are numerous outcrops of the granites in the basin and they sometimes form isolated hills and inselbergs. Example of these can be seen around Nsawam where mount Nyanao is located. It is believed that the granites were formed from granitisation of older Birimian rocks (Layton, 1958). The granites are mostly comprised of hornblende granodiorites found around Tafo area, biotite granodiorites around Suhum and epidiorites dykes around Obutu.

The Togo Series rocks occur mainly at the Southeastern part of the basin and south of Weija. The Togo formation underlies about 6% (field estimation) of the Basin and it is made up of sandstones, quartzites, quartz schist, shale, phyllites and mica schist. These rocks are folded and highly jointed. They form a chain of hills known as the Akwapim mountain ranges which extend from the coast near Accra to the Togo border.

2.5 Aquifer development and groundwater occurrence

There are two main hydrogeological provinces in the study area: the crystalline basement complex and its associated granitoids and the meta sediments which are intensely deformed.

The crystalline rocks are essentially impermeable and virtually have no primary porosity as they are formed of interlocking crystals. Aquifer development therefore, is dependent on the formation of secondary porosity as a result of fracturing or weathering (WRC, 2007).

Fractures begin to develop in rocks when the stresses acting on the rock become equal to the strength of the rock. Mechanisms such as movement of lithospheric plates, fluid pressure, changes in weight of overlying material etc. are capable of producing high stresses in the earth's crust.

Due to the heterogeneous nature of fractured crystalline rocks, well yields of aquifers of the same rock formations differ by many orders of magnitude. The hydraulic properties of crystalline aquifers are largely dependent on the mechanical and geometrical properties of the fracture network within the rock mass. The shapes and dimension of natural fractures are not well known partly because the entire extent of a fracture is extremely difficult to observe in three dimensions. The geometry of a fracture depends on how it propagates and terminates and is often controlled by factors such as the geometry

of the fractured rock mass, loading conditions and interactions with neighboring fractures.

The porosity of plutonic and metamorphic rocks like those found in the Densu basin can significantly be increased artificially through the mechanism of hydro-fracturing. Permeability resulting from fracturing is a function of the width of the opening of the fracture as well as the density of the fractures.

Weathering due to chemical decomposition and physical disintegration increases rock porosity. Consequently, most of the groundwater resources in the basin are obtained from the crystalline basement complex, principally in the upper weathered rock or within fractures in the rocks.

Springs are found in the eastern part of the basin where the crystalline basement rocks come into contact with the quartzites of the Togo series along high slopes.

Recharge to the aquifer systems in the research area occurs in two forms: direct and indirect recharge. Direct recharge occurs in the highland areas especially in the eastern part of the basin specifically within the Togo series rocks where unconsolidated soil overlies the sandy weathered zone. These soils provide the storage and permeability for rain water to percolate through the unsaturated zone to the groundwater table after satisfying the soil moisture deficit. Direct recharge also occurs through the fractured or jointed and the weathered rock outcrops of the Birimian, Togo and the basic intrusive

rocks. Rain water percolates through these fractured or jointed or weathered portions of the exposed rocks.

Indirect recharge principally occurs in the low relief and low permeability areas particularly within the area around the Weija dam at the southern portion of the basin. This happens when runoff from the watershed outside the area or a particular storm event is sufficient enough to cause runoff. The drainage courses or streams which act as conduits for this overland flow are generally weak fractured zones which allow a greater part of the runoff to infiltrate through their beds to the groundwater table. The permanent streams in the area also contribute a significant amount of water to the aquifer systems either by infiltration through permeable stream beds, bank storage through alluvial soil or when the streams intersect a fractured, jointed or fault zone.

2.6 Socio-economic conditions

The water resources of the basin contribute greatly to the livelihood of the people within and out of the basin. Water is used mainly for domestic, agriculture and industrial purposes.

The main economic activity in the basin is agriculture which provides employment for majority of the people. Both commercial and subsistence agricultural activities are undertaken in the basin which together provide the food needs and financial income of the people. There are a number of irrigation systems at Nsawam, Weija, Suhum, Mangoase, Koforidua and other localities in the basin. The Nsawam irrigation scheme

abstracts water from the Dobro River (a major tributary of the Densu River) for the cultivation of ornamental flowers. The Weija irrigation system supplies water for the production of vegetables. There are also minor irrigation schemes all over the basin for the cultivation of various crops.

Fishing is also an income generating activity in the area especially in the upper reaches of the Densu River and at the southern sector of the basin. However, fishing is mostly practiced at subsistence level.

Timber logging has recently become a wide spread economic activity in the basin and it is mainly dominant in the northern part of basin which is characterized by forest vegetation. Harvesting of fuel wood has become an important economic activity particularly in the rural communities. Small scale gold mining activities are also common in the northern part of the basin where the Birimian formation is located.

In the urban areas, the economic activities are diversified and the prominent occupations include wholesale and retail trading, manufacturing and other commercial activities. The major industries within the basin are mainly fruit processing and bottle water production industries. In addition there are large commercial shops where manufactured goods are sold and also large markets which form points of contact between the rural and urban residents. Also common are small scale industries such as saw mills, block making and local soap manufacturing as well as metal works and carpentry.

The employment situation in the basin is such that 25% are unemployed, 60% are self employed and the remaining 15% are in more organized full time employment (Ghana Statistical Service, 2000).

2.7 Utilization of water resources in the Densu basin

The Densu River is one of the most exploited rivers in Ghana. It traverses several towns and serves as the main source of water supply for many communities within and outside the basin. The river is impounded by means of weirs at Koforidua and Nsawam and by a reservoir at Weija. Water is abstracted and treated at Koforidua and Nsawam and supplied to the towns for domestic, industrial and commercial purposes. Water from the Weija dam also serves as the main source of water supply to the western part of Accra. The volume of water abstracted from the Weija dam is about 200,000m³/d. There are also water abstraction points at New Tafo, Apedwa and Akwadum (Table 2.1).

The groundwater resources of the basin contribute significantly to the water supply needs of the communities within the basin. More than 600 boreholes have so far been drilled in the basin (records from Community Water and Sanitation Agency, Koforidua). Most of the boreholes are fitted with hand pumps for the abstraction of water for small communities. There are however, mechanized boreholes for small town water supply schemes, bottled water production and other industrial purposes.

Table 2.1 Piped water supply schemes in Densu basin (WRC, 2007)

Water supply scheme	Source	Intake	Treatment capacity M ³ /day	Abstraction	
				m ³ /day	Million m ³ /year
Weija	surface water	Dam	206,000	200,000	73.00
Other schemes:	groundwater	Boreholes	-	-	-
Adeiso	groundwater	3 boreholes	-	15	0.01
Apedwa	surface water	Weir	436	20	0.01
Old/New Tafo	surface water	Weir	1,080	760	0.28
Koforidua/Adweso	surface water	Weir	4,545	5,570	2.03
Akwadum/Nankese	groundwater	1 borehole	-	25	0.01
Suhum	groundwater	4 boreholes	-	380	0.14
Nsawam	surface water	Weir	4,320	4,050	1.48
Total, other schemes				10,820	3.96

CHAPTER THREE

3.0 Research methodology and data collection

The methodology of the research is designed to meet the targets of the research. Most often there are several ways with regards to details of the methodology in flow modeling but the major steps in modeling are fairly the same except that some objectives will require the application of all the major stages in modeling whereas others do not. Figure 3.1 summarizes the general steps adopted by this study in the development of the Densu basin model.

All the major components in the methodology are strictly dependent on the modelers understanding of the hydrological conditions and properties in the basin and therefore will often vary depending on the modeler's background as well as the research objectives.

In this study the development of a mathematical model for the basin was not elaborated because model code development was not part of the activities to be undertaken within the confines of this research. However, concise demonstrations of the principles governing the mathematical equations that describe the various flow processes are presented. The transformations of the partial differential equations to the finite difference equations based on which the MIKE SHE model simulates the various flow processes have also been described.

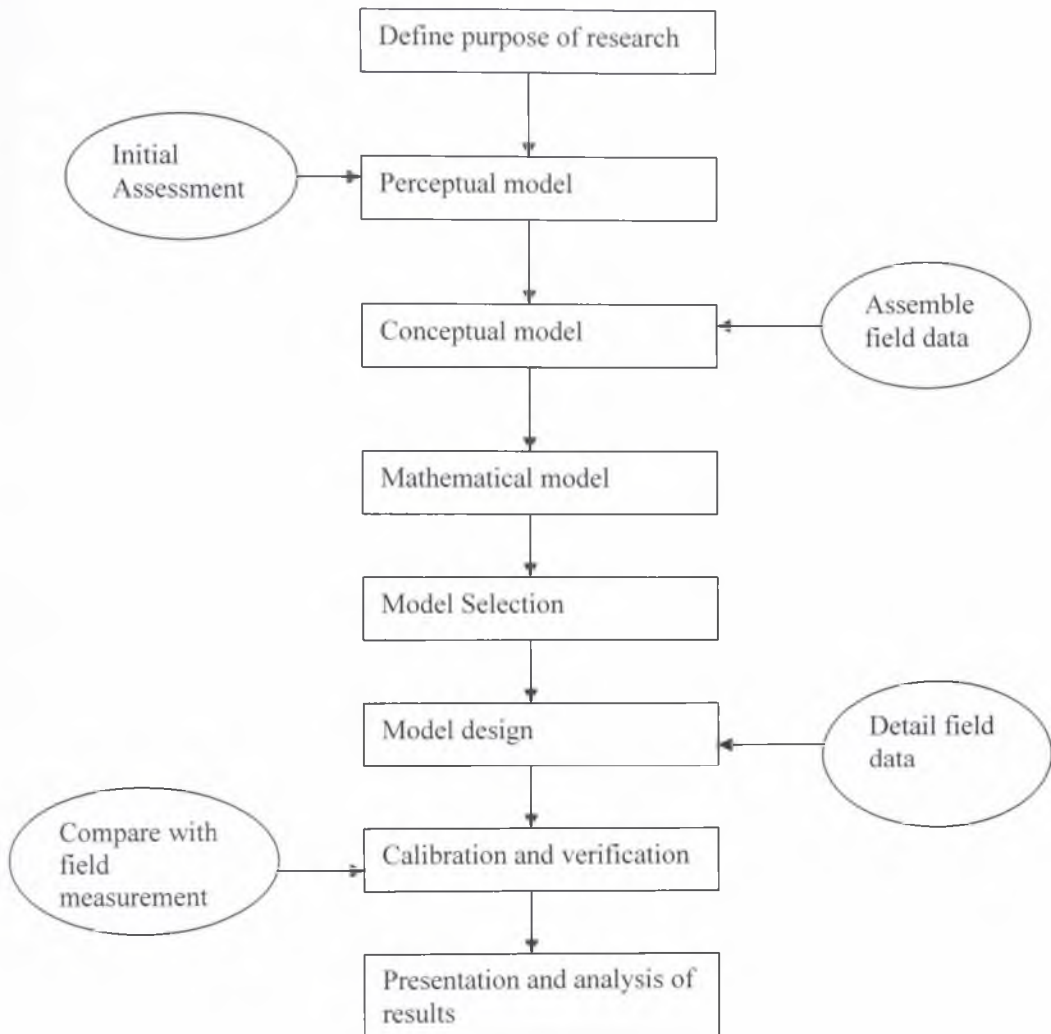


Fig 3.1 Steps in hydrological modeling in the Densu basin

3.1 Definition of research purpose

The first step in this research is defining the purpose of the research by formulating questions to be answered by the hydrological model of the basin. Most often the questions are the objectives set by the modeller but in some cases the question may vary

from the objective. The questions that are supposed to be answered by this model are designed in such a way that the objectives of the research will be addressed. The research proposal often describes in detail the extent of the problem and therefore, gives the bases for the formulation of questions to be addressed by the model.

3.2 Perceptual model.

After the purpose of the research has been clearly defined, there is the need to have a fairly informed perception of the hydrogeological / hydrological processes of the area. In reality, hydrogeological / hydrological systems are quite complex. Therefore every modeller will have his or her own perceptual model of a particular research area. This is because different modellers will consider differently, what hydrogeological / hydrological processes are most important or what are the best ways of describing such processes.

The perceptual model of the Densu basin is a fair description of the hydrological responses that may occur in different parts of the basin. Precipitation amount and intensity are not spatially uniform. The intensity and volume of rainfall in the basin show rapid variations from the upper part of the basin to the southern part. Both the volume and intensity of rainfall decrease from the northern part to the southern sector of the basin. In every storm event in the basin, some of the rainfall fall directly to the ground as direct through fall, some amount will be intercepted and evaporated from the canopy. Some of the intercepted water will drip from the vegetation canopy as through fall or run down the branches, trunks and stems as stem flow. The amount of intercepted water depends on the vegetation type and the type of canopy formed. The northern part of the

basin is likely to have more intercepted water than the southern part since the vegetation cover of the basin reduces from north to south.

Once the rainfall reaches the ground, it will start to infiltrate through the soil and fractures on rock outcrops. On the hilly part of the basin especially along the eastern boundary which is occupied by the Akwapim mountain ranges, runoff will start almost immediately. The rate and amount of infiltration depends on the amount of rainfall, the intensity of the rainfall, the local topography and the infiltration capacity of the soil. Where the input rate exceeds the infiltration capacity of the soil, water is ponded on the ground surface thereby generating runoff which is eventually routed towards the direction of lower gradient and finally to the river system in the basin. The soils in the basin exhibit high level of heterogeneity. Therefore, infiltration capacity and runoff generation vary greatly in space.

In the basin, it is possible to have recharge of groundwater occur almost immediately after rainfall through fractures on rock outcrops. Delayed recharge which is the most likely and dominant system occurs when infiltration through the soil is required. In these areas recharge occurs only when the soil is completely saturated. The infiltration capacities of soils are exceeded easily in areas where the soil permeabilities are lowest or where initial water contents are high. Once groundwater recharge has occurred, there will be a corresponding rise in water levels. Depending upon the level of the rise of the water table, there can be groundwater flow to streams often referred to as base flow or springs.

The base flow depends on the level of the groundwater table and the stream bed characteristics.

3.3 Data collection

Information on hydrogeological/hydrological and climatic conditions in the Densu basin was previously either scarce or unreliable due to lack of maintenance or neglect of the measuring stations. As a result, data obtained from these stations were not reliable and some times break down of equipment resulted in huge gaps in the data series. The situation has improved greatly in the last 5 years. The Ghana Meteorological Agency (GMA), The Water Research Institute (WRI) and the Hydrological Services Department (HSD) have been supported with funds from DANIDA to properly manage Climatic, Hydrogeological and Hydrological stations respectively. This situation has resulted in the acquisition of relatively improved data in the basin. The above mentioned institutions have also been tasked to fill in the gaps of old data to provide a complete data base of the basin.

3.3.1 Climate data

To ensure the availability of rainfall, temperature and potential evapotranspiration data, the GMA has been specifically tasked to undertake the following activities.

- Appraise all meteorological stations in the basin;
- Rehabilitate or upgrade meteorological stations in the basin;
- Collect rainfall and evapotranspiration data and make statistical evaluation of such data;

- Fill in gaps in data records.

3.3.1.1 Rainfall Data

There are a total of seven functional rainfall stations located within the Densu basin at, Koforidua, Pokuase, Kukurutumi, New Tafo, Nsawam, Suhum and Nankase (Fig.3.2). All the seven stations are capable of measuring daily rainfall through the use of rain gauges, temperature through the use of maximum and minimum thermometers and potential evapotranspiration using Piche evaporimeter and evaporation pan class A. The stations at Koforidua and Tafo have extra instrumentation such as barometers and barographs for the recording of atmospheric pressure, soil and earth thermometers to measure the soil temperature, cup – counter anemometer and wind vane for measuring the direction of the wind as well as sunshine recorders and actinographs for measuring sunshine duration and daily radiation respectively

For the purpose of this research, daily rainfall data were collected from the Ghana Meteorological Agency (GMA). The average size of basin area per gauging station is about 400 km² and that can be described as sufficient even though the basin is characterized by high spatial variability of rainfall from upstream to downstream. Rainfall data are collected at a daily time step therefore it is expected that the model will perform better in predicting runoff volumes rather than hydrograph peaks. Preliminary results indicate that the overall runoff pattern is well described. However, the timing of peak discharges are not adequately described. To improve upon the model prediction of hydrograph peaks, finer time resolution will be required. Therefore, event logger rainfall



gauges (Rain-0-matic type) were installed in four of the six synoptic stations namely, New Tafo, Koforidua, Nsawam and Pokuase (Fig. 3.2) to collect finer time resolution data on rainfall amount and intensity for a period of two years.

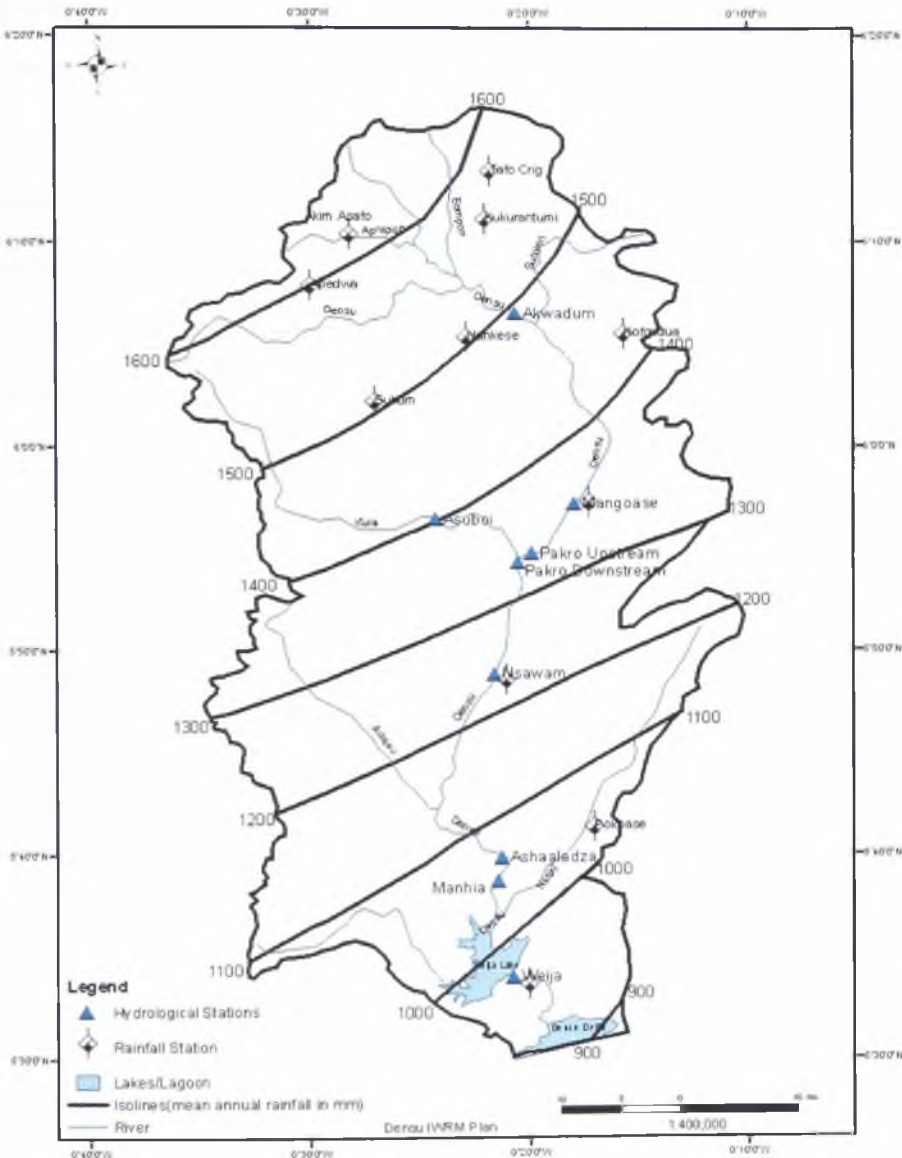


Fig 3.2 rainfall and hydrological stations in the Densu basin

3.3.1.2 Collection and processing of event logger rainfall data

Recording and computing rainfall intensity values can be done in different ways. Recording rain gauges where a pen is registering the amount of water on a chart can provide a continuous record of the intensity of rainfall by reading the slope of the curve on the chart. However, the procedure is time consuming and also prone to mechanical errors. Therefore, rainfall intensities in mm/h is now most often calculated based on recordings from tipping bucket rain gauges which facilitate the use of data loggers. The Tipping bucket rain gauges can operate either by counting the number of tips within a certain time interval e.g. 10 minutes or 1 hour and then calculate the intensity by dividing the amount of water ($\text{mm}/\text{tip} \times \text{tips}$) with the length of the time interval in seconds and multiply by 3600 seconds to get mm/h. Most tipping bucket rain gauges have tipping volumes of 0.1 to 0.25 mm rainfall. If the tipping volume is very small, the time between tips will be shorter and accuracy on time recording is likely to be inadequate. On the other hand, if the tipping volume is larger, the time between tips will be longer and therefore the accuracy will be improved. Another way to determine the intensity is by dividing the fixed volume by time between consecutive tips (seconds) and multiply with 3600 to get mm/h

In this investigation, a tipping bucket rain gauge (Rain-o-matic) type (manufactured in Denmark) was used for the collection of data (sample of recorded data in appendix 4). It has a rectangular orifice with an area of 50 cm^2 . The tipping mechanism is a single “spoon” which tips when 1 mm of rainfall has passed through the orifice. Due to the size of the gauge, interception loss of water is very small. Also the gauge is robust and



relatively cheap. The tipping mechanism is connected to a HOBO event logger that registers the time of the tip within 1 second. The accuracy of the tipping volume is approximately 2% while the time is recorded within ± 1 second. If the time between tips is 20 seconds, the time accuracy is ± 5 %. The overall accuracy on e.g. 180 mm/hour is then calculated as (Eq.3.1):

$$\sqrt{4 (2^2) + 25 (5^2)} = \text{approximately } 5.5 \%. \quad 3.1$$

The accuracy improves with lower intensities.

The event loggers are capable of recording up to 8,000 events and store the time and date of each one. Only one time per event is stored to minimize memory usage and to allow for longer time intervals for data collection. The memory storage capacity of the Hobo event loggers are large enough to store data up to 30 days in the Densu basin during the major rainfall season and up to 45 days during the minor rainfall season because of the low frequency of rainfall occurrence.

The four tipping bucket rain gauges were set up within the locations of existing synoptic stations so that the data recorded by the event loggers can be compared with those recorded by the synoptic stations operated by the Ghana Meteorological Agency (GMA). Two years of data recorded by the event loggers have been collected and processed for the purposes of rainfall duration and intensity analyses. Rainfall data from Nsawam and Pokuase were similar because of their proximity, therefore, only analyses of data from

one of them (Nsawam) was carried out to represent the entire downstream of the catchment.

The two years rainfall data collected from the four event loggers at the four different stations were sorted into different categories according to durations of rainfall events, time of the day in which the rainfall events occurred and the rainfall intensities of each tipping was computed. The daily and annual rainfall amounts from the event loggers were compared with rainfall data recorded at the existing synoptic stations for accuracy analyses. The annual rainfall of the event logger data differed from the annual rainfall from the synoptic stations data by amounts ranging from 5 mm to 9 mm representing 0.3 – 0.5 %. The sorted data were then analyzed to assess the pattern of rainfall durations, the time of the day of rainfall occurrence and the intensities in which the rains fall.

3.3.1.3 Spatial and temporal distribution of rainfall amount

The monthly averages of the two years data recorded by the event loggers and monthly averages of the same period data from existing synoptic stations are plotted to analyze the pattern of monthly rainfall amounts in the basin. Comparing Figures 3.3 and 3.4, it shows the same pattern with regards to the increase in rainfall amount from downstream (Nsawam) to upstream (Tafo).

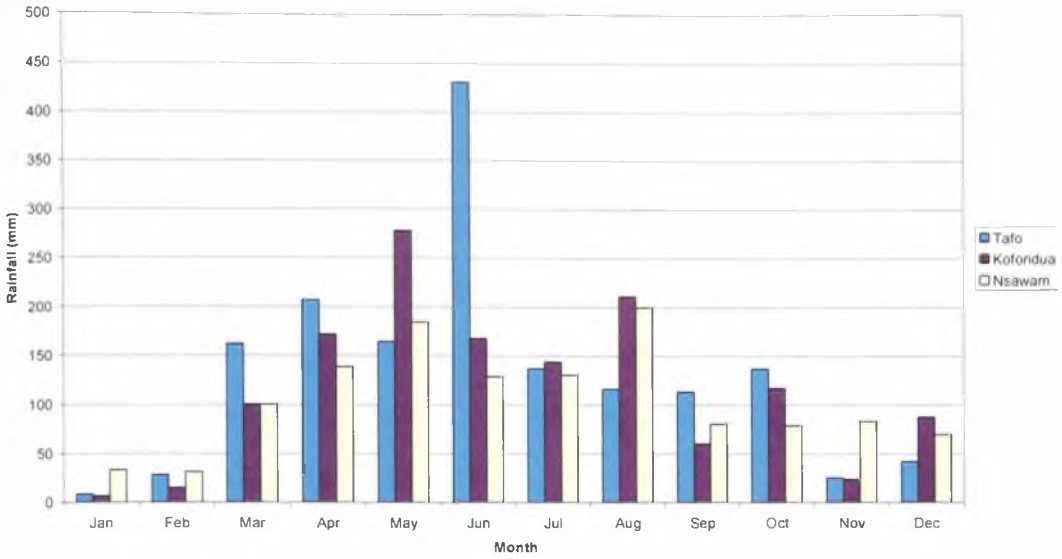


Fig. 3.3 Average monthly rainfall recorded by event loggers (2007 – 2008)

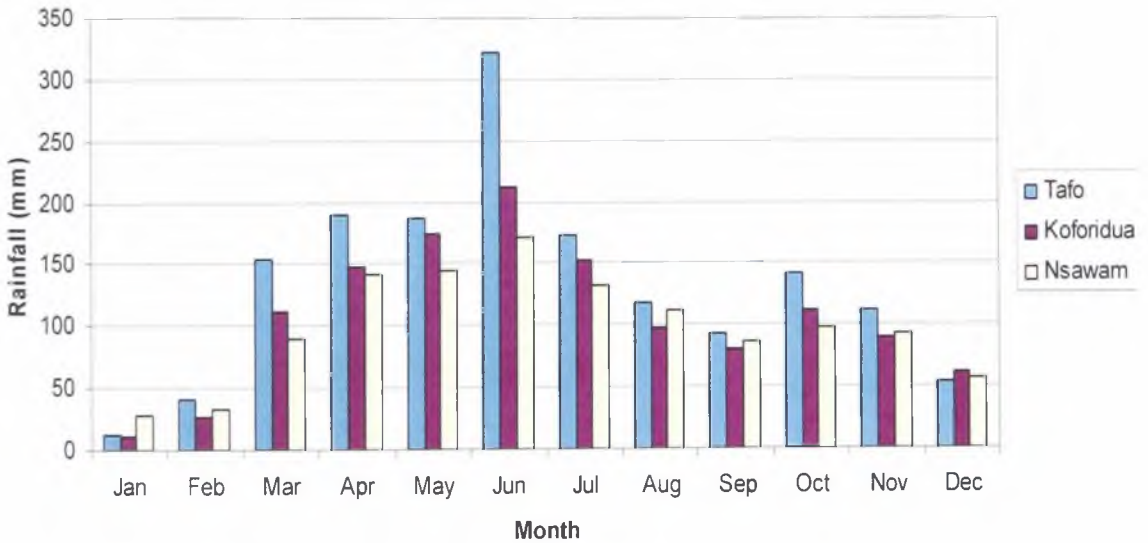


Fig. 3.4 Average monthly rainfall from synoptic stations (2007 – 2008)

3.3.1.4 Estimation of reference evapotranspiration

Over the past 60 years there has been a growing development of empirical methods for the estimation of evapotranspiration (ET_o) applying different climatic parameters. Some of the methods had regional limitations and therefore could not be calibrated to obtain global significance. Different empirical methods require different set of climatic data therefore, guidelines were developed and published in the FAO irrigation and drainage paper No. 24 entitled 'Crop water requirements'. Four methods were listed namely, the Pan Evaporation method, the Radiation method, the Blaney-Criddle method and the modified Penman method. After analysis of the performance of the four methods, the modified Penman method (Penman-Monteith) was generally considered to be relatively accurate with minimum error margin in relation to a living grass reference crop. The Penman-Monteith method can be applied in a wide range of climatic conditions as well as applicable in less data situations. However, depending on the location and the type of climatic coefficients available, the other three methods could be suitable and accurate

3.3.1.5 Computation of evapotranspiration in the Densu Basin

The Penman-Monteith method of computing evapotranspiration was used in the computation of monthly evapotranspiration values in 5 of the synoptic stations (Koforidua, Nsawam, Suhum, Pokuase and Tafo) in the basin where a reasonable amount of climatic parameters are measured. The computed evapotranspiration data for the four stations extrapolated to cover the entire basin based on a representative extrapolation method. The evapotranspiration data were then used as inputs in the MIKE SHE model which then simulates the daily actual evapotranspiration values.

3.3.1.6 Background of the Penman-Monteith method

Penman combined the energy balance equation and the mass transfer method to produce an equation for the computation of evaporation from open water surfaces using standard climatic coefficients such as sunshine, humidity, wind speed and temperature. Penman evaporation equation is presented in Equation 3.2.

$$\lambda E = \frac{\Delta(R_n - G) + \gamma E_a}{\gamma + \Delta} \quad 3.2$$

where λE represents the latent heat of evaporation ($\text{MJm}^{-2}\text{d}^{-1}$), R_n and G are the net radiation over open water (W m^{-2}) and the soil heat flux respectively ($\text{kPa}^\circ\text{C}^{-1}$), γ is the psychrometric constant ($\text{kPa}^\circ\text{C}^{-1}$), Δ represents the slope of the saturation vapour pressure temperature relationship ($\text{kPa}^\circ\text{C}^{-1}$) and $E_a = f(U)(e_s - e_a)$ where e_s and e_a are saturated and actual vapor pressures, respectively (mb). The daily soil heat flux (G) is relatively small in tropical regions compared to the net radiation (R_n). It is therefore, convenient to ignore the effect of G in the Penman equation

Equation 3.2 was later modified after simplifying assumption by Penman (1948 and 1963) to produce the Penman equation as presented in equation 3.3.

$$E_p = \frac{\Delta}{\Delta + \gamma} (R_n - G) + \frac{\gamma}{\Delta + \gamma} \frac{6.43(1 + 0.536U_2)}{\gamma} (e_s - e_a) \quad 3.3$$

Where U_2 = wind speed measured at 2 m elevation [m s^{-1}] and $(e_a - e_s)$ = average vapor pressure deficit over the estimation period [kPa].

The average vapour pressure deficit can be estimated by equation 3.4 (Shuttleworth,1993):

$$e_s - e_a = \left[\frac{e_s(T_{\max}) + e_s(T_{\min})}{2} \right] \left[1 - \frac{ARH}{100} \right] \quad 3.4$$

Where T_{\max} and T_{\min} represent maximum and minimum temperatures respectively over the period of estimation [$^{\circ}\text{C}$] and ARH is average relative humidity over the period of estimation (%).

Monteith further developed and extended the Penman method by introducing resistance factors. The resistance concept allows for the differentiations between aerodynamic resistance and surface resistance factors. The surface resistance, r_s , defines the resistance of vapour flow through stomata openings, total leaf area and soil surface. The aerodynamic resistance r_a , defines the resistance from the vegetation upward and involves friction from air flowing over vegetative surfaces (Allen, 1998). The Penman-Monteith combined equation is presented in equation 3.5:

$$ET_o = \frac{\Delta(Rn+G) + \rho C_p (e_s - e_a) / r_a}{\Delta + \gamma \left[\frac{r_s}{r_a} + 1 \right]} \quad 3.5$$

ρ_a = density of air (kg m^{-3}), $(e_s - e_a)$ represents the vapour pressure deficit of the air (Pa), c_p is the specific heat of the air and r_s and r_a are the surface and aerodynamic resistances respectively

The aerodynamic resistance determines the transfer of heat and water vapour from the evaporating surface into the air above the canopy.

The surface resistance describes the resistance of vapour flow through the transpiring crop and evaporating soil surface. In areas where the soil is not completely covered by the vegetation, the resistance factor will include evaporation from the soil surface.

The difficulty in the application of the Penman-Monteith equation is the estimations of aerodynamic and surface resistances. Ayibotele (1974) adopted values of 17.5 as the ratio of r_s/r_a in the Densu basin.

3.3.2 Hydrometric data

3.3.2.1 Hydrological measurements

Since the inception of the Water Resources Information Services (WRIS) project supported by DANIDA, a system of river gauging stations has been re-established in the basin to improve upon the hydrological data situation of the basin. There are five functional hydrological stations within the basin and they are located at Akwadum, Asuboi, Mangoase, Pakro and Ashalaja (Fig. 3.2). Measurements taken in these stations include: stage and discharge measurements which are used to establish rating curves, the rating curves are then used to calculate mean daily flows, Base Flow Index (BFI), Mean Monthly Flows, Annual Minima and Annual Maxima.

The river flow measurements were undertaken through depth sounding, either with a meter and rod assembly or with a special sounding line and weight (the wench). These were properly recorded and the number of revolution measurements was also recorded. The mean velocity at each of the measuring points in a vertical line was determined with the current meter by the following methods:

- Two-point method;
- Six-tenths-depth method;
- Vertical velocity-curve method.

Generally, the two-point method of measuring the number of revolutions in a vertical was employed where the depth of the channel is greater than 0.60m.

When the two-point method is applied, measurement of the number of revolutions of the propeller is taken at 0.2 and then at 0.8 of the depth from the water surface and using the average of the two measurements, the number of revolutions of the propeller is recorded for a period of 30 seconds. With the aid of the propeller equations, the velocities at each point in a vertical can be calculated. High accuracy is obtainable with this method, and its use is widely recommended especially in Ghana. The two-point method is however not used where the depth is less than 0.60 m. The six-tenths-depth method which consists of measuring the number of revolutions at 0.6 of the depth from the water surface is generally used for shallow flows where the two-point method is not applicable. Again,

the time set for this method is also 30 seconds. This method also gives satisfactory results.

3.3.2.2 Discharge computations

The velocity-area principle is usually used to compute discharge from current-meter data. Total discharge is determined by summation of partial discharges. A partial discharge is the product of an average point or vertical line velocity and its associated partial area, expressed in equation 3.6:

$$q_{r_i} = \bar{V}_n a_{r_i} \quad 3.6$$

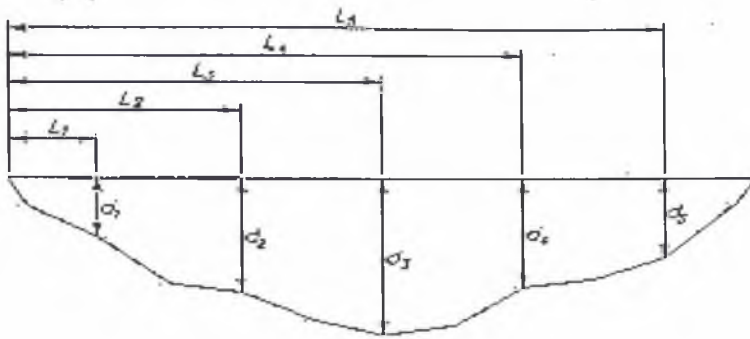
The total discharge is then computed by (Eq 3.7):

$$Q = \sum_1^n q_n \quad 3.7$$

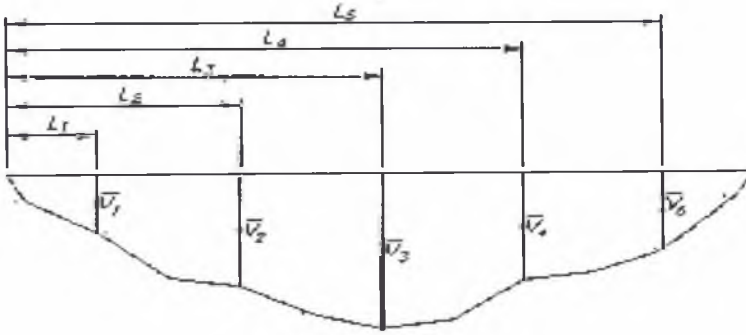
There are several methods of calculating the partial discharge in a section but the following methods were applied in the Densu Basin:

- The Simple Average Method;
- The Midsection Method;
- The Simpson's Parabolic Rule.

The simple average method is most widely used in Ghana but in the Densu basin, all the three methods listed above were used depending on the conditions of flow. The application of the simple average method is demonstrated in Fig. 3.5



Typical Cross Section



Horizontal Velocity Profile

Fig. 3.5 Calculation of discharge using the simple average method

The measured and computed variables are as follows:

q = discharge in cubic meters per second (m^3/s) for a partial area

Q = total discharge in cubic meters per second (m^3/s)

\bar{V}_n = mean velocity associated with the partial area

a = partial area of total cross section

L_1, L_2, \dots, L_n = distance to vertical measurement locations in feet from an initial point to vertical station

ΔL = the distance in feet between consecutive vertical measurement stations

$\bar{V}_1, \bar{V}_2, \dots, \bar{V}_n$ = the respective mean velocities in feet per second at vertical measurement stations

D_1, D_2, \dots, D_n = the water depths in feet at verticals

n = the number of verticals related to the partial area

3.3.2.3 Simple average method

The simple average method was employed in computing the partial discharge in a section. This method consists of taking simple average of two successive vertical depths, their mean velocity, and the distance between them. That is (Equations 3.8, 3.9, 3.10 and 3.11)):

$$\bar{U}_n = \left(\frac{u_{0.2} + u_{0.8}}{2} \right) \quad 3.8$$

$$\bar{V}_n = \left(\frac{\bar{U}_n + \bar{U}_{n+1}}{2} \right) \quad 3.9$$

$$a_n = \left[\frac{D_n + D_{n+1}}{2} \right] (L_{n+1} - L_n) \quad 3.10$$

$$q_n = \bar{V}_n a_n \quad 3.11$$

The subscript n denotes that the partial discharge, q , is for the area between two consecutive vertical measurement points as numbered.

3.3.2.4 Stage-discharge relation (rating curve)

After carrying-out discharge measurements and computations, a rating curve is developed for the station. There are several methods of developing rating curves. These include:

- Ordinary plotting of stage, h verses Discharge, Q
- Log-Log plotting of Stage, h verses Discharge, Q

The computer software, HYDATA from the Institute of Hydrology (IH), Water Resources Section, Wallingford, Oxford shire has been used in the processing of the data. The HYDATA software was used for the development of rating curves for all the hydrological stations in the basin. Hydata employs the ordinary plotting of stage verses discharge and the log-log plotting methods. A typical example of a rating curve developed using the HYDATA software for Mangoase on the Densu River is presented in Fig. 3.6. Rating equations for some of the measuring stations in the Densu basins are presented in equations 3.12, 3.13 and 3.14.

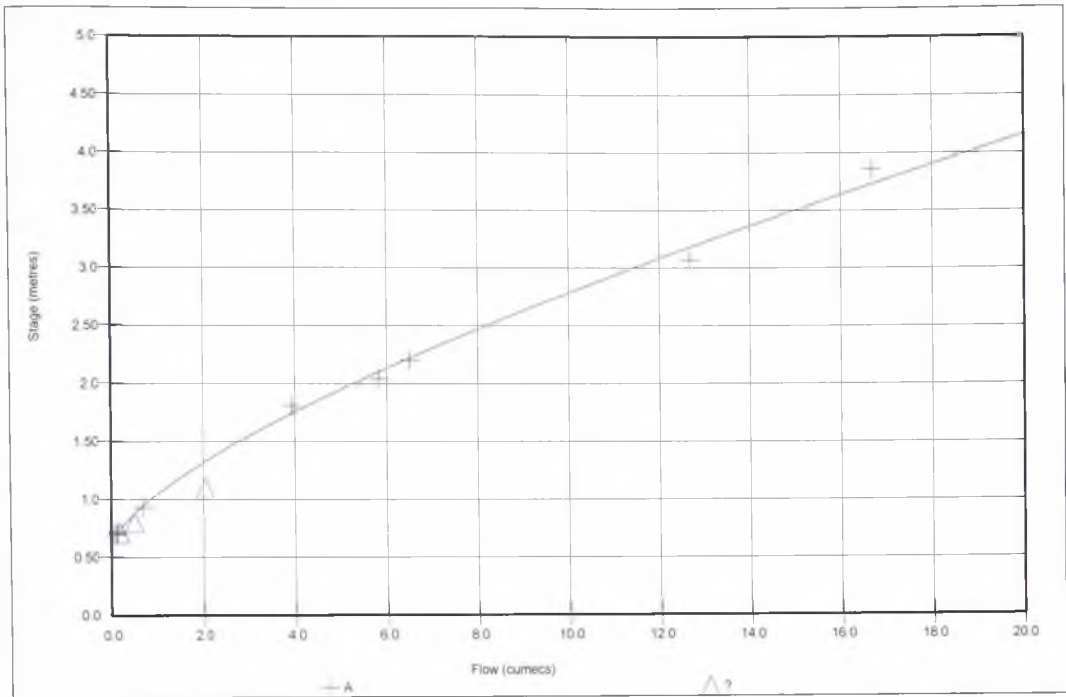


Figure 3.6 rating curve at Mangoase on Densu River

Rating equations for stations on the Densu basin:

Mangoase:

$$Q = 3.322(h - 0.614)^{1.421} \quad 3.12$$

Pakro

$$Q = 3.050(h - 0.347)^{1.529} \quad 3.13$$

Ashalaja

$$Q = 3.104(h - 0.119)^{1.794} \quad 3.14$$

3.3.2.5 River cross section data

River cross section surveys were undertaken in the Densu River and its tributaries at a chainage interval of 20,000 m and 10,000 m respectively based on minimum chainage model requirement. Seven cross section measurements were undertaken in the main Densu River. The number of cross sections taken on the tributaries varied according to the length of the rivers. The cross section survey was done to describe the shape of the rivers.

To undertake cross section measurements, the leveling instrument was mounted on the tripod and made level. Readings were taken at bench mark points by placing the leveling staff at those points. In areas where there are no bench mark points, a temporal bench mark was established either on a pillar or on top of a culvert headwall. Distances were measured along the river at required intervals for the longitudinal section. Measurements were then taken at five points across the river at different chainages. The zero point is the metering section where the flow measurements are taken at a distance of 50 m and 100 m upstream and downstream respectively of the metering section. These points have permanent pillars fixed on both sides of the bank of the river for future cross section to determine the changes that have taken place in the river channel over a period of time.

The raw data obtained from the surveys were imported into the MIKE 11 model for processing.

3.3.2.6 Groundwater monitoring data

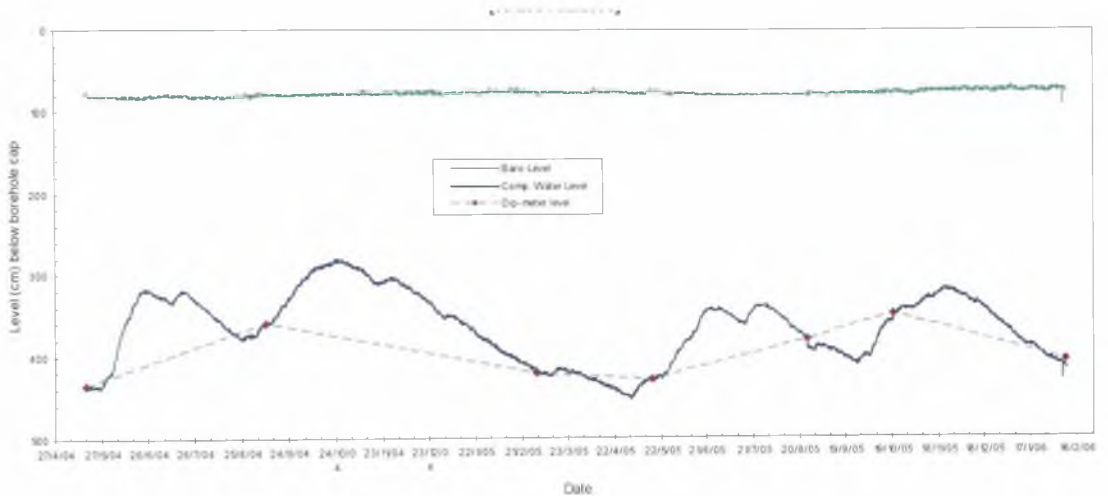
WRC through the DANIDA Water Resources Information Services (WRIS) project contracted the Water Research Institute (WRI) to undertake groundwater level monitoring in the Densu basin. Under the service agreement, data loggers (automatic water level recorders) were installed in 10 boreholes across the basin to measure the static water level and temperature at 6 hour intervals. The water levels are also measured with dip-meters to get the actual static water levels periodically. The reference points for the water level measurements are the borehole caps above the ground level. Barometric DIVERS were also installed in 3 of the boreholes to measure atmospheric pressures required for water level measurement compensations. The 10 monitoring stations are located in Tafo (CRIG), Adwumoku, Suhum, Pokrom-Nsaaba, Nsawam, Medie, Kojo Ashong, Ablekuma LP, Ablekuma CP and Domeabra.

The selection of sites for monitoring was based on the type of geology and structural features, hydrogeology and the location within the basin. Based on the above factors, 7 new boreholes were drilled and 3 existing boreholes rehabilitated for the monitoring project. The monitoring stations are distributed in such a way to cover the different geological formations in the basin. Out of the 10 monitoring stations, 1 is located in the Togo series down stream (Pokrom-Nsaaba station), 1 in the Upper Birimian formation upstream the Densu basin (Adwumoko station) and the remaining 8 are situated in the Precambrian granitoids and its associated gneisses. The Groundwater level monitoring stations are presented in Fig. 3.8.

The water level data were downloaded from the automatic recorders two times in a year but to avoid loss of data due to malfunctioning data recorders, field visits were made quarterly to inspect the DIVER.

Data was successfully collected in all the monitoring stations except the Ablekuma LP station due to defective DIVER. An example of the groundwater level measurements at Kojo Ashong monitoring station in the southern section of the basin is presented in Fig.

3.7.



3.3.3 Physical data on soils, land use and aquifers

3.3.3.1 Unsaturated zone data

The Densu basin is characterized by a variety of soil types. A total of eighteen soil pits were dug and examined in the field and samples taken for laboratory analysis of the physical and chemical properties as well as bulk densities of the soils. The sampling locations are shown in Fig. 3.9



Fig. 3.9 Densu Soil map and sample location

Based on the properties, the different soil types were categorized into three distinct major soil types which coincidentally follows the geologic setting in the basin therefore, the soils are named according to the geologic formations in the basin. The properties of each soil type were computed through averaging of six soil profiles. Table 3.1 shows the average values of the physical and chemical properties as well as bulk densities of the three different soil types.

Table 3.1 Vertical descritization and properties of the Densu basin soils

Soil type	Depth (cm)	% Sand	% Silt	% Clay	Texture	% O/M	Bulk Density (g/cm ³)
Birimian soils	0 – 20	26	29	45	Clay	2.22	1.51
	20 – 80	27	22	51	Clay	0.79	1.59
	80 – 320	30	19	51	Clay	0.46	1.51
Granite soils	0 – 20	61	17	21	Sandy Loam	2.53	1.53
	20 – 50	59	3	38	Sandy Clay	0.52	1.79
	50 – 100	52	2	46	Sandy Clay	0.43	1.71
	100-380	46	3	51	Sandy Clay	0.41	2.09
Togo series soils	0 – 70	73	13	14	Sandy Loam	0.88	1.73
	70 - 150	67	20	13	Sandy Loam	0.81	1.63
	150-400	66	18	16	Sandy Loam	0.50	1.90

Soil moisture content analysis is very important in computing water balance. It is especially useful for the estimation of groundwater recharge. The basis of the soil moisture content analysis for estimating recharge is that the soil becomes free draining when the moisture content of the soil reaches a limiting value called the field capacity; excess water then generates flow towards the aquifer. Knowledge of the hydraulic properties of soils and land use/cover is important in helping to identify important aquifer systems for development and sustainable management of groundwater resources in the basin.

The physical, chemical and bulk properties of the different soils were used as inputs parameters in an Excel spread sheet called Hypres Transfer – Function. This spread sheet calculates Van Genuchten UZ-parameters for MIKE SHE based on soil properties (% clay, % silt, % organic matter and bulk density). The two extra parameters required to complete a set up of the Van Genuchten model are saturated moisture content (θ_s) and residual moisture content (θ_r). These parameters were taken from standard textural averages of hydraulic parameters. Examples of the output curves of soil retention and hydraulic conductivity are presented in Figs. 3.10 and 3.11.

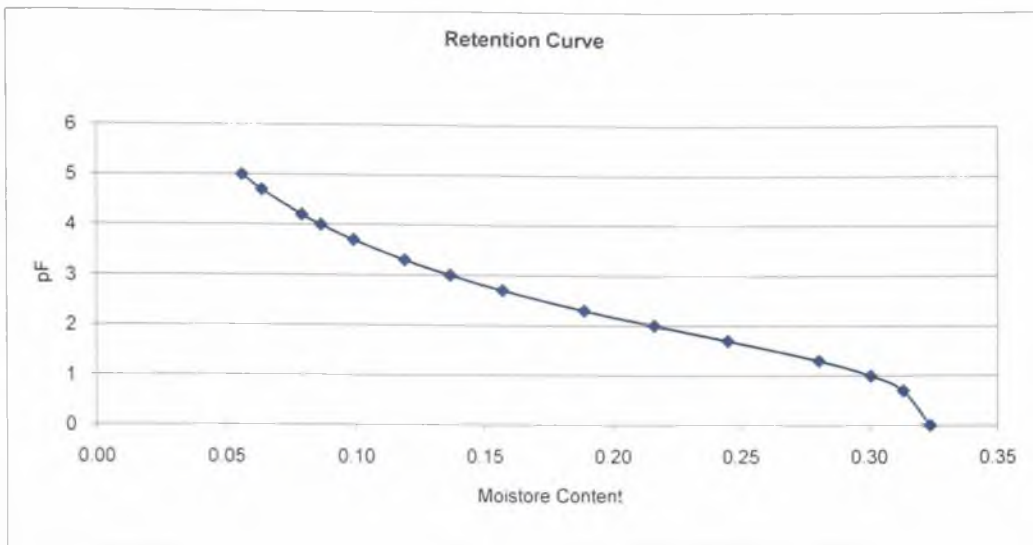


Fig. 3.10 Retention curve of the Togo series soils from 0 – 70 cm

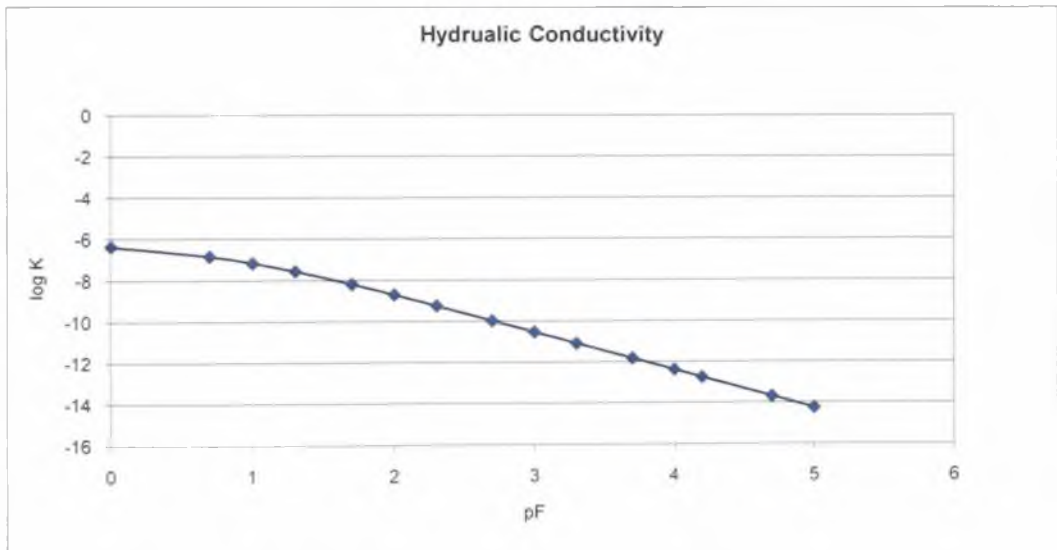


Fig 3.11 Hydraulic conductivity curve of the Togo series soils from 0 – 20 cm

3.3.3.2 Saturated zone data

There are over 500 boreholes in the Densu basin but many of them do not have data on lithology and aquifer parameters, as a result, only data on 320 boreholes were collected and analyzed for the setting up of the saturated zone and the distribution of aquifer parameters. Aquifer parameters obtained from pumping test analyses exhibit high level of heterogeneity. Transmissivity values of 100 boreholes within the same geologic formation (Granites) were analyzed and they exhibited wide variations. The transmissivity values range between 0.3 and 0.9 m²/d. As a result of the heterogeneous nature of the model area, the area was zoned into three different parts and average aquifer parameters were assigned to the different zones. Examples of the variations of aquifer parameters are shown in the pumping test analyses as shown in Appendix 3.2

Pumping tests were undertaken on four boreholes in the granite formation, two each in the Togo series and the Birimian formation to compare with pumping test data obtained from Community Water and Sanitation Agency (CWSA) and also to assess the extent of variability in aquifer characteristics. Water level measurements were recorded periodically through both pumping and recovery stages. Time-drawdown curves based on the Cooper-Jacob straight-line approximation method were used to determine the aquifer transmissivities.

3.3.3.3 Land Use/cover classification

The original vegetation of the Densu Basin was moist semi-deciduous forest with thick undergrowth featuring rich flora and fauna. Human activities through time have greatly

modified this forest ecology in a greater part of the basin as a result of farming and mining activities, timber logging and fuel wood harvesting. Within the past 15-20 years, the vegetation of the Densu Basin has changed dramatically. The thinning of the forest has intensified and at the same time the marked shift in land use caused by “urbanization” in the eastern corridor of the basin from Weija area through Nsawam to Koforidua has its ecological impacts (WRC, 2007).

At present the Densu Basin is characterized by three different types of vegetation zones. The north-western section of the basin is forested land, the mid section of the basin is characterized by scattered trees developing into areas of shrub and grass (WRC, 2007). These parts of the Basin are characterized by extensive cultivation of cassava, maize, pineapple and vegetables, and the extreme southern section of the basin is characterized by bush land interspersed with farm lands. The Weija Lake also occupies a significant portion of the southern part of the basin.

For the purpose of this research the basin is categorised into five Hydrological Response Units (HRU) based on the land Use/Cover types as presented in Fig. 3.12. Hydrologic Response Unit is considered to have homogeneous hydrological characteristics and therefore respond to rainfall in almost the same way. The classification of HRU in this case is with regards to the hydrological response to rainfall with regards to land cover/used. The north-western conner of the basin is characterised by forest vegetation (grid code 1), the north-eastern and the mid potions of the basin is characterised by savannah (grid code 2) and the southern part is occupied by bush (Grid code 3). There are

also scattered farm lands and Plantations in the basin which are represented by Grid code 4. The Weija Lake which occupies a significant portion of the southern part of the basin is represented by grid code 5. Grid code 0 defines the boundary of the model domain (Fig. 3.12).

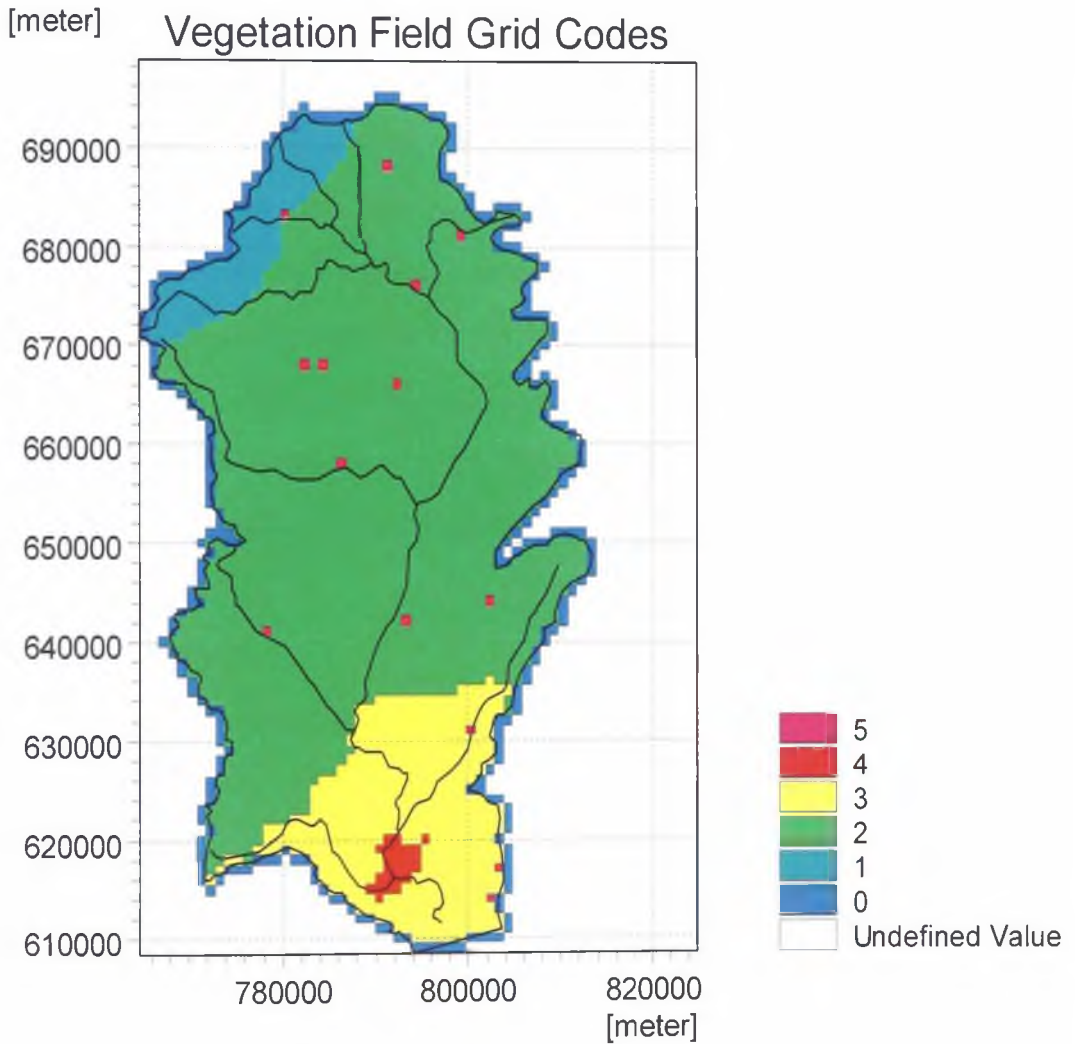


Fig 3.12 Land use/cover classification in the Densu basin

Land use/cover controls to a large extent the hydrological processes in the basin especially erosion, interception, evapotranspiration and infiltration. Land use/cover data are therefore very important in catchment modeling especially the application of physically based distributed models. Remote sensing information has become the common source of dynamic land use/cover data. Unique characteristics of different spectral bands make it possible to determine vegetation and land use types. Based on satellite image analysis, Leaf Area Index (LAI) and Root Depth (RD) time series data were derived from standard tables according to canopy development for given vegetation types. Interception storage is an important component of water balance. The amount of water that is retained on the leaves, stems and braches of vegetation depends on the vegetation type and its stage of development which is characterized by the Leaf Area Index. Leaf Area Index is defined by the area of leaves above a unit area of the ground surface and it varies according to time and vegetation type.

3.4 Conceptual model

This is a systematic description of the flow processes as well as other field conditions by assembling field data.

The first and most important step in conceptual model development is to carry out a proper characterization of the hydrogeological / hydrological conditions within the model domain. This gives a better understanding of the importance of relevant flow process.

This level of characterization requires a more site-specific field work rather than an initial assessment that is enough for a perceptual model development.

The geology of the basin can be categorized into three main geological settings. The prominent geologic formation in the basin is the granitoids which occupy close to 90% of the entire basin. The average topographic gradient of the granite area is low compared to the gradient within the Togo and the Birimian areas. The second most dominant formation is the Togo series which form a belt of mountain chains bounding the basin to the east. The third formation is the Birimian formation to the north of the basin. Aquifer development in all the three formation is as a result of weathering and fracturing. Borehole profiles analysis show that the topmost portion of the basin (average of 1 – 5 m) is occupied by soils of different kinds. Soil properties analyses show that high permeable soils overlies relatively impermeable soils within the top 5 m of the soil layer therefore it is expected that Storm overland flow will dominate the contribution of overland flow to streams. This is underlain by highly weathered zones normally between an average interval of 6 – 15 m. The slightly weathered zones occur from an average of 16 – 45 m and the fractured zones between averages of 46 – to about 70 m (Fig.3.13). Most often groundwater is abstracted from the base of the slightly weathered zone or the fractured zones or both (dual porosity aquifer system). The highly weathered zones normally provide favorable conditions for groundwater recharge but do not normally form aquifers systems.

The following hydrogeological / hydrological data have been analyzed for the characterization and conceptualization of the study area:

- Land use/cover data;
- Geologic data depicting subsurface geology/borehole logs;
- Topographic data;
- Surface water bodies and measured stream discharge data;
- soil boring logs;
- Measured hydraulic head data;
- Estimates of hydraulic conductivity derived from aquifer and slug test data.

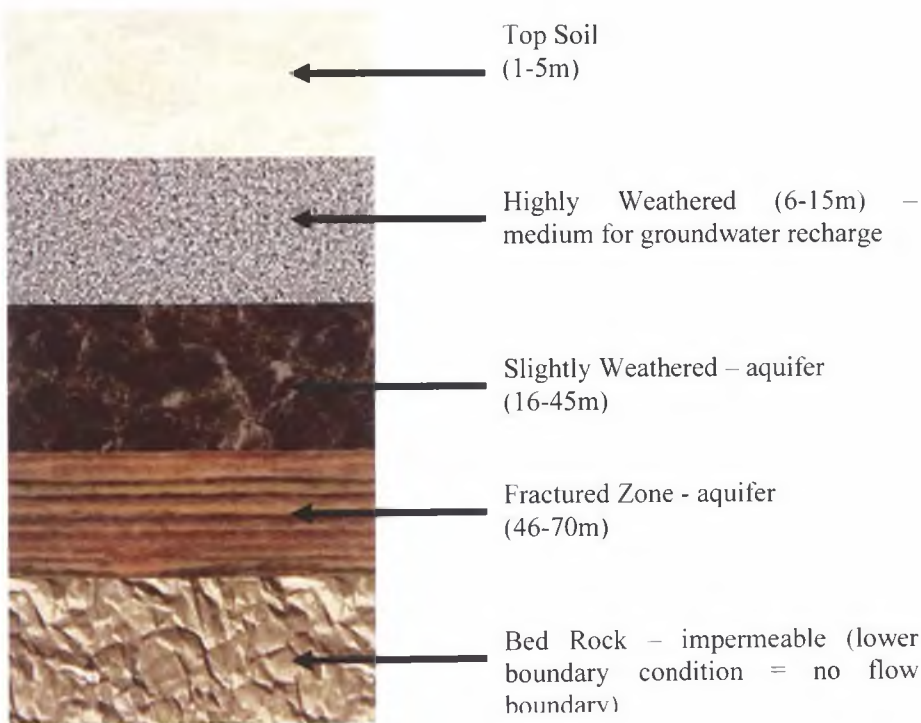


Fig. 3.13 Conceptual model of the unsaturated and saturated zone of the study area

3.5 Mathematical model

Over the last few years, computer simulation models for analyzing flow in overland, groundwater and surface water systems have become increasingly important in water resources development and management. Flow models represent the actual flow processes with mathematical equations. Computer simulation of flow systems, numerically evaluate the mathematical equation governing the flow of fluids through porous media and on the land surface. The formulation of a mathematical model requires a thorough definition of the following processes to ensure that the important processes and field conditions are well represented and described.

- define geometry of the model domain (dimensionality, shape, moving boundaries);
- determine system parameters (natural constants, material properties etc.) considering spatial or temporal variations if present;
- develop or select a partial differential equation (PDE), which is usually based on physical principles like conservation of volume or mass or energy or momentum;
- specify initial conditions (ICs);
values of the unknown function(s) at time $t = 0$;
- specify boundary conditions (BCs);
- BCs have to be specified along the complete boundary of the model domain.

In this study, the development of a mathematical model is not considered since the objectives of the study do not include the development of model codes. However, an assessment of the mathematical models was undertaken in the selection of the model

code to ensure that the assumptions of the mathematical model apply to the area under investigation.

3.6 Model selection

There are a number of hydrological modeling systems which can be grouped into three categories namely:

- Empirical black box models;
- Lump Conceptual models;
- Distributed physically based models.

The first two groups of models can be described as simple models in the sense that they require less data and also their parameters are not or only partially related to the physical processes of the catchment. The distributed physically based models on the other hand are quite complex in nature in the sense that they require a great deal of parameters which are directly related to the physical conditions of the catchment under investigation.

In the selection of a model code for the research, the following factors were considered:

- the availability of data;
- the research objectives;
- the numerical / analytical methods;
- knowledge in different models;
- the applicability of the model to the catchment under investigation;

- affordability of the model software.

The NAM model which is a lump conceptual model and the MIKE SHE model which is a distributed physically based model were selected for the research. The reason for choosing these models was to compare the strength and weaknesses of the lump conceptual models and distributed physically based models given the conditions and circumstances that prevail in the Densu basin.

3.6.1 NAM model

The NAM model is a hydrological modeling system (rainfall / runoff model) that can be classified as a lumped conceptual type. It was originally developed at the Technical University of Denmark (Nielsen and Hansen, 1973) and later modified by the Danish Hydraulic Institute (DHI) – Water and Environment.

The NAM model employs the linear reservoir principles in its operation. It accounts for the water content in 4 mutually interrelated different storages namely: Snow storage, surface storage, root zone storage and groundwater storage (Fig. 3.14). For the purpose of this research the snow component is not considered for obvious reasons. The NAM model is designed with basically 9 parameters with additional parameters for extended applications. The parameters are not directly related to the physical conditions in any one catchment.

The NAM model is a relatively simple model that requires moderate input data. The main input data in the NAM model includes, size of catchment, time series rainfall data and time series potential evapotranspiration data. Discharge measurements are included in the model for the purposes of calibration and verification of the model. The 9 parameters are calibrated to ensure a reasonable match of the simulated results and the measured data.

The NAM model apart from the less data requirement is also easy to set up and is capable of simulating high flows and low flows to a high degree of accuracy. It also has a low validated water balance error of less than 5%.

The disadvantage of the NAM model is that, it considers the entire catchment as a single unit and therefore disregards spatial variations of the input data. In addition, it uses catchment averages for simulation and also it is not physically based in the sense that the parameters are not physically linked to field conditions within the catchment under investigation.

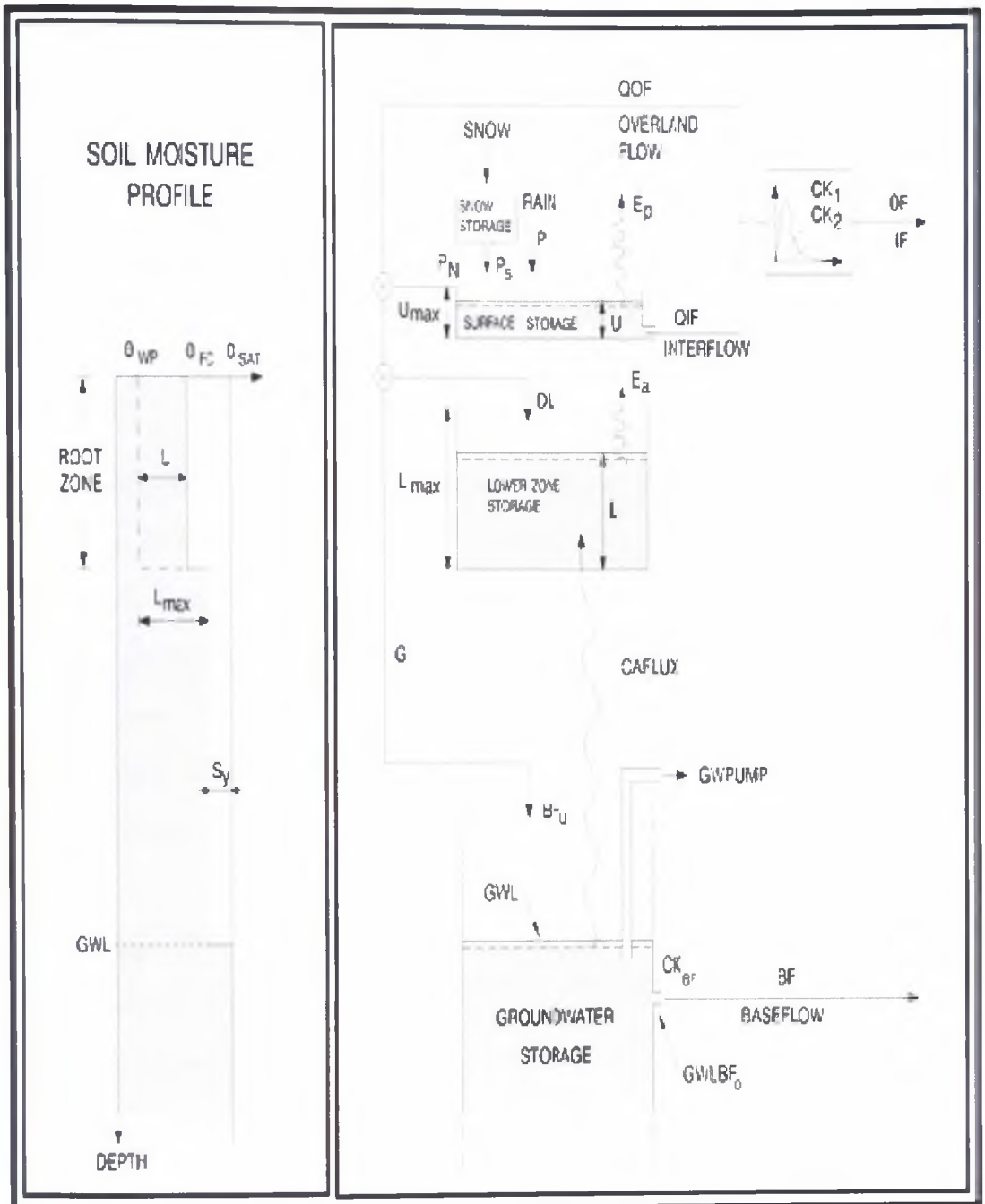


Fig. 3.14 A schematic representation of the NAM Model

3.6.2 MIKE SHE model

The MIKE SHE is a fully deterministic, distributed and physically based modeling system capable of describing the major flow processes in the land phase of the hydrological cycle (Fig. 3.15). It was first developed by a consortium of three European organizations called Systeme Hydrologique Europeen (SHE) based on the blue print of Freeze and Harlan (MIKE SHE user Guide). MIKE SHE was further developed and extended by DHI Water and Environment since the mid 1980s.

The Generic engine of MIKE SHE is capable of solving the partial differential equations that describe the major flow processes in the land phase through various dimensions. For this research, the following options were selected for the simulation of the different major flow processes in the land phase: two dimensional, kinetic wave for overland flow, one dimensional, diffusive wave for channel flow, one dimensional, Richards' equation for unsaturated zone flow and three dimensional finite difference methods for groundwater flow.

The advantage of the MIKE SHE modeling system is that it is a fully integrated model and it allows for flexibility in its applications as a result, the different major flow processes in the land phase of the hydrological cycle can be represented at different levels of temporal and spatial scales as well as different levels of complexity. It also provides the framework for the modeler to design the model based on the modeler's perceptual and conceptual model of the catchment. Furthermore, the MIKE SHE model is capable of describing complex hydrological processes.

The main disadvantage of the MIKE SHE modeling systems is that it requires a great deal of data and also it is a complex modeling system compared to the Lumped conceptual models and other distributed physically based modeling systems.

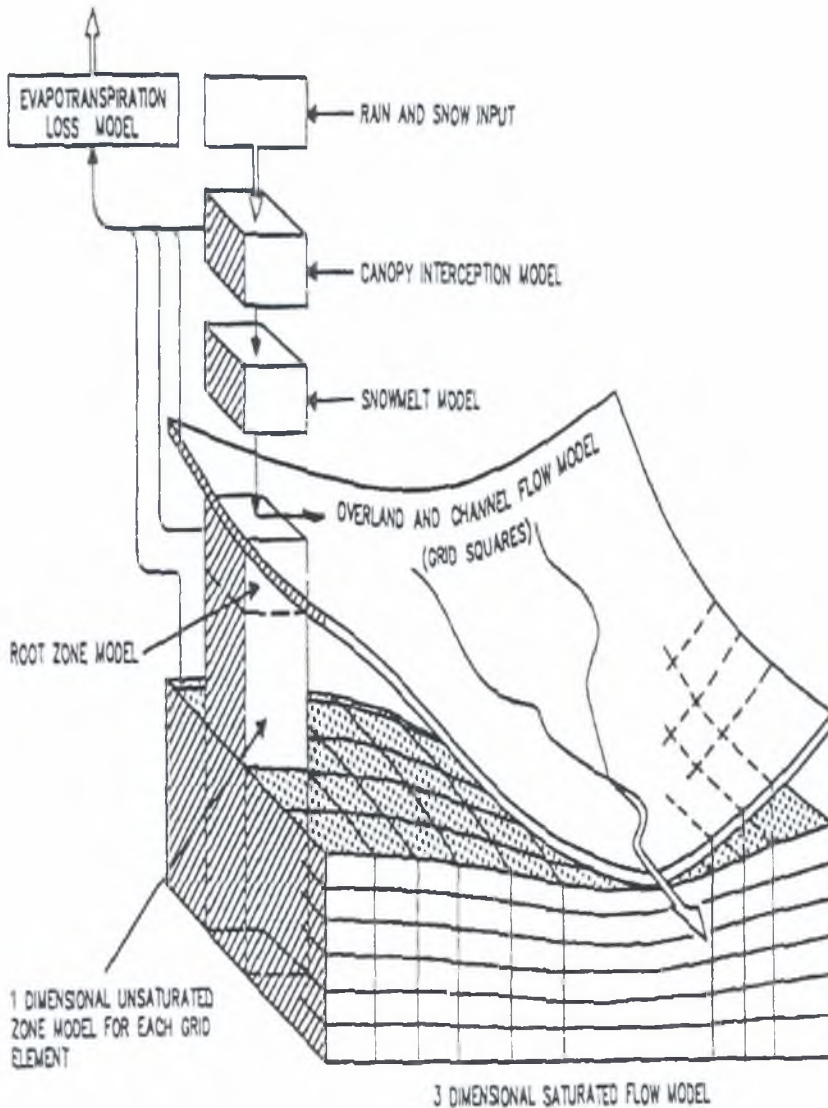


Fig. 3.15 A schematic presentation of the MIKE SHE (DHI, 1993b)

3.7 Model design

The Model was designed by transferring the conceptual model into a numerical one. The physical conditions in the field that control the flow of water were transferred into the MIKE SHE model in the form of gridded data (dfs2 and GIS shape file) as well as in the form of time series data (dfs0 files) and specified parameter values. The dimensionality of flows, spatial and temporal resolutions and boundary conditions were defined.

The Model domain and grid were defined in the simulation specification dialog. The model domain defines the boundary of the catchment to be modeled and was defined by a dfs2 file which also specified the model grid cell size (1000m x 1000m). The choice of the size of the model grid was based on the scale of data measurement in the basin. It is often difficult to determine optimal grid size for modeling since both large and small grid sizes are associated with truncation and round off errors. The resolutions of all other data layers are defined by the grid cell size. A major part of the model boundary was defined as a zero flux boundary (boundary condition of the first kind) using the topographic divide except the southern part of the catchment where water flows out of the basin into the ocean. This part of the boundary was defined as a fix head boundary because the level of water at that boundary remains constant at all times due to the interaction of ocean and the basin.

The precipitation and reference evapotranspiration data were imported in the form of both grid and time series data. The grid data defined the area of influence of each rainfall

station in the form of theissen polygons. A total of 6 theissen polygons representing six rainfall stations were defined. The rainfall and reference evapotranspiration data were incorporated into the model in the form of time series data (dfs0 files). Daily rainfall and reference evapotranspiration data from 2000 – 2005 (simulation period) were used. Land use/cover was also defined in the land use dialog. This is important for the simulation of evapotranspiration. Five land use classes were identified and their properties were defined by time series Leaf Area Index (LAI) and root depth (RD) from 2000 – 2005.

Overland flow was represented in a 2-D mode and the governing equation for water flow on the ground surface was solved using finite difference method. In MIKE SHE, Overland flow is simulated using the same time step as the unsaturated zone.

Channel flow was defined in the MIKE 11 program for the simulation of river flow. The river network made up of digitized points, calculation nodes (cross section points) and boundary conditions were defined in the MIKE 11 module and coupled with MIKE SHE. One dimensional river flow was assumed. MIKE 11 simulates unsteady water discharges and levels in rivers using an implicit finite difference formulation.

The unsaturated zone was designed by defining the different soil profiles and their corresponding vertical discretization of the different soil classes in the model area and the soil properties were defined by the Van Genuchten model. Water flow in the unsaturated zone was defined only vertically since gravity is the dominant force that drives infiltration. The flow in the unsaturated zone was simulated using the Richards equation

even though there are other options of simulating unsaturated zone flow. MIKE SHE links the unsaturated zone and the top calculation layer of the saturated zone together using an explicit coupling method. This method of coupling allows for different time steps in saturated zone and unsaturated zone flow simulations.

A 3-dimensional saturated zone flow was designed in the saturated zone dialog by defining two saturated layers based on the conceptual model of the basin. The parameters of the unsaturated zone were assigned via the geologic units that make up the different layers. The geologic units in this case represented the different forms of porosities i.e., the weathered and the fractured zones, hence the saturated zone parameters were lumped into weather zone parameters and fractured zone parameters. The bottom of the second layer served as a no flow boundary. No boundary conditions were defined between the two layers because they are hydrologically connected. The partitioning of the two layers was done in order to assign different hydrogeological parameters since the weathered and the fractured zones differ in hydrogeological properties. Hydrogeological parameters were assigned manually to the different layers.

In MIKE SHE, the 3-D mathematical equation which describes the governing processes of the saturated zone is solved numerically by iterative implicit finite difference method. There are two iterative solution methods for solving the implicit finite difference equation but in this simulation, the Successive Over Relaxation (SOR) method was chosen. The iterative solution method solves the finite difference equation in a series of forward steps. Each of these forward steps produces an intermediate result and eventually the sequence

of these intermediate results finally approaches the new head value. This process where a series of forward steps is required to solve the finite difference equation instead of a single forward computation is called iteration. The principle of iterative solution methods is demonstrated in fig. 3.16.

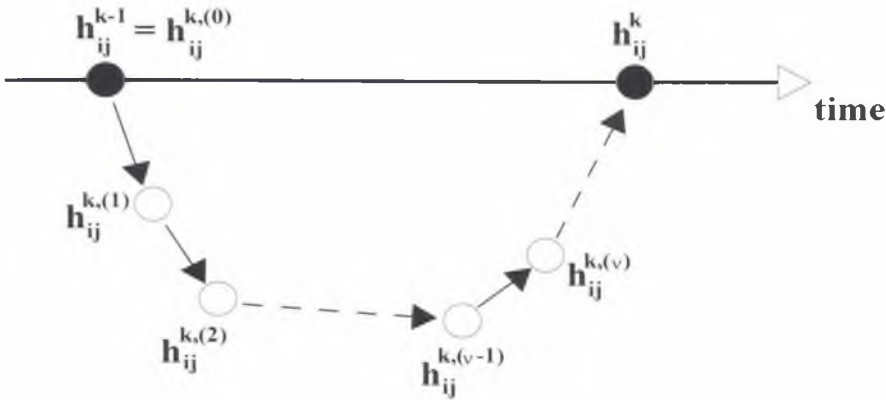


Fig. 3.16 Principle of iterative solution method (Liedl and Teutsch, 2002)

Where h = head value, ij identifies the grid cell (spatial discretization), k is the time step ($k-1$ means previous time step and k is present time step)

Figure 3.16 demonstrates that, in order to simulate present head values in a certain grid cells (h_{ij}^k), there must be known head information in the past on that particular grid cell (initial conditions = $h_{ij}^{k,(0)}$). The number of iterative steps depends on the interval of the time step. Wider time steps will require more iterative steps to arrive at present or future head information and vice versa.

3.8 Model calibration

The main objective of carrying out model calibration or inverse modeling is to improve values of model parameters such that model results will match as closely as possible with field measurements. A vigorous calibration was undertaken to estimate most of the model parameters for the MIKE SHE model because of the inadequate availability of data. The calibration was also necessary because it is practically impossible to determine parameters for each computational grid point due to differences in the scale of data collection, and sizes of model grids.

In the calibration process, parameters values were adjusted manually (adjusting parameters value one after the other) with the aim of decreasing the values of the mean absolute error (MAE) and the residual mean square (RMS) so as to obtain a reasonable reproduction of measured values. One parameter value was adjusted in each calibration step in order to determine the impact of the parameter on the improvement of the MEA and RMS (sensitivity analysis). The parameter adjustments were done based on the modeller's knowledge and understanding of the field properties and processes in the research area. The calibration steps continued until a calibrated target is achieved. This is achieved when the parameter value and its associated deviation is considered acceptable. An acceptable calibration varies from one modeller to the other depending on the objective of the modelling exercise as well as the project duration. The targeted acceptable calibration for this research is a Mean Error (ME) of less than 1.0 and Root Mean Square Error (RMSE) of less than 5.0. Calibration is a very important stage of

modelling and normally takes longer time especially if adequate field data are not available or are not reliable.

The manual method of calibration was applied to both the NAM model and the MIKE SHE model. In the case of the NAM model where the number of calibrated parameters is far less, the calibration process is far simpler than in the MIKE SHE model. Examples of calibrated results of the NAM model are presented in Figures 3.17 and 3.18.

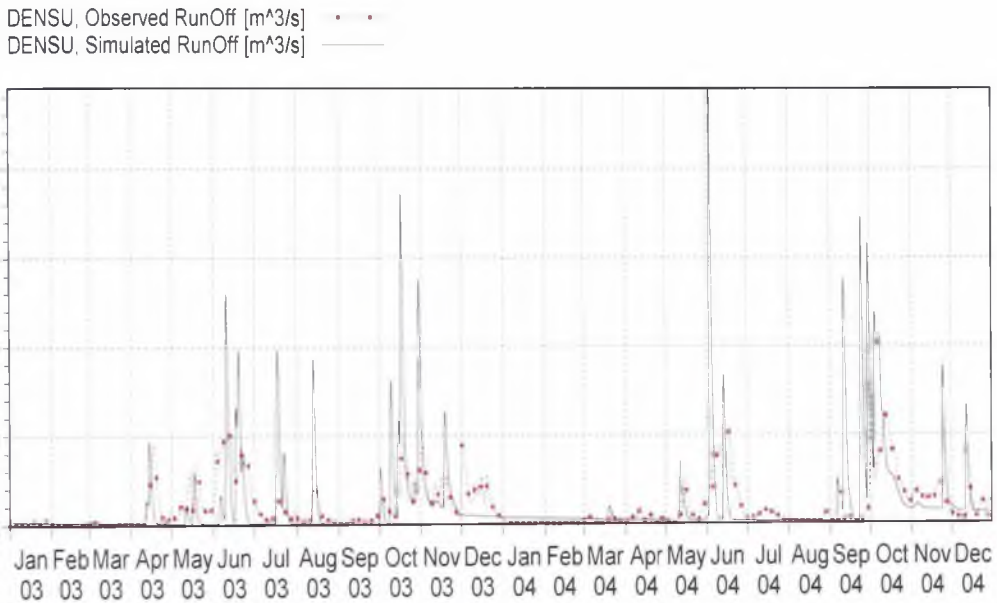


Fig. 3.17 Simulated Runoff Vrs observed Runoff at Mangoase

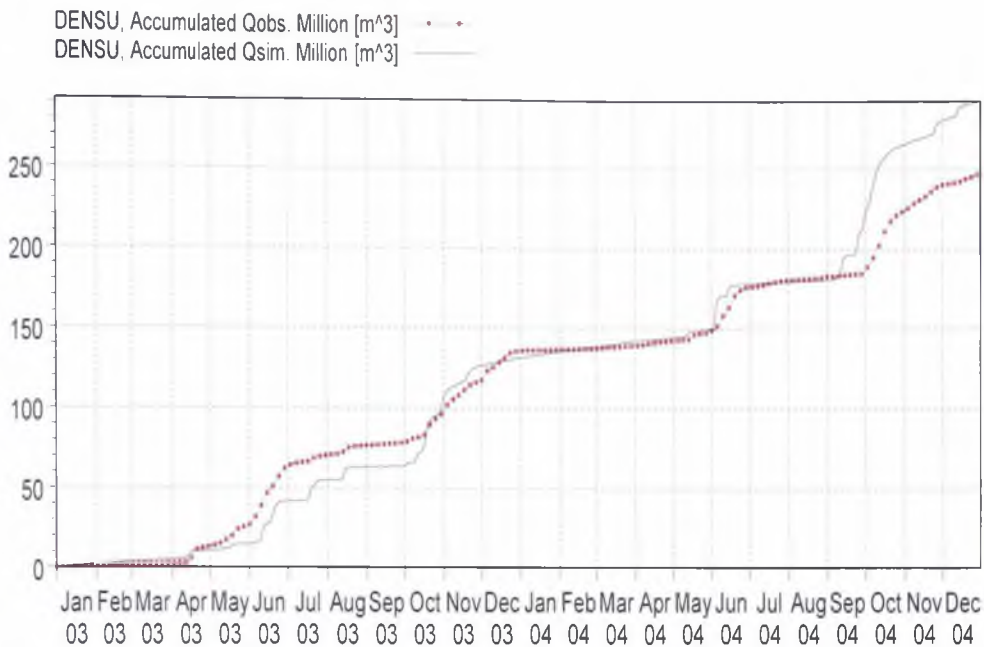


Fig. 3.18 Simulated Accumulated discharge Vrs. Observed accumulated discharge at Mangoase

It is observed that the simulated peaks are markedly higher than measured peaks (Fig. 3.17) and also the accumulated simulated runoff is about 18% more than the measured accumulated runoff (based on NAM calibration results: observed accumulated runoff is 112 mm/year and measured accumulate is 133 mm/year) (Fig. 3.18). This can be attributed to the fact that, water abstraction and storage in dams and weirs are not measured in the river flow data series where as the model simulates such water as part of river flow since water abstraction and storage in dams and weirs were not included in the model design. In order to accurately simulate river discharges and water level, it is imperative to include hydraulic structures such as dams and weirs and specify their characteristics such as size, storage volume, etc as well as the abstraction of water from



the river. This was not included in the model because of the integrated nature of the model, time constraints and less information on the hydraulic structures hence the differences in simulated and measured discharges.

CHAPTER FOUR

4.0 Rainfall analyses

There have been several studies undertaken in Africa to use remotely sensed precipitation as inputs in rainfall runoff modeling because of inadequate or lack of rainfall data or poor quality data. Hardy et al (1989) used the METEOSAT Cold Cloud Duration (CCD) estimation technique in the Senegal River basin and the results indicate no improvement in the performance of the model when conventional rainfall data were replaced with remotely sensed time series precipitation data. Pietroniro et al (1989) and Tsintikidis et al (1999) however, achieved minor improvement in model performance in some Africa river basins by using estimation techniques that employ approaches that take advantage of the spatially distributed rainfall.

Precipitation intensity determines to a large extent the partitioning of rainfall into overland flow and infiltration through the unsaturated zone to either river runoff through saturation excess flow or recharge to groundwater. If rainfall intensity exceeds infiltration capacity of the soil, Hortonian overland flow will occur by building on the surface in response to the surface roughness and depending on the gradient of the land surface and the ponded water, overland flow and runoff routing begins to take place. The amount of precipitation with intensities above the infiltration capacity will be lost to the soil moisture and groundwater storage within the local environment.

In the Densu basin, rainfall data are available in the form of daily amounts and therefore, rainfall intensities are calculated as daily averages which do not portray the rather high

variability of rainfall intensities as well as the very high short time intensity values observed in the data recorded by the event loggers. These daily average intensities are far below the real intensities in the field as demonstrated by the recording of the event loggers and are therefore not capable of describing the rather high observed runoff processes in the basin.

The pattern of rainfall duration in the basin is another important factor that needs to be investigated. For the purposes of the application of models for water balance analysis, the daily rainfall data are not sufficient as input data because they are not suitable for applications in simulations with lower time steps. Generally precipitation in the basin rarely occur over 12 hours, a high percentage of the rainfall occurs between 1 and 5 hours and therefore the daily rainfall data presents inadequate information for water balance analysis. Sensitivity analysis carried out on the response of groundwater recharge and overland flow to different rainfall intensity values shows a large shift from overland flow to groundwater recharge and vice versa with relative small changes in rainfall intensities.

Previous investigations of rainfall intensities in the Pompon sub catchment within the Densu basin (Tumbulto, 2005) have found intensities above 100 mm/h and in short time intervals, intensities up to 200mm/h and above have been recorded.

4.1 Results and analyses of rainfall occurrences

In large catchments, daily rainfall data as inputs in hydrological models may be sufficient. In small catchments, a daily time step may be longer than the storm response time of the catchment and finer time resolution may be required for adequate modeling of the dynamics of the response and the hydrograph peaks (Beven, 2001).

The pattern of the time of the day of rainfall occurrence as well as the amount of rainfall that occurs within those times of the day were analyzed for three different locations in the basin namely, Nsawam, Koforidua and Tafo representing downstream, midstream and upstream respectively. The analyses revealed that, about 70% of the rainfall in the mid and downstream parts of the basin occurs between the hours of 11 AM and 8 PM (Figs. 4.1 and 4.2). In the upstream part of the basin (Tafo) however, about 80% of the rainfall occur between 3 PM and 11 PM (Fig. 4.3). Figures 4.1, 4.2 and 4.3 depict the patterns. At Nsawam and Koforidua, a bimodal distribution is observed with a few showers in the morning and the rest mainly from noon to late afternoon whereas at Tafo (upstream) the distribution increases stepwise. A few showers between the hours of 6 AM and 2 PM graduating to a medium amount between 11 PM and 5 AM and the greater amount of rainfall occur between 3 PM and 11 PM.

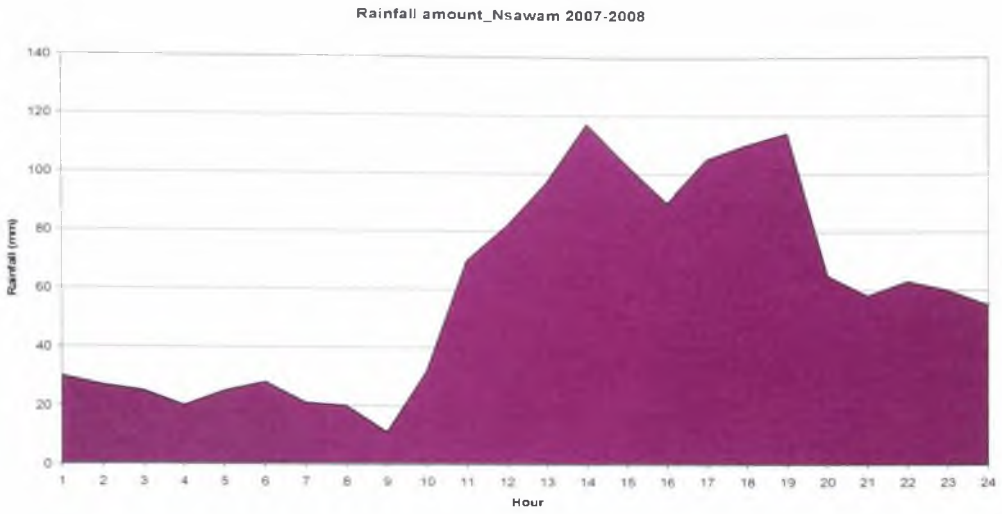


Fig. 4.1 rainfall amount Nsawam (2007 – 2008)

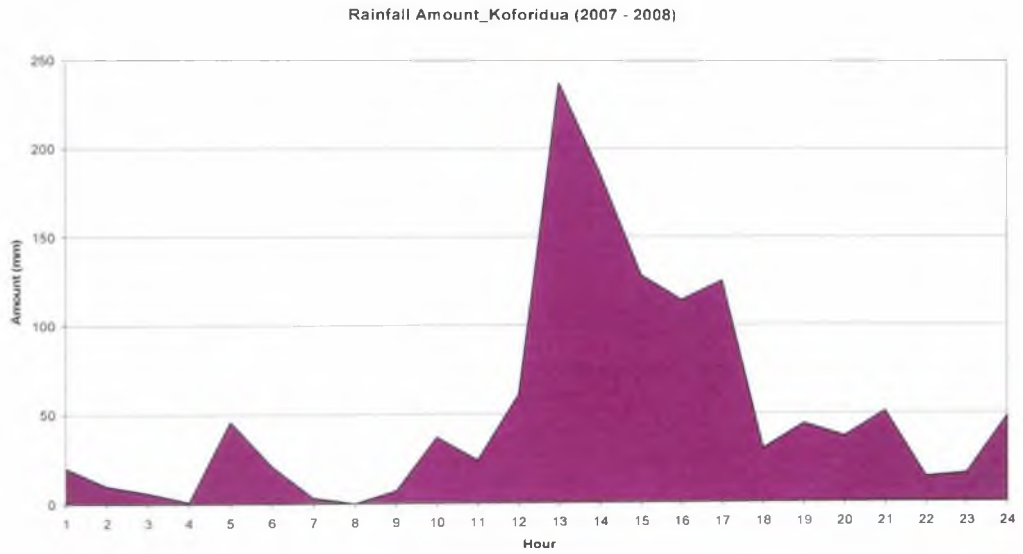


Fig. 4.2 rainfall amount Koforidua (2007 – 2008)

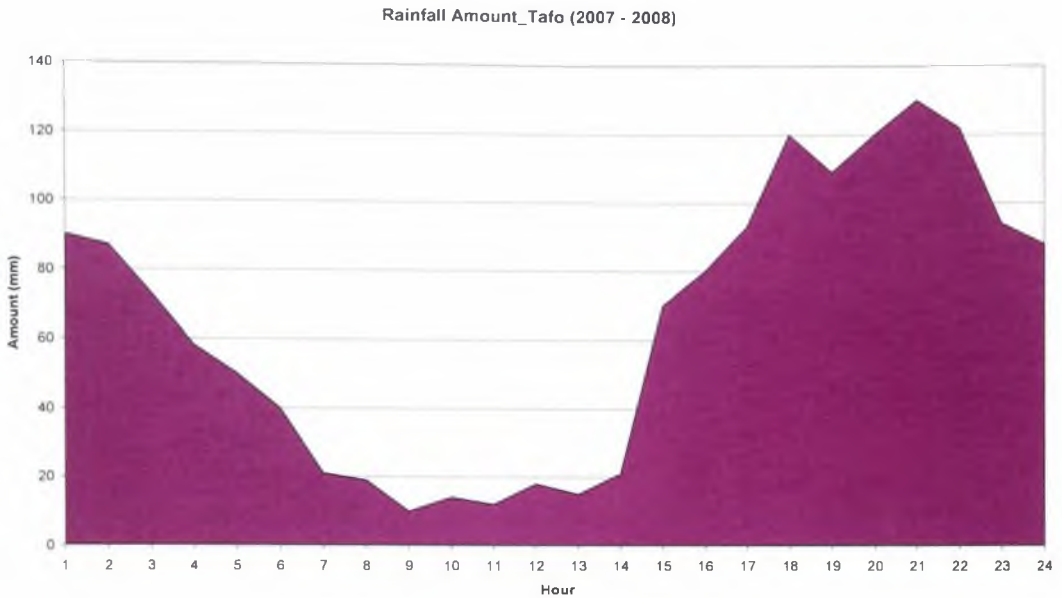


Fig. 4.3 Rainfall amount at Tafo (2007 – 2008)

4.2 Results and analyses of rainfall duration

About 400 rainfall events occurred in the Densu basin between January 2007 and December 2008. The amount of rainfall produced by these events ranges between 1mm and 80 mm. It should be noted that in some days, more than one rainfall event occurs. The duration of rainfall are plotted against the number of events to assess how many rainfall events occur and at what duration. Figures 4.4, 4.5, and 4.6 present the duration of rainfall over a two year period at the different recording stations.



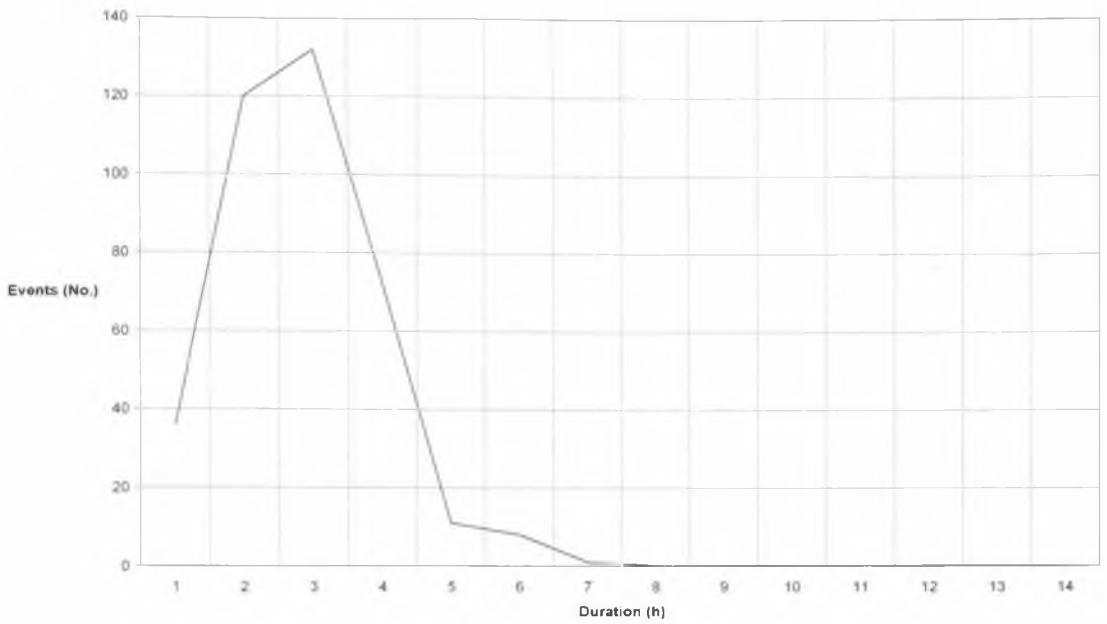


Fig. 4.4 Rainfall occurrence and duration Nsawam (2007 – 2008)

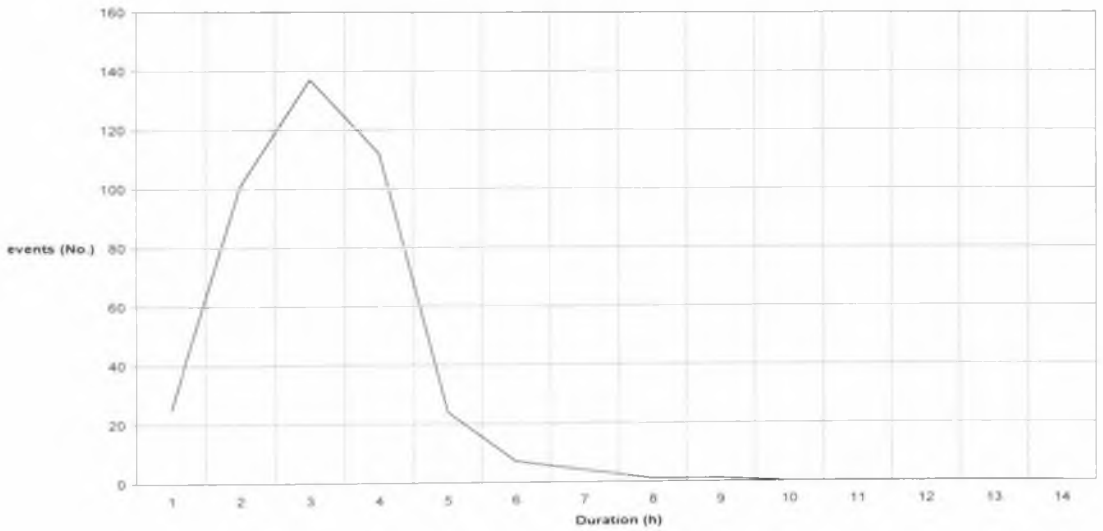


Fig. 4.5 Rainfall occurrence and duration Koforidua (2007 – 2008)

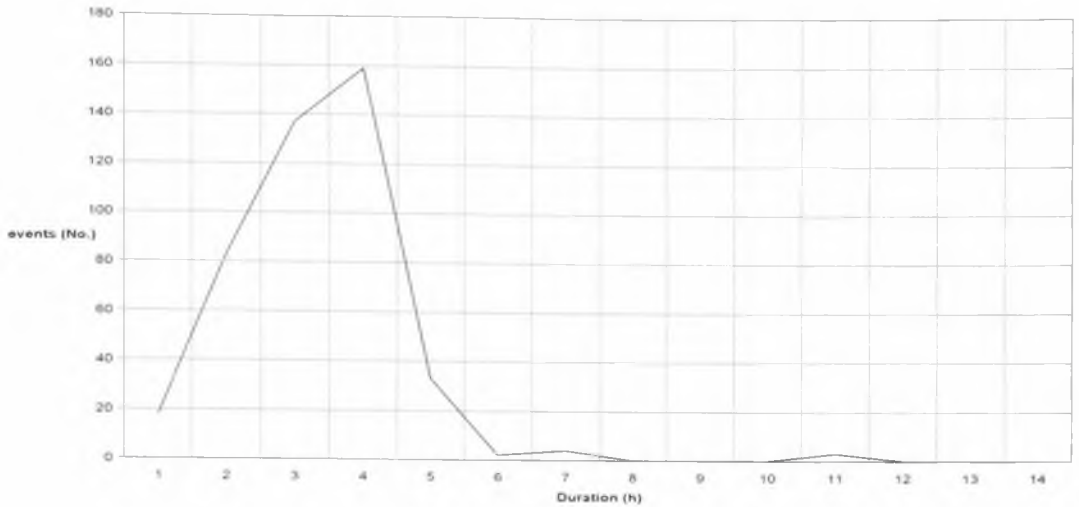


Fig. 4.6 Rainfall occurrence and duration Tafo (2007 – 2008)

It was observed that almost all the 370 rainfall events (during two years period) occurred between 1 and 5 hours duration. Table 4.1 gives a summary of percentages of rainfall events and duration for the three recording stations.

Table 4.1 Rainfall duration variations in the Densu basin

Duration (hour)	Nsawam (%)	Koforidua (%)	Tafo (%)
1	10	6	5
2	31	25	20
3	40	35	32
4	16	28	37
5	2	5	6
6	1	1	0
7	0	0	1

4.3 Results and analyses of rainfall intensity

Rainfall intensity has a significant control over the partitioning of rainfall into overland flow and infiltration. If all factors remain constant, rains falling with high intensities will favor the processes of overland flow and vice versa. It is therefore an important factor to consider in carrying out water balance analysis. Rainfall intensities were computed for every 1 mm of rainfall in the Densu catchment over a period of two years. It should be noted that a single rainfall event occurs at different intensities with time. For example a single rainfall event recorded at Koforidua in 2007 which lasted about 41 minutes occurred at 26 different intensities ranging between 1 and 200 mm/h as shown in figure 4.7. It is however, laborious to compute different intensity values for every 1 mm of rainfall for the purposes of water resources assessment. Rainfall intensities for each rainfall event are sufficient for the assessment of water resources.

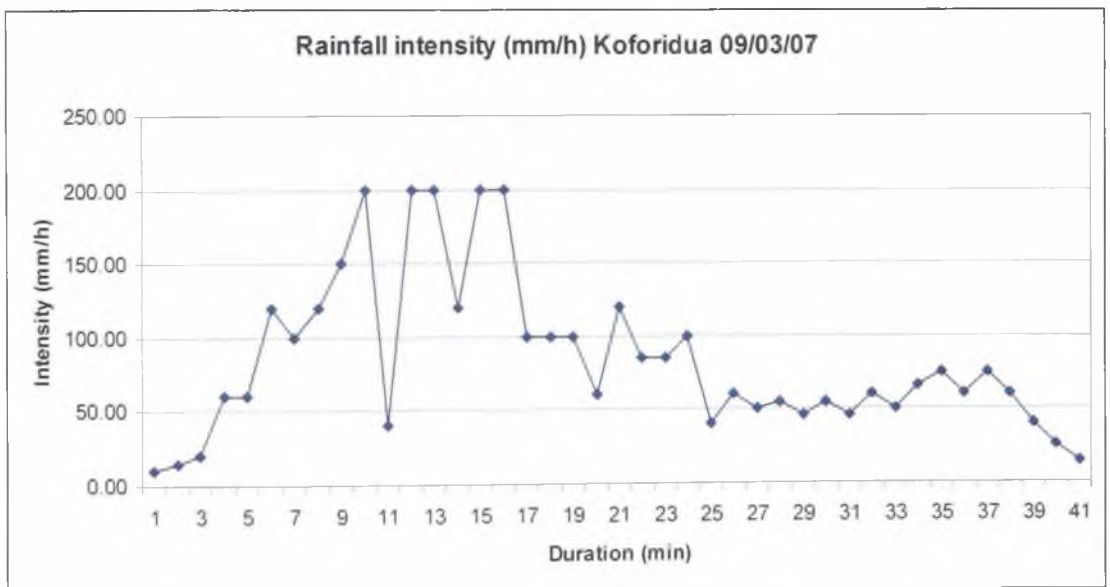


Fig. 4.7 Rainfall intensity variation within a single rainfall event

Figure 4.8 demonstrates the relationship between rainfall intensity and rainfall amount. Rains falling at higher intensities will produce more water than those occurring at lower intensities with the same duration. The cumulative rainfall amount curve is therefore steeper at durations with higher intensities and gentle at durations with lower intensity values. Rainfall cumulative curves can therefore be used to derive relative intensities of rainfall events without necessarily computing intensity values. The curvature which is a second order differential equation of a cumulative rainfall curve could be useful by comparing with standard values to estimate rainfall intensities of a particular catchment.

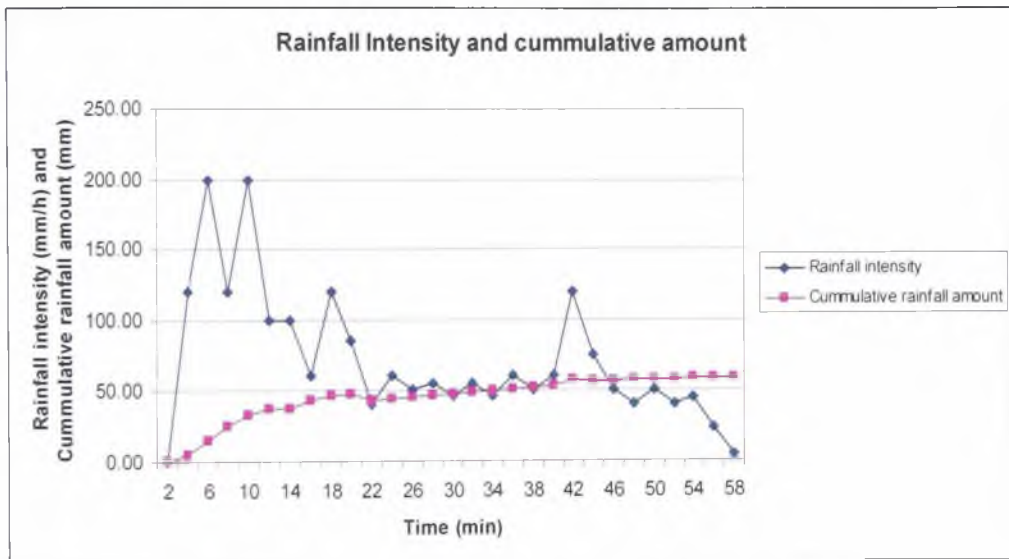


Fig. 4.8 Rainfall intensity variation and cumulative rainfall in a single rainfall event

The tipping bucket rain gauge (HOB0 event logger) cannot provide information about the actual starting time of a rainfall event. Therefore, to calculate the intensity of the first

tip it is assumed (based on field observation), that the tip occurs about 5 minutes after the beginning of the rainfall which gives an intensity of 12 mm/h.

In order to assess the general pattern of rainfall intensities in the catchment, the computed intensities were categorized into different class interval and plotted against rainfall amount to reveal the frequencies of their occurrences. Figures 4.9, 11 and 4.13 show the intensities at the three different locations in the catchment. Also, the relationship between rainfall intensity and rainfall amount in the catchment is presented in figures 4.10, 4.12 and 4.14

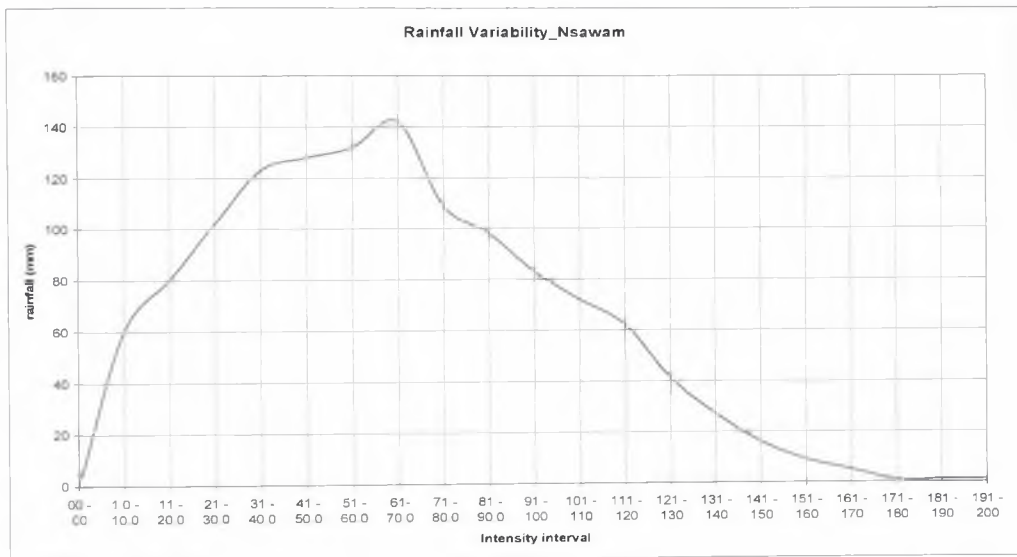


Fig. 4.9 Rainfall intensity variations in Nsawam 2007 – 2008

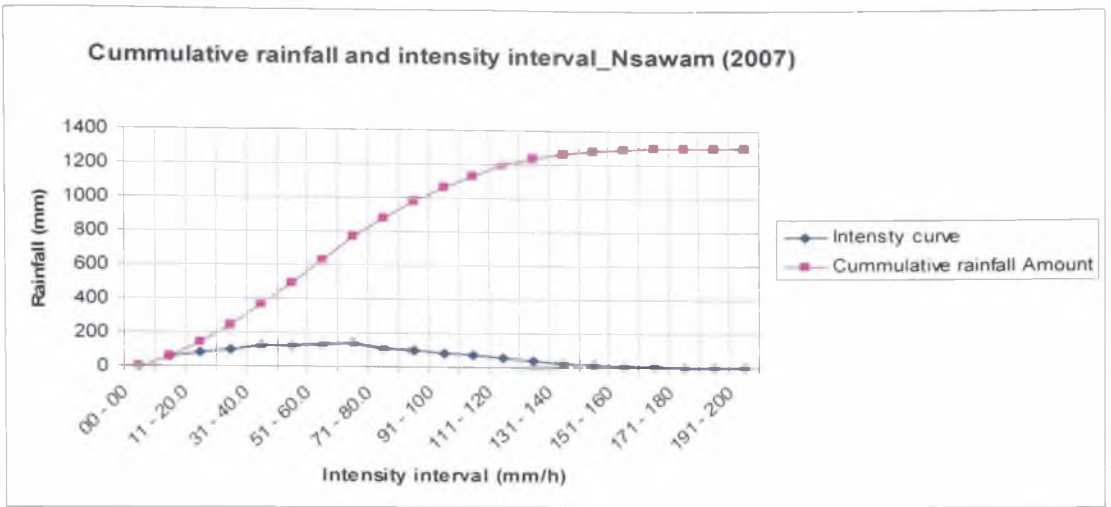


Fig. 4.10 cumulative rainfall and rainfall intensity at Nsawam (2007 -2008)

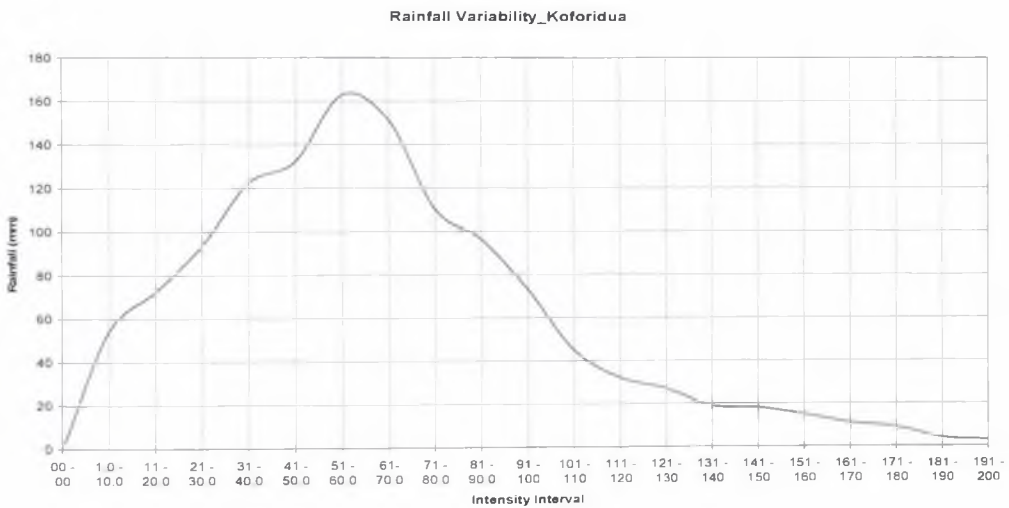


Fig. 4.11 Rainfall intensity variations in Koforidua 2007 - 2008

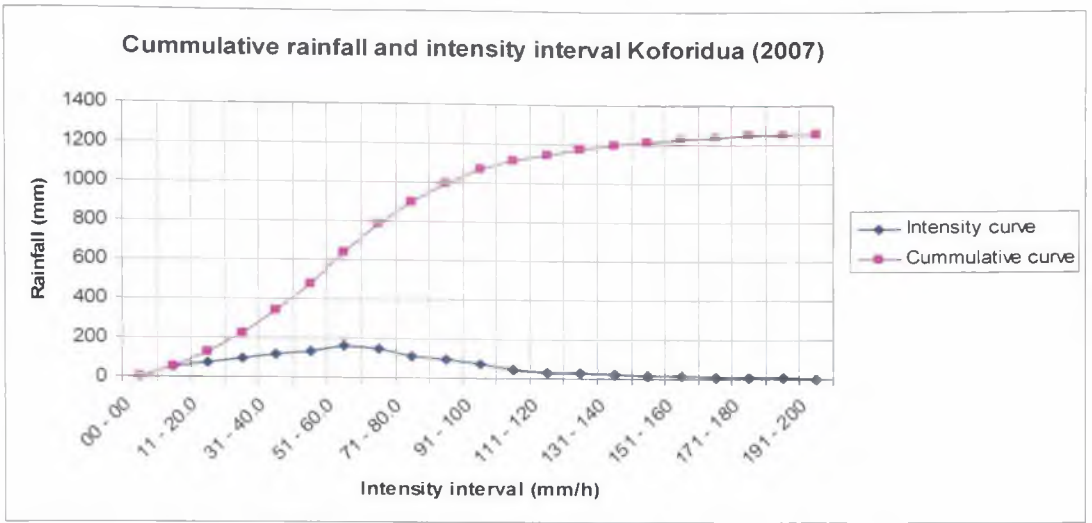


Fig. 4.12 cummulative rainfall and rainfall intensity at Koforidua (2007 -2008)

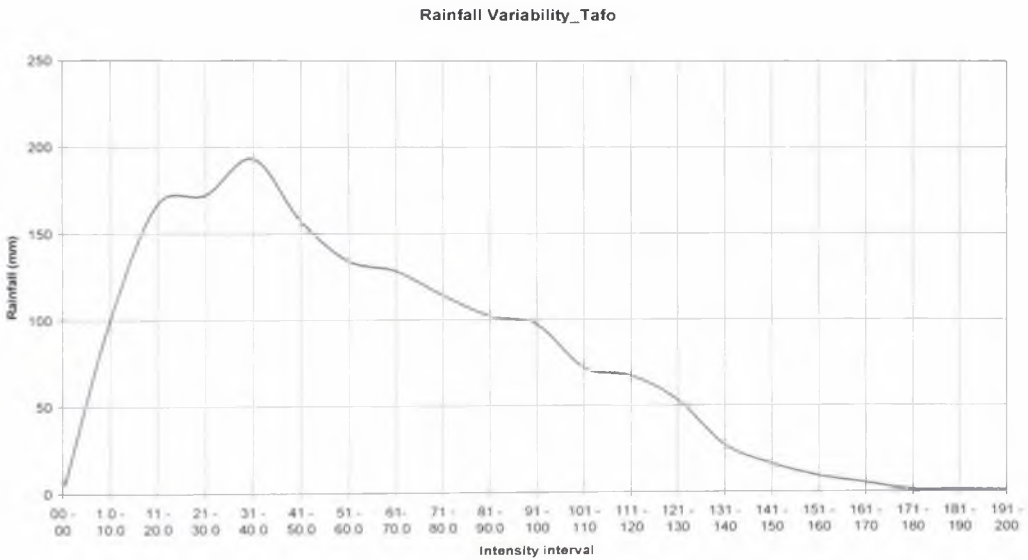


Fig. 4.13 Rainfall intensity variations in Tafo 2007 - 2008

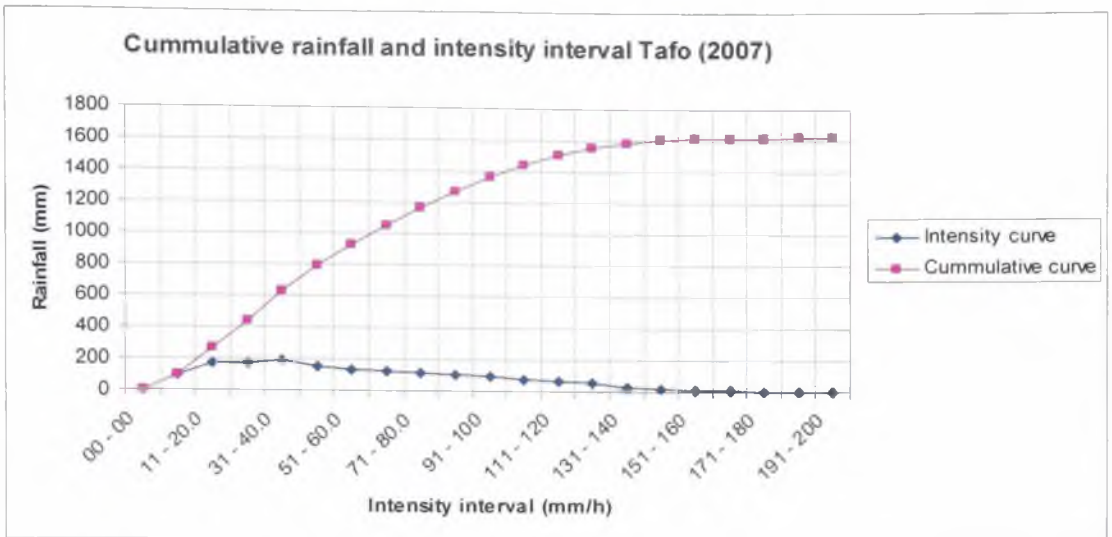


Fig. 4.14 cummulative rainfall and rainfall intensity at Tafo (2007 -2008)

4.4 Results and analyses of rainfall in the dry season

The 3 main dry months of the year namely January, February and December are critical months in terms of water resources and crop production. There are some rain showers during this months but the amount and distribution of the rainfall is greatly insignificant. This period of the year in the basin is characterized by water shortages and limited crop production through irrigation.

4.5 Observations and discussion

Generally, over 95 % of the rains in the basin fall within 1 and 5 hours duration. It is observed that there is an increasing order of rainfall within the duration of 1 to 3 hours from downstream to upstream. On the other hand there is a decreasing order of rainfall duration of 4 and 5 hours from downstream to upstream. The essence of the duration analysis is to establish a pattern of duration of rainfall events in the basin so as to

improve upon their utilizations in hydrological model for water balance analysis and characterization of flow processes. As stated earlier, rainfall data in the basin are recorded as daily amounts which when used as inputs in hydrological models produce results that over estimate groundwater recharge and obviously under estimate overland flow and stream discharges/heads. Most hydrological models when inputted with daily rainfall values, assumes 24 hours duration of rainfall which is an exaggeration of reality in the Densu river catchment. Based on this analysis, model performance can be improved by imputing the daily rainfall data as 5 hourly data.

It was observed that, in Nsawam and Koforidua, the highest amount of rainfall events occurred at intensities between 51 mm/h and 61 mm/h whereas in Tafo, the highest amount of rainfall occur at intensities between 31 mm/h and 41 mm/h. Generally, the rainfall intensity values in the basin ranges between 1 mm/h and 200 mm/h. Most of the rainfall events in the basin occur at intensities between 30 mm/h and 100 mm/h which is considered to be the domain in which all the process such as recharge, overland flow and subsurface storm flow are active.

Based on the intensity analyses with regards to the basin's water resources, it is expected that the effects of climate change will result in the reduction in available water resources due to rise of temperatures and subsequently increase levels of potential evapotranspiration. It will also increase the percentage of rainfall events that occur at higher intensities above the infiltration capacities of the soils in the basin and reduce duration of rainfall. It is therefore expected that a lot more water will be routed almost

instantly into rivers and streams that has the potential of causing floods and most importantly loss of water resources to the local environment if adequate measures are not taken to store water during these periods.

Analyses of the worse and best consecutive 80 days within the 3 dry months were carried out to assess the water resources situation in the 2 scenario cases. Figure 4.15 presents the two scenario cases. In the worse case scenario, there is the possibility to have 30 consecutive days without any rainfall and also it is possible to have only 60 mm of rainfall in 80 consecutive days. This situation can be described as a draught condition which will have negative consequences on agriculture and water resources. On the other hand, the best case scenario is only 10 consecutive days without rainfall and up to 220 mm in 80 days. The average situation within the 3 dry months is 20 consecutive days without rainfall and about 140 mm in 80 consecutive days. It should be noted that in all the scenarios, about 70% of the rainfall will be loss to evapotranspiration which will further worsen the water resources situation especially in the worse case scenario.

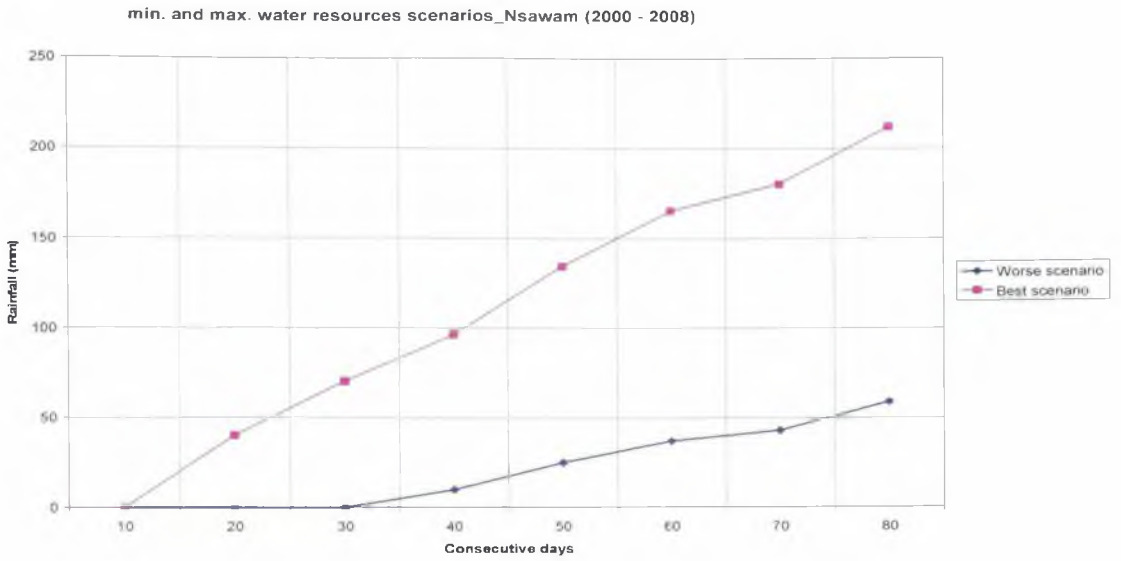


Fig. 4.15 worse and best consecutive water resources scenarios in the Densu basin

CHAPTER FIVE

5.0 Simulation of actual evapotranspiration, root water uptake and interception storage

In tropical regions, evapotranspiration which represents the atmospheric demand for water constitutes a greater part of water balance, it exceeds by far the other component of the water balance put together. It is therefore, necessary to compute the actual evapotranspiration losses from the basin so as to account for the actual available water resources in the basin.

Root water uptake and interception storage by the roots and leaves of plants respectively contribute to the total actual evapotranspiration in the basin. This is particularly significant in forest land cover areas in the basin.

5.1 Results of actual evapotranspiration

MIKE SHE model computed time series actual evapotranspiration values as shown in figures 5.1 and 5.2. The daily actual evapotranspiration in the forest land cover ranges between 0.4 mm/day (dry days) and 5 mm /day (wet days) with an average value of 4.0 mm/day (Fig. 5.1). In the savannah land cover, actual evapotranspiration ranges between 0.5 mm/day (dry days) and 4 mm/day (wet days) with an average value of about 3.0 mm/day (Fig. 5.2).

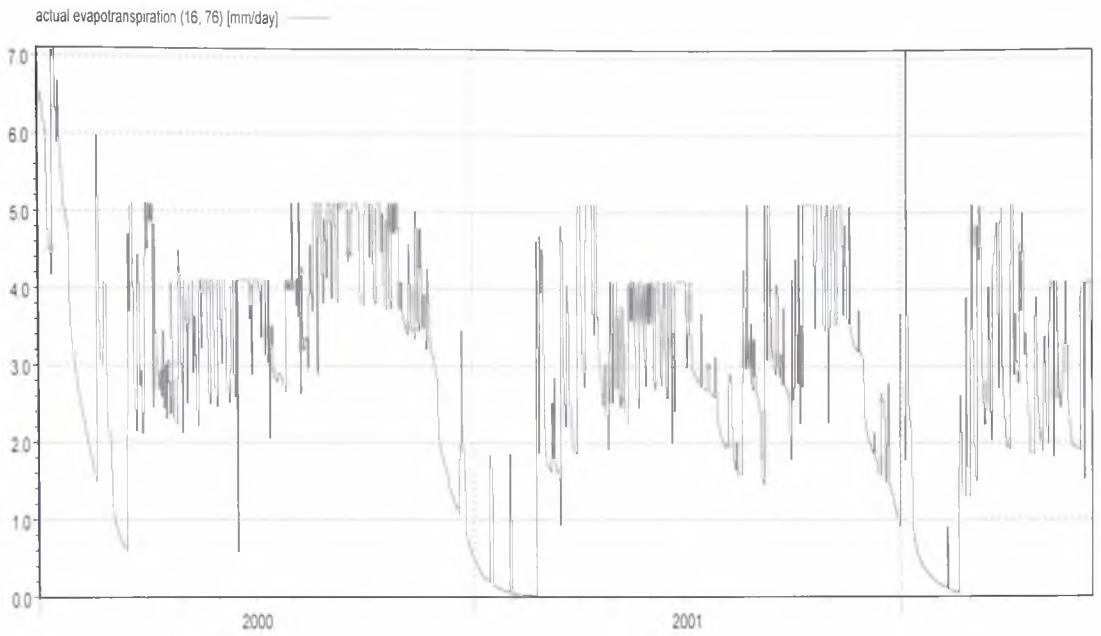


Fig. 5.1 Actual evapotranspiration in forest land cover (mm/day)

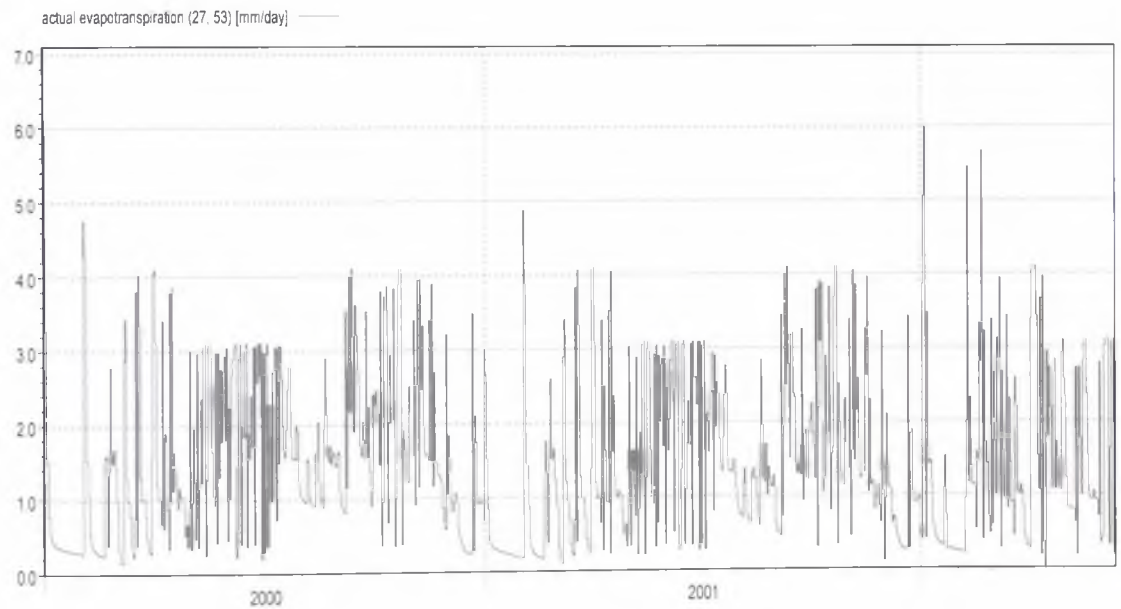


Fig. 5.2 Actual evapotranspiration in savannah land cover (mm/day)

5.2 Simulation of interception storage and root water uptake

There are different ways of conceptualizing interception storage by canopies and stems of vegetation but the one adopted by this study is the conceptualization proposed by Rutter et al (1971 and 1975). The Rutter model is the most widely applied model of interception. It divides incoming precipitation into direct through fall and canopy interception and stem flow storages (Fig. 5.3). The direct through fall goes direct into the ground without interference with canopies and stems of vegetation. The partitioning coefficients p and p_i represent the vegetation type and are a function of the climatic season. However in application they are often considered to be constant from one season to another to avoid complexity. Water begins to drain to the ground as stem flow to add up to through fall when the minimum storage capacity (C_{SF}) is exceeded, where as in the case of the canopy store, drainage occurs according to equation 5.1 (Beven, 2001):

$$D_t = D_S \exp [b \{S_{TF} - C_{TF}\}] \quad 5.1$$

Where D_t is canopy drainage and b is a coefficient, S_{TF} is the storage capacity and C_{TF} is the storage depth. D_S is the drainage rate when $S_{TF} = C_{TF}$. The result of equation 5.1 is very much dependent on the time step used in the simulation. To obtain good results from the above expression it is better to integrate the equation over the selected time step so as to simulate the storage at the end of the selected time step based on which the integrated drainage can be obtained from the change in storage.

Evaporation from stem storage and canopy storage are accounted for by the Rutter model based on the Penman – Monteith equation. If the storage of any of the components is greater than the storage capacity, actual evaporation will be equal to potential evaporation. on the other hand, if the storage is less than the storage capacity, part of the canopy will be dry and therefore evaporation will reduce proportionally according to the following expression presented in Equation 5.2:

$$E_a = E_p \frac{S_{TF}}{C_{TF}} \quad 5.2$$

Where E_a and E_p are actual evaporation rate and estimated potential evaporation rate from intercepted storage respectively.

The Rutter model requires the specification of rainfall input P , potential evaporation from stem storage P_t , the coefficient b , the storage depth C_{TF} , storage capacity S_{TF} and the drainage rate D_S .

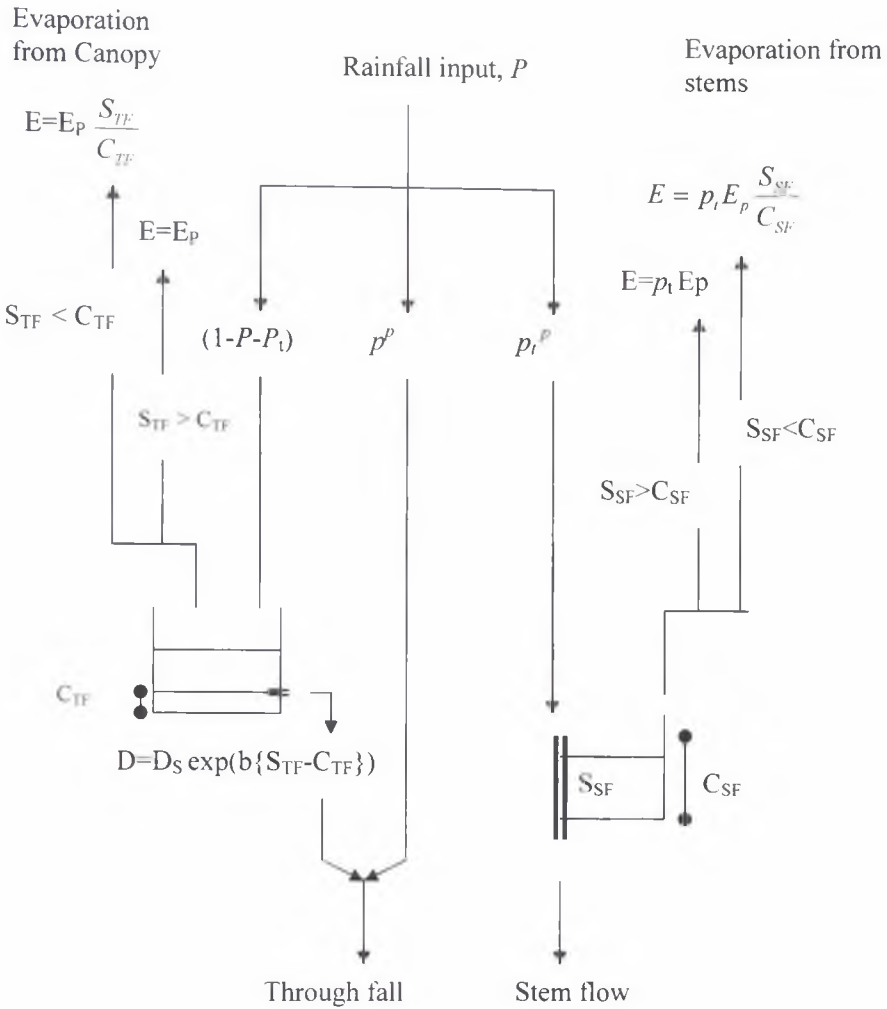


Fig. 5.3 Schematic diagram of the Rutter interception model (Beven 2001)

5.3 Results of interception storage and root uptake

Interception storage is an important component that contributes to the total actual evapotranspiration (Figs 5.4 and 5.5). In forest land covers, interception storage can form a major part of total rainfall depending on the stage of development of the forest. In the Densu basin, interception storage of the forest land cover is higher (about 5 x higher) than

that of the savannah land cover (Fig. 5.4 and 5.5). Vegetation canopy in forest land covers play an important role in determining the amount and intensity of rainfall that reaches the ground surface.

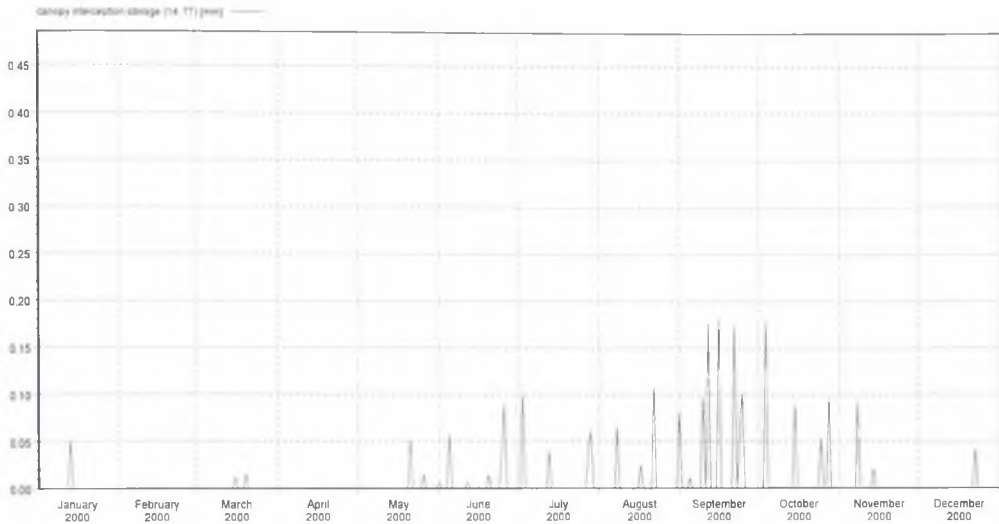


Fig. 5.4 Monthly interception storage of forest land cover

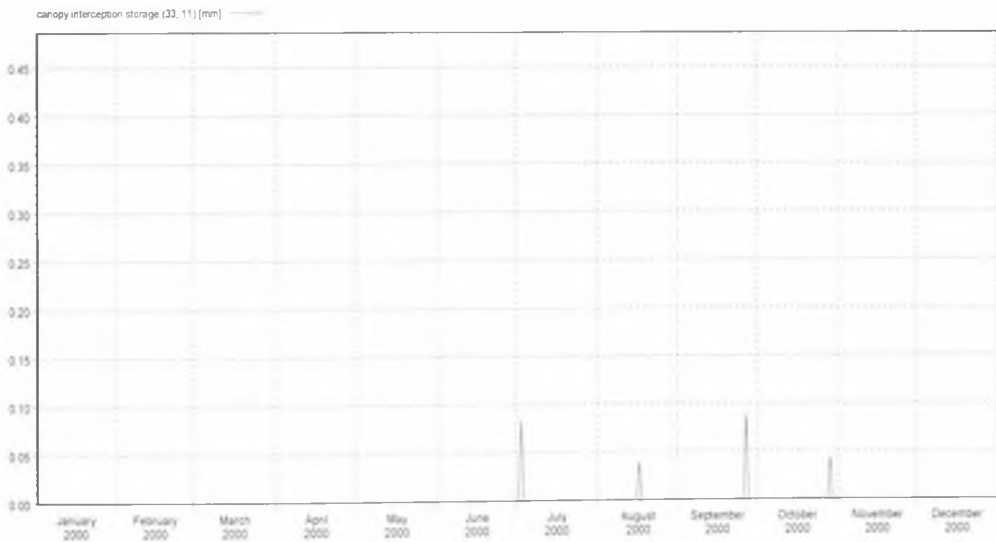


Fig. 5.5 Monthly interception storage of savannah land cover

Apart from interception storage, root water uptake by forest land cover also contributes significantly to total actual evapotranspiration. Root water uptake in the forest and savannah land covers in the Densu basin is presented in figures 5.6 and 5.7.

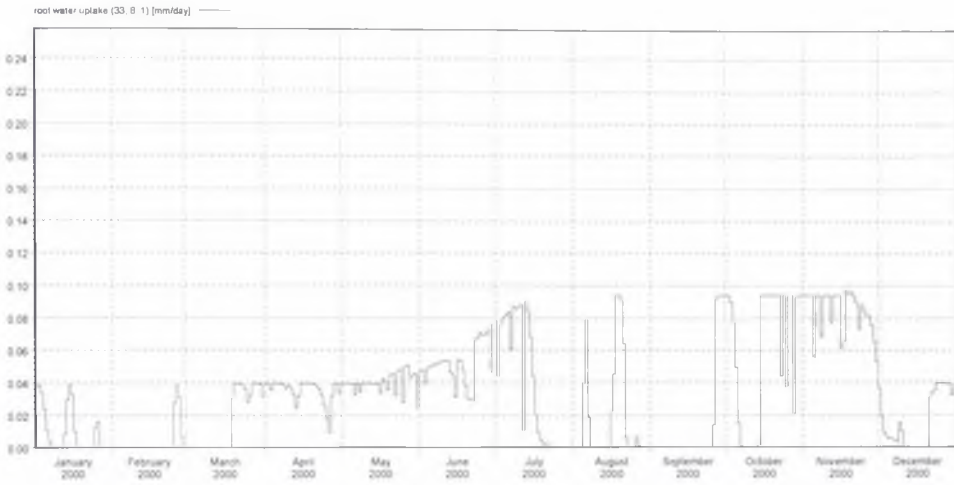


Fig. 5.6 Monthly root water uptake in forest land cover in the Densu basin

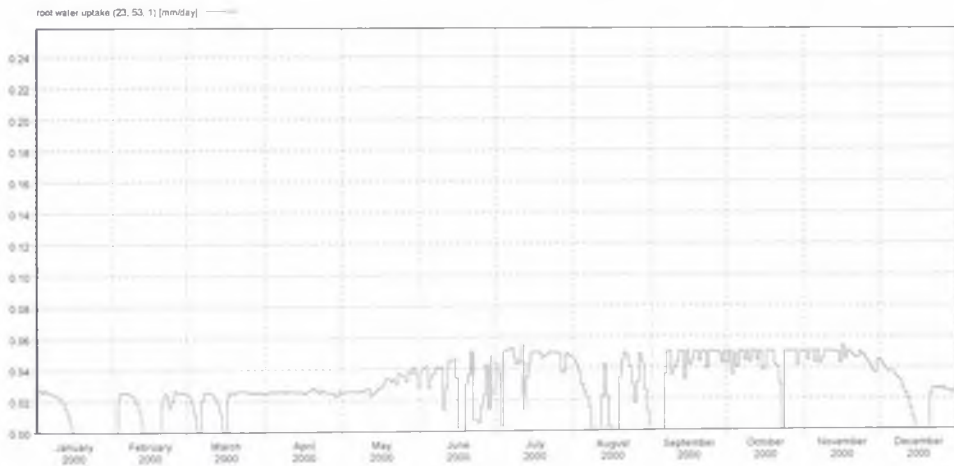


Fig. 5.7 Monthly root water uptake in savannah land cover in the Densu basin

5.4 Observations and discussion

Computations of actual evapotranspiration in the Densu basin reveal wide variations of actual evapotranspiration with time. Since actual evapotranspiration depends on the availability of water, it is not surprising to find out that actual evapotranspiration values of the same month in different years vary significantly. Actual evapotranspiration values of the driest months are very low and sometimes approach zero.

Comparing the simulated actual evapotranspiration (Figs. 5.1 and 5.2) and actual evapotranspiration values use in the IWRM plan which were derived from a study of water balance in the Pompon sub-catchment of the Densu basin (WRC, 2007), WRC used actual evapotranspiration values of 1.3 mm/day in driest months and 4.0 mm/day in wettest months for the entire basin without considerations to the spatial variability of actual evapotranspiration due to differences in land cover and other unsaturated zone properties. The simulated actual evapotranspiration in savanna land cover in the basin ranges between 0.5 mm/day – 4.0 mm/day and in a few dry days within a year, actual evapotranspiration approaches zero (Fig. 5.2). In the forest land cover, actual evapotranspiration ranges between 0.4 mm/day in the driest days and 5 mm/day in the wettest days. (Fig.5.1). The lower limit of 1.3 mm/day in dry days adopted by WRC is a higher estimation and therefore has resulted in a higher annual actual evapotranspiration of 77% of annual rainfall compared with 72% arrived at by this study.

The combination of interception storage and root water uptake of water by plants forms a reasonably significant component of water balance in the Densu basin especially in the

forest area where the Leaf Area Index (LAI) and Root Depth (RD) is quite significant. The contribution of these two factors to actual evapotranspiration explains why actual evapotranspiration in forest areas is much higher than savannah areas. It is expected that the effects of LAI and RD will lead to reduction of water resources in forest areas. Groundwater recharge in particular will be affected by the effects of root water uptake where as the effects of interception storage is on both groundwater and surface water resources.

These results reveal the importance of root water uptake and interception storage in the simulation of water balance which is normally assumed to be insignificant and therefore are not normally considered in water balance analyses.

CHAPTER SIX

6.0 Simulation of overland flow

Hortonian overland flow occurs when precipitation rate exceeds the rate of infiltration. When this occurs, water is ponded on the surface of the ground and begins to flow down hill and finally ends up in rivers or in other surface water bodies. The route, amount and rate of overland flow depend on the surface gradient (topographic differential), flow resistance of the surface of the land, rate of infiltration and evaporation.

Overland flow (infiltration excess flow and saturation excess flow) is simulated by the MIKE SHE Overland flow module. In the MIKE SHE overland flow module, the outer boundary condition for overland flow can be represented by a specified head based on the initial water depth in the outer nodes of the model domain or it can be specified as a no flow boundary on the outer boundary of the model domain using the Separated flow areas option in the overland flow module. The separated flow areas set up was used to define the boundary condition so as to keep all overland flow in the model. If the initial water depth is used to define the boundary condition of the model domain, it allows for exchange of overland flow across the model boundary. If the actual water depth inside the model is less than the specified initial water depth on the boundary, the boundary will become a source of water for the model. On the other hand if the water depth inside the model is greater than the initial water depth on the boundary, water will flow out of the model.

In MIKE SHE if the finite difference method is selected in the simulation specification dialog. The main components that are important for the simulation of overland flow include the following:

- Detention storage;
- Initial water depth on the ground surface;
- Manning number;
- And Separated overland flow Areas (optional).

Detention storage describes the amount of water on the ground surface that must be exceeded before overland flow can be generated. Detention storage varies from one place to another depending among other things the gradient of the land surface and depressions on the land surface. Under normal circumstances, the higher the gradient, the smaller the detention storage.

Initial water depth on the ground surface describes the initial condition on the land surface in relation to the water depth at the beginning of the simulation period. It can also be used to describe the boundary condition of the model by specifying the initial water depth on the boundary of the model domain. In this simulation, the initial water depth in the Densu basin was specified as 0 mm since the simulation period begins on the 1st of January, which is a dry period of the year within the coastal basins in Ghana.

Manning number (n) describes the smoothness or roughness of the ground surface and it is an inverse of the Manning M which is equivalent to the Stickler roughness coefficient.

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Manning number (n) describes the smoothness or roughness of the ground surface and it is an inverse of the Manning M which is equivalent to the Stickler roughness coefficient.

Values of the Manning number (n) normally range between 0.01 – 0.10. The lower the value of n , the smoother the surface and values of n approaching 0.10 represent a thickly vegetated surface. The spatial distribution of the Manning number in the basin is represented in map 5.2. The Northern part of the basin is relatively thickly vegetated and therefore is characterized by high values of Manning number (n).

6.1 Overland flow conditions in the Densu basin

In the Densu basin the amount of detention storage varies in space within the basin therefore, detention storage data were applied in a distributed manner according to factors such as gradient, depressions, flow resistance etc. Values ranging between 0.02mm to 0.28mm characterize the detention storage in the basin. These values were obtained through model calibration. It was observed that, the Manning number and detention storage controls the amount of ponded water on the land surface. Water that is specified as detention storage is available for evaporation and infiltration. Figure. 6.1 shows the spatial distribution of detention storage in the basin. The middle to southern portion of the basin exhibits high detention storage because the gradient of the land surface is relatively gentle compared to the northern, western and eastern boundaries of the basin.

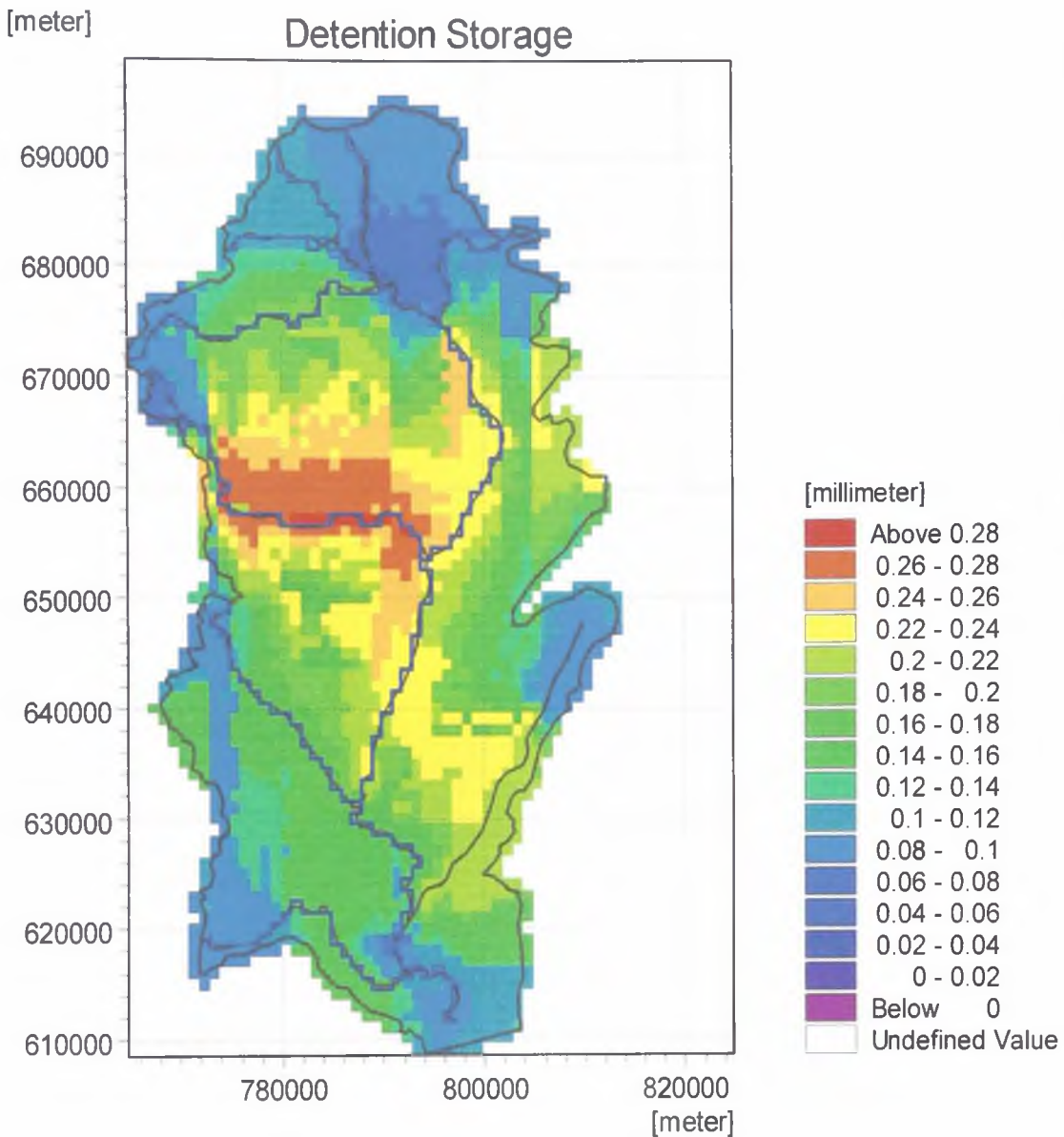


Fig 6.1 Spatial distribution of detention storage in the Densu basin

The distribution of the Manning number in the basin which was also arrived at through model calibration is presented in Fig. 6.2. Detention storage, initial water depth and

Manning number are often difficult to measure. In the case of detention storage it is often practically difficult to estimate in the field. On the other hand initial water depth and Manning number can fairly be estimated using the land use classification in the case of the Manning number and the case of the initial water depth, the beginning of the simulation period can be used to estimate the initial water depth

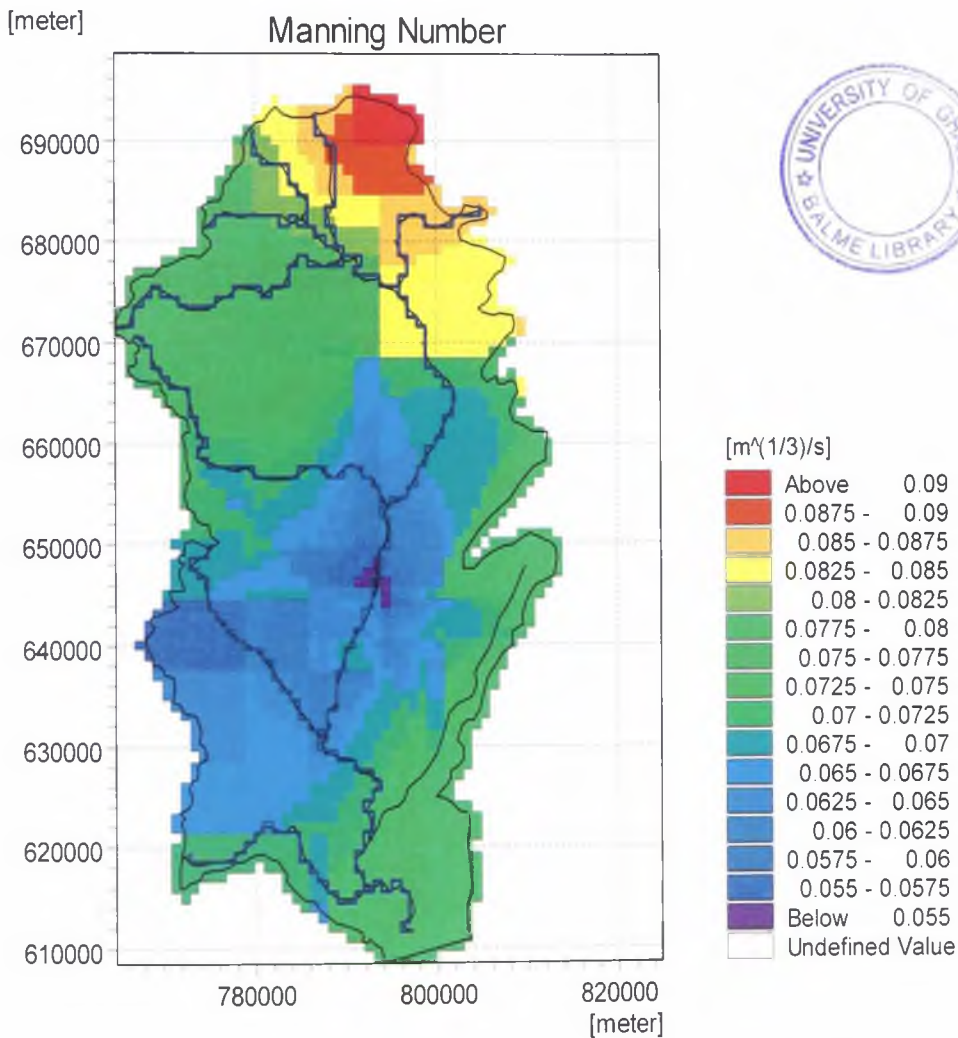


Fig. 6.2 Spatial distribution of Manning number in the Densu basin

6.2 Mathematical principles of overland flow

The MIKE SHE overland flow module computes water flow on the ground surface applying two main approaches namely, the finite difference method and the subcatchment based method. In the calculation of the overland flow in the Densu basin, the finite difference method was selected in the simulation specification dialog. The finite difference method is based on the diffusive wave approximation of the Saint Venant equation which employs the principles of the conservation of mass and the momentum equations (Equations 6.1, 6.2 and 6.3). Considering overland flow in two dimension (x and y directions), level of ground surface (Z_g) in both x and y directions, h (x, y) representing the flow depth above the ground surface, u (x, y) and v (x,y) for the flow velocities in the x and y directions respectively. If the net rainfall input into overland flow is given as I (x, y), then the conservation of mass and the momentum equations can be written as follows (Equations 6.1 – 6.3):

$$\frac{\partial h}{\partial t} + \frac{\partial}{\partial x} (uh) + \frac{\partial}{\partial y} (vh) = i \quad (\text{Conservation of mass equation}) \quad 6.1$$

$$S_{fx} = S_{Lx} - \frac{\partial h}{\partial x} - \frac{u}{g} \frac{\partial u}{\partial x} - \frac{l}{g} \frac{\partial u}{\partial t} - \frac{qu}{gh} \quad (\text{Momentum equation in the x – direction}) \quad 6.2$$

$$S_{fy} = S_{Ly} - \frac{\partial h}{\partial y} - \frac{v}{g} \frac{\partial v}{\partial y} - \frac{l}{g} \frac{\partial v}{\partial t} - \frac{qv}{gh} \quad (\text{Momentum equation in the y – direction}) \quad 6.3$$

Where S_f is the friction slopes in both x and y directions and S_L is the slop of the surface of the ground. Equations 6.1, 6.2 and 6.3 are called the Saint Venant equations based on

which two dimensional overland flow can be described. Due to the numerical complexity of the Saint Venant equations, the momentum losses represented in the last three terms in equations 6.2 and 6.3 are ignored. The resultant simplified equations (Equations 6.4 and 6.5 are called the diffusive wave approximations which are employed by the MIKE SHE model in the computation of overland flow. By employing the diffusive wave approximations, MIKE SHE is able to compute overland flow with varying depths of flow between neighboring cells as well as backwater conditions. It must however be noted that, when the velocity of flow is very low and the slope of the water surface is shallow, numerical problems may occur (DHI, 2005).

$$S_{fx} = S_{Lx} - \frac{\partial h}{\partial x} = - \frac{\partial z_s}{\partial x} - \frac{\partial h}{\partial x} \quad 6.4$$

$$S_{fy} = S_{Ly} - \frac{\partial h}{\partial y} = \frac{\partial z_s}{\partial y} - \frac{\partial h}{\partial y} \quad 6.5$$

the relationship between the velocities and the depths can be written as follows (Equations 6.7 and 6.8):

$$Uh = K_x \left(\frac{\partial z}{\partial x} \right)^{1/2} h^{3/2} \quad 6.7$$

$$Vh = K_y \left(\frac{\partial z}{\partial y} \right)^{1/2} h^{3/2} \quad 6.8$$

Finding explicit solutions for the overland flow equations (Equations 6.7 and 6.8) is extremely difficult. It is therefore necessary to obtain approximate solutions by

employing numerical methods. In numerical modeling, results stand for numbers and not expressions. There are efficient and reliable algorithms for obtaining approximate results for partial differential equations. Algorithms are usually designed and implemented in digital computers thereby increasing computational speed.

Digital computers are not capable of evaluating partial differential equations. The only arithmetic operations which can be performed by digital computers are additions (+), subtractions (-) multiplications (*) and divisions (/) (Liedl and Teutsch, 2002). To make it possible for digital computers to solve the above equations, it is therefore, necessary to transform the partial differential equations by replacing the partial derivatives with difference ratios.

6.3 Runoff generation and routing

Different catchments respond differently to rainfall in terms of the hydrological processes on the land surface. The nature of the overlying soil and the type of bed rock determine the amount of runoff that will be generated and the path it will follow to reach a stream channel.

There are many theories on runoff generation and routing. Amongst them is the infiltration-excess Overland Flow (IOF) by Horton (1933). The IOF concept considered infiltration as central to the hydrological processes on the land surface. Horton considered that infiltration divides precipitation into two parts, one part through overland flow to streams and the other part goes through the soil to the groundwater system and

subsequently to the stream or to atmosphere through evapotranspiration. Horton theory however did not account for Subsurface Storm Flow (SSF) where permeable soils overlie impermeable ones. Dunne (1978), proposed the Saturation-excess Overland Flow (SOF) and SSF to address the limitation of the Horton theory. According to Dunne (1978), both SSF and SOF may occur at rainfall intensities far below those required to generate IOF.

Runoff generation is favorable in areas where the soils are either less permeable or initial water content of the soils is very high. Runoff generation and routing determines to a large extent how much water flows into the streams within the period of the rainfall and after. The distinction between processes of runoff generation and routing is some times very difficult to define especially in areas where soil permeabilities are very low and where differential gradient of the land surface is very high couple with high intensity rain storms (typical in the Densu basin). Under these conditions, both processes occur almost simultaneously.

The northwestern part of the basin is characterized by clay soils overlying the Birimian formation couple with relatively high intensity rainfalls and therefore, it is expected that runoff generation will occur faster in that part of the basin and slowest in the other part of the basin characterized by sandy soils. It should be noted however that, the high interception storage as a result of the forest land cover in the northwestern part of the basin characterized by the clay soil, will have an impact on how fast runoff generation occurs. The eastern part of the basin is bounded by the Akwapim mountain ranges with steep slopes towards the direction of the Densu River. The upper part of the basin is also

characterized by high elevations. The differential gradients as a result of these high altitudes provide favorable conditions for runoff generations and routing. It is therefore not surprising that most of the major tributaries and the main Densu River in the basin flow towards the west and the south respectively.

Overland flow routing in MIKE SHE is based on an empirical relation between flow depth and surface detention as well as the Manning equation describing the discharge under turbulent flow condition (Crawford and Linsley, 1966). MIKE SHE framework allows for the interaction of overland flow with the other components such as infiltration into the soil, evaporation from the ponded water, drainage into the river channel network, etc. There are two options in which MIKE SHE simulates routing of overland flow into rivers. The first option is that overland flow generated in higher zones is routed to adjacent lower zones based on the integer code values of the two zones within a subcatchment. That means that at the beginning of the time step, the overland flow leaving the upper zone simulated in the previous time step is distributed evenly across all the cells in the receiving zones. The practical limitation of this option of routing overland flow is that, if the receiving cells in the lower zones have higher infiltration capacities, the overland flow generated in the upper zone may never reach the stream network. The second option addresses this limitation by routing overland flow generated in each cell directly into the stream network. In otherwise, overland flow generated in any of the zones is not routed through adjacent cells in lower zones but rather it is added to the MIKE 11 module as lateral flows.

6.3 Results and discussions of overland flow

Observations of groundwater level measurement in six hour intervals in the basin were correlated with rainfall intensities. It was observed that groundwater heads do not respond to rainfall events with intensities lower than 20 mm/h in the entire basin except a few events that lasted over 6 hours. About 7% of the rainfall in the basin occurs at intensities lower than 20 mm/h. Also insignificant responses of groundwater heads to rainfall events with intensities higher than 70 mm/h, 90 mm/h and 100 mm/h in the Birimian, Granite and Togo soils respectively were observed. Based on these observations, coupled with the saturated hydraulic conductivity values of the different soils, threshold intensities for groundwater recharge were established. It therefore, implies that intensities above the threshold values will generate Hortonian overland flow and those below 20 mm/h will replenish soil moisture. Based on the threshold intensities analyses, percentages of potential groundwater recharge and overland flow was computed (Table 6.1). It must be emphasized that about 70% of rainfall in the basin is loss through evapotranspiration.

Rainfall from Tafo Station which is located close to the Birimian formation was used in the computation in the Birimian area and Nsawam rainfall data was used for the computation of the Togo series and the Granite areas for the same reason.

Table 6.1 Annual potential groundwater recharge and Hortonian overland flow in the Densu River basin

Soil type	Potential recharge (mm)	Potential HOF (mm)
Birimian	120 (8% of annual rainfall)	391 (24% of annual rainfall)
Granite	140 (12% of annual rainfall)	260 (22% of annual rainfall)
Togo series	153 (13 % of annual rainfall)	240 (20% of annual rainfall)

CHAPTER SEVEN

7.0 Simulation of unsaturated zone processes

The flow and movement of water in the unsaturated zone varies spatially due to the complexity of the heterogeneity of soils and rocks in the basin as a result of natural soil and rock forming processes and/or land use practices. Land cover plays an important role on the movement of water in the unsaturated zone in the sense that the amount of water that enters the unsaturated zone is greatly influenced by the leaf area index which is a function of the vegetation type. Water is also taken away from the unsaturated zone by the roots of plants and that also determines the amount of water available in the unsaturated zone. The main difficulty in unsaturated zone modeling is the extent of heterogeneity of soil formations. Several field researches undertaken by Nielsen et al. (1973); Byers and Stephens (1983); Russo and Bresler (1980), Jensen and Refsgaard (1988) and many others have revealed the significance of the large variability of hydraulic properties of soils such as soil retention capacity, hydraulic conductivity etc and highlighted the difficulties associated with the prediction of flow in the unsaturated zone.

7.1 Model description

The application of the MIKE SHE model in the simulation of the unsaturated zone flow in the Densu basin was done through vertical discretization of the soil according to a set of relevant properties determined through averaging of different sample points.

To calculate the hydraulic conductivities and soil retention capacities which control the flow of water in the soils, the Van Genuchten formula was applied for the various classes of soils as follows (Equations 7.1 and 7.2):

$$\theta(\psi) = \theta_r + \frac{(\theta_s - \theta_r)}{\left[1 + (\alpha\psi)^n\right]^m} \quad 7.1$$

$$K(\psi) = K_s \frac{\left[\left(1 + |\alpha\psi|^n\right)^m - |\alpha\psi|^{n-1} \right]^2}{\left(1 + |\alpha\psi|^n\right)^{m(l+2)}} \quad 7.2$$

Where θ_s and K_s represent saturated moisture content and saturated hydraulic conductivity respectively, θ_r represents residual moisture content, l is a shape factor and α , n and m are empirical constants

The application of unsaturated zone models to field scale research is often done through vertical discretization of the soil according to a set of relevant hydraulic properties determined through averaging of different sample points.

MIKE SHE computes the unsaturated flow using a fully implicit finite difference solution. For each time step, the upper boundary condition is a constant flux (rainfall rate at the ground surface). The lower boundary is a pressure boundary defined by the water table. In MIKE SHE the primary evapotranspiration module is based on empirically derived equations that follow the work of Kristensen and Jensen (1975). The main inputs in the model are precipitation and hydraulic properties of the various soil types in the

form of the Van Genuchten model, Leaf Area Index (LAI) and Root Depth (RD) parameters.

There are three different methods in which MIKE SHE simulates flow in the unsaturated zone but the Richards equation is the most computationally intensive but also the most accurate representation of the conditions prevailing in the Densu basin. The Richards equation is also suitable when the flow in the unsaturated zone is dynamic, hence the choice of the Richards equation for this study. The Richards equation allows for the use of soil profile with different soil types at different depths. The hydraulic properties of the soils are defined by an unsaturated zone soil property file. The vertical discretization of the soil profiles were specified with increasing cell thickness with depth.

7.2 Mathematical principles governing unsaturated zone flow

The fundamental principle of Richards' equation holds that the driving force of water flow in the unsaturated zone is the gradient of the hydraulic head h , which includes both a gravitational component (z) and a pressure component (ψ).

$$h = z + \psi \tag{7.3}$$

The gravitational head (z) at a point is the elevation of the point above the datum. The reference level for the pressure head component is the atmospheric pressure. Under unsaturated conditions, the pressure head (ψ) is negative due to capillary forces and short range adsorptive forces between the water molecules and the soil matrix (DHI, 2005).

The vertical gradient of the hydraulic head is the driving force for vertical flow of water in the unsaturated zone. Thus,

$$\Delta h = \frac{\partial h}{\partial z} \quad 7.4$$

Based on Darcy's law and the continuity equation, the vertical flow of water in the unsaturated zone can be described by the Richards' equation as follows:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z} \left(k(\theta) \frac{\partial \psi}{\partial z} \right) + \frac{\partial k(\theta)}{\partial z} - S(z) \quad 7.5$$

Where θ is the volumetric soil moisture, K is the unsaturated hydraulic conductivity and S is the root extraction sink term. When the concept of soil water capacity is incorporated into the equation, the resultant equation is referred to as Richard's equation and it is given as follows:

$$\frac{\psi}{\partial t} = \frac{\partial}{\partial z} \left(K(\theta) \frac{\partial \psi}{\partial z} \right) + \left(\frac{\partial K(\theta)}{\partial z} \right) \quad 7.6$$

The finite difference approximations of the partial differential equations are used by MIKE SHE in the simulation of the unsaturated zone flow. The finite difference approximation of vertical flow in an interior node is presented in equation 7.7:

$$\left[q_{j+\frac{1}{2}}^{n+1} = -K_{j+\frac{1}{2}}^{n+\frac{1}{2}} \left(\frac{\psi_{j+1}^{n+1} - \psi_j^{n+1}}{\Delta Z_{j+1}} + 1 \right) \right] \quad 7.7$$

Also the discrete form of equation 7.1 is presented in equation 7.8:

$$\left[C_j^{n+1} \frac{\psi_j^{n+1} - \psi_j^n}{\Delta t} = \left[K_{j+\frac{1}{2}}^{n+\frac{1}{2}} \left(\frac{\psi_{j+1}^{n+1} - \psi_j^{n+1}}{\Delta Z_{j+1}} \right) - K_{j-\frac{1}{2}}^{n+\frac{1}{2}} \left(\frac{\psi_j^{n+1} - \psi_{j-1}^{n+1}}{\Delta Z_j} \right) \right] \frac{1}{\frac{1}{2}(\Delta Z_{j+1} + \Delta Z_j)} - S_j^{n+1} \right] \quad 7.8$$

J and n denotes the increment in space and time respectively.

7.3 Results and discussions on unsaturated zone water content

The actual water content in the unsaturated zone in the basin as computed by the MIKE SHE model varies from one soil type to another (Figures 7.1, - 7.3).

The water content of the Birimian soils (Fig 7.1) is almost two times more than the water content of the Granites and Togo series soils (Fig 7.2 and 7.3) therefore it is expected that more rainfall will be required to achieve saturation in the Birimian soils than in the Granite and Togo series soils. Groundwater heads in the Togo and Granite zone aquifers will therefore, respond to rainfall faster than groundwater heads in the Birimian zone aquifers. Groundwater recharge begins to take place when the moisture content requirement of the unsaturated zone is exceeded.

Groundwater head fluctuations in the Birimian aquifers are not as frequent as fluctuations in the Togo series and the Granite aquifers (Based on observation of groundwater monitoring data). This is because some rainfall events that will generate groundwater recharge in the Granite and Togo series aquifers may not be enough to generate recharge in the Birimian zone aquifers due to the high water demand of the unsaturated zone of the Birimian formation.

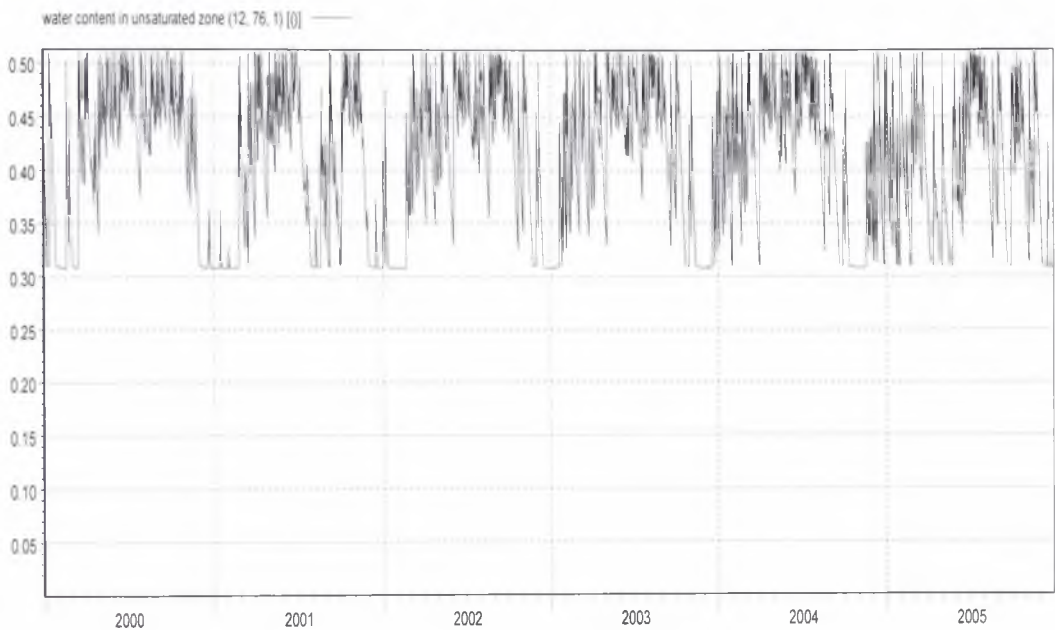


Fig. 7.1 Unsaturated zone water content in the Birimian

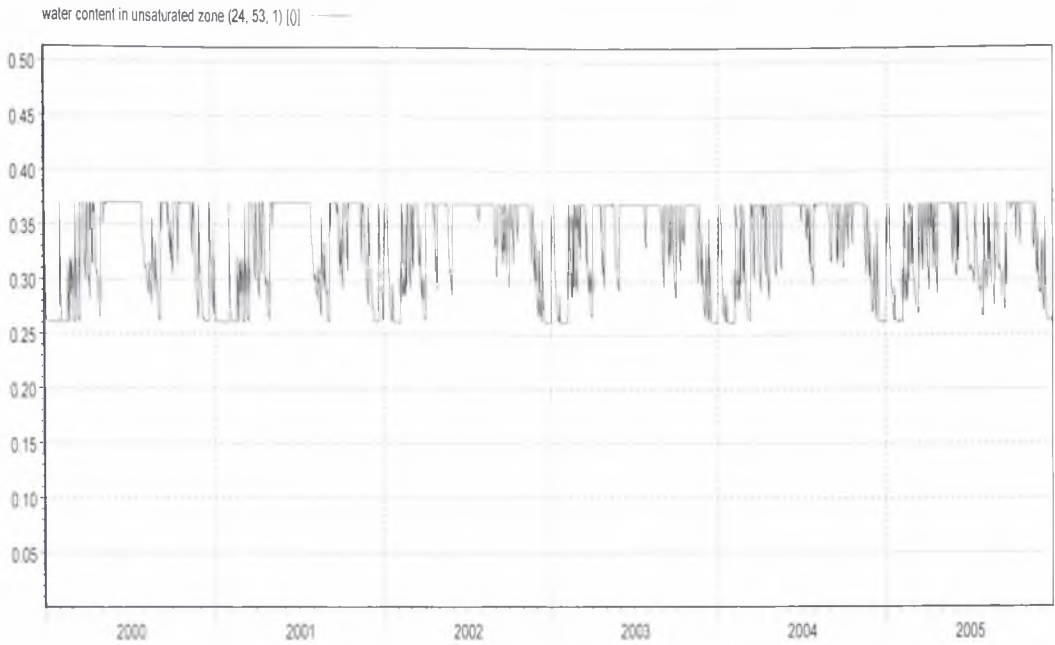


Fig. 7.2 Unsaturated zone water content in the Granite

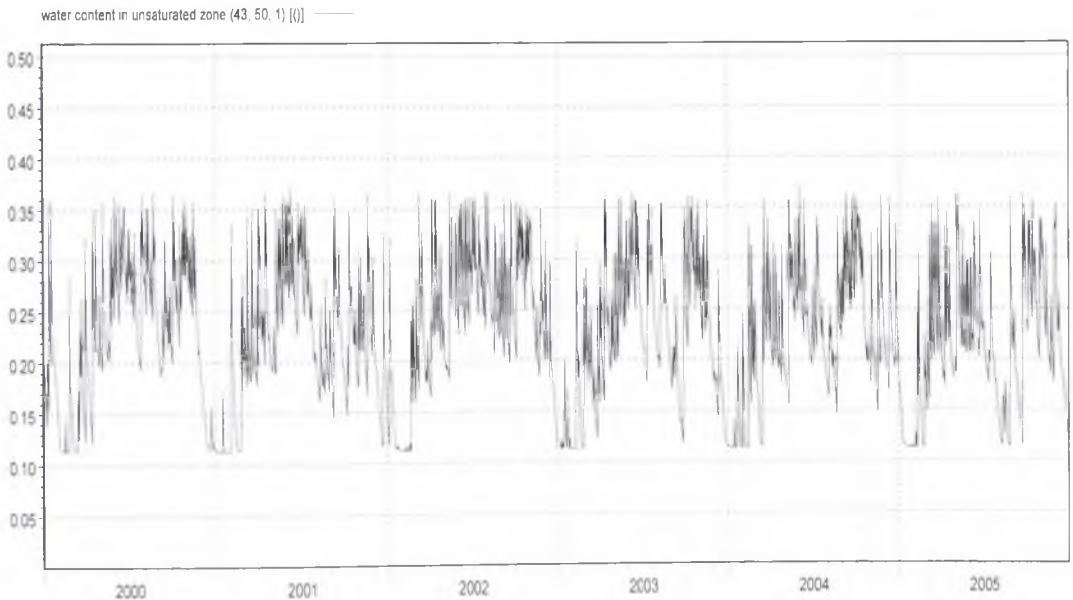


Fig. 7.3 Unsaturated zone water content in the Togo series

7.4 Results of groundwater recharge simulation

The estimation of groundwater recharge in the Densu basin was determined by analyzing the rate of exchange of water between the unsaturated zone (UZ) and the saturated zone (SZ). The impact of the various soil types and land use/cover on groundwater recharge is presented in figures 7.4 – 7.9. Positive and negative exchanges represent upward and downward movement of water respectively.

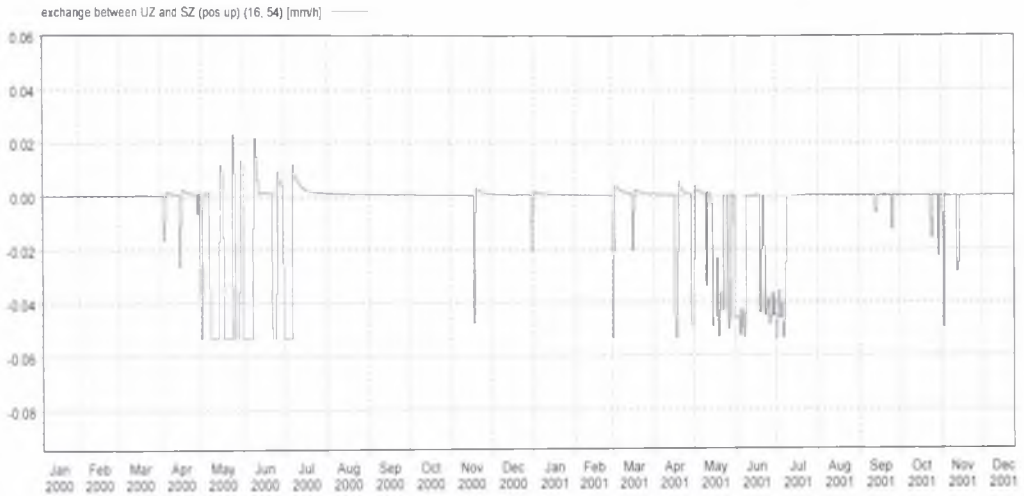


Fig. 7.4 Rate of groundwater recharge in the Granite soils in Savannah land cover



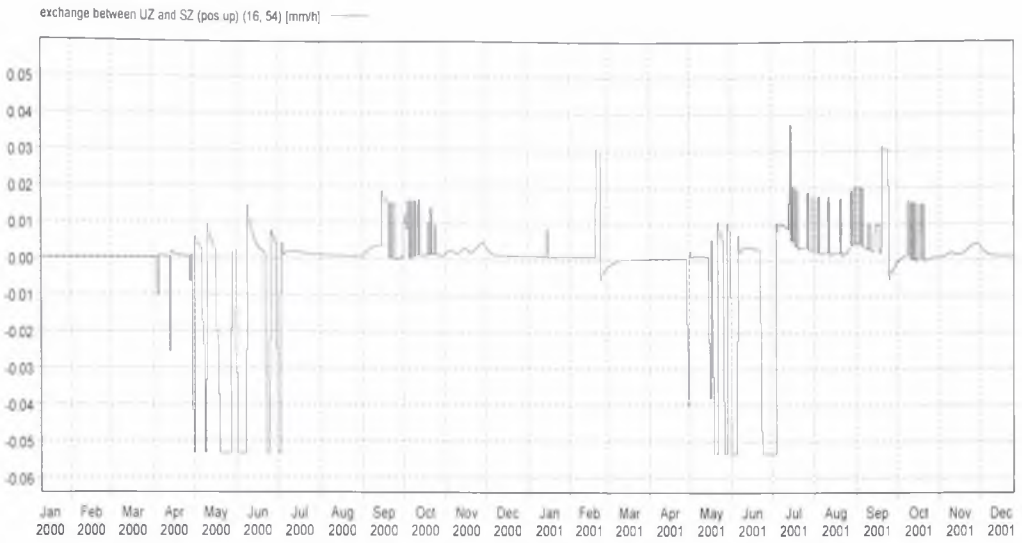


Fig. 7.5 Rate of groundwater recharge in the Granite soils in Forest land cover

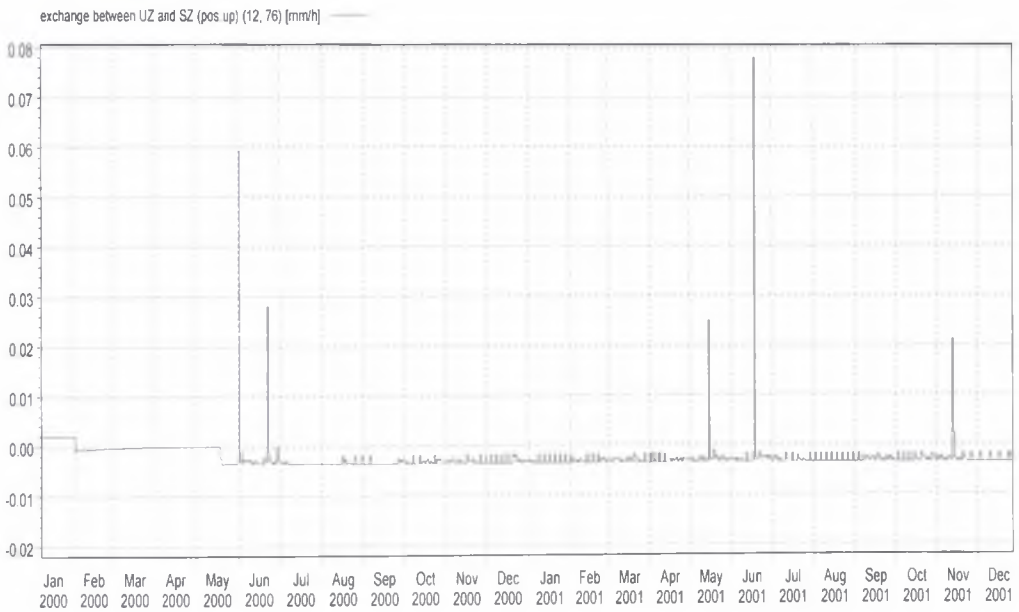


Fig. 7.6 Rate of groundwater recharge in the Birimian soils in Savannah land cover

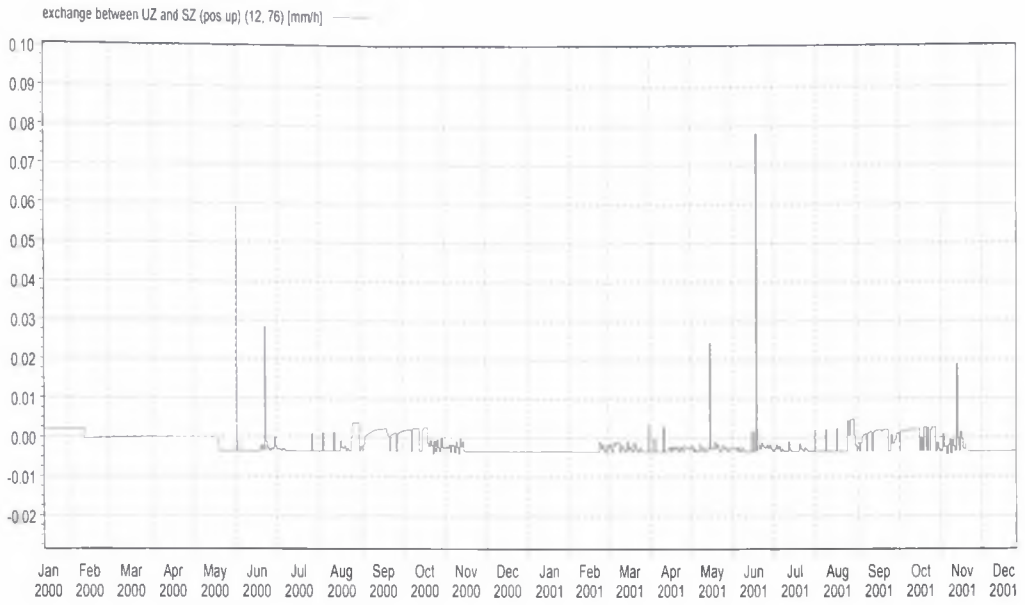


Fig. 7.7 Rate of groundwater recharge in the Birimian soils in forest land cover

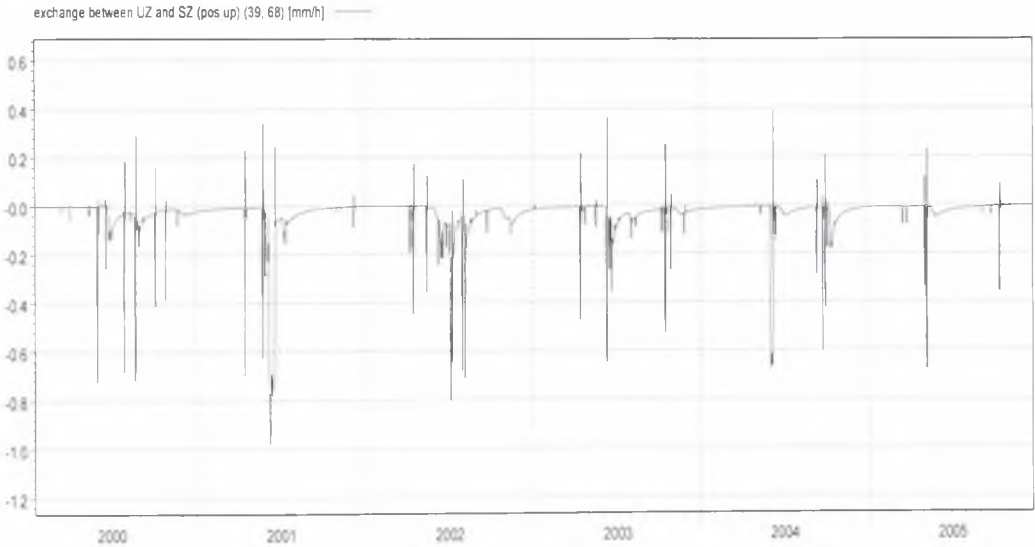


Fig. 7.8 Rate of groundwater recharge in the Togo soils in savannah land cover

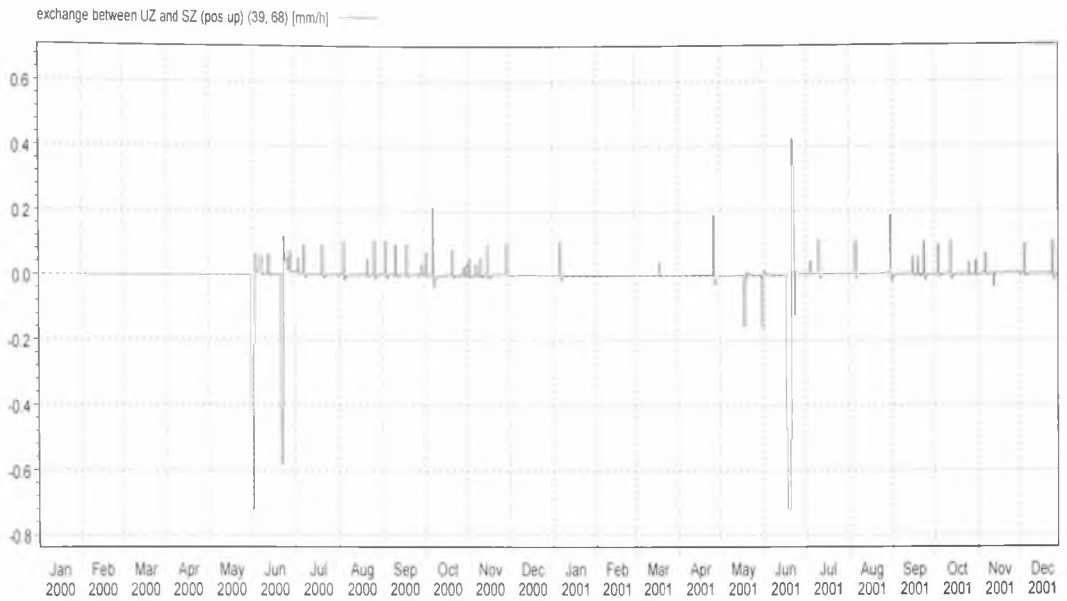


Fig. 7.9 Rate of groundwater recharge in the Togo soils in Forest land cover

Summary of water flow in the unsaturated zone in the three different geological formations and land use/cover types is presented in Table 7.1.

Table 7.1 Groundwater recharge analysis in the Densu basin

Soil/land cover type	Mean recharge rate (mm/h)	Mean Recharge duration (month/year)	Rate of flow from SZ to UZ (mm/h)	Duration of Flow from SZ to UZ (month/year)	Mean Actual evapotranspiration during wet season (mm/d)
Granite forest	0.05	3	0.015	5	5
Granite Savannah	0.05	4	0.015	2	4
Togo Forest	0.5	2	0.100	6	5
Togo Savannah	0.5	2	0.100	3	4
Birimian Forest	0.001	7	0.004	2	5
Birimian Savannah	0.001	7	0.004	2	4

7.5 Observations and discussion

The results indicate that the Togo series soils provide a better medium for groundwater recharge with a maximum recharge rate of 0.7m/h and an average rate of about 0.3m/h (Figs 7.8 and 7.9). The recharge rate in the granite soils is an order of magnitude lower

than that of the Togo series soils but longer recharge duration than in the Togo series soils (Figs. 7.4 and 7.5). The Birimian soils are almost impermeable and therefore the recharge rate is as low as 0.003m/h or 0.072 m/d (Figs. 7.6 and 7.7).

The results illustrate the effects of land cover on groundwater recharge. Analyses of the results show that the forest land cover allows for the same rate of percolation as the savannah land cover but the duration of recharge is significantly reduced in the forest land cover due to water loss through high evapotranspiration.

Another effect of the forest land cover on groundwater storage is the upward water movement from the saturated zone to the unsaturated zone. The rate of upward water movement as a result of the forest land cover is about half of the rate of percolation. It therefore implies that the effect of the forest land cover can reduce groundwater storage by about 50% through the combine effects of reduction in recharge duration and increase in upward movement of groundwater to the unsaturated zone. This effect only applies to areas where the groundwater table is not deep enough (less than 5 m). If the groundwater table is deeper than 5 m, the effects of root water uptake from aquifer storage will be minimal, however soil water uptake can still lead to reduction in groundwater recharge

In the Birimian soils, the differences in the upward movement of water in the forest and savannah land cover are quite minimal because of the high capillary forces of the clay soils. The upward movement of water in this soil is greatly due to the capillary forces of the clay soils.

CHAPTER EIGHT

8.0 Simulation of saturated zone processes

Groundwater flow in the Densu basin is controlled by pores resulting from both weathering and fracturing. The aquifer systems in the basin can be described as dual porosity aquifers and aquifers of high uncertainty. The weathered zones normally overlie the fracture zones therefore providing high porosity for groundwater flow. Boreholes in the Densu basin are constructed to abstract water from both the weathered and the fractured zones. Generally, the base of the weathered zone is the high yielding zone. In the Togo series rocks in particular, the weathered zone aquifers produce more water than the fracture zone aquifers. In most cases the two zones form a single aquifer system with different flow patterns.

Groundwater flow in fractures is controlled by the aperture of the fractures, the number of fractures per unit distance and the cross sectional area. It also depends on the fracture hydraulic conductivity and the bulk porosity.

Groundwater in the basin like in all aquifer systems possesses mechanical, chemical and thermal energy. If the amounts of the different forms of energy vary spatially, the water is forced to move from one region to another in an attempt to neutralize the energy differential and attain equilibrium. Apart from these energies, there are also external forces such as gravity, pressure and molecular attraction acting on groundwater. Gravity pulls water downwards through the unsaturated zone to the aquifer systems and therefore contributing significantly to groundwater recharge. Pressure on groundwater is mainly as

a result of atmospheric pressure and pressure resulting from the weight of the overlying material. The molecular attraction force causes water to adhere to solid surfaces. The total energy contained in a groundwater body can be expressed by the Bernoulli equation as follows:

$$H = \frac{p}{\gamma} + \frac{V^2}{2g} + Z \quad 8.1$$

Where P = Pressure, γ = specific weight of water, V = Velocity of flow, g = Acceleration due to gravity and Z = elevation.

The pressure head (P/γ) is the energy contained in a water mass as a result of the forces confining the water. A measure of this force is the rise or expansion of the water when the force is removed. The velocity head ($v^2/2g$) is the energy component resulting from the movement of the water. The energy resulting from the movement of groundwater is not normally important because the flow of groundwater is extremely slow. The elevation head (Z) is a latent form of energy

8.1 Mathematical principles governing saturated zone processes

The development of the 3-dimensional mathematical equation describing the governing processes of groundwater flow of a confined aquifer is based on two main principles:

- The conservation of water volume and
- The Darcy law

The conservation of water volume can be expressed by the following mathematical relationship.

$$\frac{\Delta V_w}{\Delta t} = Q_{in} - Q_{out} \quad 8.2$$

Equation 7.2 states that, the change of water volume over a certain time interval is equal to the difference of total inflow and total outflow within the same time interval. To apply this expression to water contained in an aquifer system, the variables are defined as:

V_w = volume of water in an aquifer system (aquifer storage)

Q_{in} = Recharge of the aquifer system

Q_{out} = Flow out of the aquifer system (abstraction, base flow, evapotranspiration etc)

Darcy's law on the other hand is an empirical relationship which states that, the specific discharge (v_f) is proportional to head differences ($\partial h/\partial l$) and the proportionality factor is given by the hydraulic conductivity (K). Darcy's law can be expressed by the relationship

$$v_f = -K \frac{\partial h}{\partial l} \quad 8.3$$

where

v_f = Darcy flux or specific discharge

K = Hydraulic Conductivity

h = hydraulic head and

l = flow distance

The negative sign in the Darcy's expression indicates that flow is from higher head values to lower head values.

To demonstrate the formulation of a 3-dimensional mathematical equation governing the quantitative processes of groundwater flow in the Densu basin based on the conservation of water volume and the Darcy's law, the basin is conceptualized as a control 3-dimensional flow unit.

It is considered that the volume of groundwater in the basin at a given time interval is the difference between recharge and outflow (sources and sinks) within the same time interval. Based on the conservation of mass principles and the Darcy equation as well as the conceptualization of the 3-dimensional groundwater flow, the general equation describing groundwater flow in confined aquifers is presented in equation 7.12 based on which the finite difference equation is approximated.

$$S_s \frac{\partial h}{\partial t} = \frac{\partial}{\partial x} \left(K_x \frac{\partial h}{\partial x} \right) + \frac{\partial}{\partial y} \left(K_y \frac{\partial h}{\partial y} \right) + \frac{\partial}{\partial z} \left(K_z \frac{\partial h}{\partial z} \right) + q \quad 8.4$$

This equation describes a 3-dimensional, confined, anisotropic, presence of sources and sinks and transient flow of groundwater which represents the flow characteristics in the Densu basin. It has to be noted that the equation is a second order partial differential equation with head as the dependent variable which defines the curvature of the potentiometric surface. In order to determine a unique solution of such a mathematical equation, it is necessary to specify boundary conditions around the flow domain for the dependent variable.

The groundwater flow equation (Eq. 8.4) represents a problem rather than a solution to a problem, to solve equation 8.4 for h in space and time is a difficult task. For most

practical applications, there is no explicit solution for h in space and time as presented in equation 8.4. A numerical solution to the equation is therefore required to make it practically useful.

Practically, groundwater heads can only directly be measured at discrete points through the drilling of boreholes. To know the groundwater head level at all point in the model area, the slope of the head gradient between two or more boreholes points must be adequately determined. An approximation of the curvature of the head gradient applying different ratios (finite difference approximations) is required to simulate groundwater heads.

The computation of difference ratios is associated with errors arising from spatial discretization of the model into model grids. An illustration of errors associated with computing difference ratios is presented in Figure 8.1.

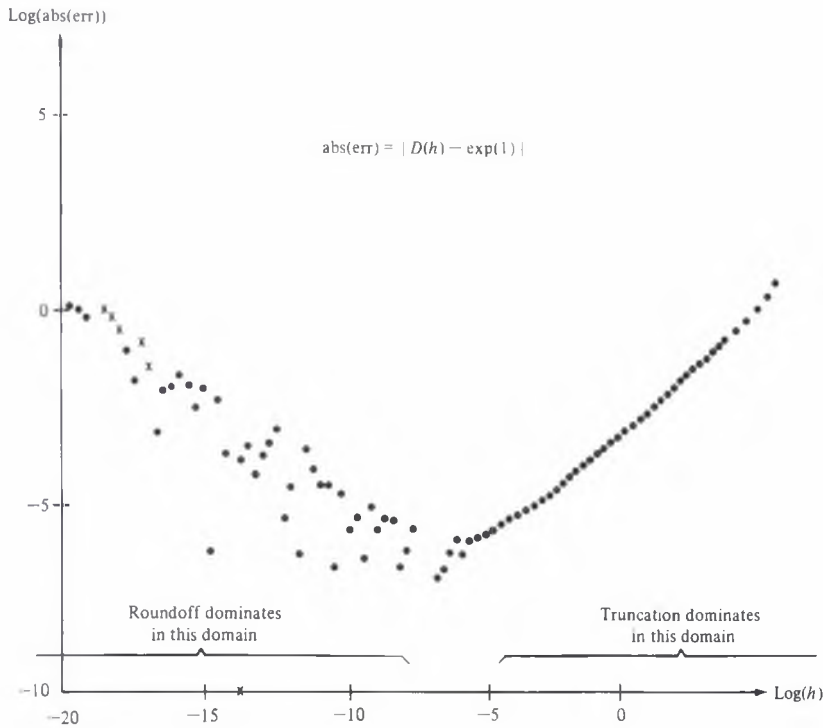


Fig. 8.1 Truncation errors and rounding errors (Yakowitz and Szidarovsky, 1989)

As illustrated above (Fig. 8.1), truncation errors are associated with larger spatial discretization whereas round off errors which occur if differences of similar values are computed, dominate smaller spacing.

Combining spatial and temporal discretizations, the explicit finite difference approximation of the groundwater flow equation based on which MIKE SHE simulates groundwater flow can therefore, be expressed as follows (Eq. 8.5):

$$h_{ij}^k = h_{ij}^{k-1} + \Delta t \frac{T}{S} \left(\frac{h_{i+1,j}^{k-1} - 2h_{ij}^{k-1} + h_{i-1,j}^{k-1}}{\Delta x^2} + \frac{h_{i,j+1}^{k-1} - 2h_{ij}^{k-1} + h_{i,j-1}^{k-1}}{\Delta y^2} \right) \tag{8.5}$$

It should be noted that, the above expression is only capable of approximating heads of inner cells therefore boundary conditions describing groundwater heads in the boundary cells must be specified.

8.2 Characterizations of saturated zone processes

There are various ways in which the saturated zone can be characterized by MIKE SHE; it is possible to characterize the aquifer systems by geologic units, geologic layers and geologic lenses or a combination of any of the above. In the Densu basin, the aquifer systems were characterized into both geologic layers and geologic units. Due to lack of detail information in the basin, geologic lenses could not be defined. The saturated zone was divided into two geologic layers namely layers 1 and 2. The weathered zone was represented by layer 1 and the fractured zone represented by layer 2. It is known that the fractured zone cannot be described as a layer in the true meaning of the term “layer” but for the purpose of model characterization, it is convenient to characterize it as a layer. The two layers were defined by the type of geologic unit or the type of porosity that characterize the layer, that is: weathered and fractured aquifers. The aquifer hydraulic properties of the layers such as the horizontal and vertical hydraulic conductivities, the specific yield, storage coefficient and porosity of the layers were defined through the geologic units.

Lithological data of boreholes in the basin were analysed for the characterization of the different layers and geologic units of the saturated zone. The limitations associated with

the borehole data are that, all the boreholes were not fully penetrating therefore the thickness of the bottom layer (fractured zone aquifer) is likely to be under estimated. The depth of the deepest borehole is about 90 m below surface.

Analyses of pumping test data in the basin revealed that there is no particular pattern in the values of the hydraulic properties of the different geologic formation. However, the values of the hydraulic properties of the weathered zone were found to be higher than those of the fractured zone. Average values were therefore computed for both layers and used as inputs into MIKE SHE. The distributed nature of the saturated zone with regards to hydraulic properties was therefore compromised.

The lower limits of the two layers were used to characterize the unsaturated zone. MIKE SHE computes the thickness of the top layer by using the depth of the unsaturated zone and the lower limits of the top layer. In the same way the thickness of the bottom layer (fractured zone aquifer) is computed by using the lower limits of the top layer and the lower limits of the bottom layer.

MIKE SHE has a computational layer option where the initial potential head, the, boundary conditions and internal boundaries of each layer can be defined. The initial potential head of both the upper and boundary layers are the same since both layers make up a single aquifer system. The initial potential was obtained from 10 monitoring boreholes in the basin. There is a major limitation to the accuracy of the potential head across the basin since only 10 discrete points were used to extrapolate across the basin.

The outer boundary conditions of the two layers are also the same with most part of the boundary defined as a no flux boundary except the boundary to the south where a fixed head boundary condition was defined due to the flow between the aquifer and the sea water (Fig. 8.2). No internal boundary in the model domain was defined. MIKE SHE allows for the definition of internal boundaries such as groundwater divides but due to lack of detail knowledge of the saturated zone in the Densu basin, it is practically impossible to accurately define groundwater divides even though it is expected that within the model domain there exist some groundwater divides. The topographic features of the basin do not reveal the presence of groundwater divides but in most cases secondary porosity aquifers especially through fracturing are localized in nature and therefore require internal boundaries. The definition of the boundary conditions of the model is presented in Figure 8.2.

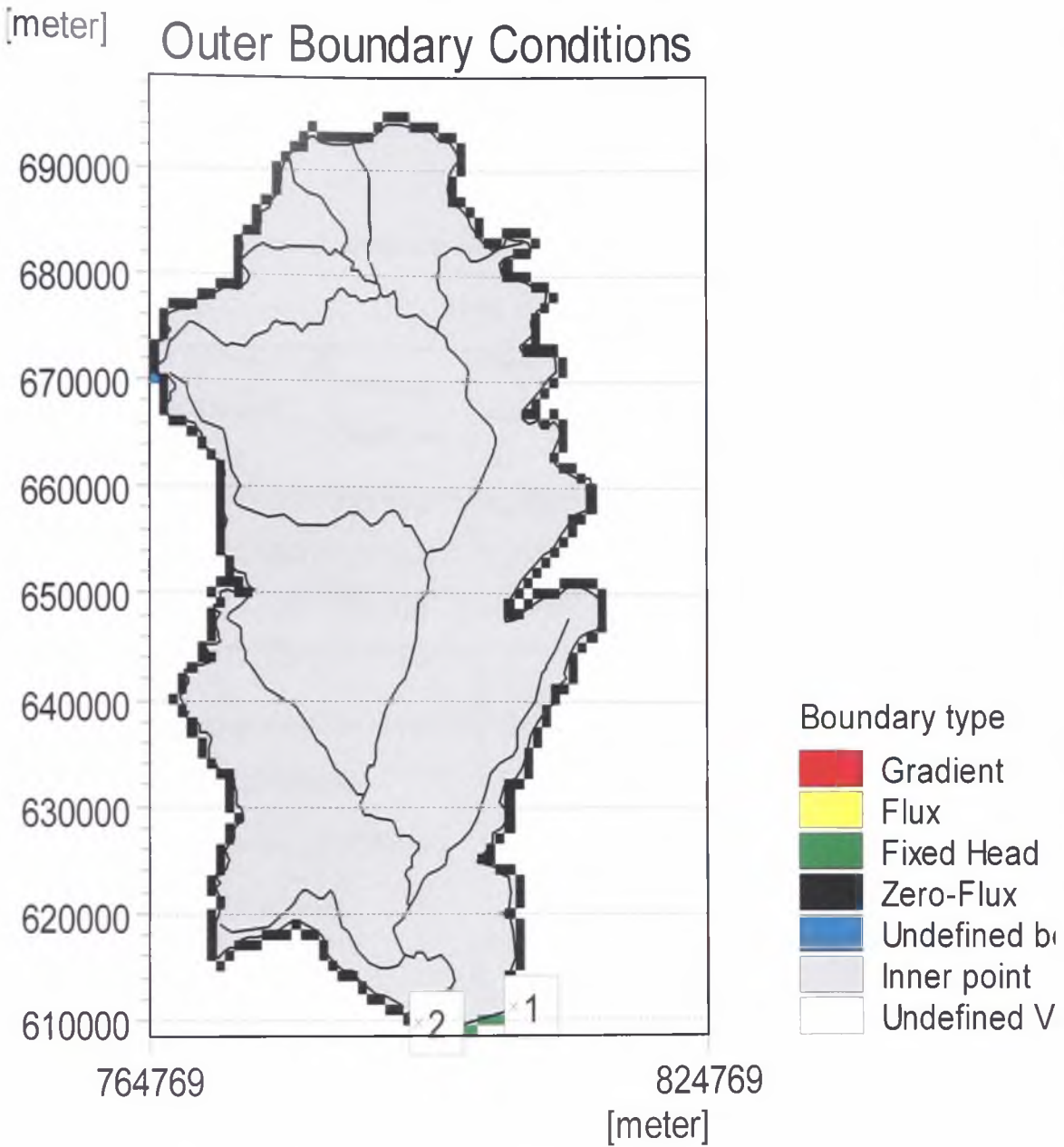


Fig 8.2 Outer boundary condition of the model domain

Table 8.1 and Figures 8.3 and 8.4 provide a summary of the statistical characteristics of aquifers in the different geologic zones and type of porosity in the Densu Basin based on the analyses of 500 boreholes.

Table 8.1 Characteristics of aquifers in the three geologic formations in the Densu Basin

Geological zone	Depth of borehole (m)	Thickness aquifer (m)	Depth to aquifer top (m)	Static water level (m)	Borehole yield (m^3/hour)
Granites	9.1 - 70.0	2.0 - 37.0	3.0 - 43.0	0.7 - 15.0	0.1 - 3.0
Birimian rocks	25.0 - 60.0	3.0 - 30.0	10.0 - 35.0	0.8 - 18.0	0.7 - 9.0
Togo series	28.0 - 65.0	2.0 - 40.0	4.0 - 45.0	1.5 - 19.0	0.6 - 6.0

For the three geological zones, the average yield is found to be as follows:

- Granitic zone: $2.0 \text{ m}^3/\text{hour}$;
- Birimian formation: $3.7 \text{ m}^3/\text{hour}$;
- Togo series: $2.8 \text{ m}^3/\text{hour}$.

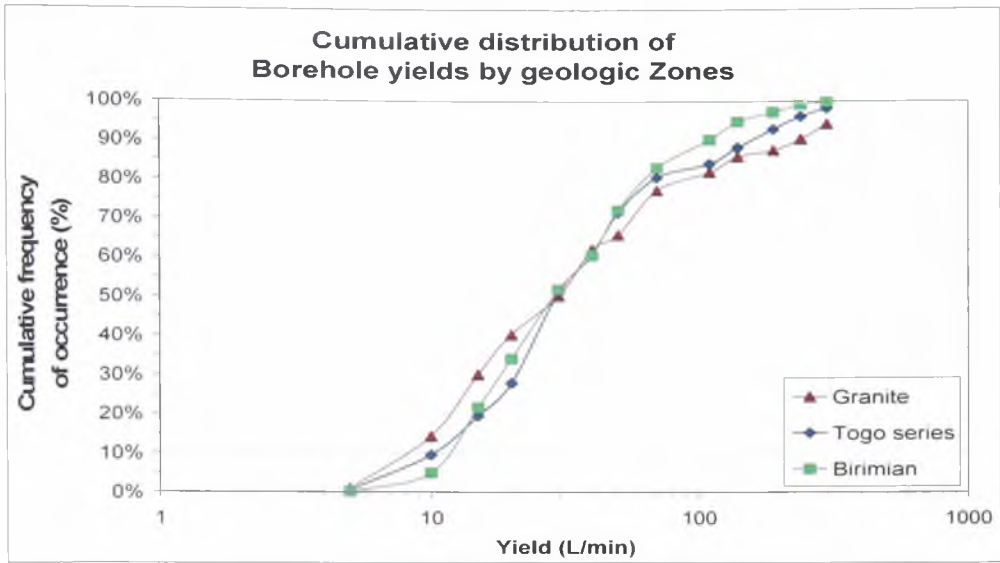


Fig 8.3 Cumulative distribution of borehole yields by geologic zones

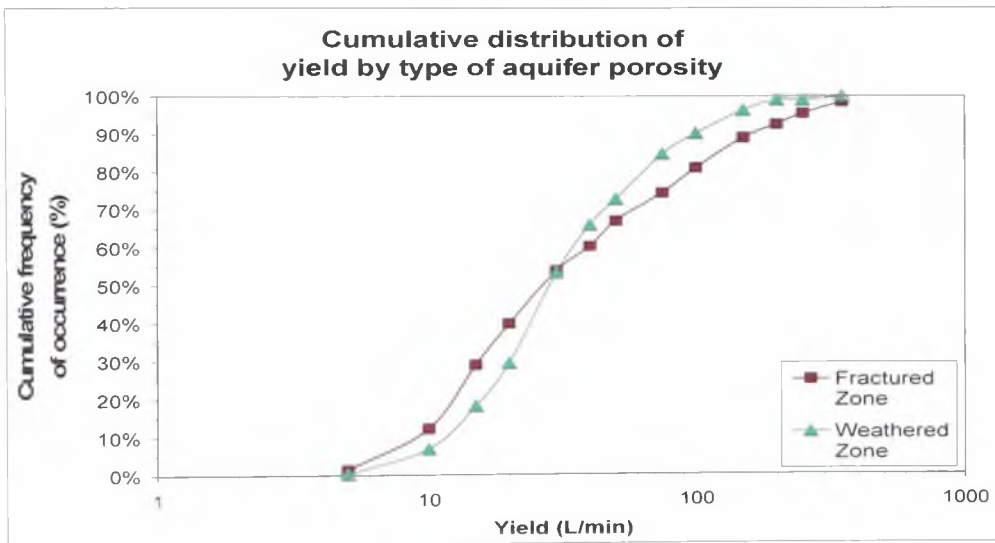


Fig 8.4 Cumulative distribution of borehole yields by aquifer type

8.3 Results of groundwater flow simulation

Groundwater head elevations were simulated by MIKE SHE and a comparison of the simulated heads vrs measured heads are presented graphically. The flow in the z direction (negative flow represents recharge and positive flow represents extraction of groundwater by the roots of vegetation and evaporation) is also presented to assess the response of groundwater recharge on groundwater heads. The elevations represent groundwater heads for both the weathered and the fractured zones since they form dual porosity aquifers. The differences in head values in the different geological formations can be said to be influenced by the unsaturated zone processes, topography, rainfall pattern, boundary conditions and the initial potentials. This is because the hydraulic properties of the aquifers in the different geological formations were not differentiated and therefore will not respond differently. It should be noted that measured groundwater heads are available for only two years (2004 – 2005) where as the simulation period is between 2000 and 2005. It is therefore only possible to compare simulated and measured groundwater heads for the two years (Figs. 8.5, 8.11 and 8.15).

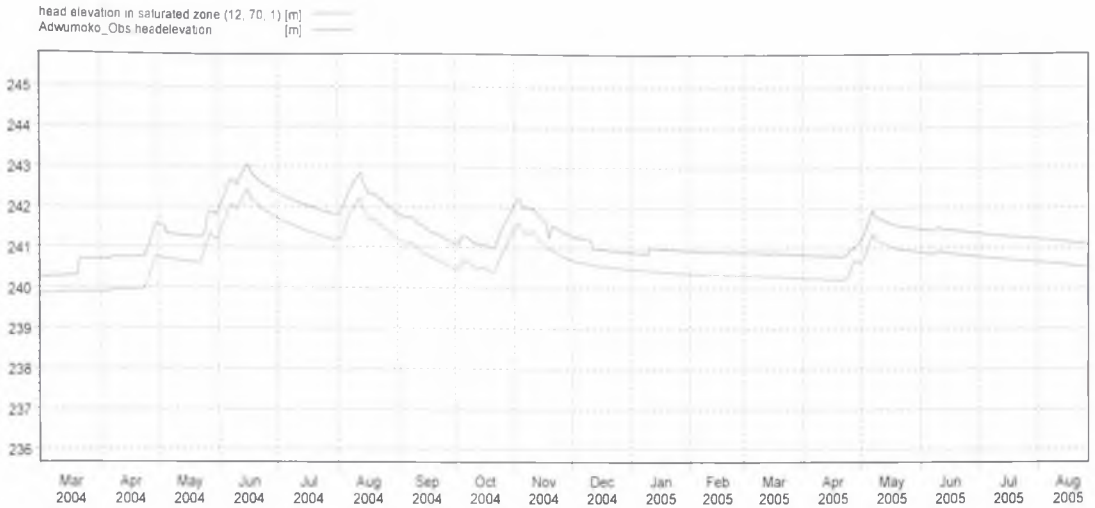
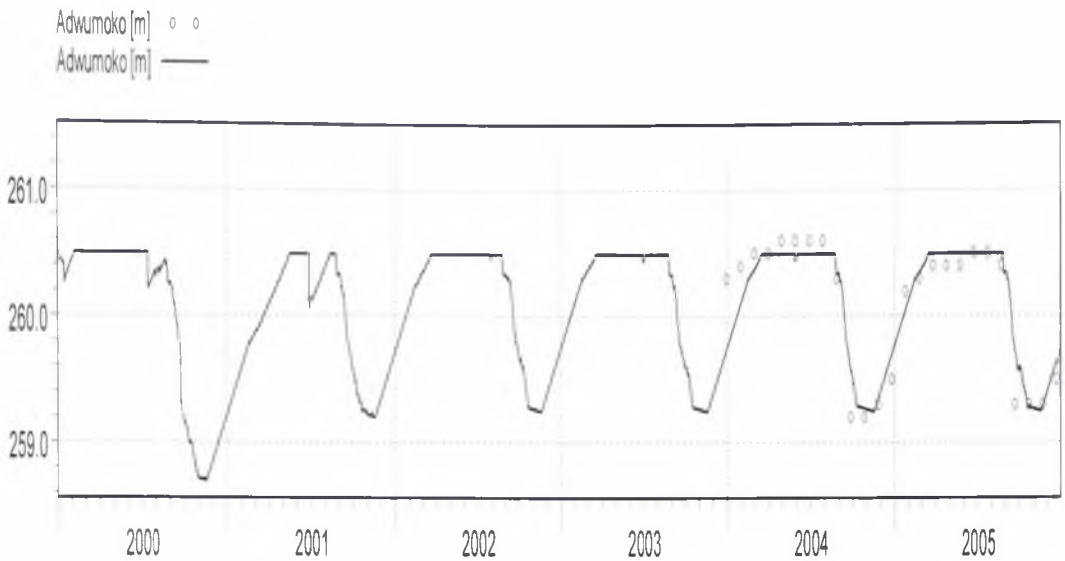


Fig 8.5 Simulated Vrs measured groundwater head elevations in the Birimian formation from Mar 2004 – Aug 2005)



Fig 8.6 Groundwater level – time graph at Adwumoko monitoring stations (Water Research Institute 2006)



ME=-0.00197388

MAE=0.136105

RMSE=0.192809

STDres=0.192799

R(Correlation)=0.934603

R²(Nash Sutcliffe)=0.869352

Fig 8.7 Groundwater head elevation in the Birimian formation at Adwumoko (simulated head elevation (-) for the entire simulation period and measured groundwater head elevation (ooo) for two years)

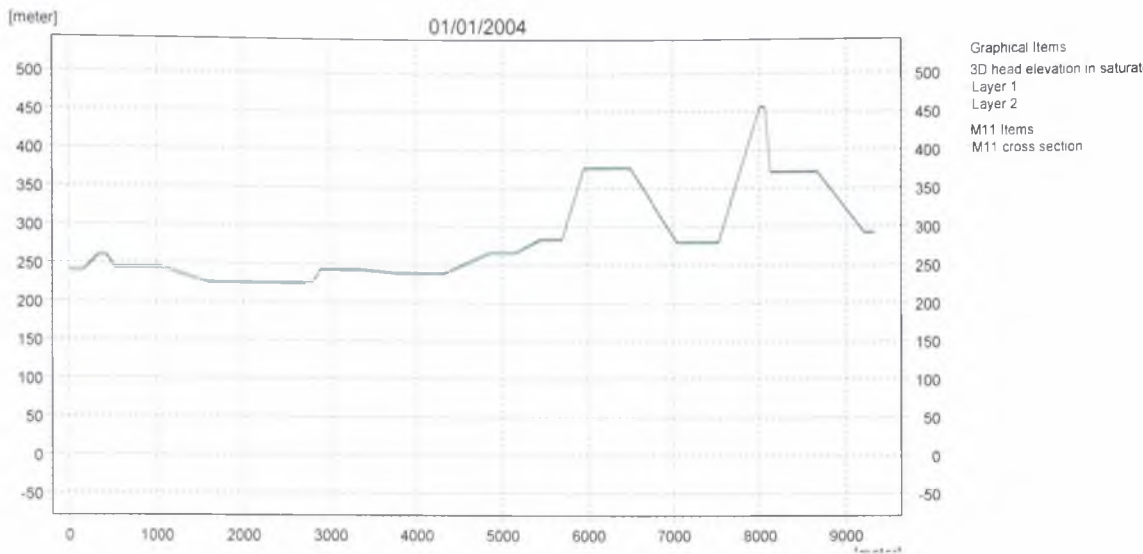


Fig 8.8 head elevation profile (North – South cross section) in the saturated zone of the Birimian zone

The rate of groundwater flow in the Birimian formation is presented in Figures 8.9 and 8.10. In Figure 8.9, positive flow represents upward movement of water as a result of capillary forces and root water uptake whereas negative flow represents groundwater recharge. Figure 8.10 demonstrates the rate of groundwater flow in the x-direction. The rate of groundwater flow in the x-direction increases in the rainy season and reduces in the dry season. There is however, a delay of one month in the increase in the rate of the flow due to the high retention capacity of the unsaturated zone of the Birimian formation (Fig. 8.10).



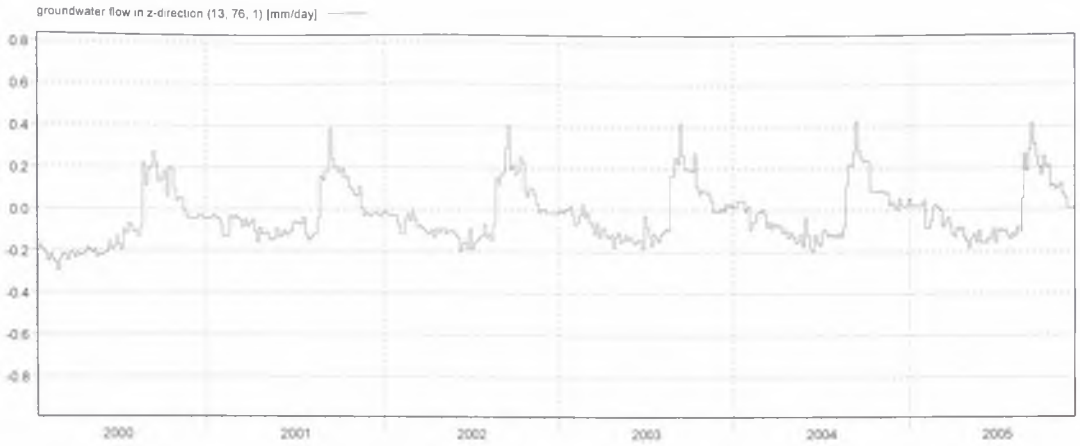


Fig 8.9 Groundwater flow in the z direction in the Birimian formation

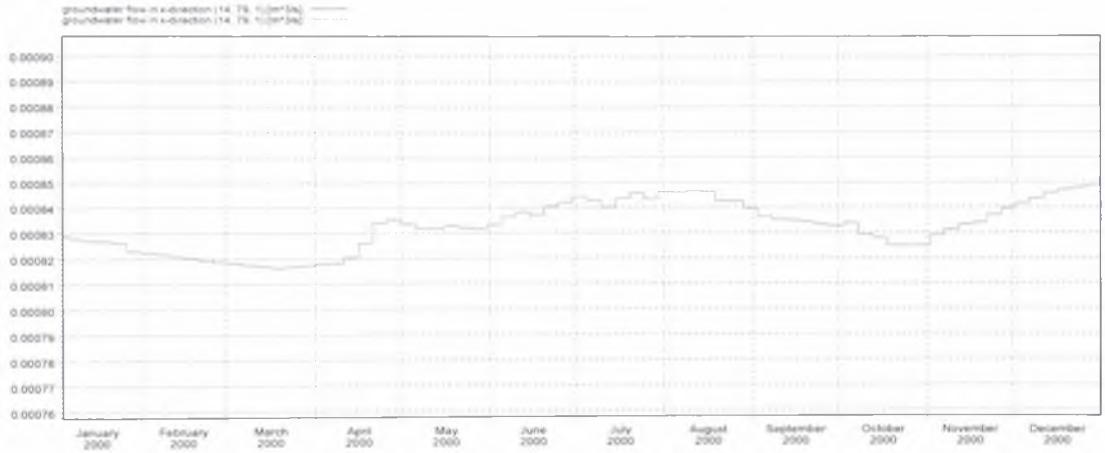


Fig 8.10 Groundwater flow in the x – direction in the saturated zone of the Birimian formation

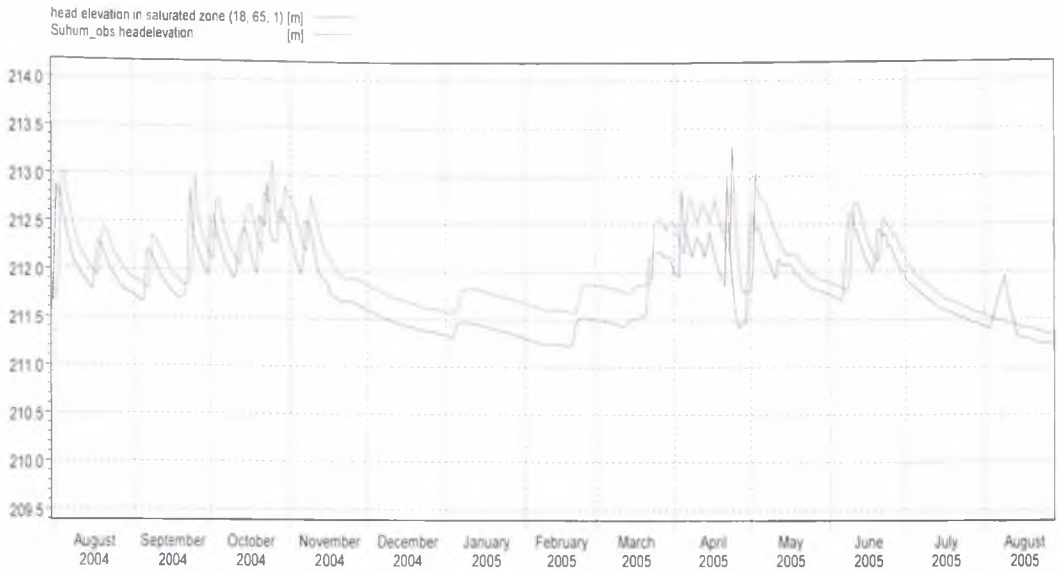


Fig 8.11 Simulated Vs measured groundwater head elevations in the granite (Suhum) from April 2004 – September 2005

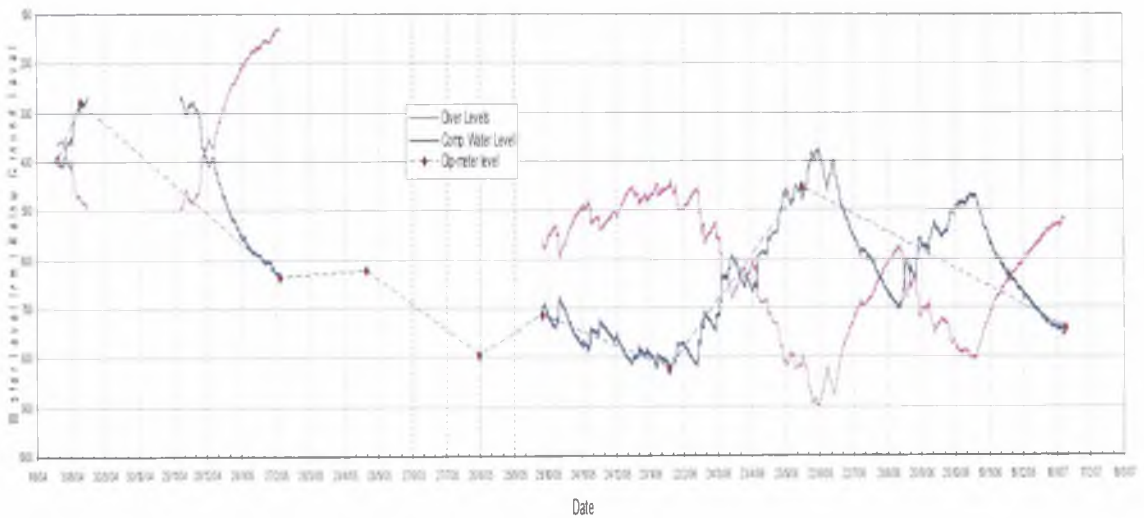


Fig 8.12 Groundwater level – time graph at Suhum monitoring stations (Water Research Institute 2006)



Fig 8.13 Groundwater head elevation in the Granite for the entire simulation period (2000 – 2005)

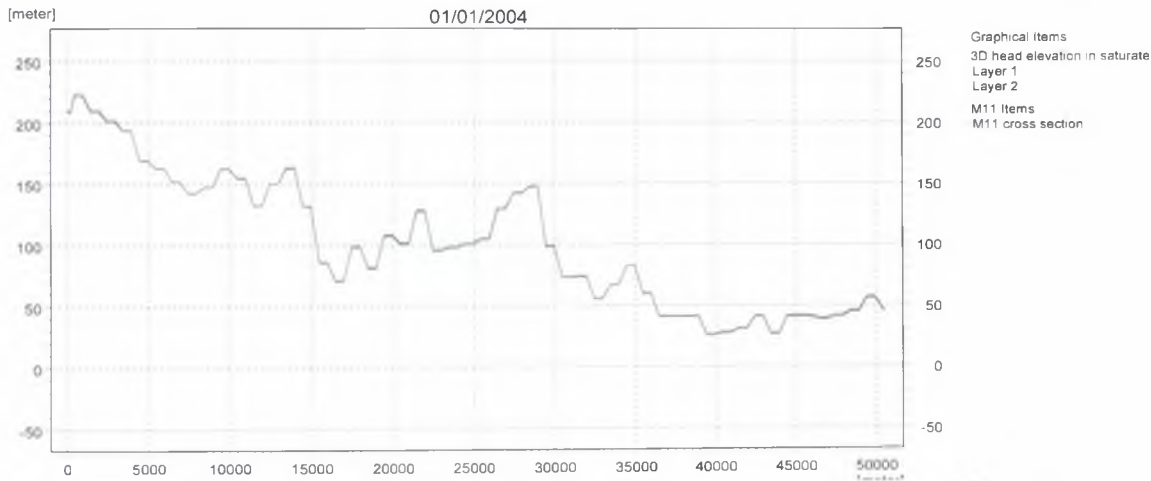


Fig 8.14 head elevation profile (north – south cross section) in the saturated zone of the granite zone

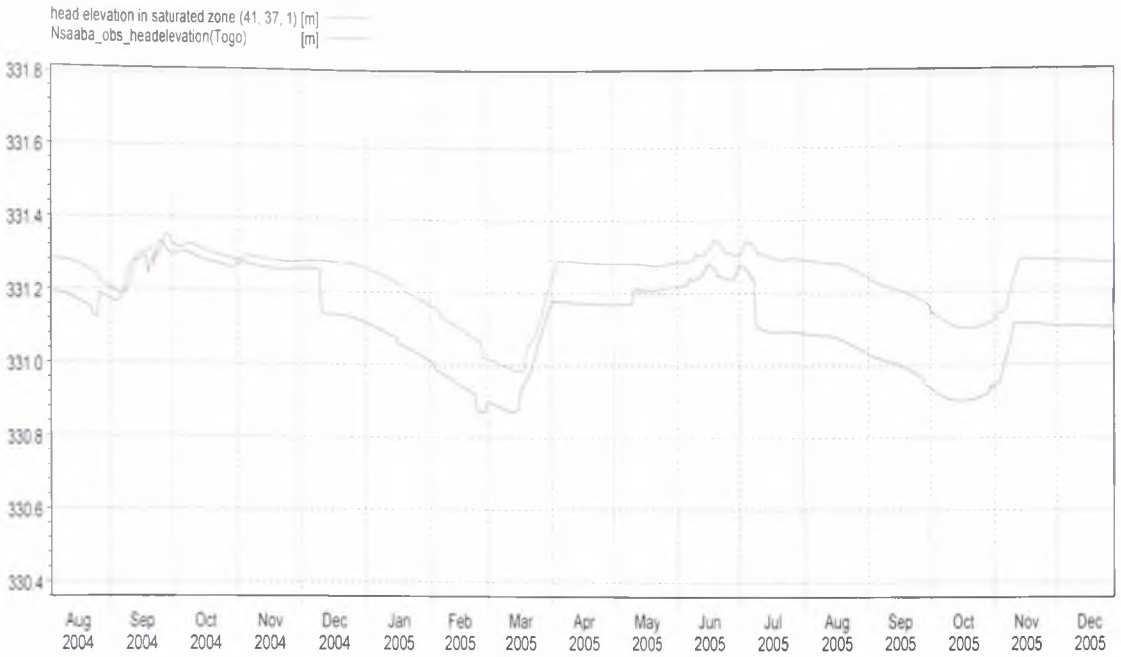


Fig 8.15 Simulated Vrs measured groundwater head elevations in the Togo formation (Nsaaba) from Aug 2004 – Dec 2005

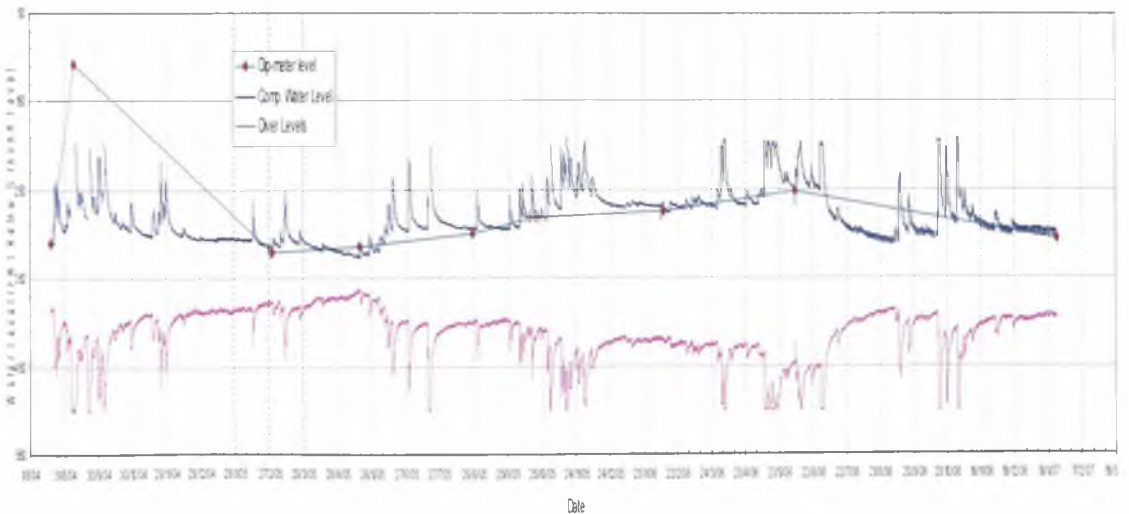


Fig 8.16 Groundwater level – time graph at Nsaaba monitoring stations (Water Research Institute 2006)

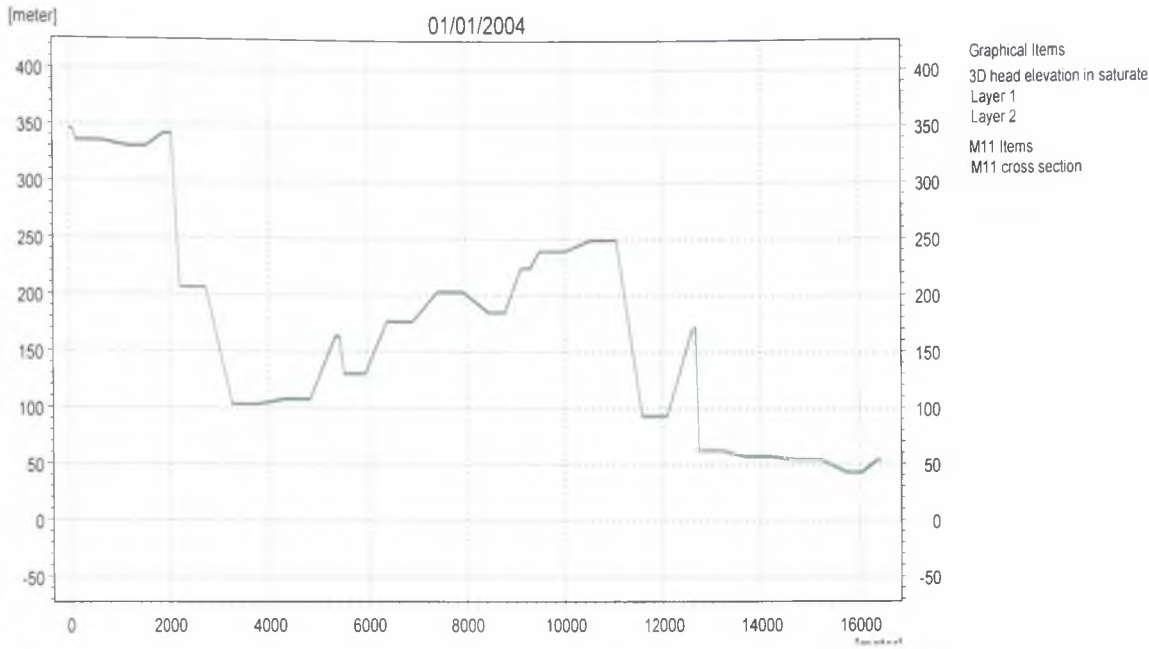


Fig 8.17 head elevation profile (north – south cross section) in the saturated zone of the Togo series zone

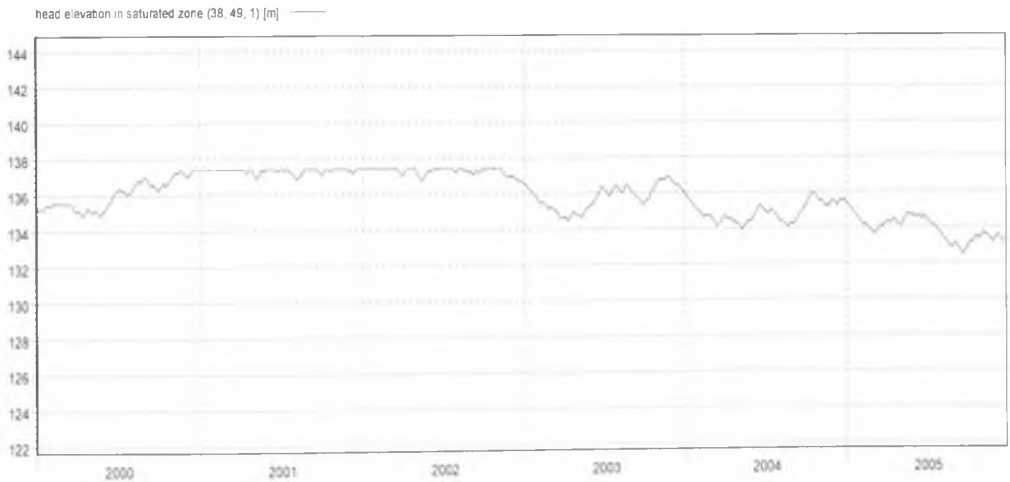


Fig. 8.18 Groundwater head elevation in the Togo series



8.4 Observations and discussion

The groundwater head elevations in all the three geologic formations show annual fluctuations of about 2 m between the wet and dry seasons (Figures 8.5, 8.11 and 8.15). Head fluctuation in the Birimian formation is quite stable and “smooth” compared to that of head fluctuations in the granites and the Togo rocks. This is because the unsaturated zone of the Birimian formation has a much higher water retention capacity than the unsaturated zones of the Granites and Togo formations and therefore, groundwater heads in the Birimian formation do not respond to rainfall as quick as groundwater heads in the other two formations (refer to chapter 7 on simulation of unsaturated zone water content).

It has also been discovered in this research through rainfall analyses that, rainfall events with intensity below 20 mm/h and above 70 mm/h do not contribute significantly to groundwater recharge where as the rainfall intensity windows for recharge in the Granite and Togo formations are between 20 mm/h – 90 mm/h and 20 mm/h – 100 mm/h respectively (refer to chapter 5 on rainfall intensity analyses).

Measured groundwater head elevations are higher than simulated heads in the Birimian formation (Fig.8.7) whereas in the Granites and Togo Series formation, measured groundwater head elevations are slightly lower than simulated heads (Figs. 8.11 and 8.15). The reason for higher measured heads in the Birimian could be explained by two theories:

1. Indirect recharge to the Birimian aquifers through fractures and joints which were not mapped in the field and captured by the model conceptualization or/and

2. Cross groundwater flow from the Granite aquifers. Given that, the Granite and Togo series formations have higher groundwater recharge than the Birimian formation, it is expected that groundwater heads will be much higher than that of the Birimian formation. However, this is not the case, given reason to suggest cross flow from the Granite formation to the Birimian system.

Groundwater head profile in the Birimian formation indicates a general flow direction from south – north with a few localized north - south directions (Fig 8.8). On the other hand, the flow direction in the Granite and Togo formations is from north – south with a few localized south – north directions (Figs. 8.14 and 8.17). The slope of the potentiometric surface corresponds to the slope of the surface topography.

CHAPTER NINE

9.0 Simulation of river flow

There are various classification schemes for river channel morphology. An example is the Rosgen's classification system (Rosgen, 1994) which is a well known classification system and most frequently used in river management studies. The Rosgen classification system involves seven major categories, based on variables such as channel patterns and slopes (Robert, 2003). Rosgen classification is however not process based (Montgomery and Buffington, 1998) and this may limit its usefulness when assessing the response of stream channels for instance, disturbances. A process based classification of rivers should involve bed material size, channel gradient and channel depth (Whiting and Bradley, 1993).

A simple classification of stream channels based on channel size and sediment size can be established. This classification system is based on the ratio of average flow depth (d) to median grain size index (D). The ratio d/D controls flow resistances and related processes in channels (Church, 1992). There are three types of river channel classification based on the ratio d/D , namely:

- Small channels ($d/D < 1$);
- Intermediate channels ($1 < d/D < 10$);
- Large channels ($d/D > 10$).

Based on this classification, the Densu River belongs to the intermediate type of channels. Intermediate channels are usually characterized by channel gradients varying

between 0.1 and 1% (Robert, 2003). An upper limit for channel width can not precisely be determined but most rivers in this category are characterized by a channel width of up to 20 – 30 m (Church, 1992)

9.1 Principles of river flow

The basic principle governing river flow is based on the principles of mass continuity (conservation of matter). The discharge of a river is determined by the cross sectional area and the velocity of flow, the relationship can be expressed as:

$$Q = A * U \quad 9.1$$

Where Q = river discharge, A = cross sectional area and U = mean velocity. If along a river channel, there are successive cross- sections with areas A_1 A_2 , if the cross sectional areas vary and the discharge is constant in space and time and assuming the fluid is incompressible (constant density). The expression for the conservation of mass (and volume) is given as:

$$Q = A_1 U_1 = A_2 U_2 = \frac{\partial(AU)}{\partial x} = 0 \quad 9.2$$

where x is the direction of flow.

Equation 9.2 is also known as the one dimensional equation of continuity. Based on Equation 9.2, it can be deduced that, velocities of water flows into narrower cross sectional areas must increase (convictional acceleration) and must decrease as the cross sections expand (convective deceleration). Water flows along a stream where, the

velocity and cross sectional area do not vary are called uniform flows and the opposite is termed non uniform flows.

Turbulent flow is generated in a river when the magnitude and direction of the flow velocity vectors, at any point in the flow change with time over time intervals of a second - seconds. On the other hand, Laminar flows occur where the magnitude and direction of the velocity vectors do not change with time at time scale of seconds or less (Bridge, 2003). In turbulent flows, the fluid, the fluid particles move in irregular paths causing an exchange of momentum from one portion of the fluid to another (Bradshaw, 1985). When the velocity of stream flow does not change with time, the flow is described as steady flow and the opposite is referred to as unsteady flow.

9.2 River design in MIKE 11

The River flow characteristics were defined by MIKE 11 module and coupled to the MIKE SHE model. River network, boundary conditions, River cross sections and hydrodynamic parameters were designed using the MIKE 11 input set up editors. The individual MIKE 11 editors were integrated using the MIKE 11 simulation editor which allows for the exchange of information amongst the individual editors. The coupling between MIKE 11 and MIKE SHE was done via river link network which is created by MIKE SHE set up program based on the coupling reaches. MIKE SHE then exchanges water with the coupling reaches. In the MIKE SHE set up, rivers and their tributaries are represented by lines between model grid cells (Fig. 9.1)

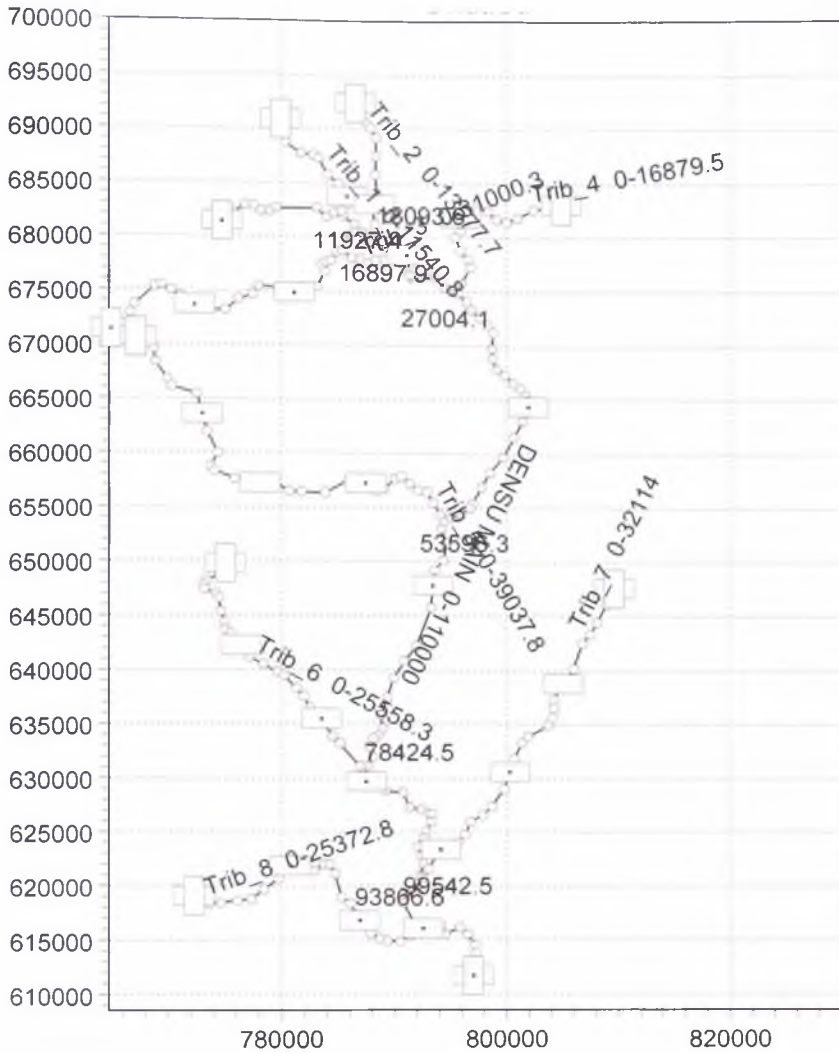


Fig. 9.1 River network set up in MIKE 11 showing positions where boundary conditions are defined (Blue squares) and cross section points (Red squares)

Figure 9.1 presents a graphical view of the set up of the Densu River and its tributaries in MIKE 11. The blue squares represent the position of boundary conditions and the red squares represent cross section points where MIKE 11 computes time series water levels.

9.3 River network and cross sections

The river network editor provides a platform for digitizing rivers and their branches, hydraulic structures such as dams, weirs, culverts etc. It therefore gives a graphical view of the river structure. The Densu River has many tributaries but only the major branches were included in the set up. Cross sections were defined along the main Densu River and its tributaries at a chainage interval of 10,000 m using the MIKE 11 cross section editor. (Fig. 9.1). The cross section editor then generates intermediate cross sections by extrapolating from the nearest defined cross section. MIKE 11 simulates H values at locations where cross sections are defined and Q values are simulated at points in between cross section points. The names of the rivers, unique identification numbers, and the datum of the point of the cross section are also defined using the cross section editor. The datum information is very important since MIKE SHE has a unique topographical value for each grid cell. When the datum values provided in the cross section points are not the same as contained in MIKE SHE, instabilities will occur when MIKE 11 is coupled to MIKE SHE and ultimately generate inaccurate water balance simulation.

Inflows and outflows boundary conditions of the River and its branches are also required in MIKE 11 like in MIKE SHE by using the boundary condition editor. There are different types of boundary conditions such as open, closed, point source, global etc. but the open type was used to describe the boundaries of the Densu River and its tributaries. Constant inflow values and water level were defined at the inflow and outflow points of the rivers respectively. Where time series inflow hydrographs and water levels are available, it can be used to specify boundary conditions.

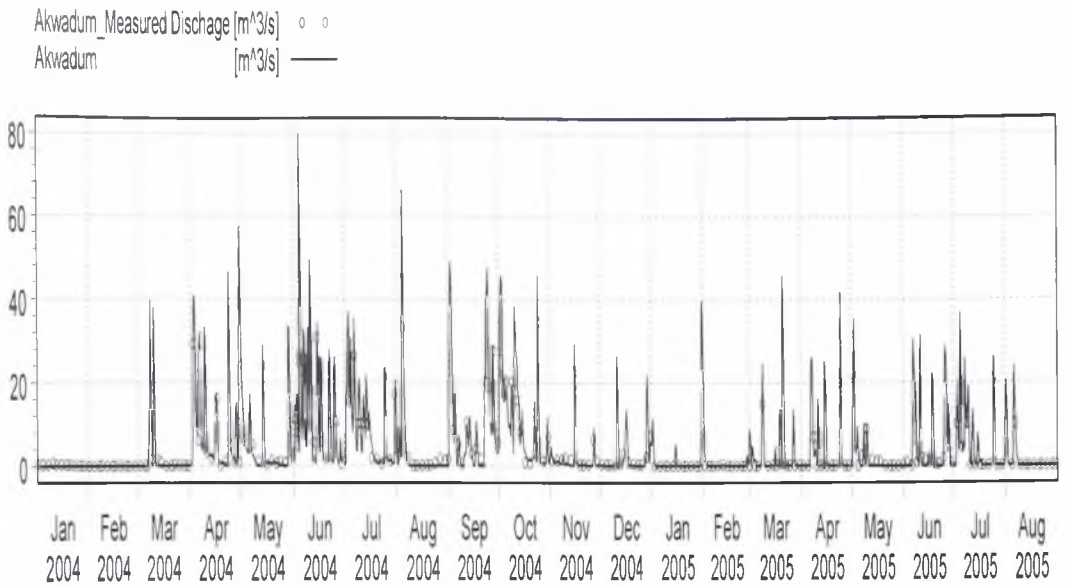
The simulation of river flows and water levels in the basin was done using a fully dynamic Saint Venant equation. The Hydrodynamic Module contained in the MIKE 11 model constitutes the nucleus of the modelling system and provides the platform for the computation of the Saint Venant equations. There are different methods of simulating river flow but the fully dynamic method was chosen in this simulation. The hydrodynamic editor allows for selection of simulation methods and the specifications of other parameters such as channel resistance (Manning M), stratification, groundwater leakage etc.

9.4 Results of simulation of river discharge and water level

There are five measuring stations in the Densu basin namely, Akwadum, Mangoase, Pakro, Nsawam and Ashaladza where daily discharge measurements are carried out. However, a whole year continuous measurements are barely available except at Akwadum which is located upstream where continuous flow data of up to one and half years is available. Ashaladza which is the most downstream measuring station has not been functioning over the past five years and therefore discharge measurements are not available within the simulation period to be used for model calibration and validation. Also, discharge measurements are not available for the tributaries therefore simulated discharges and water levels for the tributaries cannot be calibrated. Pakro downstream which is located at midstream is the most downstream station with adequate flow data that can be used to compare with simulated flows in the Densu river.

Simulated discharges have been observed to have higher peaks than the measured discharges. This could be attributed to the effects of damming, abstractions and flooding. In the case of the stations downstream dams and weirs there is a wide difference between simulated discharge peaks and measured discharge peaks. At Akwadum however, the difference in simulated discharge peaks and measured discharge peaks is not as pronounced as in the case of the stations downstream dams at Koforidua and Nsawam (Fig. 9.2). These minimal differences in peaks can be attributed to the fact that flooding and water abstraction was not included in the model set-up therefore, flooded and abstracted water has been included in river flow and simulated as discharges by the model whereas measured discharges do not include flooded and abstracted water.

The simulated discharges in the low flow periods match relatively well with measured discharges as compared to simulated results in the high flow periods (main rainy season). This is because in the dry season, there is no flooding as well as little damming effect on the simulated discharges. An example of dry season flow and rainy season flow is shown in Figures 9.3 and 9.4. It is also observed that, in the high flow periods, the simulated discharge have delayed peaks relative to measured discharge peaks (Fig. 9.4) as compared to low flow periods (Fig. 9.3). Simulated vs measured discharges and water levels at different measuring stations along the Densu River are presented in Figures 9.5, 9.7, 9.8, 9.10, 9.11 and 9.13. Simulated discharge (Q) vs head (H) curves are also presented in Figures 9.6, 9.9 and 9.12.



ME=-0.630286

MAE=1.71312

RMSE=4.52281

STDres=4.47868

R(Correlation)=0.914063

R²(Nash Sutcliffe)=0.663148

**Fig. 9.2 Simulated (-) vrs measured (....) discharges of the Densu River at Akwadum
 from Jan 2004 – Aug 2005**

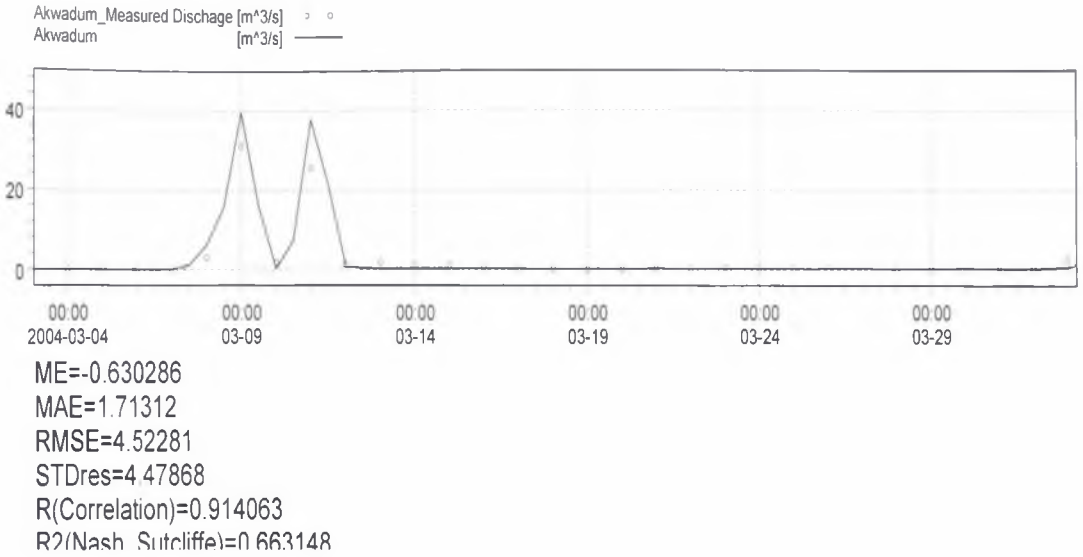


Fig. 9.3 simulated (-) vrs measured (...) discharges of the Densu River at Akwadum in the Low flow period (March)

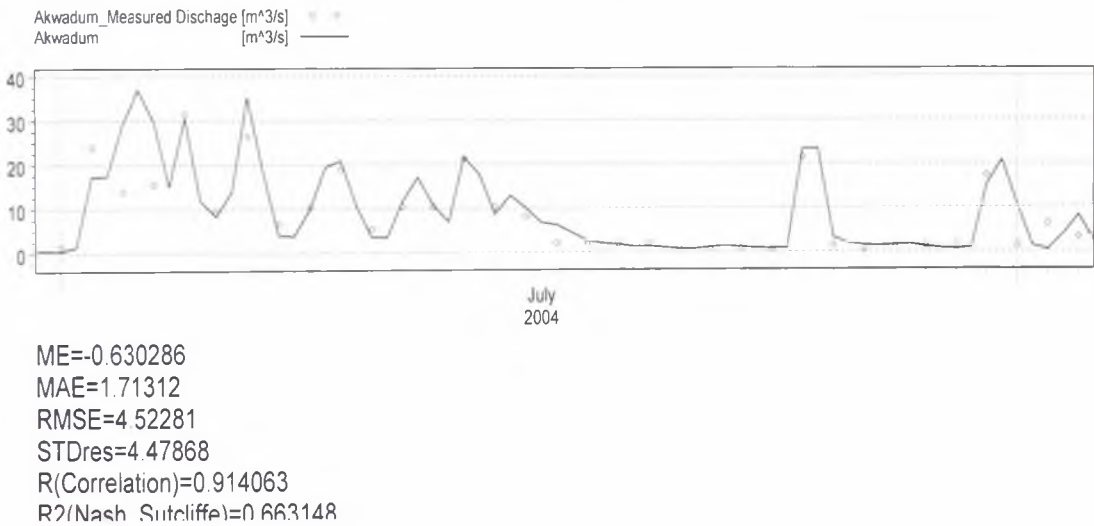


Fig. 9.4 simulated (-) vrs measured (...) discharges of the Densu River at Akwadum in the high flow period (July)

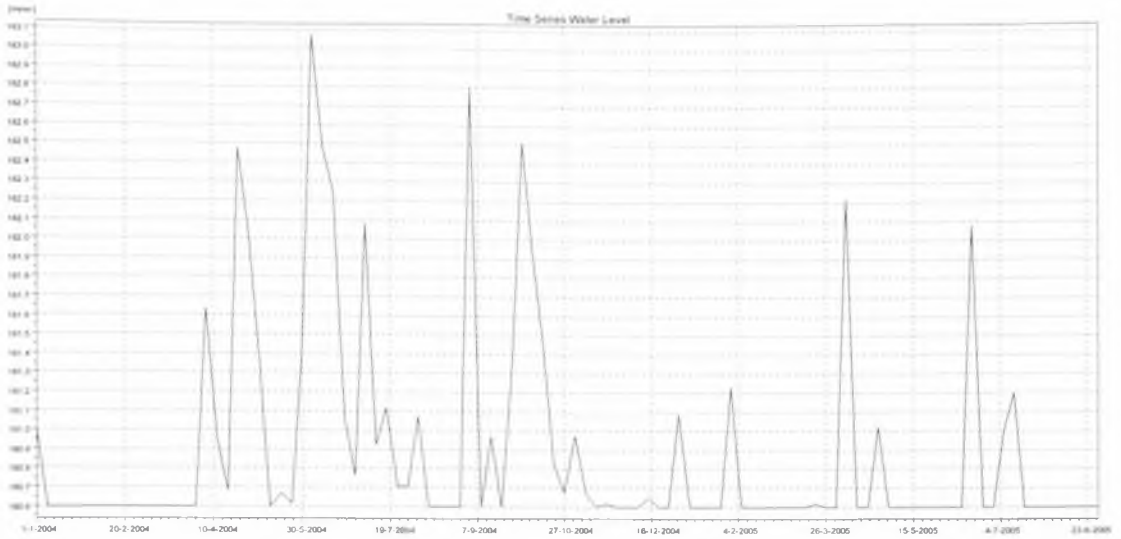


Fig. 9.5 Simulated time series water level of the Densu River at chainage 20,000 m (downstream Akwadum, Jan 2004 – Aug. 2005)

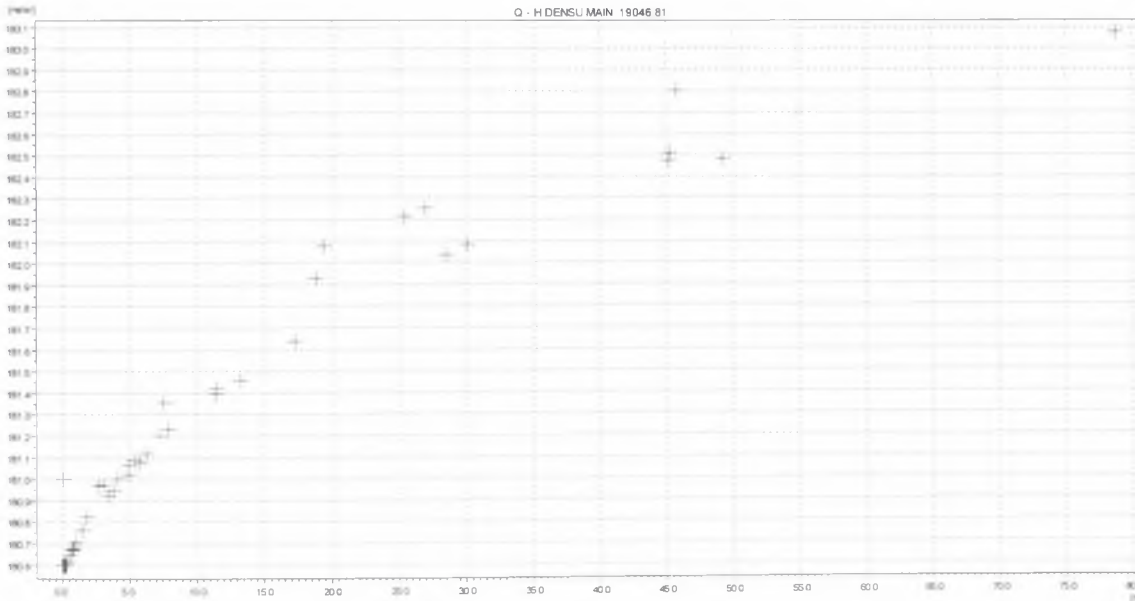


Fig. 9.6 Q-H curve at Akwadum

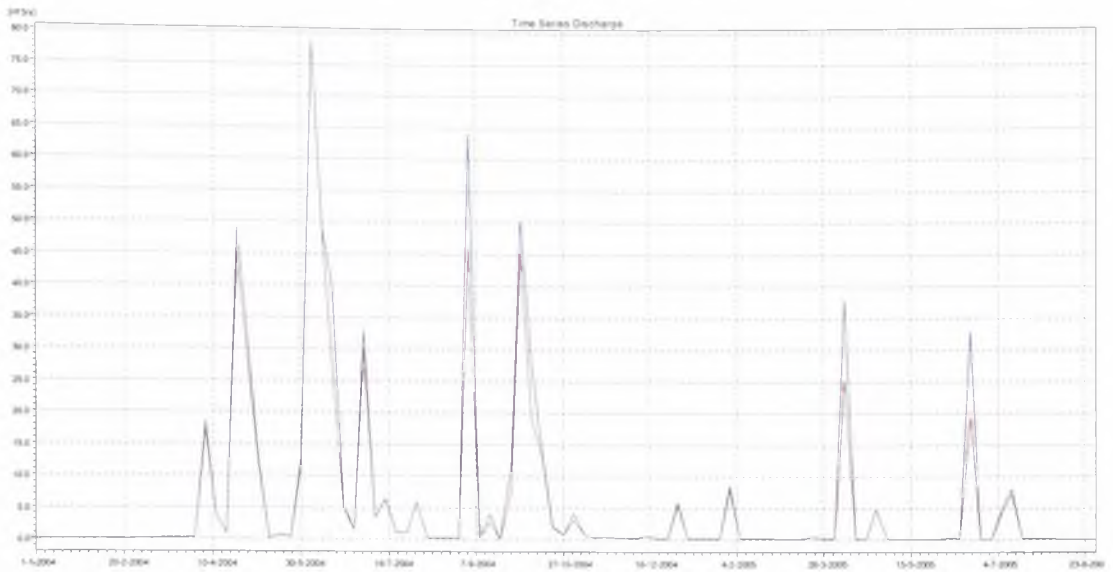


Fig. 9.7 simulated (Blue line) vrs Measured (Red line) discharges of the Densu River at Mangoase

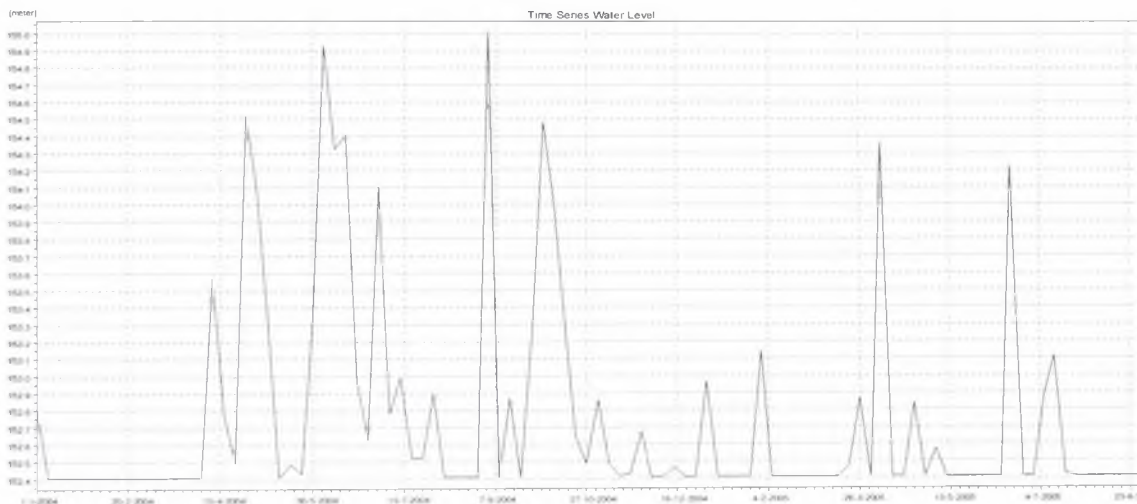


Fig. 9.8 Simulated time series water level of the Densu River at chainage 33,502 m (Upstream Mangoase Jan 2004 – Aug. 2005)

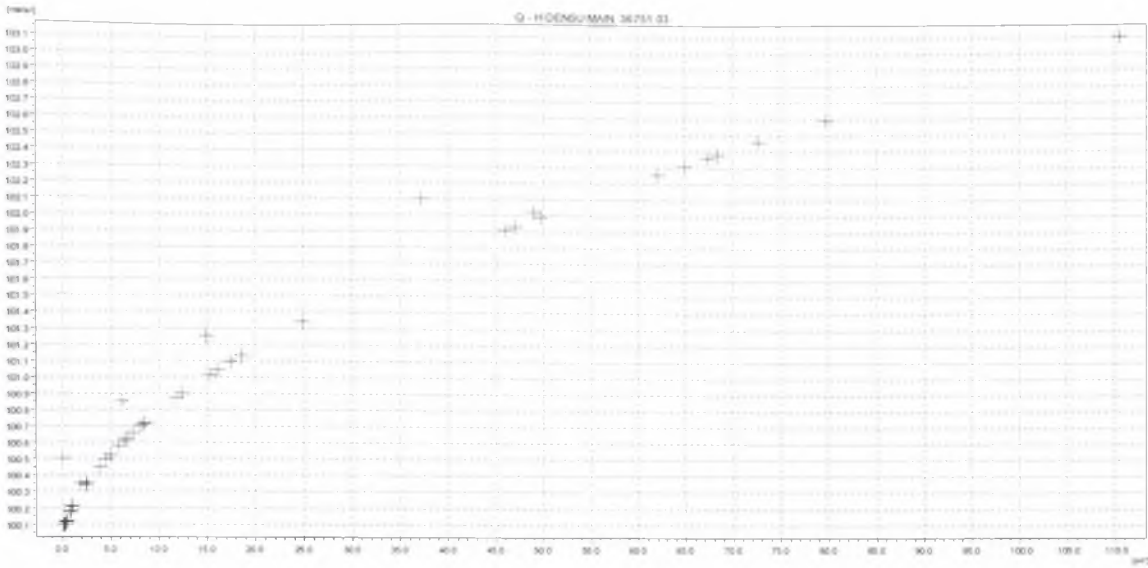


Fig. 9.9 Q-H curve at Upstream Mangoase

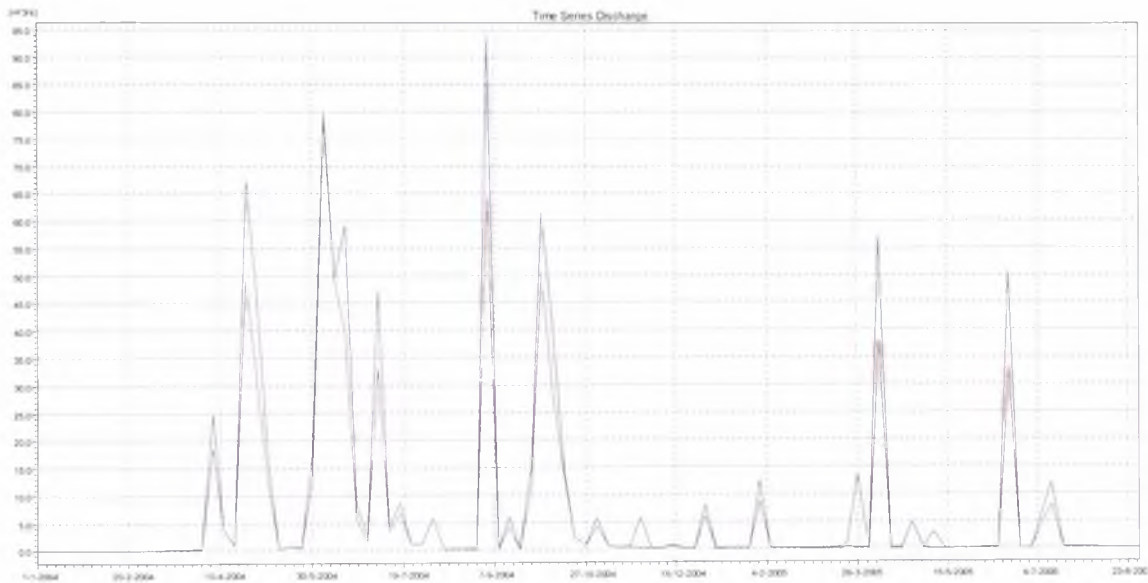


Fig. 9.10 simulated (Blue line) vrs Measured (Red line) discharges of the Densu River at Pakro upstream.

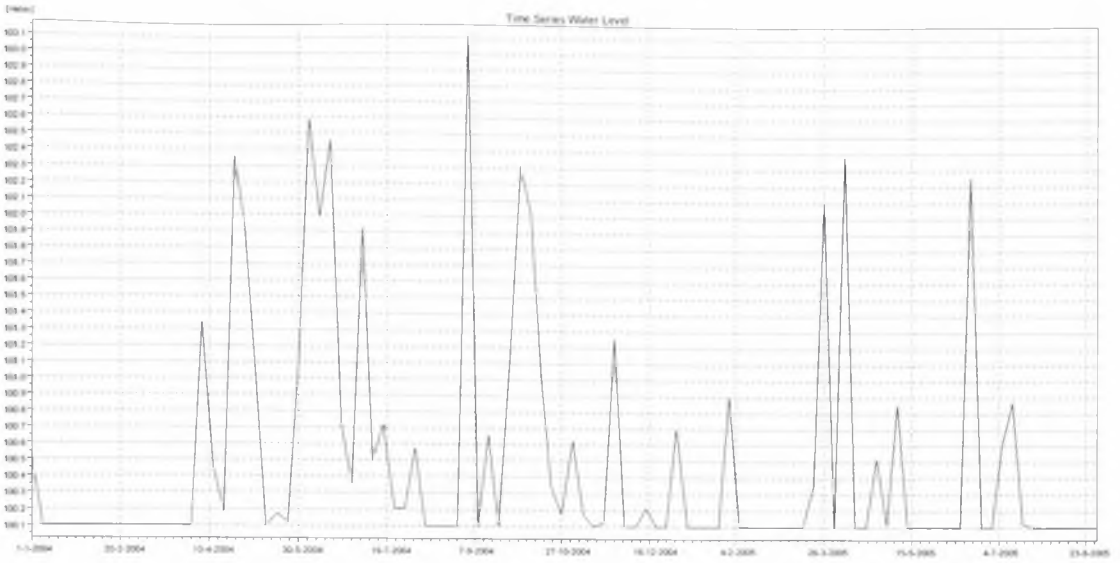


Fig. 9.11 Simulated time series water level of the Densu River at chainage 46,798 m (Upstream pakro Jan 2004 – Aug. 2005)

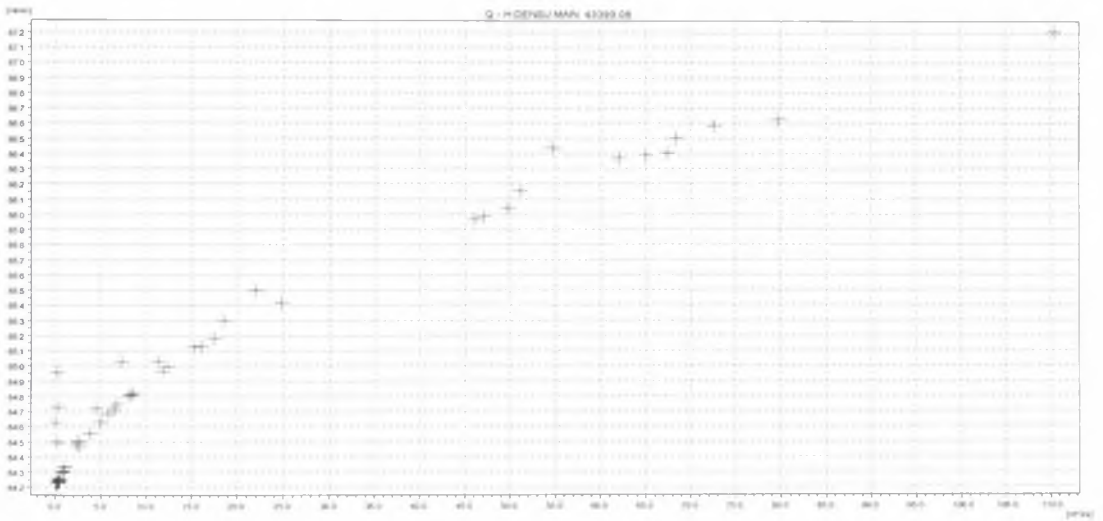


Fig. 9.12 Q-H curve at Pakro upstream

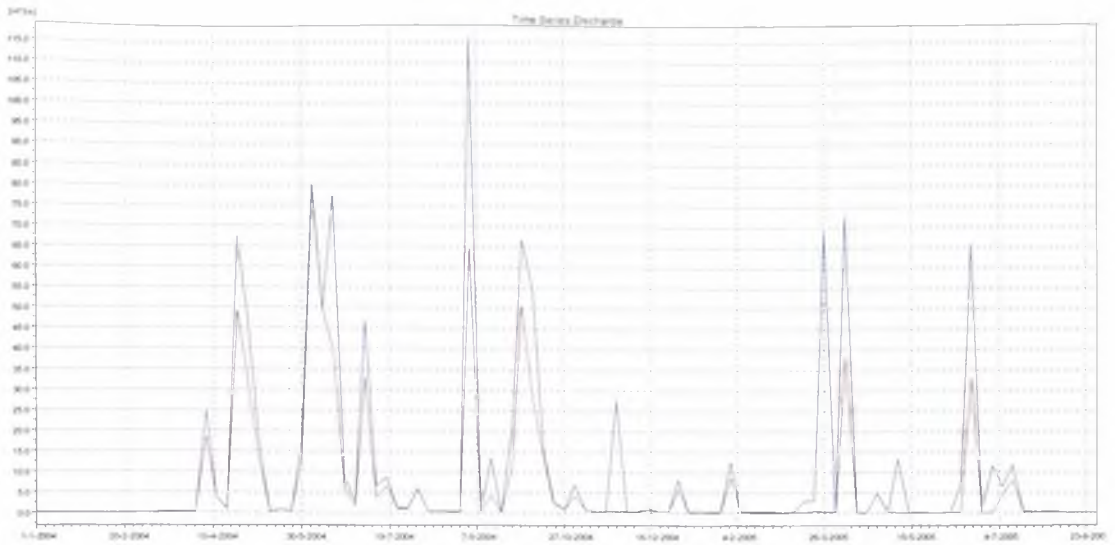


Fig. 9.13 simulated (Blue line) vrs Measured (Red line) discharges of the Densu River at Pakro downstream.

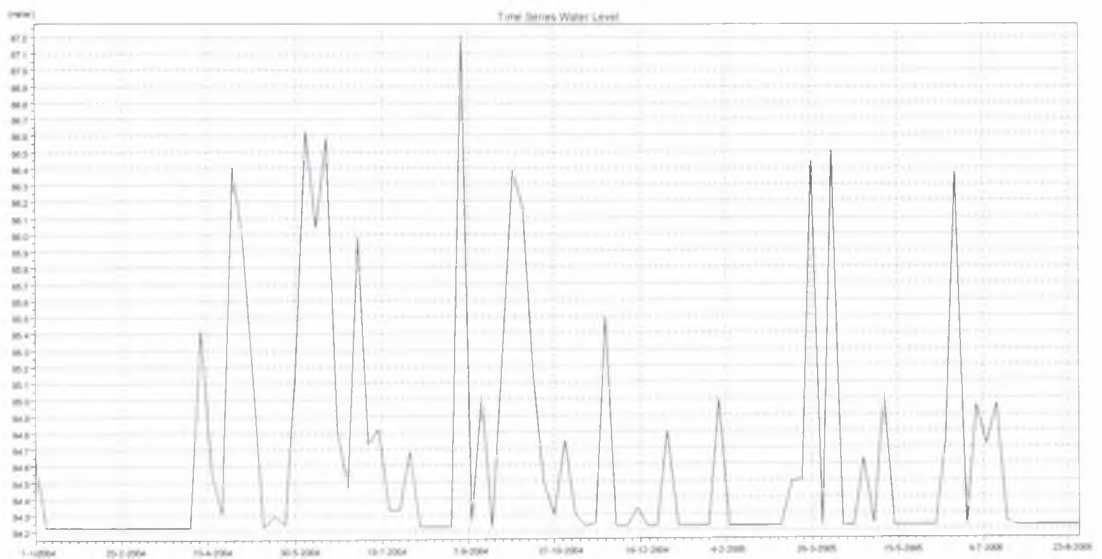


Fig. 9.14 Simulated time series water level of the Densu River at change 53,596 m (downstream pakro Jan 2004 – Aug. 2005)

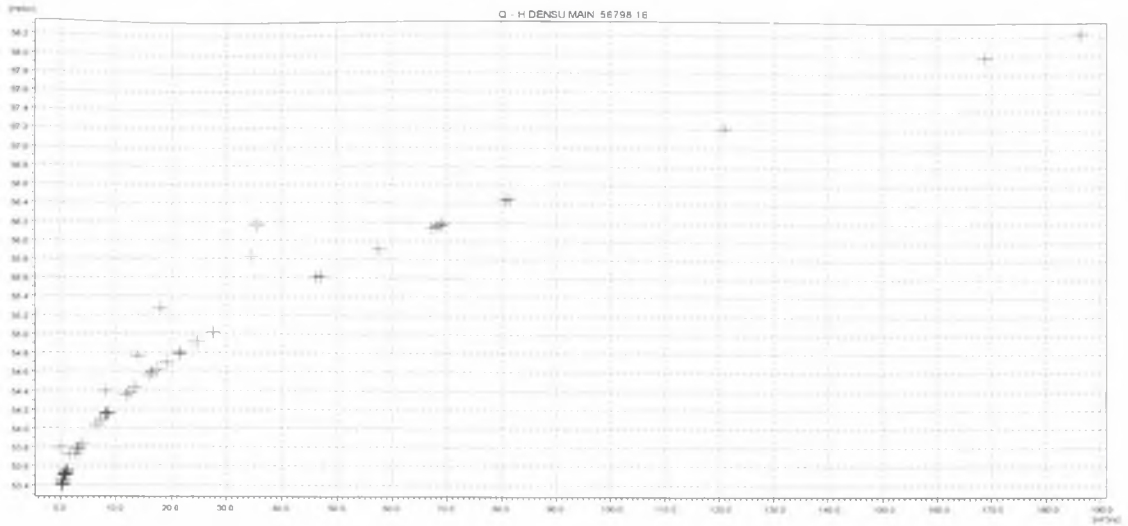


Fig. 9.15 Q-H curve at Downstream Pakro

9.5 Observations and discussion

The gaps in the measured discharges (red line) are as a result of lack of measured discharge data for certain time intervals. As mentioned earlier, continuous discharge data for a complete year is unavailable except at Akwadum where measured data are available for almost two years (Fig. 9.2).

In the simulation of river discharge, it is imperative to include hydraulic structures (dams and weirs) in the model set up especially if the storage capacities of the hydraulic structures are large enough to significantly alter the natural flow pattern. It is also important to include 1-D or 2-D River flooding in the model especially in tropical regions where convective storm events produce high intensity precipitation events therefore leading to frequent flooding which results in the loss of large volumes of water. If

flooding and hydraulic structures are not included in the model set up, there is the tendency to have higher peaks of simulated discharges than measure discharges. Also, some simulated discharge peaks are not reflected in measured discharges due to the effects of damming (Figs 9.10 and 9.13). In the absence of the flood component in the model set up, it becomes compelling to artificially increase the width and depth of the river channel in order to contain the flow in the model which leads to exaggerated simulated discharges and time series water levels.

Another important difficulty that worked against accurate simulation of river flow in the Densu river is the definition of accurate datum level at cross sectional points. MIKE 11 generates the slope of the river based on the datum levels defined at the cross sectional points. If therefore accurate datum levels are not defined at these locations, the slope of the river will not reflect the actual slope and therefore simulated flows will vary greatly from measured flows since the gradient of the river bed determines to a large extent the flow characteristics. In coupling MIKE 11 to MIKE SHE, if the datum levels defined in MIKE 11 do not match with the topographic values in MIKE SHE, the model will experience instability. This is a major problem when coupling MIKE 11 to MIKE SHE therefore, the datum levels should be defined more carefully. The practical solution to this problem is to design MIKE 11 in a way that it can automatically adopt the datum levels from the digital elevation model in MIKE SHE.

CHAPTER TEN

10.0 Water balance assessment and demand analyses

Water balance of river basins is controlled by the physical, chemical and biological features and processes of the basin. Therefore, in order to arrive at the computation of water balance, a deeper understanding of the features and processes of the basin should have been developed. The general dispositions of precipitation over any particular basin are interception storage, infiltration, depression storage and overland flow (Fig. 10.1).

Evapotranspiration is a major component of water balance but it transgresses all the other processes. There are also intermediate processes such as drainage flow, base flow etc. that needs to be accounted for in the computation of water balance of a catchment.

Water balance computation in the Pompon catchment within the Densu basin has been undertaken by Tumbulto (2005) but all the computations were done using different methods to estimate the different components in the water balance. For instance, the Thornthwaite Mather and Nam model were used in combination to compute water balance. The results of the computations show that annual runoff was less than 4% of annual rainfall. Actual evapotranspiration was also estimated at about 95% of annual rainfall which is very high. The limitations in combining methods in water balance computations are that, the different processes of water balance are treated as if the processes do not occur simultaneously. One component of the water balance is normally computed followed by another. Also, the errors associated with each model in the



computation of the different processes add up and therefore it is generally difficult to attain convergence.

The application of physically based numerical models in computing water balance is done through the input of parameters that describe the components of water balance. The processes are simulated simultaneously as prevails in the field. This allows for convergence in the simulation. Numerical models also provide the platform to adequately present the disposition of precipitation in the basin (Fig. 10.1) as well as regulate the simulation time step for each process. Generally, some processes in the water balance component occur at faster rates than others, it is therefore appropriate to specify different time steps to different processes according to the modeller's conceptualization of the processes.

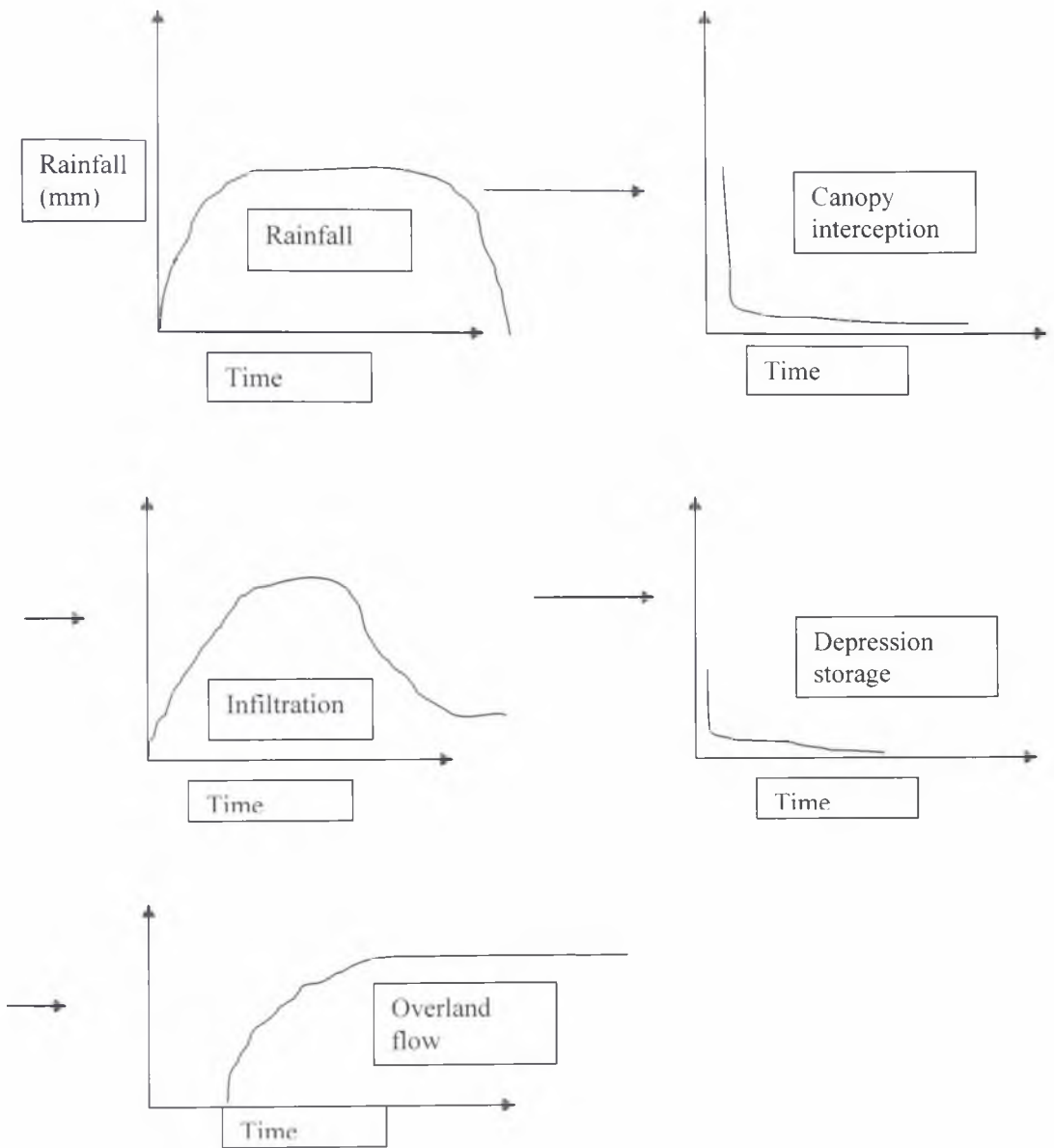


Fig. 10.1 Disposition of precipitation falling over a catchment (Adapted from Viessman 1990 and modified)

10.1 Principle of water balance assessment

The general principle usually applied for water balance computations is based on the mass balance equation where the processes on the land surface are measured or derived and equated to the total rainfall. The general principle states that inflows into a particular catchment over a given time interval must be equal or greater than outflows from the catchment within the same time interval. The mathematical expression of the mass balance principle is given as:

$$\Sigma | Q_{in} | \geq \Sigma | Q_{out} | \quad 10.1$$

Where Q_{in} = total water input in the basin and Q_{out} = total water taking from the basin

The Densu basin can be described as a closed unit, except the downstream boundary, the entire boundary of the basin can be described as no flux boundary (topographic divide). This means that the basin does not interact with neighbouring boundaries with regards to water flow and all the other processes that determine flow in the basin. For example, groundwater heads in neighbouring basins do not affect groundwater flow in the Densu basin. likewise, runoff in the neighbouring basins do not affect runoff in the Densu basin. The only source of water in the basin is therefore the amount of rainfall that occurs in the basin. The simplified total water balance equation can therefore, be described as:

$$I = Q + ET + \Delta W \quad 10.2$$

Where = Total rainfall input in the basin, Q = runoff, ET = evapotranspiration, ΔW = Change in water storage (groundwater storage, surface water storage, unsaturated zone storage, depression storage and canopy storage).

10.2 Results and discussions of water balance of the Densu basin

Total water balance assessment was simulated using the MIKE SHE model. There are different methods of estimating water balance in a catchment (isotopic studies, chloride mass balance, etc), most of these methods require that measurements of three of the variables (Eq. 10.2) are undertaken before water balance estimation can be done. In most cases precipitation and runoff are the measured parameters. In the case of the MIKE SHE model simulation, only rainfall is required as a measured input, MIKE SHE computes the other three variables by using physically based parameters that control the processes of evapotranspiration, runoff and change in water storage in the basin. However, the model also requires measured parameters for calibration and validation.

The advantage of applying numerical models (MIKE SHE) in water balance computation is that, when the model is validated for a particular basin, it can be used for future water balance assessments of the basin without necessarily requiring measured parameters except precipitation. However, if the physical features and hydrological conditions of the basin change with time, these changes must also be incorporated into the model so that the various processes can be adequately described according to the prevailing conditions.

The MIKE SHE model was also applied in the simulation of the sub components of water balance such as Canopy storage, depression storage, base flow, drainage flow, unsaturated zone storage and evaporation from the unsaturated zone. Six years (2000 – 2005) water balance was computed for the Densu basin. The accuracy of the water balance computations is greatly dependent on the accuracy of input parameters and how those parameters are designed in the model in terms of both temporal and spatial resolutions.

Hourly and daily rainfall data were used to assess the effect of temporal resolution with regards to the accuracy of rainfall partitioning computations. It was observed that, with the daily rainfall data, a relatively higher percentage of rainfall infiltrated and recharged the aquifer systems. On the other hand overland flow was very minimal (Table 10.1). This is because the daily rainfall was considered to have occurred in 24 hours therefore the average intensities of the rainfalls were relatively lower. Since rainfall intensity is a very important parameter in determining the partitioning of rainfall into the different water balance components, it is not surprising to note that overland flow generation was minimal.

Table 10.1 Rainfall partitioning analysis using daily rainfall data as inputs in the MIKE SHE model

Evapotranspiration	73 % of annual rainfall
Overland flow	5 % of annual rainfall
Infiltration	22 % of annual rainfall

Hourly rainfall data were also used by reducing the daily rainfall data into 5 hourly data based on rainfall duration analysis in the basin. The results show an increase in overland flow and a decrease of groundwater recharge as well as evapotranspiration (Table 10.2).

Table 10.2 Rainfall partitioning analysis using hourly rainfall data as inputs in the MIKE SHE model

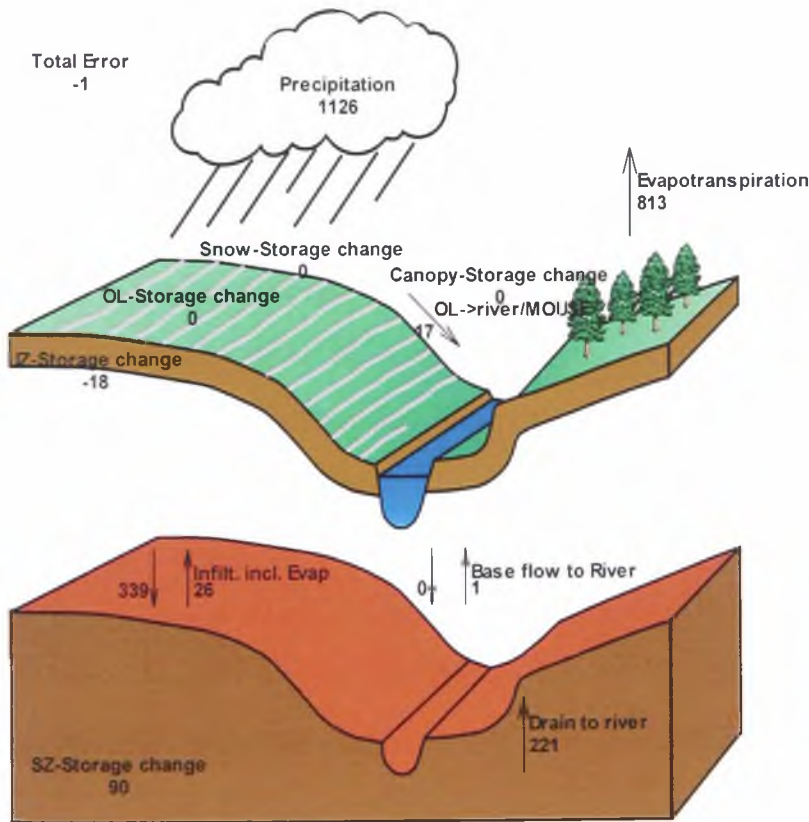
Evapotranspiration	69 % of annual rainfall
Overland flow	16 % of annual rainfall
Infiltration	15 % of annual rainfall

Base on the analysis (Tables 10.1 and 10.2), it is convenient to assume that, the practical optimal temporal resolution of rainfall data for water balance computations and the description of hydrological processes is hourly data. It is expected that a much finer temporal resolution rainfall data (minutes) could produce even accurate water balance computations but this has practical limitations since it will be time consuming and requires longer computation time as well as larger computer storage space.

Stream discharges and heads simulated by MIKE SHE were however, the same for both the hourly rainfall inputs and daily rainfall inputs with a minimal delay in hydrograph peaks in the case of the daily rainfall inputs. This is because in the case of the daily rainfall inputs, saturated excess flow dominates the contribution to stream flow where as in the case of the hourly rainfall inputs both infiltration excess flow and saturated excess

flow contribute almost equally to stream flow. The use of hourly or daily rainfall data does not therefore significantly change the water balance if annual water resources evaluation and quantifications are to be simulated, but if detail hydrological processes are to be adequately described, hourly rainfall data are appropriate.

MIKE SHE simulation of annual water balance in the Densu is presented in fig. 10.2 and summarized in table 10.3.



Accumulated waterbalance from 02/01/2000 to 01/01/2001. Data type : Storage depth [millimeter].
 Flow Result File : D:\Densu_Maps_UTM\SHEPar11\SHEPar11
 Title : DENSU MODEL Text : FULLY INTEGRATED MODEL

Fig 10.2 A schematic representation of MIKE SHE Water balance analysis

Table 10.3 Annual water balance analysis in the Densu basin with 1% error margin

Water Balance component	Amount (mm)	Percentage (%) rainfall
Rainfall	1126	100
Evapotranspiration	813	72
Stream flow	238	21
Groundwater recharge	90	8
Base flow	1	0.0009
Soil moisture deficit	18	0.016

10.3 Discussions on water balance, demand and availability

Based on the 2000 Population and Housing Census, the population of the Densu basin was computed in categories of settlement settings (rural and urban settlement). Per definition, a settlement is classified as rural if the population of the settlement is less than 5000 people. On the other hand urban population refers to settlement of more than 5000 people (Ghana Statistical Service, 2000).

The urban population was computed by adding the population of the individual urban settlement in the basin which were adequately captured by the 2000 Census. On the other hand, the population of the rural settlements was lumped together into a district total in the 2000 Census. The rural population was therefore, computed by estimating the percentage of the area of the district in the basin and using that percentage to compute the rural population of the districts in the basin (WRC, 2007). The Population of the various

districts were projected to 2020 based on annual growth rates obtained from the district poverty profile reports (Table 10.4)

Table 10.4 Population projection of area of districts within the basin (WRC, 2007)

District	Settle- ment type	2000 popula- tion	2005		2010		2015		2020	
			p.a. %	Popula- tion	p.a. %	Popula- tion	p.a. %	Popula- tion	p.a. %	Popula- tion
Fanteakwa	Rural	800	1.4	858	1.4	920	1.4	986	1.4	1,057
	Urban	0	1.4	0	1.4	0	1.4	0	1.4	0
Yilo Krobo	Rural	1,200	1.4	1,286	1.4	1,379	1.4	1,478	1.4	1,584
	Urban	0	1.4	0	1.4	0	1.4	0	1.4	0
East Akim	Rural	27,500	1.4	29,480	1.4	31,602	1.4	33,877	1.4	36,316
	Urban	47,000	1.4	50,383	1.4	54,010	1.4	57,898	1.4	62,067
New Juabeng	Rural	22,000	2.6	25,013	2.6	28,438	2.6	32,332	2.6	36,759
	Urban	114,100	2.6	129,725	2.6	147,489	2.6	167,686	2.6	190,649
Suhum/ Kraboa/ Coaltar	Rural	101,700	1.4	109,022	1.4	116,872	1.4	125,287	1.4	134,307
	Urban	31,000	1.4	33,232	1.4	35,624	1.4	38,190	1.4	40,939
Akwapim North	Rural	19,700	1.8	21,538	1.8	23,547	1.8	25,744	1.8	28,146
	Urban	5,000	1.8	5,466	1.8	5,976	1.8	6,534	1.8	7,144
Akwapim South	Rural	53,100	1.6	57,486	2.3	64,408	3.3	75,760	5.3	98,080
	Urban	43,000	1.6	46,552	2.3	52,157	3.3	61,350	5.3	79,425
West Akim	Rural	10,500	1.4	11,256	1.4	12,066	1.4	12,935	1.4	13,867
	Urban	8,200	1.4	8,790	1.4	9,423	1.4	10,101	1.4	10,829
Ga West	Rural	125,500	8.7	190,468	8.0	279,860	7.0	392,518	5.0	500,964
	Urban	341,100	8.7	516,318	8.0	758,639	7.0	1,064,031	5.0	1,358,003
Ga East	Rural	2,300	8.7	3,477	8.0	5,109	7.0	7,166	5.0	9,145
	Urban	6,400	8.7	9,670	8.0	14,209	7.0	19,929	5.0	25,435

Accra Metro	Rural	2,100	4.3	2,592	4.3	3,199	4.0	3,892	3.0	4,512
	Urban	25,700	4.3	31,722	4.3	39,155	4.0	47,638	3.0	55,225
Awutu/Efutu /Senya	Rural	8,800	2.1	9,764	2.1	10,833	2.1	12,019	2.1	13,335
	Urban	10,000	2.1	11,095	2.1	12,310	2.1	13,658	2.1	15,154
Densu Basin	Rural	375,200		462,240		578,233		723,994		878,072
	Urban	631,500		842,953		1,128,992		1,487,015		1,844,870
Densu Basin, total		1,006,700	5.4	1,305,193	5.4	1,707,225	5.3	2,211,009	4.3	2,722,942

In addition to the domestic demand for water in the basin, irrigation, industries, manufacturing and other commercial activities are springing up across the basin and therefore adding to the demand of water resources. The main industries and irrigation schemes in the basin include:

- Voltic (Gh) Ltd (Medie);
- Blue Skies Products (Gh) Ltd (Medie);
- Akwaaba Mineral Water (Medie);
- Still Pure Water (Medie);
- Astek Fruit Processing Company Ltd. (Nsawam);
- Cocoa Research Station (Tafo);
- Intravenous Infusions Ltd. (Koforidua);
- Brick/tile factory (Weija);
- Weija irrigation scheme (about 220 ha).

Water demand for domestic, industry and agriculture was computed based on the per capita water demand estimation by the Ghana water company (Table 10.6) and water use permits granted by the Water Resources Commission as well as the irrigation development authority's projection of water demand. Both present and future demands were computed (Table 10.5).

Table 10.5 Water demand projection in the Densu basin (WRC, 2007)

User category	2005		2010		2015		2020	
	m ³ /day	10 ⁶ m ³ /yr	M ³ /day	10 ⁶ m ³ /yr	m ³ /day	10 ⁶ m ³ /yr	m ³ /day	10 ⁶ m ³ /yr
Urban population	80,100	29.2	112,900	41.2	163,600	59.7	221,400	80.8
Rural population	16,200	5.9	20,200	7.4	25,300	9.2	30,700	11.2
Irrigation	11,000	4.0	12,300	4.5	16,400	6.0	20,500	7.5
Livestock	2,400	0.9	3,000	1.1	3,800	1.4	4,600	1.7
Industry	6,400	2.3	9,000	3.3	13,100	4.8	17,800	6.5
Densu Basin, total	116,100	42.3	157,400	57.5	222,200	81.1	295,000	107.7

Table 10.6 Unit water demand (litres/capita/day)

Settlement size	2005	2010	2015	2020
< 2,000)	200 persons per water point			
2,000-5,000	30	30	35	35
5,000-15,000	55	65	75	85
15,000-50,000	85	85	90	95
> 50,000	105	110	115	120
Densu Basin, rural	35	35	35	35
Densu Basin, urban	95	100	110	120

From the water balance analysis (Table 10.3) the annual surface water resources amount to 238 mm, groundwater recharge per annum is 90 mm. The total annual surface water resources in the basin amount to about 595 million m³ [computed by multiplying the rainfall in meters (0.238m) by size of basin (50000m * 50000m)].

Measured flow at Akwadum gives an average daily discharge of 3.8m³/s. The annual discharge at Akwadum (120 million m³) is computed based on the measured average daily discharge. The catchment area of Akwadum is a little below ¼ of the entire basin and therefore the total annual flow of the basin can be computed by multiplying the annual discharge at Akwadum by 4.3. This results to about 516 million m³. The measured annual discharge is about 74 million m³ (12%) less than the simulated annual discharge. This short fall is partly as a result of water abstraction/storage upstream Akwadum measuring station especially at Koforidua which is not captured in the measured flow data but included in the simulated annual discharge.

The total amount of groundwater resources in the basin is about 234 million m³. Comparing Tables 10.3 and 10.5, it shows clearly that there are far more surface water resources in the basin compared to annual demand. However, in reality there are occasional water shortages in the basin especially during the dry seasons. This is because more surface water resources are lost to the basin due to inadequate storage facilities to store water during the rainy season. Also, it has to be noted that, during flooding events, a

greater amount of the surface water is loss to evaporation which was not accounted for by the model.

There is a vast difference between the water balance analysis in the IWRM plan of the Densu basin (WRC 2007) and the water balance computed by this study. The WRC estimate of annual surface water resources in the basin is about 280 million m^3/annum (Table 10.7) compared with 595 million m^3/annum by this study. In the WRC's estimation, it was assumed that all infiltrated water recharges the aquifer system and therefore is not available to contribute to river run off. However, from the model simulation, it was observed that a greater part of the river flow comes from saturation excess flow (which is part of infiltrated water). Actual infiltration excess flow (Hortonian overland flow) contribution to stream flow is very minimal (Fig.10.2). Also, the evapotranspiration used by WRC in the water balance computation is very high (77%) of rainfall. This percentage was derived from a water balance studies of the Pompon sub-catchment by Tumbulto (2005). It should be noted that drainage flow as presented in Fig. 10.2 should not be confused with base flow. The drainage flow is within 1 m from the ground surface which is not part of groundwater flow but rather infiltration excess flow to rivers. As a result of the differences in conceptualization of the flow processes by WRC 2007 and this study, the simulation of various water balance components namely evapotranspiration, groundwater storage and river runoff vary significantly.

Table 10.7: Mean annual flow volume, Densu River system (WRC 2007)

River/locality	Area of sub-basin (km²)	Mean annual runoff (million m³)
Densu at Koforidua	510	55
Densu at Nsawam	1,440	155
Densu at Manhea (Weija Lake)	2,300	248
Kuia sub-basin	408	44
Adeiso sub-basin	338	36
Nsaki sub-basin	152	16
Total Densu basin	2,600	280

With regards to groundwater, it has to be admitted that it is difficult to accurately quantify the volume of groundwater abstracted from the basin's groundwater resources. An estimation of groundwater abstraction in the Densu basin is about 1.4 million m³/anuum (WRC, 2007) based on Community Water and Sanitation Agency's borehole design criteria of 200 persons per water point and an abstraction rate of about 4.8 m³/day compared to annual groundwater recharge of about 234 million m³. This implies that groundwater recharge far exceeds abstraction in the basin and therefore groundwater abstraction can be doubled without altering the annual groundwater head fluctuations.

CHAPTER ELEVEN

11.0. Summary, conclusions and recommendations

The findings of this research are summarised according to the main categories of the research namely: Applicability of the MIKE SHE model in the characterization of the hydrological processes in the Densu basin, Rainfall analyses in the basin, actual evapotranspiration, groundwater resources, surface water resources and water demand and availability.

11.1 Application of MIKE SHE in the Densu basin

The applicability or suitability of the MIKE SHE model in the characterization of hydrological processes in the basin as well as comparison of the MIKE SHE model and the NAM model were assessed as follows:

- The application of MIKE SHE model requires a great deal of data. The Densu basin has been fairly researched therefore there is a reasonable amount of field data which can be used as inputs in the MIKE SHE model. As a result the application of the model in the basin was successful;
- The major limitation in the application of the MIKE SHE model however is the heterogeneous nature of the basin and the lack of data in the required scale. It is difficult to deterministically assign parameters to grid cells without applying statistical methods or compromising the distributed nature of the model;

- The undulating nature of the basin also poses a challenge in the application of MIKE SHE model. In the Densu basin, it has been observed that topographic values differentials of up to 200 m between adjacent grid cells exist. This situation leads to a large amount of pondered water in the simulation of overland flow. MIKE SHE however has an option to route each grid cell overland flow directly to streams without interacting with neighbouring cells. This option allows for the routing of overland flow in areas with irregular topography;
- With regards to validation of the Model, a long time series observation data (groundwater water monitoring data and river discharge measurements) is required to compare with model simulation before such a conclusion can be arrived at. The duration of available observed data is not long enough and also the observation points are not representative enough to be used for the validation of a model;
- The lump conceptual model (NAM) model simulates stream discharges with the same accuracy as the distributed physically-based numerical (MIKE SHE – MIKE 11) model but with less data requirement and less complexity. It is therefore more convenient to apply conceptual models in the simulation of stream discharges than the application of distributed, physically-based models. However, the MIKE SHE model provides a comprehensive platform for the simulation of hydrological processes which is not possible with the NAM model;

- The annual accumulated discharge at Mangoase (located at the center of the basin) simulated using the NAM model is 290 million m³ (for the entire basin ≈ 580) and that of MIKE SHE for the entire basin is 595 million m³.

11.2 Rainfall analyses

The major findings and recommendations of the rainfall analyses include the following:

- The use of event loggers for collection of rainfall data allows for detailed analyses of the spatial and temporal variability of rainfall amount, duration and intensity. The annual error margin of the tipping bucket rain gauge is below 1 % even with intensities of up to 200 mm/h contrary to expectations that the time between the tipping and the return of the bucket to position could result in loss of appreciable amount of water therefore, greatly under estimating the amount of rainfall leading to wide error margins;
- Rainfall events in the Densu basin occur in relatively shorter durations. About 95% of the rainfall events in the basin occur between 1 hour and 5 hours;
- A bimodal distribution is observed with a few showers in the morning and the rest mainly from noon to late afternoon in the downstream part of the basin. In the upstream part of the basin, the distribution increases stepwise. A few showers between the hours of 6 AM and 2 PM graduating to a medium amount between 11 PM and 5 AM and the greater amount of rainfall occur between 3 PM and 11 PM;

- The analyses revealed that, about 70% of the rainfall in the mid and downstream parts of the basin (Koforidua and Nsawam) occurs between the hours of 11 AM and 8 PM. In the upstream part of the basin (Tafo), about 80% of the rainfall occur between 3 PM and 11 PM;
- Rainfall intensity variation in the basin is wide and high. The intensity of rainfall events range between 1mm/h to 200 mm/h;
- The use of hourly and daily rainfall data on hydrological models does not result in significant differences in the computations of annual water balance or evaluations of annual water resources. However, if detail hydrological processes are to be adequately described, hourly rainfall data are appropriate;
- Draught situation analyses in the basin reveal a possibility of 30 consecutive days without rainfall and as low as 60 mm of rainfall in 80 consecutive days.

11.3 Actual evapotranspiration

Research findings on the simulation of actual evapotranspiration are as follows:

- Average annual actual evapotranspiration in the Densu basin is 72% of annual rainfall;

- Daily actual evapotranspiration in the forest land cover area ranges between 0.4 mm/day (dry days) and 5 mm /day (wet days) with an average value of 4.0 mm/day. In the savannah land cover, actual evapotranspiration ranges between 0.5 mm/day (dry days) and 4 mm/day (wet days) with an average value of about 3.0 mm/day;
- The contribution of interception storage and root water uptake of water by plants to actual evapotranspiration in the forest land cover area in the basin is significant.

11.4 Groundwater resources

The main findings in the unsaturated zone processes leading to groundwater recharge as well as groundwater resources in the basin include the following:

- Direct groundwater recharge in the Togo series formation is highest followed by the Granite formation. The Birimian soils are almost impermeable and therefore direct groundwater recharge is minimal;
- There is a significant amount of indirect recharge in the Birimian area due to the presences of cracks in the otherwise impermeable clay layers which allow for a higher rate of percolation;

- Forest land cover and bare lands are not favorable conditions for groundwater recharge due to the effects of deeper roots of trees and less overland flow resistance respectively. The optimal condition for groundwater recharge is adequate ground cover by bushes and shrubs (Savannah land cover);
- The effect of forest land cover can reduce groundwater recharge/storage by about 50% through the combine effects of reduction in recharge duration, increase upward movement of groundwater to the unsaturated zone and eventually high actual evapotranspiration;
- Rainfall intensity windows for groundwater recharge in the Birimian, Granite and Togo formations are 20 mm/h – 70 mm/h, 20 mm/h – 90 mm/h and 20 mm/h – 100 mm/h respectively;
- Groundwater recharge in the basin (8% of annual rainfall = 234 million m³) far exceeds groundwater abstraction;
- Groundwater contribution to surface water flow (base flow) is very minimal (0.0009% of annual rainfall) due to the semi-unconfined nature of the aquifers, the deeper level of groundwater heads and the low permeabilities of river bed material;
- Average horizontal groundwater flow in the basin is about $1.0 \times 10^{-4} \text{ m}^3/\text{s}$;

- Groundwater heads in the basin are not significantly affected by groundwater abstractions. Both simulated and observed groundwater heads show full recovery of groundwater heads during the rainy season and a reasonable lowering of groundwater heads in the dry season;
- Groundwater head fluctuation in the Birimian formation is quite stable compared to that of head fluctuations in the granites and the Togo formation aquifers.

11.5 Surface water resources

- Measured and simulated stream discharges show a reasonable match except that simulated discharges have higher peaks than measured peaks. This is because hydraulic structures such as dams and weirs were not included in the model set up. Low flows during the dry season were more accurately simulated than high flows in the rainy season;
- Annual surface water resources in the basin (21% of annual rainfall = 595 million m³) far exceed annual surface water demand. However, these water resources are not available for use in the basin due to lack of adequate water storage structures to store water in the rainy season;

- Hortonian Overland Flow (HOF) contribution to river runoff is insignificant compared to contributions of Saturation excess Overland Flow (SOF) and Subsurface Storm Flow (SSF);
- Unsaturated zone studies reveal high permeability soils overlying relatively low permeability soils which promote subsurface storm flow generation and routing to rivers/streams.

11.6 Recommendations for further studies

- The application of the MIKE SHE model for the description of hydrological processes and water balance computations should be extended to other basins in Ghana;
- Hydrological models require accurate and continuous long time series monitoring data for accurate simulations, it is therefore recommended to ensure that modern techniques of data monitoring and collections are adopted by the institutions responsible for data collection (HSD, GMA, WRI etc) to improve upon the reliability of the data;
- The two years rainfall data used for the analyses of rainfall durations and intensities is not adequate, therefore further rainfall measurements and analyses in the basin are required to validate the findings of this research. The event logger

rainfall gauge (Rain-O-Matic type) is recommended for use in the recording of rainfall events;

- A detailed rainfall – runoff model incorporating flooding and hydraulic structures is required to accurately simulate river discharges/heads and also to delineate flood prone areas in the basin;
- For the purposes of water resources management, daily rainfall data are adequate as inputs in hydrological models;
- The application of modelling frameworks for infilling missing data (rivers discharges) should be undertaken to develop complete long time series data for model calibration and validation;
- Water management plans in the basin should emphasize on innovative ways of storing water to ensure availability of water resources in the basin;
- Modern techniques of groundwater exploration should be emphasized to ensure that groundwater resources are developed to complement surface water resources for socio-economic development.

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Appendix 1 Hypress – function model

<i>Theta_s</i>	<i>% Clay</i>	<i>% Silt</i>	<i>% Organic Matter</i>	<i>Bulk Density</i>	<i>Topsoil</i>	
<i>Ths</i>	<i>Clay</i>	<i>Silt</i>	<i>OM</i>	<i>BD</i>	<i>Yes=1, No=0</i>	
	20.08	20.4	0.3	1.61	0	

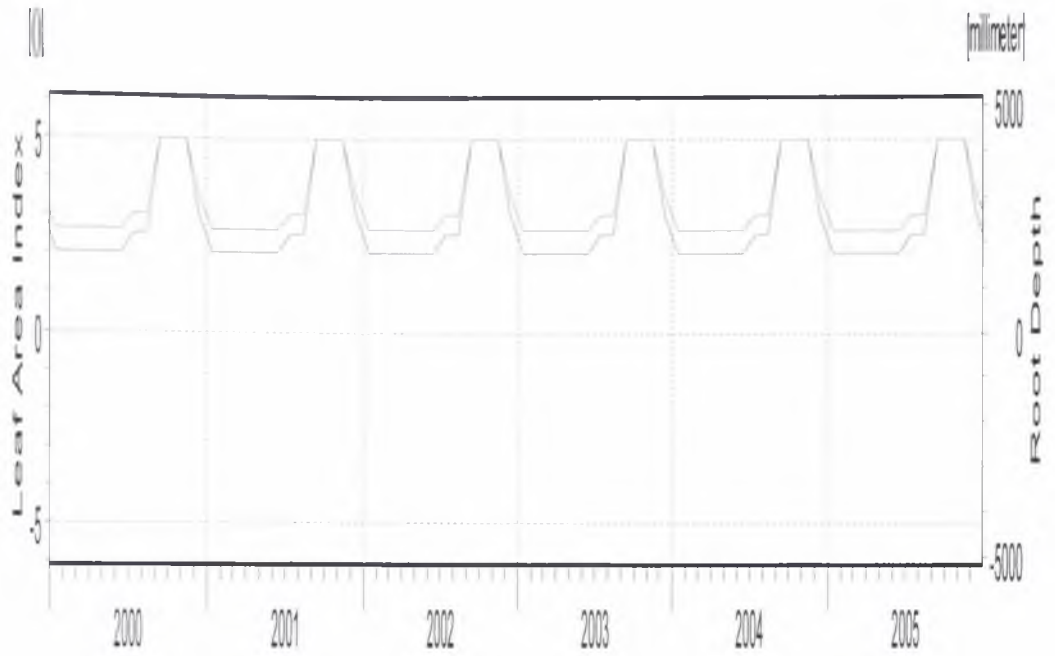
OUTPUT PARAMETERS

<i>Theta_s</i>	0.37349					
<i>Alpha*</i>	-2.78325		<i>alpha</i>	6.1837m-1		0.0618cm-1
<i>N*</i>	-1.68190		<i>n</i>	1.1860		
<i>Lambda*</i>	-0.48057		<i>lambda</i>	-2.3577		
<i>Ksat*</i>	2.91633		<i>Ksat</i>	18.4733cm/d		2.14E-06m/s

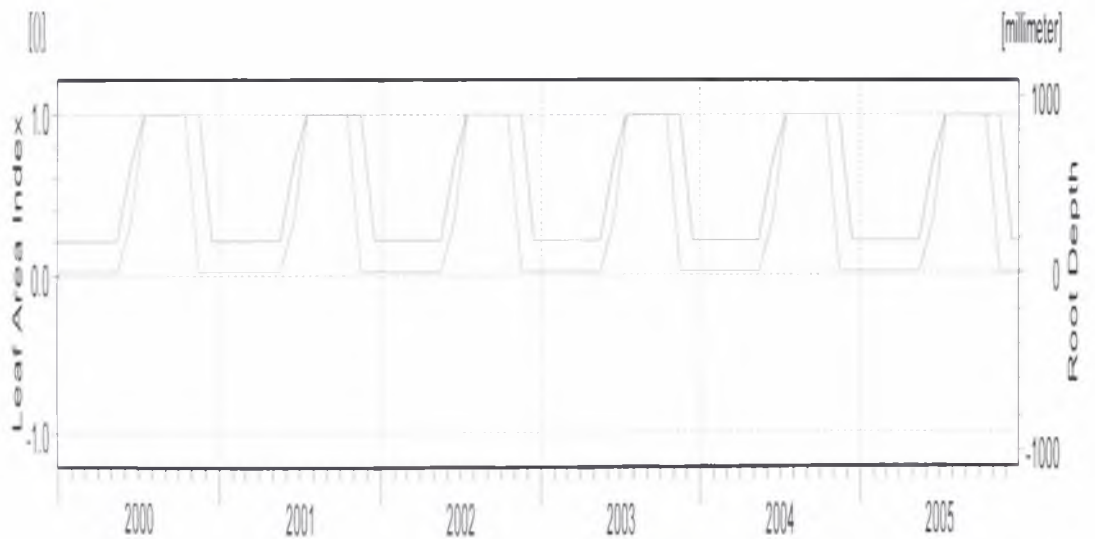
Appendix.2 Aquifer characteristics

<i>Location (BH ID)</i>	<i>BH Depth (m)</i>	<i>Geology</i>	<i>Pumping Rate (m³/h)</i>	<i>Pumping Duration (mins.)</i>	<i>Drawdown (m)</i>	<i>Specific Capacity (m²/h)</i>	<i>Transmissivity (m²/h)</i>
<i>1. Tafo (CRIG) (DB 1)</i>	<i>23.1</i>	<i>Granite</i>	<i>0.45</i>	<i>135</i>	<i>12.69</i>	<i>0.03</i>	<i>0.005</i>
<i>2.Nsawam (ASTEK) (DB5)</i>	<i>47.3</i>	<i>Granite</i>	<i>0.45</i>	<i>120</i>	<i>31.78</i>	<i>0.01</i>	<i>0.002</i>
<i>3. Medie (AKWAAB A) (DB6)</i>	<i>38.46</i>	<i>Granite</i>	<i>4.80</i>	<i>210</i>	<i>28.80</i>	<i>0.17</i>	<i>0.05</i>

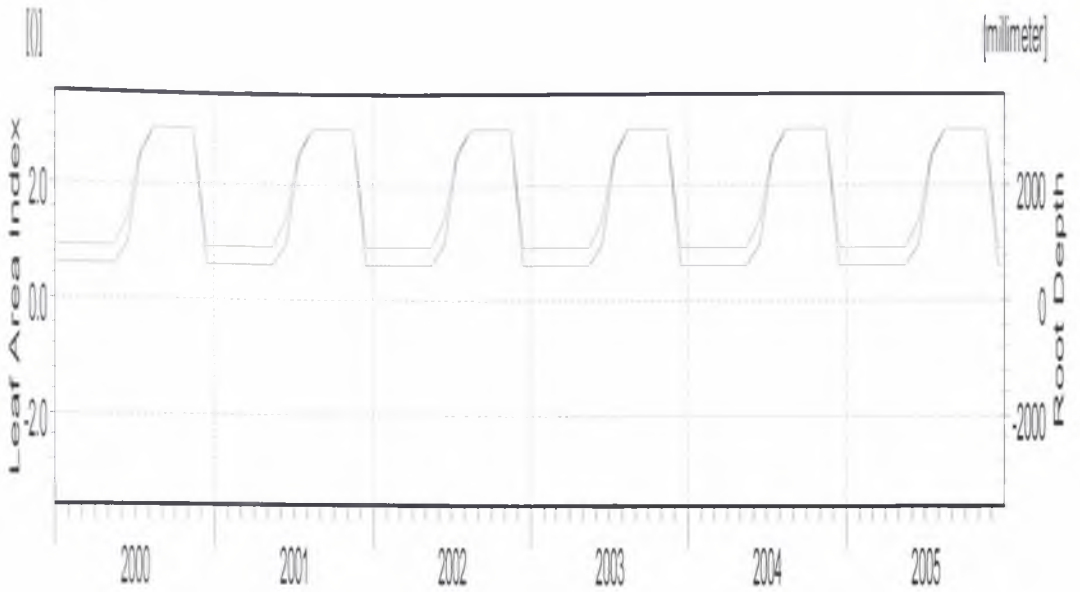
Appendix 3 Time series Leaf Area Index and Root Depth of different land cover types



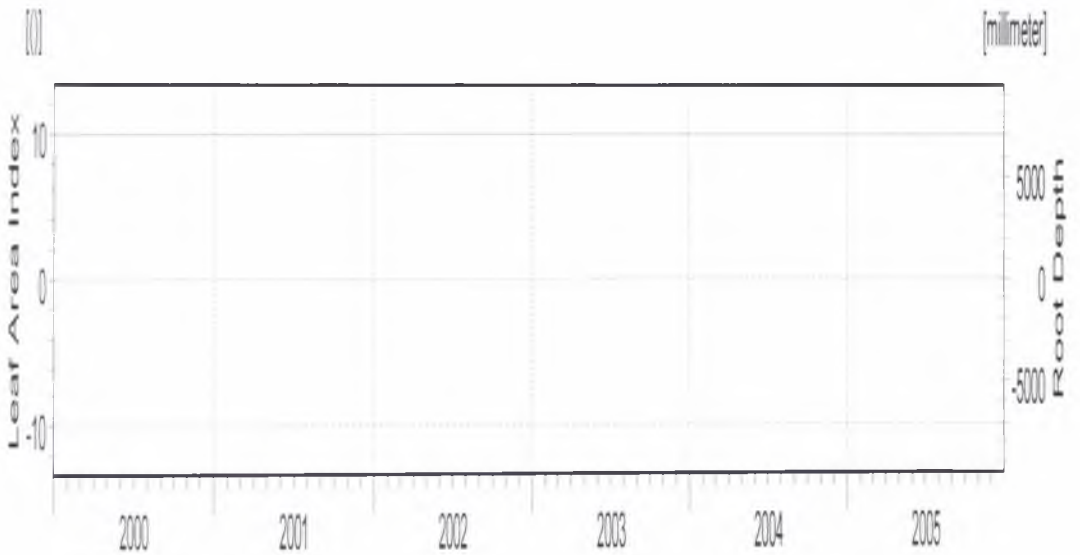
Time series LAI and RD of the forest (Grid code 1)



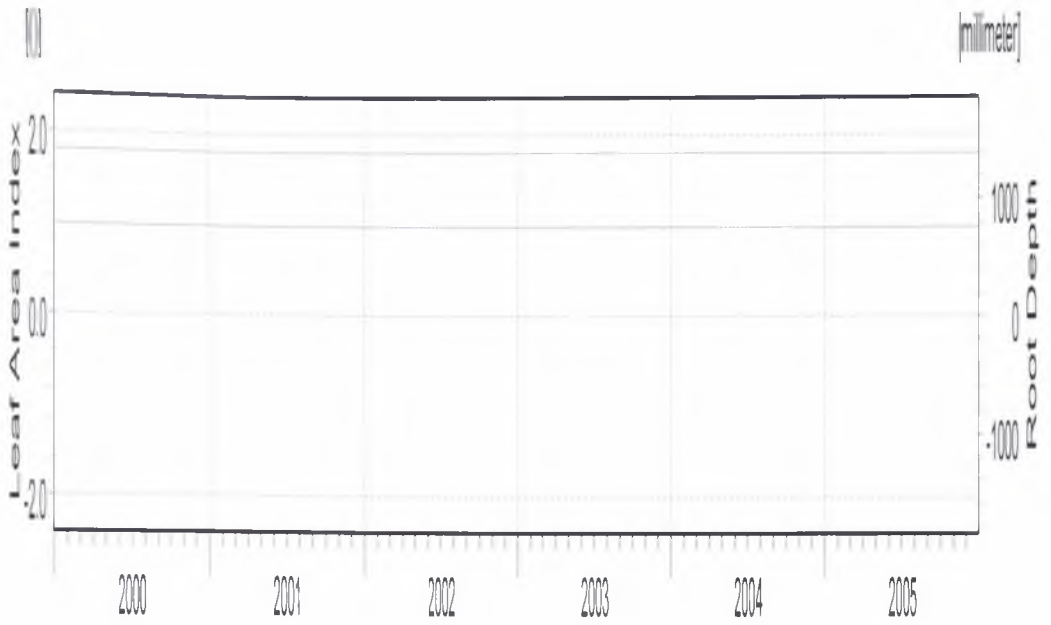
Time series LAI and RD of the Savannah zone (Grid code 2)



Time series LAI and RD of Bush Land (Grid code 3)



Time Series and RD of water body (Grid code 4)



Time series LAI and RD of agriculture land (Grid code

**Appendix 4: Sample of rainfall data recorded by event loggers (Rain-o-Matic type)
at Koforidua.**

Date	Time	mm	
03/01/07	12:00:45.0	0	Start
03/08/07	15:50:45.5	1	
03/08/07	15:54:42.0	2	
03/08/07	15:56:59.0	3	
03/09/07	15:48:05.5	4	
03/09/07	15:49:09.0	5	
03/09/07	15:49:37.0	6	
03/09/07	15:50:22.0	7	
03/09/07	15:50:52.0	8	
03/09/07	15:51:16.0	9	
03/09/07	15:51:35.5	10	
03/09/07	15:52:02.0	11	
03/09/07	15:52:23.5	12	
03/09/07	15:52:45.5	13	
03/09/07	15:53:16.0	14	
03/09/07	15:53:43.0	15	
03/09/07	15:54:10.5	16	
03/09/07	15:54:51.5	17	
03/09/07	15:55:31.0	18	
03/09/07	15:56:12.5	19	

03/09/07 15:57:11.5 20
03/09/07 15:57:48.5 21
03/09/07 15:58:32.5 22
03/09/07 15:59:23.5 23
03/09/07 16:00:27.5 24
03/09/07 16:02:03.0 25
03/09/07 16:03:07.0 26
03/09/07 16:04:20.0 27
03/09/07 16:05:32.0 28
03/09/07 16:06:54.0 29
03/09/07 16:08:06.0 30
03/09/07 16:09:23.5 31
03/09/07 16:10:27.0 32
03/09/07 16:11:11.5 33
03/09/07 16:12:01.0 34
03/09/07 16:12:47.5 35
03/09/07 16:13:44.0 36
03/09/07 16:14:34.5 37
03/09/07 16:15:35.0 38
03/09/07 16:17:04.0 39
03/09/07 16:19:35.5 40
03/09/07 16:23:34.0 41

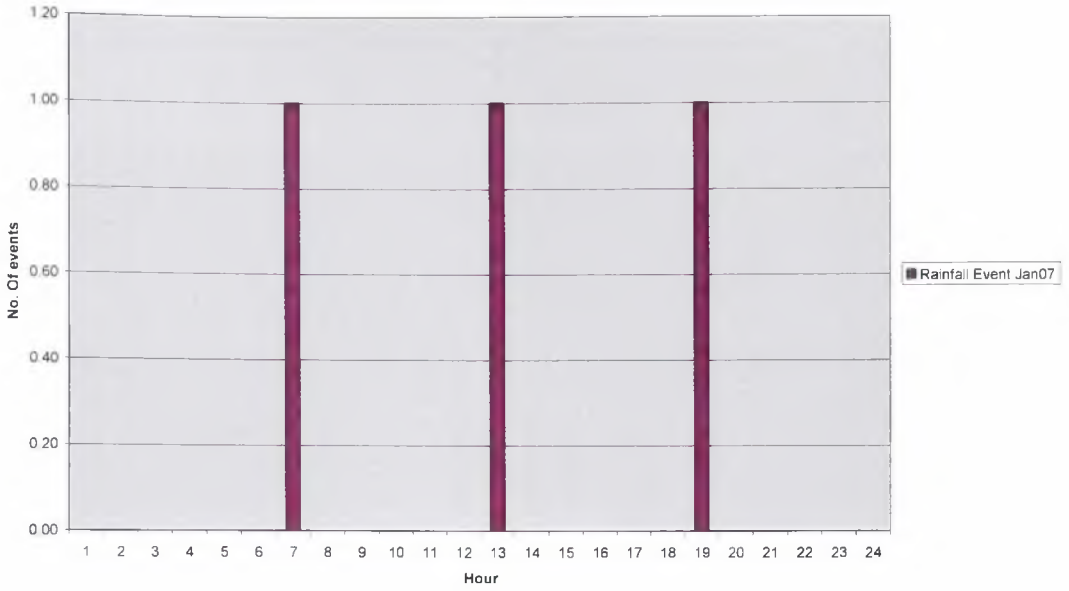
Date	Time	mm	
04/17/07	09:37:14.0	0	Start
04/22/07	17:43:00.0	1	
04/22/07	17:54:30.0	2	
04/22/07	18:09:44.0	3	
04/22/07	18:12:36.5	4	
04/22/07	18:25:31.0	5	
04/23/07	17:13:29.5	6	
04/23/07	17:16:13.0	7	
04/23/07	17:27:00.5	8	
04/23/07	17:38:28.5	9	
04/23/07	17:41:13.5	10	
04/23/07	17:49:49.0	11	
04/23/07	17:53:22.0	12	
04/23/07	17:55:36.5	13	
04/23/07	17:57:44.0	14	
04/23/07	17:59:10.0	15	
04/23/07	18:00:26.5	16	
04/23/07	18:03:17.5	17	
04/27/07	15:05:03.0	18	
04/27/07	15:09:03.0	19	
04/27/07	15:47:00.5	20	
04/29/07	13:47:55.0	21	

04/29/07 13:49:03.0 22
04/29/07 13:49:34.5 23
04/29/07 13:50:15.5 24
04/29/07 13:50:47.0 25
04/29/07 13:51:12.5 26
04/29/07 13:51:45.5 27
04/29/07 13:52:24.0 28
04/29/07 13:52:53.5 29
04/29/07 13:53:19.0 30
04/29/07 13:53:46.0 31
04/29/07 13:54:21.5 32
04/29/07 13:54:53.0 33
04/29/07 13:55:34.5 34
04/29/07 13:56:32.0 35
04/29/07 13:57:28.0 36
04/29/07 13:59:28.5 37
04/29/07 14:01:26.0 38
04/29/07 14:04:22.5 39
04/29/07 14:08:56.5 40
04/29/07 14:22:37.0 41
04/30/07 15:08:08.5 42
05/05/07 16:27:29.5 43
05/05/07 16:38:01.5 44

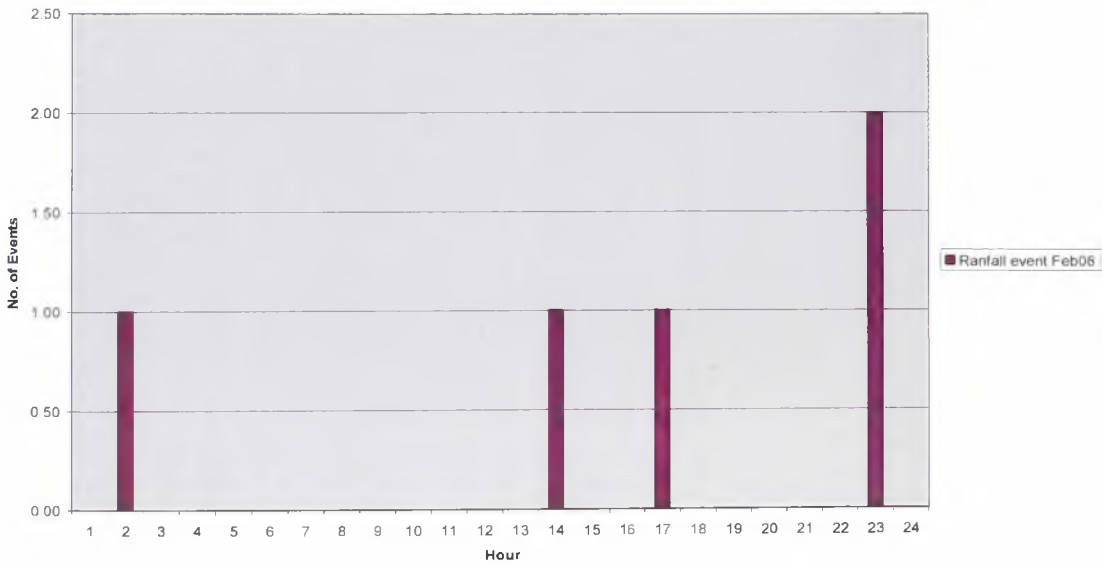
05/05/07 16:47:13.0 45
05/05/07 17:06:11.0 46
05/08/07 16:36:45.0 47
05/10/07 15:54:41.0 48
05/10/07 16:03:50.0 49
05/10/07 16:09:27.0 50
05/10/07 16:17:41.0 51
05/10/07 16:51:28.0 52
05/10/07 16:55:39.0 53
05/10/07 16:57:28.5 54
05/10/07 16:58:17.0 55
05/10/07 16:58:47.0 56
05/10/07 16:59:15.5 57
05/10/07 16:59:39.5 58

Appendix 5 Time of Rainfall occurrences at Koforidua (2007)

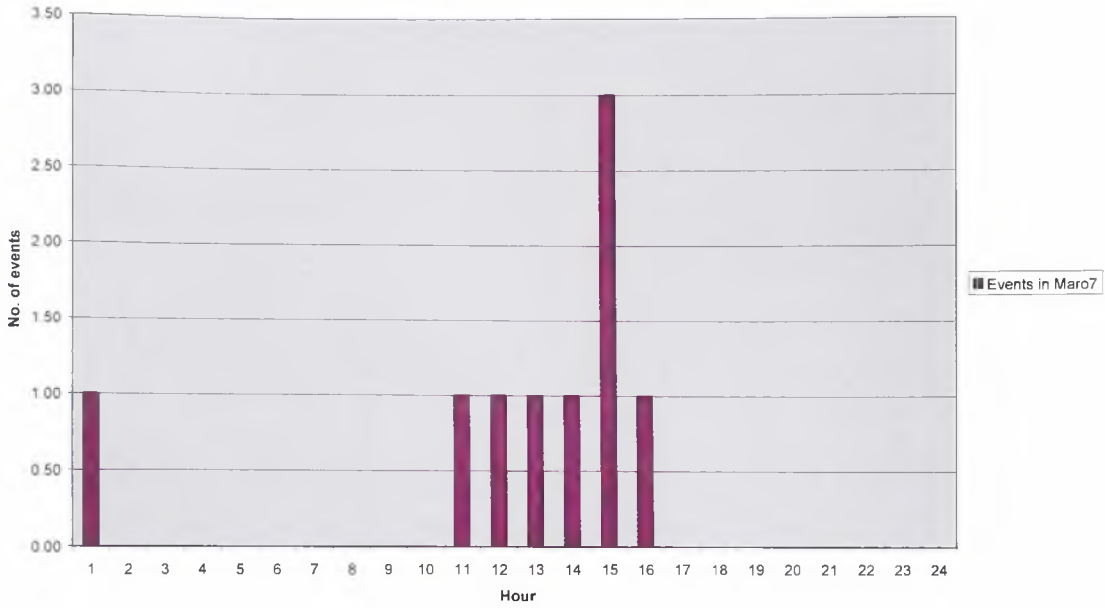
Rainfall Event Jan08



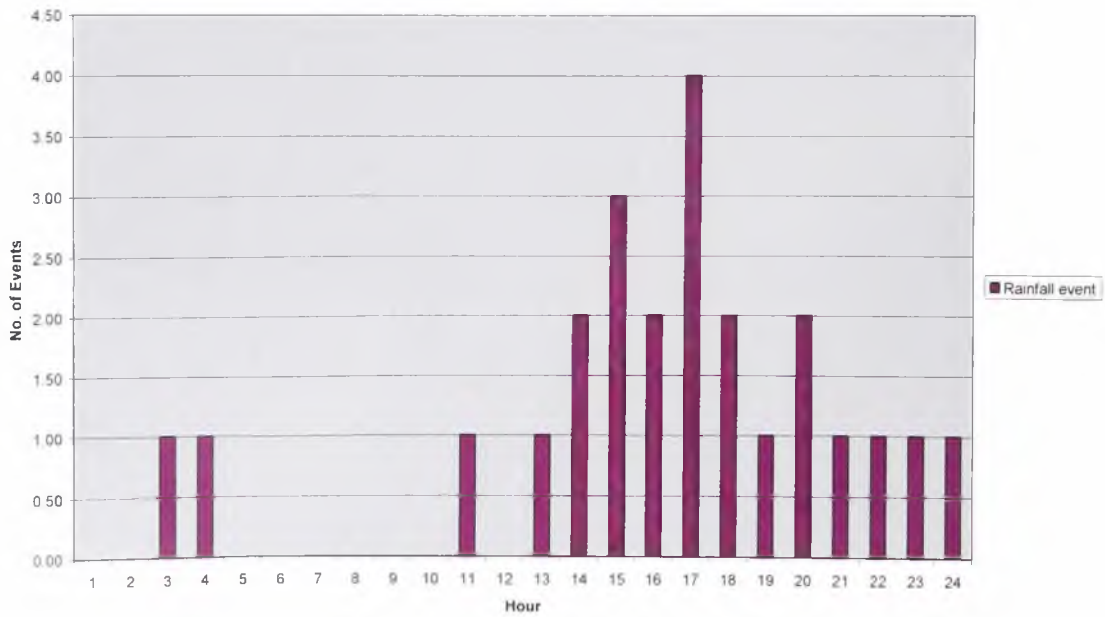
Ranfall event Feb08



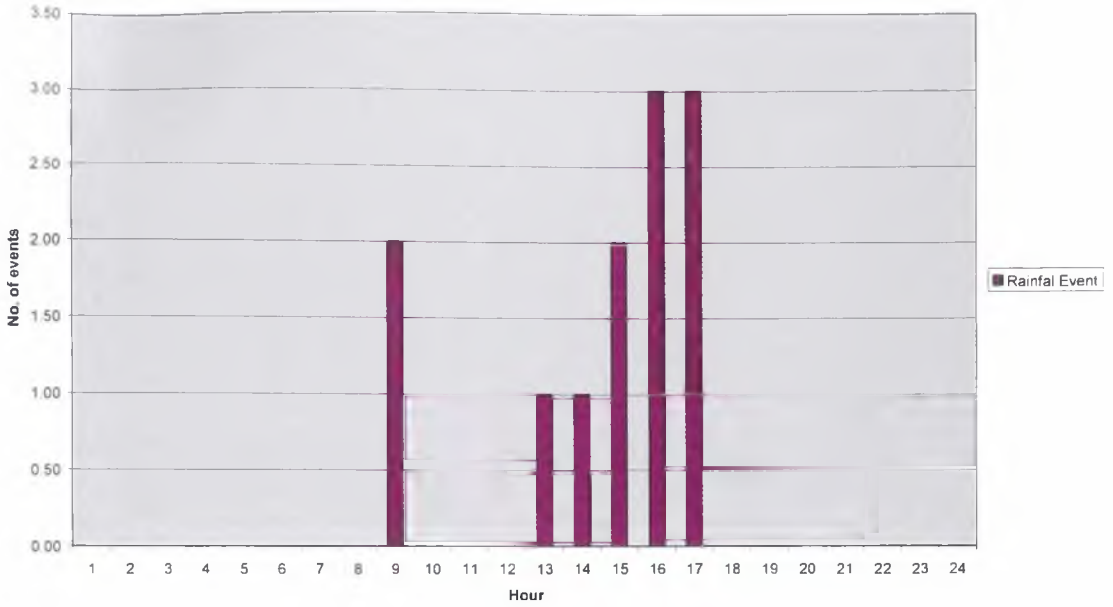
Events in Mar07



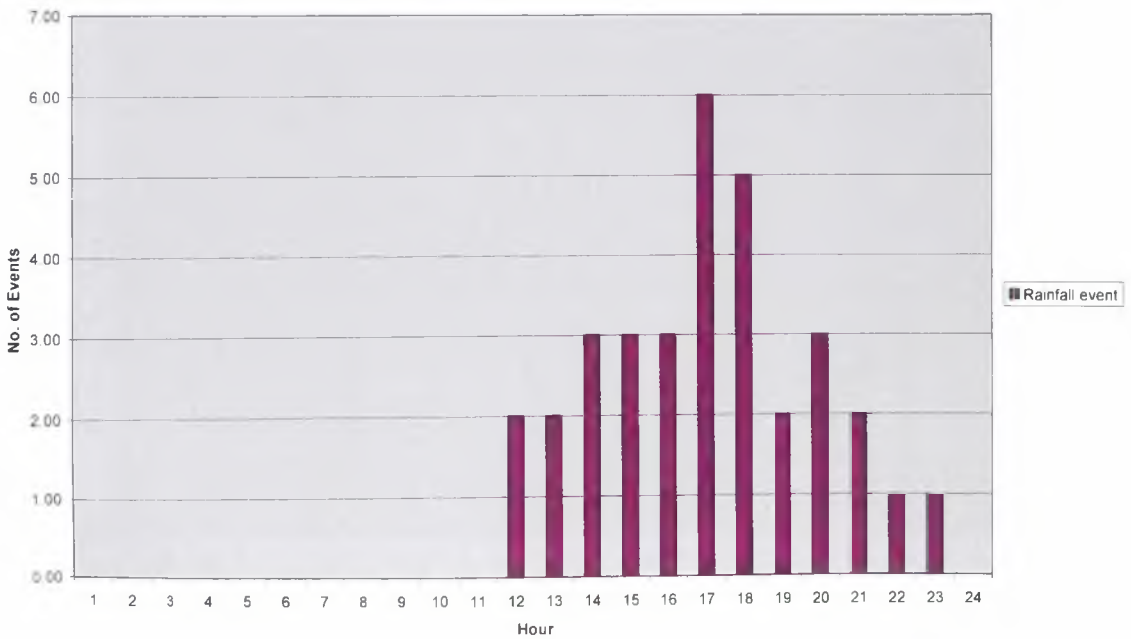
Rainfall event Apr07



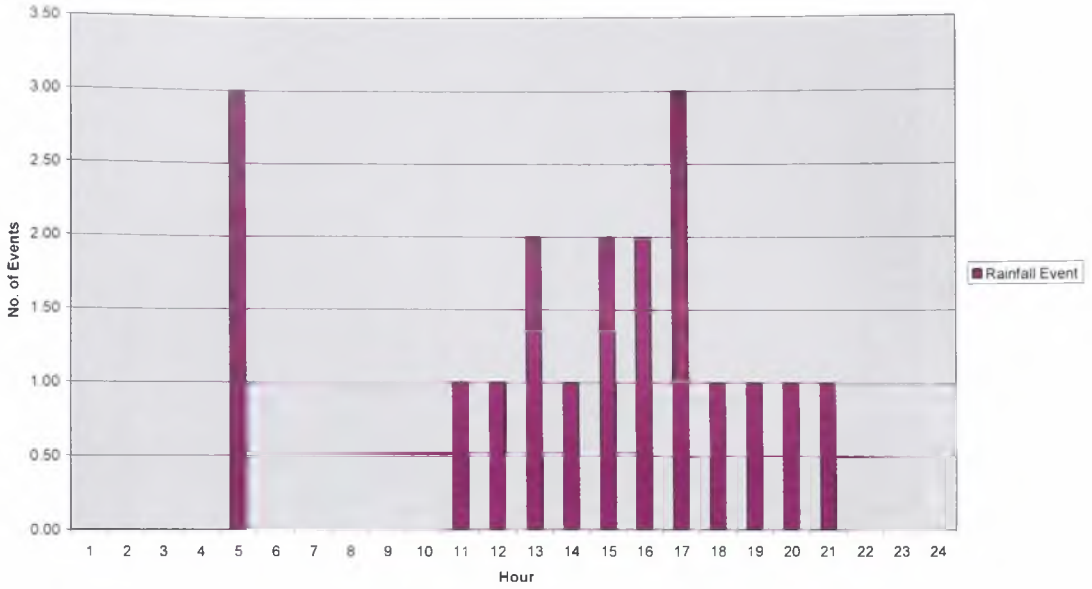
Rainfal EventMay07



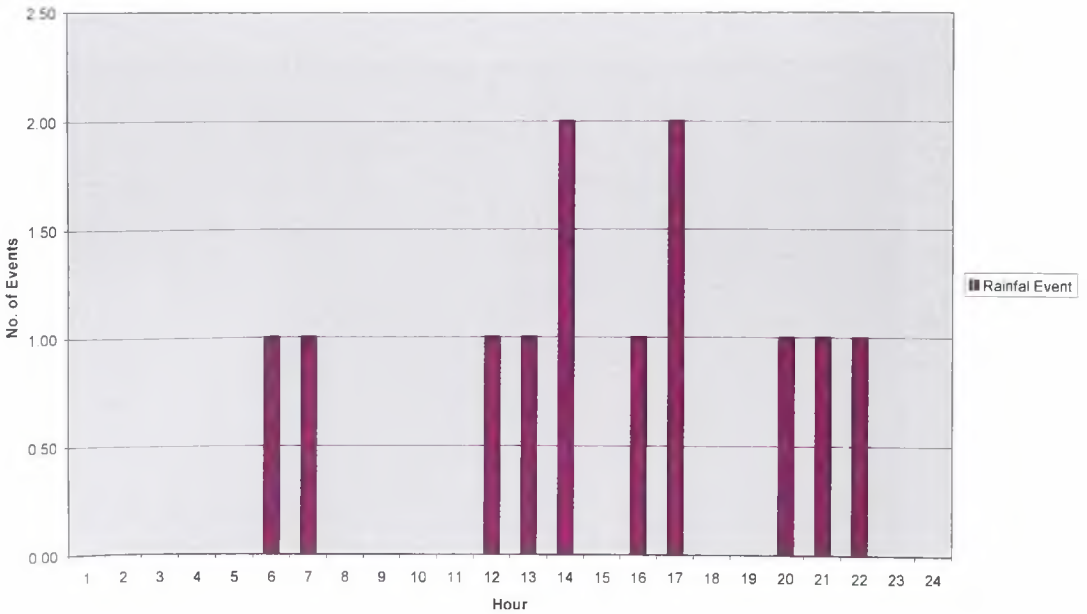
Rainfall event Jun07



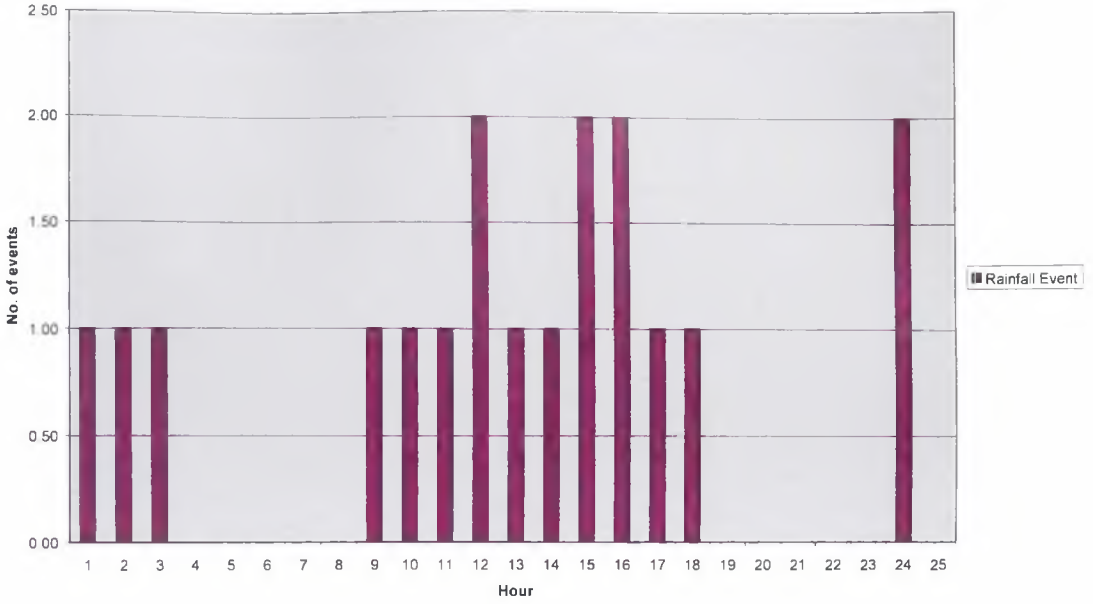
Rainfall Event Jul07



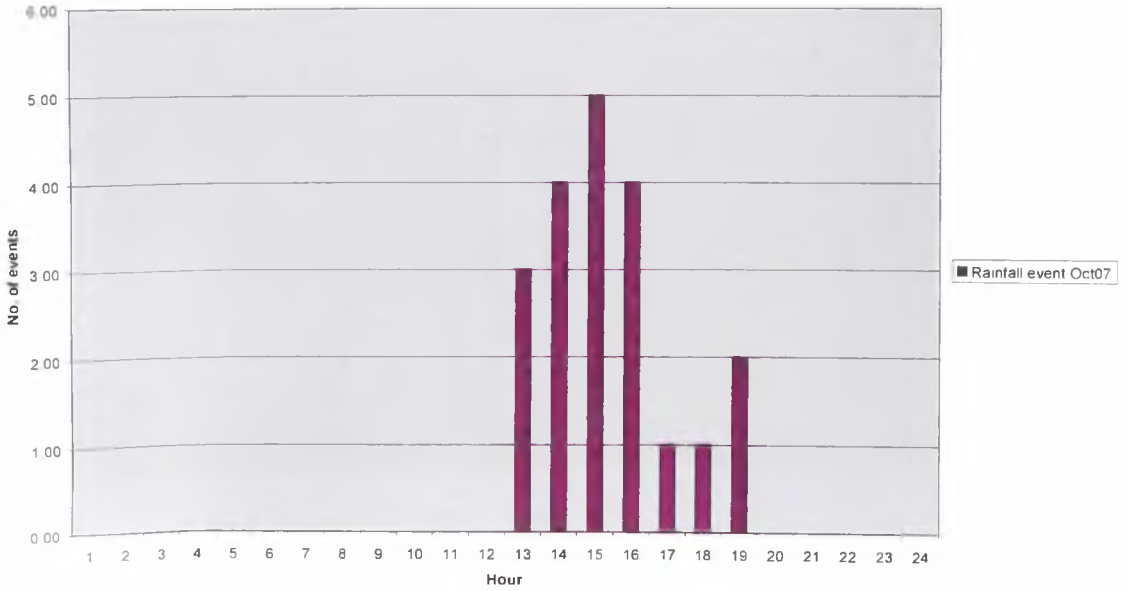
Rainfal Event Aug07



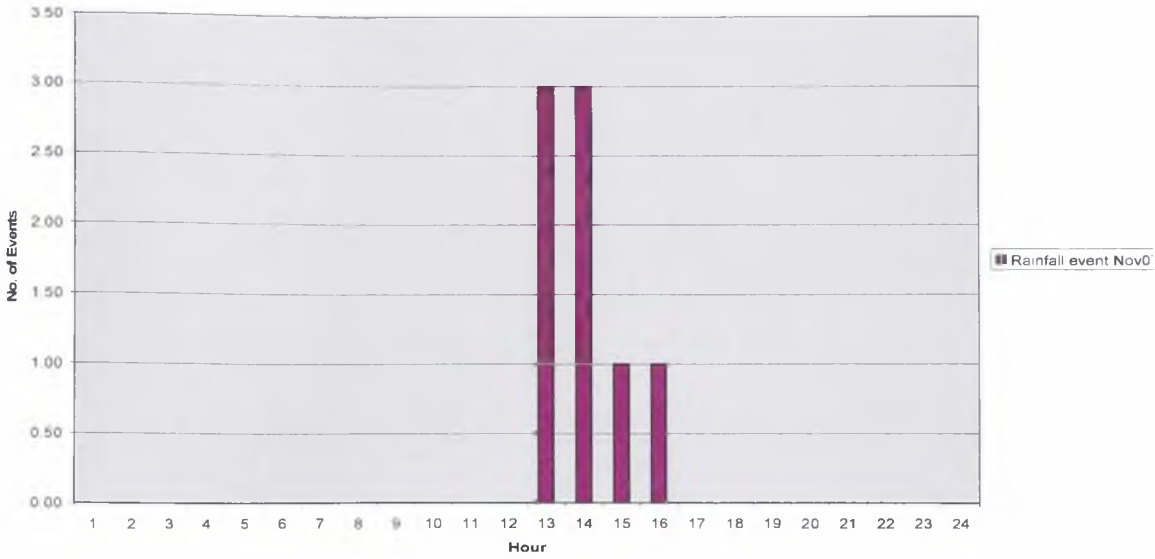
Rainfall Event Sep07



Rainfall event Oct07



Rainfall event Nov07



Rainfall event Dec07

