

**Cranfield University at Silsoe
Institute of Water and Environment**

**PhD Thesis
2005**

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**Application of a hydrological model in a data-poor
tropical West African catchment: a case study of the
Densu Basin of Ghana**

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November 30 2005

**This thesis is submitted in fulfilment of the requirements for the Degree of
Doctor of Philosophy.**

Acknowledgements

I would like to express my profound gratitude to Dr. Ian Holman for his invaluable contribution through supervision of this PhD research. He had a paramount input into this research through his guidance from initial proposition to its completion and brought out the best of me. Thank you.

I am also very grateful to the thesis committee members Dr Tim Hess and Dr. Peter Robbins for their criticism and suggestions in refining my ideas and approaches in all the thesis committee meetings.

I wish to also thank members of the ACRU user Group through Dr. Trevor Lumsden, Andrew Pike and Professor Schulze all of School of Bioresources Engineering & Environmental Hydrology, University of Natal South Africa for their valuable assistance in making me understand the ACRU model when I was handicapped.

Many thanks also go to the Government of Ghana through the Scholarship Secretariat and the Council for Scientific and Industrial Research (CSIR) for awarding the PhD scholarship and also, to the Water Research Institute of CSIR for granting the study leave.

I am indebted to my family members especially my junior brother Jerry (DK), and his wife Oforiwa who have been around for me ever since I stepped foot in UK, my mum and dad, Mr. and Mrs Obeng Bekoe, sisters Aku, Christy and Betty and Mr and Mrs Dwamena of Kempston for their spiritual support and encouragement. I also acknowledge my friends Nana Opare and wife, Shalom, Ericus, Jewel, Lina, Mariam, Mohamed and Dr. Lord Abbey who created a lively environment during my stay in England.

Finally I am so grateful to the Almighty God for all we have received and all that is yet to come. God Bless

Dedication

I dedicate this PhD thesis to the memory of my darling wife
Finale who passed away through cancer before defending
this thesis, and to my three lovely children Akosua, Abena,
and Kofi.

Abstract

This thesis reports on the suitability of using a hydrological model to predict the impact of future catchment changes on the surface water resources of tropical West African catchments, as a basis for sustainable watershed management strategies. The economically-important but data-poor Densu Basin (2100km²) in Ghana is used as a case study. Prior to the identification of an appropriate model, a range of model selection criteria to achieve the research objectives were developed, which included minimum data requirements. Following a review of available models, the ACRU hydrological model was chosen using these selection criteria. As this is the first use of the ACRU model in the Tropics, a sensitivity analysis was performed to gain a better understanding of the correspondence between the data and the physical processes being modelled and to inform future data collection priorities. The most sensitive parameters identified were rainfall; soil water content at field capacity and monthly crop coefficients. The sensitive parameters were different from those previously identified for semi arid regions, thereby improving the wider understanding of the behaviour of the ACRU model in a new climatic region of Africa for future studies. Although the ACRU model performed well during calibration (e.g. Nash and Sutcliffe Efficiency > 0.8), it performed poorly during the validation period (e.g. NSE < 0.5). Aggregation of the daily output to monthly averages improved the performance appraisal statistics to a level where the model is appropriate for longer term water management issues such as irrigation planning and water supply planning. However, the prediction of the hydrological consequences of future catchment changes using the model could not be performed due to the variable model performance. A detailed analysis of input data quality and model performance identified a number of contributory reasons which included the poor distribution of available data from rain gauges and evaporation stations, poor data management and problems with groundwater processes within ACRU. Recommendations to the Densu River Basin Management Board to address the main problem area of data quality include ensuring that all data (new as well as existing) is subject to QC/QA procedures, the development of data archiving / back-up systems, making

historical data available to the wider hydrological community; and guidance on deriving model inputs from available data for future modellers. Finally recommendations on which areas need further study during future research using the ACRU model are given.

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Abbreviations and Acronyms

ABRESP	Fraction of “saturated” soil water to be redistributed daily from the topsoil (A horizon) into the subsoil (B horizon) when the topsoil is above its drained upper limit
ACRU	Agricultural Catchments Research Unit Model
ADJIMP	Fraction of the catchment occupied by adjunct impervious areas, i.e., areas joined (connected) directly to a watercourse, from which precipitation contributes directly to quickflow)
AESC	Architectural Engineering Services Department
AET	Actual Evapo-Transpiration
AGNPS	AGricultural NonPoint Source
ANSWERS	Areal Nonpoint Sources Watershed Environment Response Simulation Model
Apr	April
ARS	Agricultural Research Service
Aug	August
AWBM	Australian Water Balance Model
BFRESP	Fraction of “saturated” soil water to be redistributed daily from the subsoil to the intermediate/groundwater store when the subsoil is above its drained upper limit.
CAY	Average monthly crop coefficients, K_{cm} for the pervious land cover of a catchment/subcatchment specified month by month.
CERGIS	CEntre for Remote sensing and GIS
CN	Curve Number
COFRU	Coefficient of baseflow response. It is the fraction of water from the intermediate /groundwater store that becomes streamflow on a particular day
COIAM	Coefficient of initial abstraction, i.e. a coefficient given month by month which is used to estimate the rainfall retained by interception, detention storage and infiltration before stormflow commences
CONST	Fraction of the plant available water of a soil horizon at which total evaporation is assumed to drop below the maximum evaporation during drying of soil to detect onset of plant stress

CORPAN	Monthly adjustment factors to be applied to evaporation pan dataset to correct for screening and systematic errors
CSIR	Council for Scientific and Industrial Research
DATSCR	DATa SCReening
Dec	December
DEM	Digital Elevation Model
DEPAHO	Depth of the topsoil of the soil profile
DEPBHO	Thickness of the subsoil of the soil profile
DISIMP	Fraction of the catchment occupied by impervious areas which are not adjacent to a watercourse (e.g. house roofs discharging onto lawn)
DOS	Disk Operating System
DR3	Distributed Routing Rainfall-Runoff Model
DRBMB	Densu River Basin Management Board
DRMS	Daily Root Mean Square error
DUL	Drained Upper Limit
E	Extremely sensitive
Eapan	Evaporation of A pan
EIA	Environmental Impact Assessment
EPA	Environmental Protection Agency
Es	Soil Water Evaporation
Esm	Maximum Soil Water Evaporation
Et	Actual Plant transpiration
ET _o	Reference Evapo-Transpiration for grass
FAO	Food and Agricultural Organization
FC1	Soil water content (m.m^{-1}) at drained upper limit for the topsoil.
FC2	Soil water content (m.m^{-1}) at drained upper limit for the subsoil
Feb	February
FOREST	Variable to specify to simulate wet canopy evaporation at an enhanced rate which occurs under forest conditions, and to inform ACRU that a dynamic file generator has to be used
FORTTRAN	FORmula TRANslation
GDP	Gross Domestic Product

GWCL	Ghana Water Company Limited
GWP/TAC	Global Water Partnership/Technical Advisory Committee
GWP-WATAC	Global Water Partnership-West African Technical Advisory Committee
H	Highly sensitive
H ₁	Alternate Hypothesis to the Null Hypothesis
HEC-HMS	Hydrologic Engineering Centre-Hydrologic Modeling System
H ₀	Null Hypothesis
HSPF	Hydrologic Simulation Package-Fortran IV
I	Insensitive
IHACRES	Identification of Hydrographs And Components from Rainfall Evapotranspiration and Streamflow data
ITCZ	Inter Tropical Convergence Zone
IWRM	Integrated Water Resources Management
Jan	January
Jul	July
Jun	June
KINEROS	Kinematic Runoff and Erosion Model
K _p	Pan Coefficient
kPa	Kilo Pascal
LAI	Leaf Area Index
M	moderately sensitive
Mar	March
MIKE SHE	Generalized River Modelling Package-Systeme Hydroloque European
MMS	United States Geological Survey Model
MOFA	Ministry of Food and Agriculture
MOU	Memorandum of Understanding
MPER	Model Parameter Estimation Routines
MSD	Meteorological Services Department
NCWD	National Council on Women and Development
NDPC	National Development Planning Committee
NOAA	National Oceanic and Atmospheric Administration

Nov	November
NSE	Nash and Sutcliffe Efficiency
Oct	October
ODE	Ordinary Differential Equation
PBIAS	Percent BIAS
PDE	Partial Differential Equation
PhD	Doctor of Philosophy
PME	Performance Model Efficiency
PO1	Porosity of topsoil ($\text{m}^3.\text{m}^{-3}$).
PO2	Porosity of subsoil ($\text{m}^3.\text{m}^{-3}$).
PTF	Pedo Transfer Functions
PWP	Permanent Wilting Point
PWP ₁	Permanent Wilting Point for top soil
PWP ₂	Permanent Wilting Point for sub soil
RMSE	Root Mean Square Error
ROOTA	Fraction of the effective root system in the topsoil horizon, specified month by month
RORB	Rainfall Routing Model
R _{sp}	Spearman's Rank Correlation Coefficient
S	Slightly sensitive
SCS	Soil Conservation Service
SD	Sustainable development
SEE	Standard Error of Estimate
Sept	September
SHE	Système Hydrologique Européen
SMMDEP	Effective (critical) depth of soil (m) from which stormflow generation takes place
SRID	Statistics, Research and Information Directorate
SSARR	Streamflow Synthesis and Reservoir Regulation
StDEV	Standard DEviation
STOIMP	Surface storage capacity (i.e. depression storage, or initial abstraction) of impervious surface, which needs to be filled before stormflow commences
STORM	Storage, Treatment, Overflow Runoff Model

SWAT	Soil Water Assessment Tools
SWMM	Storm Water Management Model
SWRRB	Simulator for Water Resources in Rural Basins
TOPMODEL	Physically Based Runoff Production Model
t_t	T Test Statistics
UN	United Nations
UNCHS	United Nations Centre for Human Settlements
UNEP	United Nations Environment Programme
US	United States
USA	United States of America
USDA	United States Department of Agriculture
USGS	United States Geological Survey
VEGINT	Interception loss (mm.rainday ⁻¹) by vegetation, specified month by month
WARM	WATER Resources Management study
WMO	World Meteorological Organization
WP1	Permanent Wilting Point of topsoil (m ³ .m ⁻³)
WP2	Permanent Wilting Point of Subsoil (m ³ .m ⁻³)
WRC	Water Resources Commission

List of Symbols

m^3	Cubic metre
m	Metre
m^3/day	Cubic metres per day
$m^3 \cdot \text{day}^{-1}$	Cubic metres per day
mm	millimetres
min	minutes
Fig	Figure
%	Percentage
cm	centimetre
et al.	And others
m/a	Metres per annum
mm day^{-1}	Millimetres per day
$^{\circ}\text{C}$	Degree celsius
km^2	Square kilometre
$m^3 \cdot m^{-3}$	Cubic metre per cubic metre
km	kilometre
$^{\circ}$	degree
$^{\circ}\text{N}$	Degree north
$^{\circ}\text{S}$	Degree south
Mg m^{-3}	Milligrams per cubic metre
mm hr^{-1}	Millimetres per hour
<	Less than
>	Greater than
$\leq$	Less than or equal to
$\geq$	Greater than or equal to
mm/a	Millimetres per annum
km^3	Cubic kilometre
m^3/s	Cubic metres per second
m^2	Square metre
Tmin	Minimum daily temperature
Tmax	Maximum daily Temperature

=	Equals to
ft	Foot or feet
ms ⁻¹	Metres per second

1. Background

In 1972, 70 governments met in Stockholm, Sweden for a conference, after leaders of the world recognized the need for global environmental planning - out of which was born the United Nations Environment Programme (UNEP) (United Nations, 1994). The worry at the time was the globally unsustainable pressures on water resources, causing concerns for long term sustainability and human life observed in the participating countries. This gathering led to the development of the concept of sustainable development (SD) as a basis for the Human Environment (United Nations, 2005a). SD has been defined by United Nations as “Development that ensures that the use of resources and the environment today does not restrict their use by future generations” (United Nations, 1994; United Nations, 2005b). In 1992 in Rio de Janeiro, the United Nations Conference on Environment and Development was organized, culminating in the “Agenda 21” global action plan as a follow-up to reaffirm the Declaration of the 1972 meeting, “Agenda 21” contains principles and recommendations aimed at sustainable development for the 21st century (United Nations 2005b). Water resources management has become critical in many parts of the world because population and economies are growing, increasing the demand for water (Figure 1.1) (Global Water Partnership/Technical Advisory Committee or GWP/TAC (2000)) and culminating in the need for allocation and conflict resolution for water resources.

Lee (1995) observed that because a river basin system is comprised of many components (e.g. precipitation, floodplains, lakes and swamps etc.) with interdependencies, piecemeal approaches to river basin development and management have often failed to lead to an optimal outcome in management, resulting in inefficient water and land resource use, economic losses and environmental degradation. On the other hand water according to GWP/TAC (2000) is seen to be so special to manage because a) all life and sectors of the economy depend on it b) we all live in - and with - the hydrological cycle: water is constantly being recharged, used, returned and reused and c) we all depend

on each other. These challenges faced in water resources management are described as a delicate balance (Figure 1.2) between water

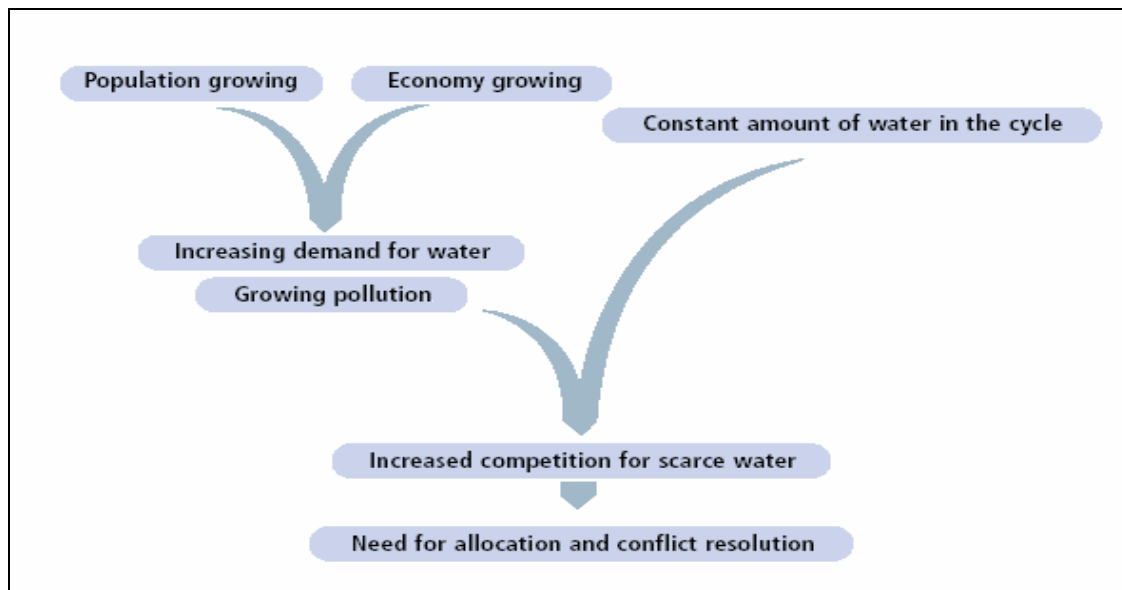


Figure 1.1 Diagram showing why water resources management is critical (from GWP/TAC, 2000)

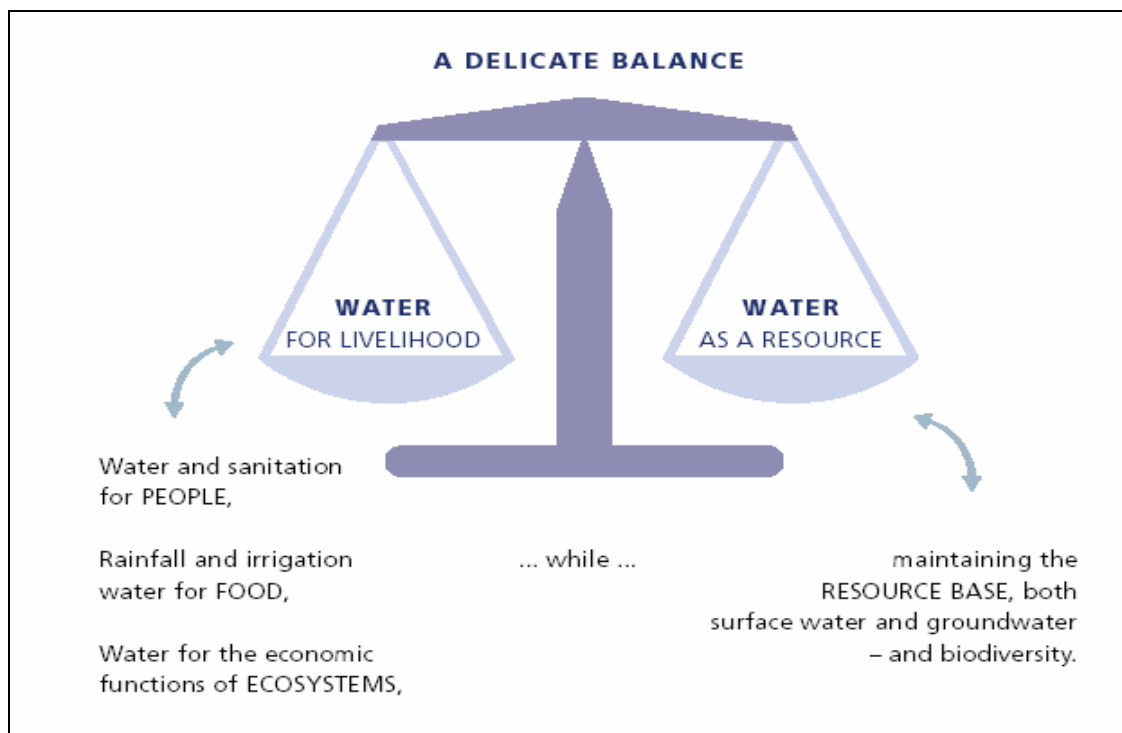


Figure 1.2 The main challenges facing water resources management (from GWP/TAC, 2000)

for livelihood and water as a resource (GWP/TAC, 2000). This interdependence of water necessitates integration of the natural system between land and water use; between surface water and groundwater; between water quantity and quality; between the freshwater system and coastal waters and between upstream and downstream on one hand and, on the other hand, integration in our management of the natural system and calls for Integrated Water Resources Management (IWRM) (GWP/TAC, 2000) where:

- mainstreaming water in the national economy is important
- ensuring co-ordination between sectors
- ensuring partnership between public and private sector management and
- involving everybody.

IWRM is defined by GWP/TAC (2000) as a “process which promotes the coordinated development and management of water, land and related resources in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability”.

Following from above, four principles (Figure 1.3), which became issues of great concern during the Rio Agenda 21 meeting, culminated in a new paradigm i.e. “from sub-sectoral to cross-sectoral water management” (GWP/TAC, 2000) and gave rise to what constituted the ‘enabling environment’ for water resources management (GWP/TAC, 2000). This enabling environment according to GWP/TAC should be government acting as an enabler rather than a top-down manager where the roles of Government should be to:

- formulate national water policies
- enact water resources legislation
- ensure separation of regulating and service provision functions
- encourage and regulate the private sector
- encourage dialogue with neighbouring countries (50% of all land lies in shared river basins)

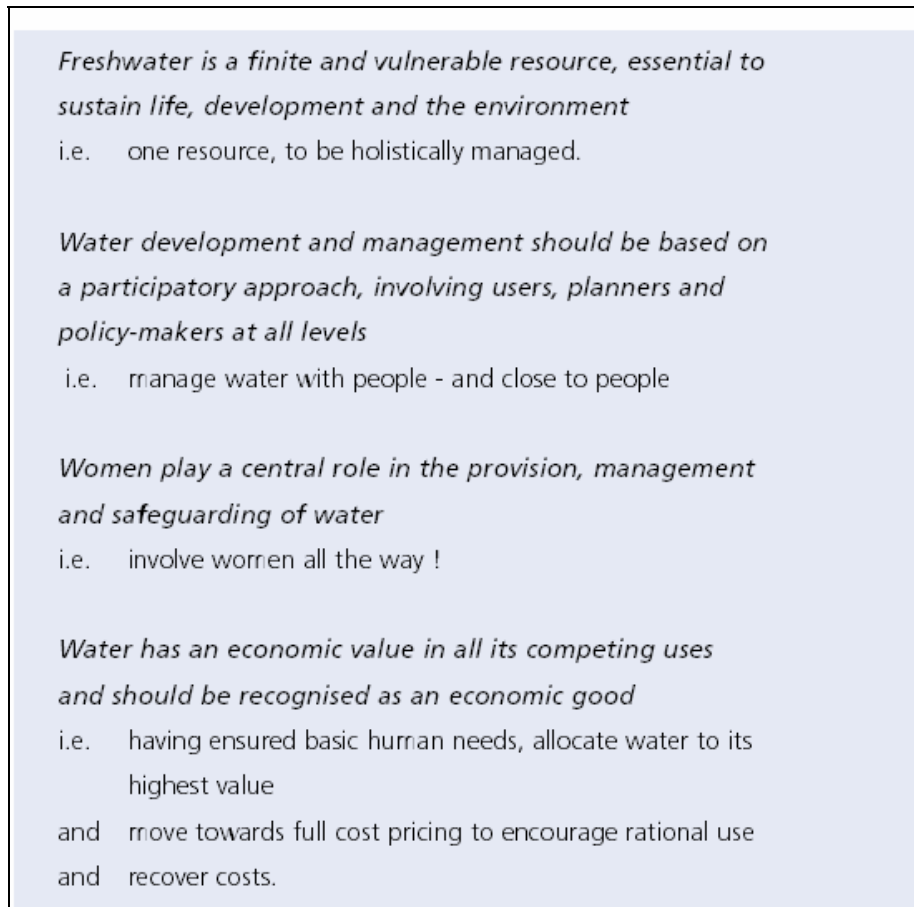


Figure 1.3 The four principles as basis for the Agenda 21 forum
(from GWP/TAC, 2000)

However, for these roles of government to be successful, there have to be institutional roles of IWRM (GWP/TAC, 2000) where all organizations and agencies at all levels and across sectors should be participating and talking to each other by:

- anchoring the coordination at the highest apex level
- creating coordination bodies at the river basin level
- by devolving responsibility to the lowest appropriate level and
- by developing human and institutional capacity.

Then there are the practical 'management instruments' of IWRM for water managers which GWP/TAC (2000) recommended need practical 'tool boxes' to work with. These are water resources assessment, communication and information: allocation and conflict resolution and formulation of regulatory

instruments. However for the IWRM projects to be sustainable GWP/TAC (2000) advocated for the implementation of these principles that the "user pays, polluter pays; and subsidize the good and tax the bad".

Yet advocating of IWRM principles (Lee, 1995; GWP/TAC, 2000) there are still piecemeal approaches to water resources management problems known to culminate in environmental degradation such as 1) over exploitation of the surface water resources due to lack of good planning and effective water saving measures resulting in decrease in ground water recharge by nearly 74% from the 1960's to 1990's as a result of population increase in China (Ma et al., 2005); 2) Ngana et al., (2004) concluded that unsustainable utilization and management of natural resources (land, pasture and water resources) were the core problems in Tanzania that led to environmental degradation such as shortage of land and decreased river flows in the Lake Manyara sub-basin; 3) Singh (2000) showed that in the Haryana province of India, environmental degradation occurred as a result of over exploitation of groundwater which caused an attendant increase of the shallow water table height of over 1m/a since 1985, culminating in water logging and attendant floods. This he noted occurred even though the green revolution which brought about self sufficiency in food production is a success in that basin.

For the solution to some of these water resources management problems, one approach to assisting sustainable development within river basins, and to contribute to the water resources assessment 'toolkit', is the development and use of mathematical modelling of watershed hydrology (Singh and Woolhiser, 2002 and Borah and Bera, 2003). Considerable work has been undertaken in understanding and modelling the processes involved in the hydrological cycle, enabling models to have been developed to address a wide spectrum of environmental and water resources problems (Singh and Woolhiser, 2002 and Borah and Bera, 2003)). Examples of models used to solve hydrological problems (Singh & Woolhiser, 2002) include the HEC-HMS¹ model, which is

¹ Hydrologic Engineering Centre-Hydrologic Modelling System (HEC, 2000)

considered to be the standard model in the private sector in the United States of America for design of drainage systems and for quantifying the effect of land use change on floods; HSPF² and its extended water quality model are the standard models adopted by the Environmental Protection Agency (EPA) of USA; the MMS model of the USGS³ is the standard model for water resources planning and management works especially those under the purview of the U.S. Bureau of Reclamation; TOPMODEL⁴ and SHE⁵ are used for hydrologic analysis in many European countries (Singh & Woolhiser, 2002).

The uses of hydrological models include a capability to predict streamflow from routinely measured weather data and catchment parameters (Wooldridge et al., 2001), for extending stream-flow series (Post et al., 1999), forecasting of floods (Kouwen, 2000) and low flows (Ye et al., 1997) and providing inflow to river models (Chiew et al., 1996). However, the ability of models to predict the range of effects caused by varying types and intensities of land-use still remains uncertain (Wooldridge et al., 2001) and this uncertainty they noted arises because the task of predicting the hydrologic implications of land-use change is complicated by the need to infer the combined impact of scale and heterogeneity on hydrological response. Landuse in this context means man's activities such as: deforestation, afforestation, urbanization and agriculture. One consequence of deforestation was observed in Amazonia, Brazil where a reduction of basin average precipitation by 0.73 mm day⁻¹ was observed (Costa and Foley, 2000). In another study, increased precipitation in Norcross was suspected to have been caused by possible enhanced increased atmospheric humidity as a result of increased urbanization in a study in Atlanta, Georgia (Diem and Mote, 2005). These landuse effects, together with the experience of Ngana et al. (2004) in Tanzania explained earlier in this Chapter; show that land use has considerable impact on a catchment's characteristics and subsequently its hydrological regime.

² Hydrologic Simulation Package-Fortran IV (Bicknell et al., 1993)

³ U.S. Geological Survey Model (Dawdy et al., 1978)

⁴ Physically Based Runoff Production Model (Bevern, 1995)

⁵ Systeme Hydrologique European (Barthurst 1986)

Despite the successes that hydrological models can bring to water resources problems Singh & Woolhiser (2002) noted that even though many spatially distributed environmental models have been developed, their (in the case of spatially distributed models) application at a regional scale (e.g. large drainage basins) was hitherto not very successful since they were 'scale specific' and further noted that lack of input data as well as poor data quality was a limiting factor hindering good modelling. However, Singh & Woolhiser (2002) concluded that the scope of mathematical models is growing, and the models are capable of simulating both water quality and quantity, with their use becoming common and encompassing several disciplinary areas.

Falkenmark (1997) and Wallace and Batchellor (1997) (cited by van de Giesen, 2000) observed that the need for process-level hydrological understanding in West Africa has only increased over time. This has arisen because the high population growth puts increasing pressure on the natural resource base and public funding is scarce, such that optimal investments to safeguard availability and quality of water are a necessity. Despite numerous examples (e.g. Ma et al., 2005, Ngana 2004 and, Singh 1995 & Singh & Woolhiser, 2002) of hydrological modelling being employed as a tool to assist in addressing a wide spectrum of environmental and water resources problems in many climates, limited studies have been conducted in the tropical regions of the world, and the hydrological modelling knowledge of the tropics has lagged behind that in other geographical and climatic regions (Chevallier and Planchon, 1993; van de Giesen et. al., 2000 and Giertz & Diekkruiger, 2003). Geirtz & Diekkruiger (2003) further stated that the bulk of hydrological process research is carried out in the temperate climate zone and that investigations, especially of soil physical properties with regard to runoff generation processes, are scarce in tropical regions. However, the capacity to conduct hydrological modelling has improved in many tropical countries with the advent of affordable high-speed computers and this has awakened the interest of hydrologists, researchers and water resource managers in the tropics. Examples of recent studies are in Puerto Rico, where Carter et al. (2000) used hydrological models to

quantitatively forecast precipitation; in Benin, where Bormann and Diekkruger, (2003) employed the use of regional hydrological models for environmental change studies and in Ghana where Larmie et al. (1989) modelled the water quality of a basin and Darko (2002) estimated the natural direct groundwater recharge in southwest Ghana using water balance simulations.

Unfortunately, this improvement in hydrological modelling is hampered by the lack of requisite input hydrometeorological data which has generally been noted to be poor in the tropics (Balek, 1972, 1983; Ayibotele, 1993; McGregor and Nieuwolt 1998), and in West Africa, (Opoku Ankomah, 1986, WRC, 2000; Label et al., 2000; Nii Consult, 2001 and Giertz and Diekkruger 2003). Balek (1972) observed the following about inadequacy of data in the African tropical region that, “Hydrological data available in African tropical regions consist of long precipitation records, rather short water level and discharge records and very short data for small, separated experimental catchments” yet the situation still persists as noted by subsequent authors.

Ghana, which lies within the tropical West Africa region, faces many of the typical pressures facing the tropical region. It has a highly variable rainfall and hydrological regime leading to a high pressure on the available water resources of the country (WARM, 1998). This pressure is expected to increase steadily due to the rapidly expanding population (Ghana Statistical Service, 1991 & 2000), such that water shortages are becoming evident in this humid and tropical country (WRC 2000).

1.1 The Problem

The Densu basin (Figure 1.4) is a coastal river catchment in southern Ghana of approximately 2564 km² which lies in a region with a mean daily temperature ranging between 24°C and 31°C. Even though the Densu river is a relatively small river compared to others in the country, with a mean annual flow volume of about 499x10⁶ m³, from mean annual rainfall of 1190mm and mean annual potential evapotranspiration of 1095-1460mm per annum (WARM, 1998), the

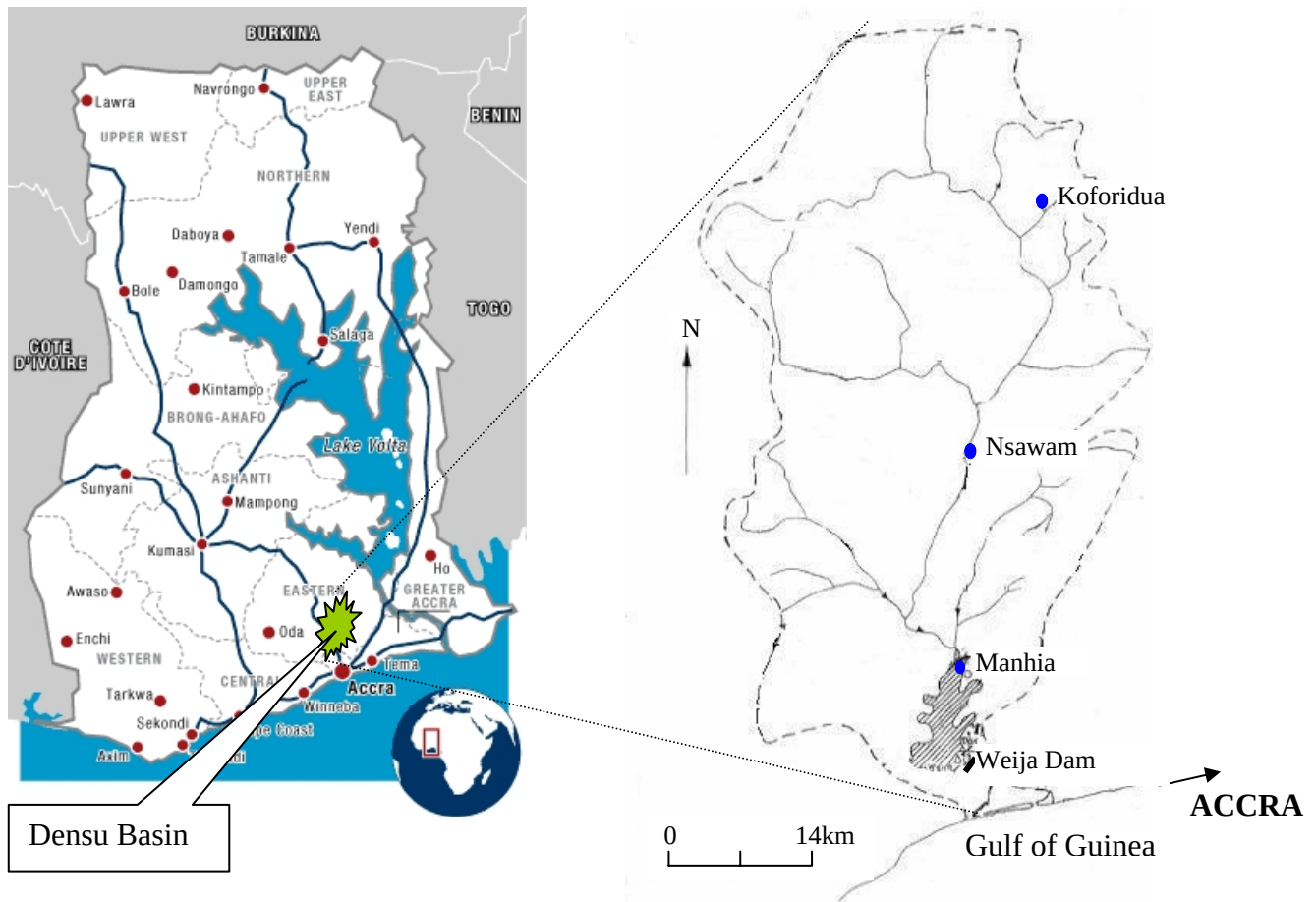


Figure 1.4 Map of Ghana (Adapted from: <http://www.volu.org/map.html>) showing the position of Densu Basin and its hydrological map.

Densu is considered to be one of the most important rivers in the country with respect to its social and economic importance as a water supply source to communities along its route (WARM, 1998, WRC, 2000). In addition, it is also the main source of the drinking water supply for the western part of the capital city of Accra because it flows into the Weija Reservoir, which is a major source of potable water for south western Accra. The cost of treating water from the Densu River is about ten times that from the Volta River at Kpong (which is well managed by the Volta River Authority because of the Akosombo hydroelectric project scheme on the River Volta), but because it is supplied by gravity it makes it more economical than the water from the Volta which must be pumped to Accra.

However, like many other watersheds in Ghana and West Africa, it faces conflicting water uses, i.e. providing public water supply at Koforidua and Weija (Figure 1.4) with water for agricultural, tourism and recreational uses, whilst maintaining the quality of water for water supply. However, various human activities within the Densu Basin have resulted in serious ecological problems which risk the environmental degradation of the river basin (WARM, 1998 and WRC, 2000).

- Erosion due to farming within the catchment with attendant siltation causes occasional serious flooding;
- Extensive deforestation particularly along the river banks as a result of lumbering, fuel wood extraction and clearing of land for farming;
- High levels of air pollution due to poor domestic and industrial waste disposal;
- Nutrient contamination of surface waters from inefficient use of fertilizers;
- Growth of aquatic weeds in the river and downstream in the impoundment at Weija reservoir, due to unapproved use of chemicals for fishing, and the human introduction of exotic alien water plant species e.g. Water Hyacinth; and
- General loss of biological diversity has been observed in certain parts of the basin.

The human-induced problems described above are exacerbated by:

1. Lack of institutional capacity for water management at both Government and water providers' level and
2. Water shortages due to low flows and drying-up of streams upstream in the basin with attendant reduction in water levels of reservoirs downstream are observed annually.

Water shortages are experienced frequently in the whole basin but especially in the uppermost section in the dry season when 1) demand for drinking water cannot be met from the intake weir at Koforidua due to low water levels and 2)

poor water delivery structures which have, over the years, been producing below their installed capacities due to worn out mechanical plants (WRC, 2000).

The resultant effects of these environmental problems within the basin culminated in a public outcry over the quality and quantity of water supplied from the Weija Reservoir within the basin, resulting in a ban on farming along the Densu river by the government (e.g. Daily Graphic, Friday 14/09/2001) and a call to use water resources judiciously (Daily Graphic, Thursday 18/09/2001) as shown in Figure 1.5.

As a result of the growing public concern, the government of Ghana signed a Memorandum of Understanding (MOU) in 1999 with the United Nations Centre for Human Settlements-Habitat (UNCHS) to collaborate in a project on “Managing Water for African Cities”. The project was meant to find solutions to the increasing water demand in the fast growing African cities of which Accra, and subsequently the Densu basin, featured. The resulting report by Nii Consult (2001), concluded:

“the Densu River Basin is being degraded by intensified agriculture involving the use of agrochemicals, timber logging, fuel-wood extraction, urban wastes (excreta, garbage, and liquid). This is threatening the livelihood and also the natural resources on which the majority (farmers) depend. In addition the survival of the terrestrial bio-diversity is at risk”.

Nii Consult (2001) also recommended the formation of a Densu River Basin Management Board (DRBMB) with the objective to facilitate the co-ordination and integration of the plans and programmes of the different institutions at the district level. The DRBMB was inaugurated in Accra on March 22 2004 comprising of 17 Board members who come from (Ghanaweb, 2004) five out of the eight districts within the basin; government ministries (i.e. Environmental Protection Agency (EPA); Ministry of Food and Agriculture (MOFA); Ministry of Health (MOH); Ghana Water Company Limited (GWCL)); religious bodies, non-governmental organizations, the National Council on Women and Development (NCWD), traditional rulers, the Water Research Institute (WRI) of the Council for

THE DEPUTY MINISTER of Agriculture and Livestock, **Mr. Theresa Amuge**, Tugue, has been active along the southern bank of the Denesha River.

The directive is to graze the river, which serves as the source of drinking water for residents in the Greater Acra Region, from being polluted.

The minister gave the directive, when she paid a visit to the communities along the banks of the river on Wednesday.

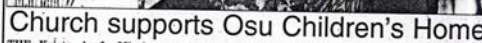
She, however, appealed to the farmers to plant tree crops such as mango and papaya, and provide a vegetative cover to the river and its banks as a source of livelihood.

The Tugue, who was accompanied by some local officials from the Ministry of Agriculture, the Water Company Limited and the Greater Acra Region, visited Ganyu and Mungu villages on the banks of the river at the village of Mungu in the Ga District of the Greater Acra Region.

Mr. Amuge stated that the poultry farm could pollute the water and the drinking water. The treatment of the water, however, is not a hazard to consumers.

Mr. Tugue said, the water, through the

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(The Anglo-African Mission
 (Christ Reformed Church)
 was yesterday led by its
 leader and founder Apostle
 Kwadwo Sarfo to again pre-
 sent an amount of one million
 to the inmates of the Orphan
 Children's Home in Accra.

Farming along Inusu banned

Chana Water Company, is to embark on an expansion programme at the Weija Water Works in supply water to newly developed areas in the metropolis.

The government's initiative towards the provision of safe drinking water to rural communities is hampered by the activities of illegal settlements and pollution of the river.

She also expressed concerns about the activities of cattle farmers in the area and advised owners of the farms to confine their herds to the kraal.

The deputy minister also visited Kwame Ninsin, a resident of Dombiani, and Amankwa, where she met with the residents and elders of those communities.

NOTICE TO TENANTS OF NEW SHOPS-MAKOLA NO.2 MARKET, ABBOGBLOSHIE

The undersigned tenants of the New Makola No. 2 Market, Abboleshie, who were allocated the new shops are to contact the Operations Officer of the Metropolitan Assembly.

'Don't give false fire alarms'

The Northern Regional Fire Officer, Mr Charles Jitah, has appealed to residents of Tamale to desist from giving false alarms about fire outbreaks to the regional and municipal fire officers.

Name	Facility No.
1. Rebecca Pratt	SH 195 Axx
2. Emella Abrokwah	SH 206 Axx
3. Auntie Comfort	Sh 208 Axx

Mr Yitah said	stintlines, such callers cast insinuations	1. Ife Isele Aikandra	SH 220 Acc
and insult	personal people who receive their calls.	5. Adesoleke Ayo Mary	SH 212 Ayo
On the	protection of the public.	6. Stephen K. Agbewali	SH 213 Ayo
subsequent	quick response is draining our limited	7. Rose Bemokwa	SH 224 Ayo
resources	and causing tear and wear to our equipment,	8. Rosaline Crabbe	SH 225 Ayo
and we	don't want to ignore any call, since some of them	9. Peace Berko	SH 228 Ayo
may	be real and, therefore, very serious.	10. Bunsu Ama Serwah	SH 230 Ayo
Mr Yitah	described the new fire tender as a dual purpose	11. Comfort Owusu	SH 233 Ayo
one	that can combat all types of fire. It has the		
capacity	to store about 4,500 litres of water and 225 litres		
of	foam.		

He said the region would soon receive about three core of the vehicles to add to the existing ones to enable them to combat the menace of fire outbreaks.

The minister, on his part, called on residents of the municipality to co-operate with personnel of the service since their best

By order of Management

 **MAKOLA
MARKET
COMPANY
LIMITED**

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The underlisted tenants of the New Makola No. 2 Market, Agbogloboshie who were allocated the new shops are to contact the Operations Officer at the Makola Market Company's Agbogloboshie Office within seven days of this date of publication for an important discussion in connection with processing fees paid at the time of allocation.

Failure of any tenant to comply will compel Management to employ all available means to retrieve all outstanding processing fee balances plus interest at the prevailing treasury bill rate or repossess the facility.

Name	Facility No.
1. Rebecca Pratt	SH 195 Axx
2. Emelia Abrokwhah	SH 206 Axx
3. Auntie Comfort	SH 208 Axx
4. Ire Jesse Alexandra	SH 220 Axx
5. Adolescence Adu Mary	SH 212 Axx
6. Stephen K. Agbewali	SH 213 Axx
7. Rose Bemokwa	SH 224 Axx
8. Rosaline Crabbe	SH 225 Axx
9. Peace Berko	SH 228 Axx
10. Bonsu Ama Serwah	SH 230 Axx
11. Comfort Owusu	SH 233 Axx

By order of Management

 **MAKOLA
MARKET
COMPANY
LIMITED**

HIC, Tuesday, September 18, 2001.

venue, Adabraka
Primary School near
P. O. Box CT 5032,
Accra.
59621 Fax: 7011951
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By Charles B.

TWO HUNDRED ex-convicts at Ashanti Gold Corp. Limited today went on strike in protest to protect their end-of-agony.

Wearing placard-bearing signs since they have nine months of the end of the month of their release is due them.

They later petitioned to the Castle, O.

the opening session of a three-day workshop on the theme, "Implementing Integrated Water Resources Management in West Africa" in Accra yesterday.

The workshop, which has brought together 60 participants from the 16 West African countries, also discusses, among other things, Africa-West Africa vision for the year 2025.

Participants would also formulate policies that would help address

ment for dragging their feet on their grievances against the government. They have been working for more than 6 years on the average as casual workers, but their contract is against the labor laws.

Some of the inscriptions on the placards read "10 per cent tolerance for corruption in Ghana Mine" and "We are not above the law." "We want our end-of-service package now or else," among others.

The workers, who set off from Obuasi at 1:30 a.m., were met by the Ghana Union Congress headquarters.

trans-boundary water pollution in the sub-region.

Mr Bartels said to achieve such a goal, the general public, particularly communities along water basins, would need to be sensitised about the social, economic and environmental implications of water pollution.

He said the Government's Poverty Reduction Strategy places a high premium on increasing access to potable water and ensuring good sanitation in the sub-region.

He said that high incidence of waterborne diseases such as guinea worm and cholera in the sub-region under the current management is the impetus for the implementation of an integrated water resource management that would conserve water resources to prevent over-use, over-exploitation and pollution.

The Regional

Kwasi Adu-Amankwah.

Amidst singing and dancing, they took off under heavy police guard through the National Stadium to the Accra Sports Stadium where their leaders were asked to carry the workers' statement to the government representatives at the Castle, Oss.

The workers were received at the entrance of the gate to the Castle by the Chief of Staff and the Minister of Presidential Affairs, Mr. Jake Oboeche-Lemley and the National Security Adviser, General Joshua Hamidu.

representative of Food and Agriculture Organization (FAO). Mr. Bamidele F. Dada, said sustainable management of water resources in the sub-region should take the form of systematic integrated management. He would recognise the interdependence of all sectors of governance.

He said to pursue the strategic priorities of ensuring global food security, irrigation development should be strengthened to address

contract was in force in what the President described as "extraordinary circumstances" and has refused to leave entitlement to the pension. The President has agreed to consider the various aspects of the case.

Mr. Ashanti Amankwaa, Chairman of the Ghanaian Association of Management and Professional Workers, said that Mrs. Cecilia has yielded to the President's decision and is now all aware of the situation. He said that the Ghanaian Association of Management and Professional Workers is aware of the situation and is now all aware of the situation.

President to use his office to ensure that all administrative bottlenecks and foot-dragging tactics are removed to speed up the process of granting the benefits due them.

Mr. Obetsebi-Lampson said that he would present the petition on their behalf to the President and ensure that it will be given urgent attention.

Meanwhile, a letter from the Chief Labour Officer, Mr. E.A. Ntiom, noted that "the contents of their petition have been read carefully and every issue noted accordingly."

needs of rural communities.

Mr Dada said to meet the food demand of future generations, such focus should be placed on food production through the introduction of inputs such as improved varieties of seeds and fertiliser, and the better use of harvest and rainwater.

In his welcoming address, the Chairman of the Water Resources Commission, Professor Clement Dorn-Azobu attributed 50 per cent of losses in domestic water supply to illegal connections, leakages and other connected losses.

He said the cost of exploiting new water supplies, treatment and distribution of potable water has risen sharply, making it very difficult to supply water to all sectors in the country.

Tamale proje

From Zakaria Alihasan, Tamale

IT has been established that about 96 per cent of work has been completed on the e1 billion Tamale

done for
ments h
been effe

The r
ther stat
to find a
essidents

By Charles Benoni Okine ment for dragging their Kwasi Adu-Amankwah, tors said their contract was President to use his off-

[illegible]

Emmanuel Obeng Bekoe Phd Thesis Chapter 1 Background and Problem

Scientific and Industrial research (CSIR); National Development Planning Committee (NDPC) and Lands Commission. They are mandated to evolve plans for the conservation, development and utilization of water resources in the basin. The activities of the DRBMB are to create awareness and mobilize political will; ban farming in buffer zones; introduce environmental and farmer friendly systems of agricultural production (crops and livestock); desilt drains; improve hydrological data collection; and to control clay and sand extraction and the quarrying of stone. Other activities include to enforce mandatory preparation of Environmental Impact Assessments (EIAs) for development projects; monitor and assess the state of natural resources, and to implement the community small towns and urban towns' water supply system rehabilitation in the districts. Finally, the DRBMB is to tackle other issues not mentioned but necessary at the local level within the basin to improve effective river basin management that will help to reverse the degradation of the basin and restore it to good health, in order to enable the basin to provide the necessary services required of it.

The Densu river basin, following from the problems enumerated earlier shows that there is a need for a basin-wide planning approach because of its scale (2564km²) and this (basin wide planning approach) is also seen from some of the activities granted to the DRBMB which includes involving stakeholder participation, awareness raising, public meetings, capacity building and training is in order. As part of the DRBMB activity to “monitor and assess the state of natural resources”, the Government of Ghana and the Council for Scientific and Industrial Research (CSIR) commissioned this PhD study to provide 1) an analysis of environmental and hydrological interactions within the basin to facilitate knowledge and understanding of the hydrological regime through hydrological modelling 2) to assess the impact of land use on the future water resources of the basin and 3) to provide recommendations based on the outcome of (1) above that would facilitate improved water resources management of the basin.

1.2 Aims and Objective of Study

The aim of the thesis is to assess the suitability of using a hydrological model to predict the impact of future catchment changes on surface water resources as a basis for the sustainable watershed management strategy of tropical West African catchments: an example for Nsawam and Manhia catchments in the data-poor Densu Basin in Ghana.

To accomplish this aim, the research was undertaken with the following objectives:

1. Selection of an appropriate hydrological model for use within a data poor basin in Tropical West Africa to predict the impact of future catchment changes on water resources.
2. Assess model sensitivity to key hydrometric and hydrologic parameters to inform model understanding and to provide guidance for prioritizing future data collection to support modelling activities.
3. Simulate the hydrology of the basin, splitting the available hydrometeorological data for calibration and validation purposes.
4. Evaluate the model performance by taking land use changes in the catchment into consideration. This would be done to assess model performance after nearly twenty years of non-flow data for future forecasting.
5. Simulate the impacts of scenarios of future change i.e. urbanization, landuse/social change, abstraction, demand/supply etc. on the water resources of the basin. This would be done to ascertain the influence of these factors on the basin which will enhance the understanding of the future behaviour of the basin and assist with better formulation of policies to mitigate any potential water resources management problems.
6. Give recommendations based on the study to the Densu River Basin Management Board on how the results could be integrated into sustainable catchment management strategies of the basin and other West African basins for future guidance.

The remaining chapters of the thesis have the following structure. Chapter 2 discusses tropical hydrology and the study area; Chapter 3 describes a review of hydrological models and the model selection. Chapter 4 discusses data availability, analysis, data constraints and model set up; Chapter 5 describes the hydrological modelling of the Densu basin in both lumped and semi-distributive mode and presents results which include sensitivity analysis, calibration and validation. Chapter 6 discusses the results and their wider implications and Chapter 7 gives the conclusions and recommendations.

2. Hydrology of Tropical West Africa and the Study Area

2.1 Introduction

The Densu Basin is a very important catchment in the tropical country of Ghana and faces many of the challenges that are common to Ghana (Section 1.1) and tropical West Africa in general (e.g. population pressures and land use change). The findings from this study within the Densu Basin are therefore likely to have wider applicability within Ghana and the wider region of tropical West Africa. In this chapter a review of tropical regions, West Africa, Ghana and the study area is undertaken to highlight some of the common climatic conditions and hydrology that prevails in this region.

The socio-economic characteristic for the West African (Figure 2.1) sub region was summarized by the West African Conference on Integrated Water Resources Management, Ouagadougou, March 1998 in Table (2.1) (Global Water Partnership-West African Technical Advisory Committee or GWP-WATAC, 2000). The following make up the sub-region:

There are sixteen (16) nations within the sub-region (Figure.2.1) of which:-

- Twelve coastal countries: Benin, Cote d'Ivoire, Gambia, Ghana, Guinea, Guinea Bissau, Liberia, Mauritania, Nigeria, Senegal, Sierra Leone, Togo;
- Three land-locked countries: Burkina Faso, Mali, Niger;
- One island state: Cape Verd.

The surface areas of the countries vary by a factor 1 to 300 between the smallest territory (Cape Verd) and the largest (Mali). In spite of the differences shown in Table 2.1, West African countries have many common features such as geology, culture, as well as economies and social conditions which place all of the countries in the group of developing countries. Some of the countries are well endowed with water resources, whilst others face serious scarcity problems (GWP-WATAC, 2000). The total population of the sub-region is over 200

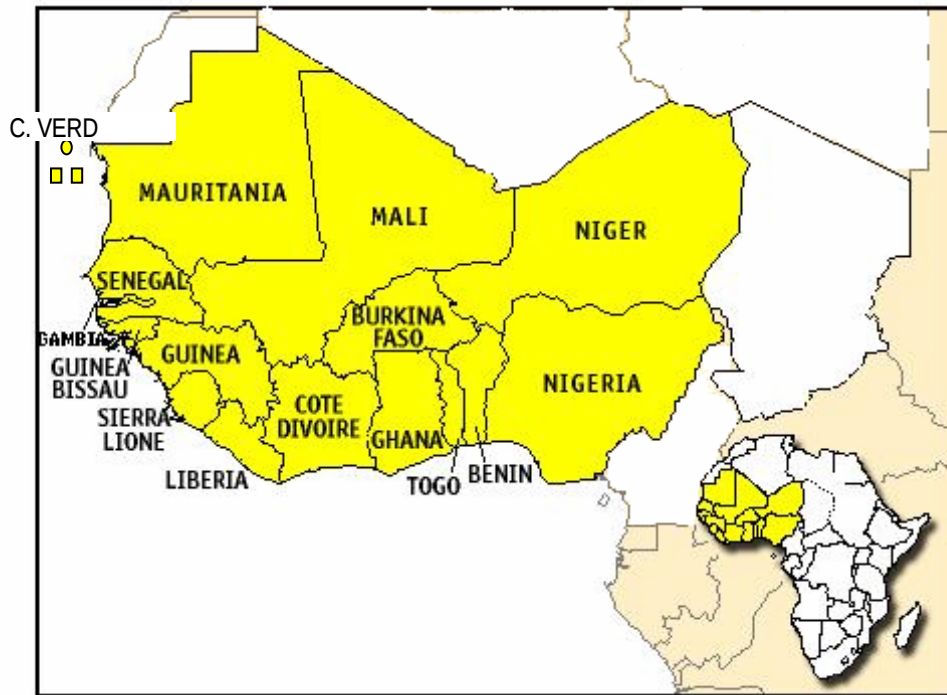


Figure 2.1 Map of West Africa (source: <http://www.snowcrest.net/ouranou/r4.gif>)

Table 2.1 Indicators of Socio-economic Development

Country	Surface area km ²	Pop. Million 1995	Annual Pop. Growth rate % 1995-2000	Urban Pop. % 1999	Pop. Density Inhab/km ²	GNP/ Capita 1998 \$	Infant Mortality No Deaths/1000 births 1995-2000	Life Expectancy at birth years 1995	Adult illiteracy rate %
BENIN	113	5.40	3.23	41	48	380	77	50	
BURKINA FASO	274	10.14	3.02	10.5	38	240	116	51.2	
COTE D'IVOIRE	322	13.80	3.83	43.6	45	700	79	56.4	
CAPE VERD	4.0	0.44	3.21	32	109	1060	32	68	29
GAMBIA	11.3	1.10	2.58	26.3	87	340	122	47	67
GHANA	239	17.4	3.10	35.1	74	390	73	58	
GUINEA	246	6.56	3.12	29.3	27	540	124	46.5	
GUINEA-	36.1	1.08	2.20	22.2	30	160	129	45.5	66
LIBERIA	111.4	2.97	3.30	51.5	27		113	57.5	52
MALI	1240	10.6	3.22	20.9	9	250	149	48.0	
MAURITANIA	1026	2.30	2.92	53.8	2	410	107	50.0	
NIGER	1267	9.20	3.33	23.1	7	190	114	48.5	
NIGERIA	924	101.0	3.17	39.3	109.3	300	87	54.5	
SENEGAL	197	8.30	2.86	41.1	43	530	72	51.3	
SIERRA LEONE	72	4.40	2.75	36.2	66	140	132	45.0	
TOGO	57	4.30	3.22	29.5	73	330	77	57.0	
TOTAL		227.4	3.18	36.1			93	52.9	

Source: Synthesis Report-West African Conference on Integrated Water Resources Management-1998. In: GWP-WATAC (2000).

million inhabitants with an average density of 32.4 inhabitants/km² with the highest population density being in Nigeria (109 inhabitants/km²) and the lowest in Mauritania (2.2 inhabitants/km²). The majority of the population are employed in agricultural activities while the urban population comprises between 10-50% of the total populations (GWP-WATAC, 2000)

2.2 Tropical Regions

The tropical regions of the world represent a huge but relatively little studied part of the globe with regard to the study of hydrology (Bonell et al., 1993; van de Giesen et al., 2000 and Giertz & Diekkruiger, 2003). This region is noted by McGregor and Nieuwolt (1998) to be perhaps an ill defined region which is climatically diverse and therefore needs to be subdivided into a number of sub-regions, of which West Africa is part of the one on which the thesis will focus. The term tropics is defined by McGregor and Nieuwolt (1998) as “a word derived from the Tropics of Cancer and Capricorn, the parallels 23.5°, which indicate the outer limits of the area where the sun can be in a zenith position”. McGregor and Nieuwolt (1998) observed that the tropical areas are mainly found between these two lines yet realized that these boundaries are too rigid because latitude is not the only factor in climate and major climates frequently deviate from parallels. They noted that a better approach to determining a climate boundary is to define a major common feature of an area, which for the tropics is absence of a cold season referring to the old adage “where winter never comes” (McGregor and Nieuwolt, 1998). A further complementary definition is given by Gourou (1935) who noted “tropics” as used by geographers as “regions where sufficient rainfall is received to carry out most forms of crop agriculture without irrigation”. The delineation of the tropics by McGregor and Nieuwolt (1998) into humid tropics and dry tropics is shown in Figure 2.2.

According to McGregor and Nieuwolt (1998) the temperature difference between the seasons in the tropics are generally small because of the

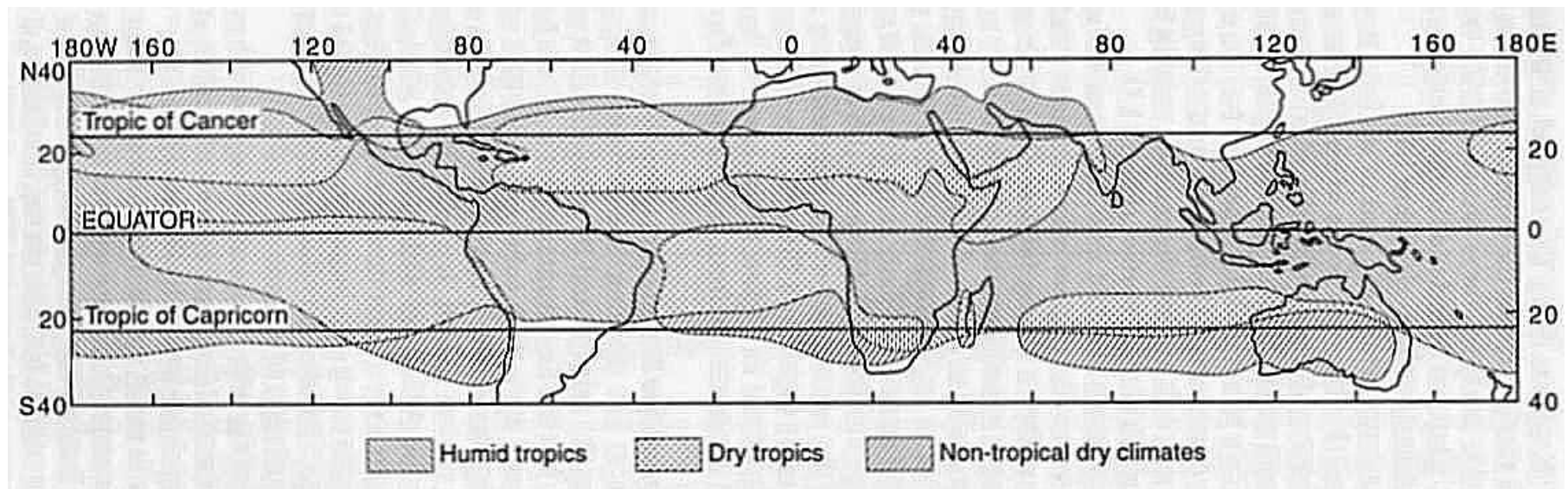


Figure 2.2 Map of humid and dry tropics and adjacent areas (source: McGregor and Nieuwolt, 1998)

absence of a cold season. The mean annual temperature range i.e. the difference between the mean of the coolest and the hottest months of the year is typically between 2°C and 4°C. Annual precipitation totals are substantial, being in excess of 1000 mm, although such regions have wet and dry seasons (Keller, 1983, Manton & Bonell. 1993). The humid tropics can be further separated (see Figure 2.3) into one which is affected by tropical cyclones and one that is not (WMO, 1983). The Non-

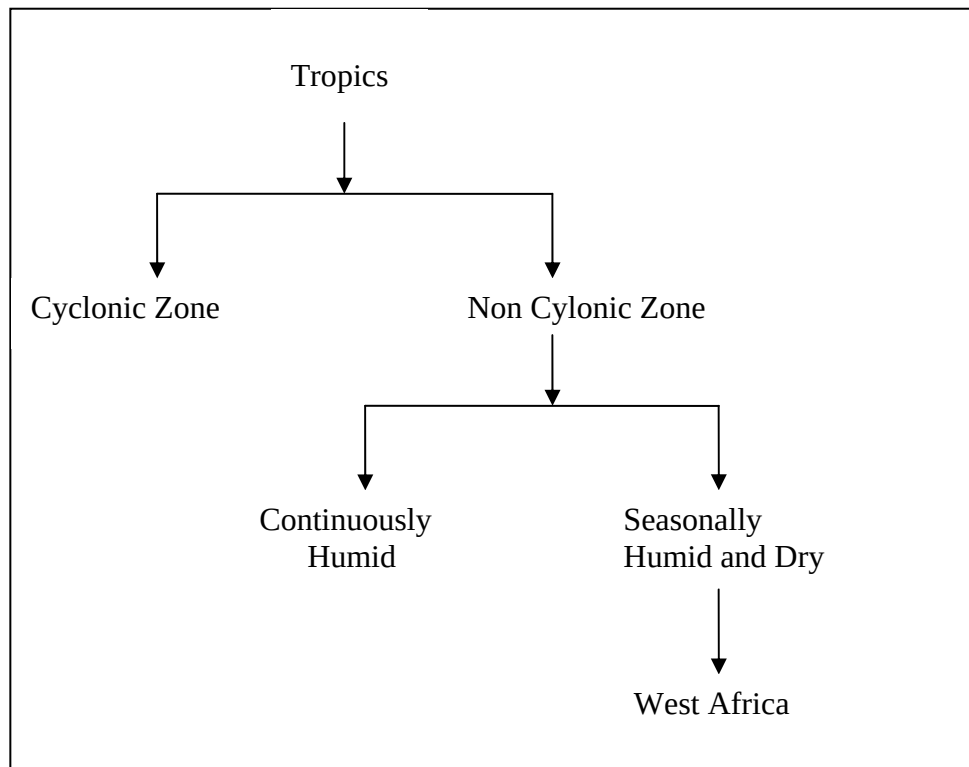


Figure 2.3 Illustration of the Tropics (adapted from Trewartha In: WMO (1983), McGregor and Nieuwolt (1998) & Keller (1983))

Tropical-cyclone sub-region may again be subdivided into two sub-climate zones: one that is continuously humid and one that is seasonally humid and dry in terms of rainfall (Keller, 1983; Manton and Bonell, 1993). The continuously humid zone is mainly found within a relatively narrow band at 3°N-5°S latitude. Most of West Africa (Figure 2.1) lies in the latter i.e. seasonally humid and dry in terms of rainfall. The emphasis of this research is on West Africa and therefore further discussion of the humid tropics will be limited to the seasonally humid and dry region.

2.3 Hydrology

2.3.1 Rainfall

Hayward and Oguntinyinbo (1987) reported that, of all the meteorological variables in the tropics, rainfall is the one most frequently discussed because, in conditions of reasonably uniform and high temperature, it is rainfall that, by its presence or absence, scarcity or abundance, and reliability or variability, determines the seasons, the production or failure of crops and pasture, and even life and death. The rainfall regime within the West African tropics is observed by Hayward and Oguntinyinbo (1987), Ayibotele (1993) and GWP-WATAC (2000) to be under the dependence of the north-south migration of the Inter Tropical Convergence Zone (ITCZ) with the latter further observing that, north of the ITCZ, high pressure originating from the Sahara prevents any rainfall, except in the case of rare descents of cold air from the north during the boreal winter. They noted that even when the rainy season is well established, sudden retreats southward of the ITCZ are not uncommon and that the annual rainfall depends heavily on the duration of the rainy season.

Convection or thunderstorms are the main rain-generating mechanism in the seasonally humid and dry tropics (WMO, 1983; Manton and Bonell, 1993 McGregor & Nieuwolt, 1998) and West Africa (Hayward and Oguntinyinbo, 1987), with most of the precipitation coming in the summer.

Annual rainfall, as noted by Keller (1983) and Manton & Bonell (1993), of the tropics is greater than 1000mm but ranges up to 4000mm. Annual precipitation amounts of five tropical West African countries along the Gulf of Guinea (Côte d'Ivoire, Ghana, Benin, Togo and Nigeria) were noted by Paturel et al. (1997) to range between 1200mm and 1800mm. However a wider picture of the rainfall patterns in West Africa was given by Hayward and Oguntinyinbo (1987) of the mean annual totals and rainy days per annum (Figures 2.4 and 2.5 respectively).

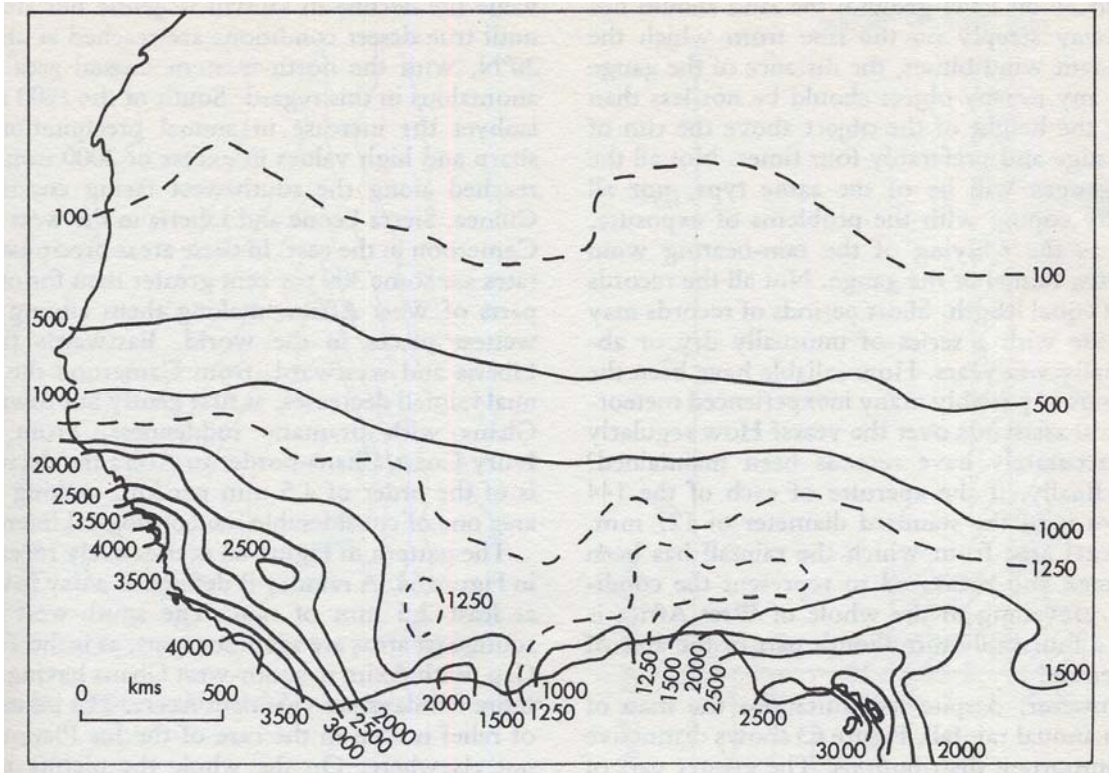


Figure 2.4 Mean annual rainfalls (mm) for West Africa (Source: Hayward and Oguntinyinbo, 1987)

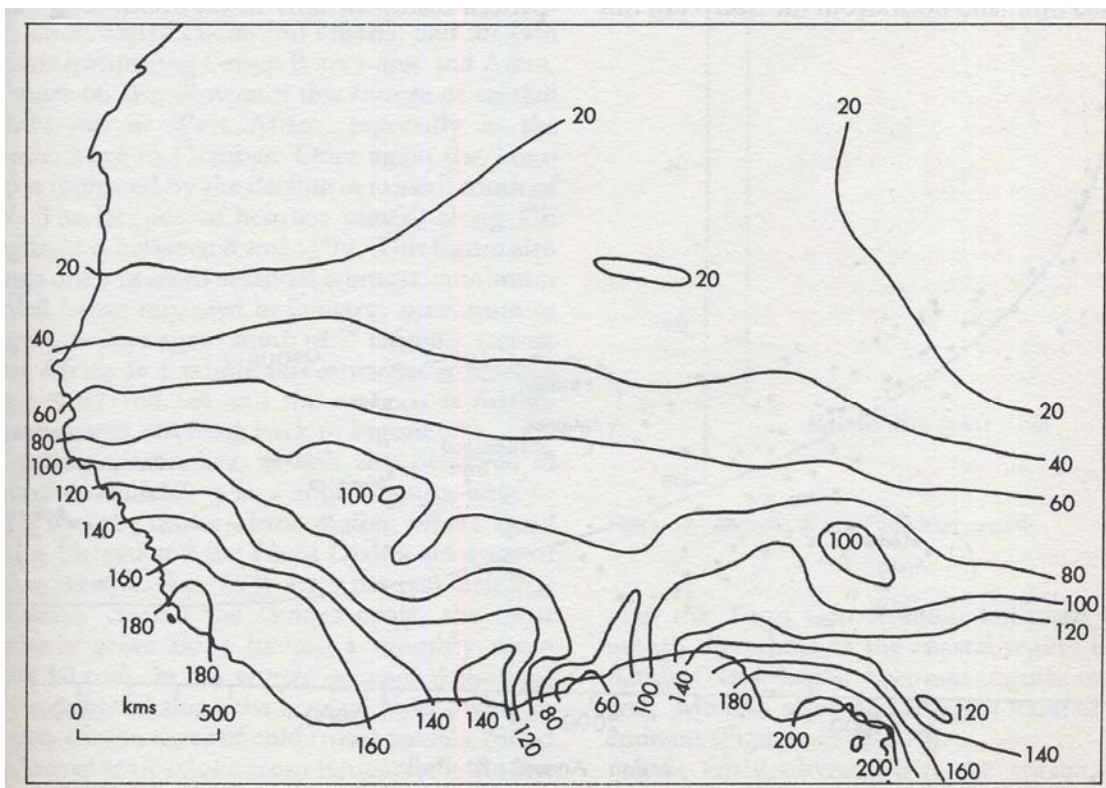


Figure.2.5..Mean number of raindays per annum for West Africa (Source: Hayward and Oguntinyinbo, 1987)

Jackson (1978) noted that 10-15% of rain days account for about 50% of rainfall in the tropics.

Hayward and Oguntinyinbo (1987) alluded to this variability in rainfall and observed that much rainfall in West Africa is derived from storms or showers lasting three to six hours, when possibly 100 drops in excess of 2 mm diameter may fall per cm^2 , assuming the intensity of 25 mm hr^{-1} , which will produce runoff and soil loss in open farmland. Similarly, Manley and Askew (1993) and Masiyandima et al. (2003) corroborated the intense nature of the rainstorms, with the former realizing that the rainfall intensities can be high in the tropics inducing erosion and flooding whilst the latter reported that rainfall events can last less than 30 minutes in the humid and dry zone of West Africa. This variability in rainfall intensities according to Jackson (1978) can exist between nearby locations and this he illustrated in a tropical catchment in Tanzania (East Africa) where for time periods of a month or longer, rainfall totals differed by between 16%-33% at nearby locations (from < 1 km–20 km apart), even when the rainfall stations are in an area of uniform relief and their long term averages are similar. Although spatial rainfall variability is universal and not confined to tropical areas, it is less important in temperate regions where rain is often general over wide areas (Jackson, 1978). Jackson (1978) concluded that this degree of 'localness' of spatial rainfall variability patterns is important in the tropics because of the small scale peasant rain-fed agriculture practised in such regions, and has considerable implications for rainfall measurement and analysis. McGregor and Nieuwolt (1998) also observed that other rainfall characteristics, such as its seasonal and diurnal distribution, intensity, duration and frequency of rain-days also demonstrate spatial and temporal variations, where intensities can be high but with short durations.

2.3.2 Evaporation and Evapotranspiration

The combination of two separate processes whereby water is lost from the soil surface by evaporation and from the crop by transpiration is referred to as evapotranspiration (Allen et al., 1998). Balek (1983) noted that one of the main

features of tropical regions is the very high absorption of heat from the sun and its low emanation and that the tropical regions can be seen as a substantial reservoir of heat energy, whilst McGregor and Nieuwolt (1998) adds that the energy for transpiration which is mainly provided by solar radiation is available in large quantities in the tropics. Ayibotele (1993) calculated that the radiation balance (defined by McGregor and Nieuwolt (1998) as “the total radiation inputs and outputs from the earth-atmosphere system”) of the West Africa region to be about 70 kcal/cm²/year (Figure 2.6). The potential evapotranspiration (PET), defined by Irmak and Haman (2003) as “the amount of water transpired in a given time by a short green crop, completely shading the

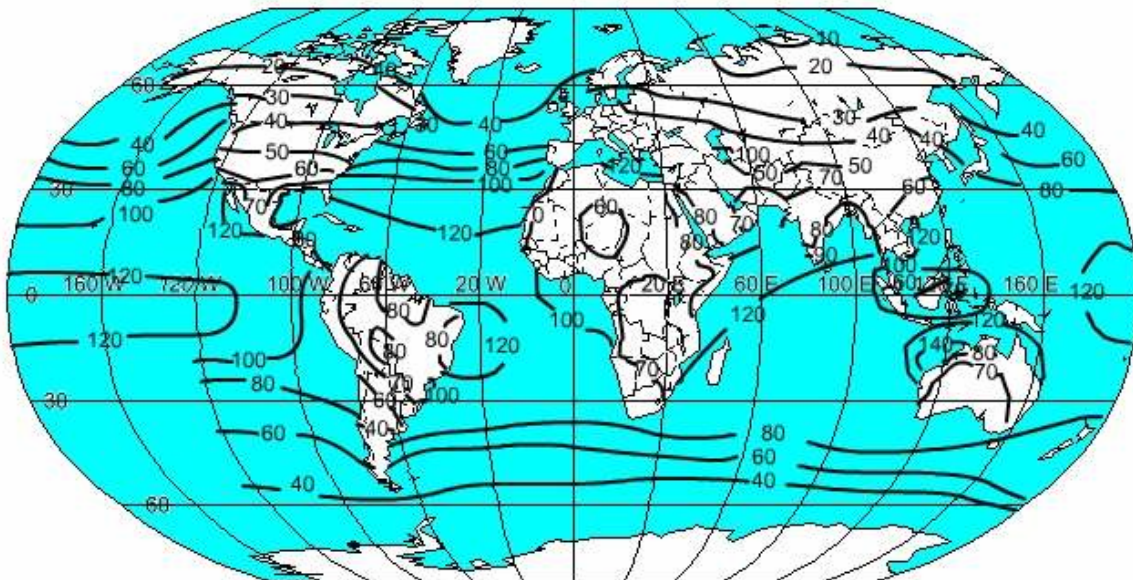


Figure 2.6 Global annual net radiations (i.e. radiation balance) in kcal/cm²/year (Source: After Budyko, (1958).

ground, of uniform height and with adequate water status in the soil profile” or by Piderwerny (2005) as “a measure of the ability of the atmosphere to remove water from the surface through the process of evaporation and transpiration assuming no control of water supply” in the West African region amounts to about 1,300 mm/a in the humid regions and increases to about 2,000 mm/a around latitude 20°N (GWP-WATAC, 2000). Actual evapotranspiration (AET), defined by Piderwerny (2005) as “the quantity of water that is actually removed

from a surface due to the process of evaporation and transpiration”, values for the West African region are hard to come by in publications and this was noted by Hayward and Oguntinyinbo (1987) who attributed this scarcity to the unreliability of the evaporation data because of the several methods used to compute them. Hayward and Oguntinyinbo (1987) computed the mean evaporation (calculated from Piche evaporimeters) for March (the month with highest evaporation levels) and August (the month with lowest evaporation) which are shown in Figures 2.7 and 2.8 and annual potential evaporation for the region of West Africa in Figure 2.9. Similarly, Ojo (1969) (cited by Hayward and Oguntinyinbo, 1987) produced, using the Penman method, the Potential evapotranspiration maps shown in Figures 2.10 and 2.11 for January and July, respectively, for the West African region.

WMO (1994) concluded that the many methods used in temperate zones to compute evapotranspiration are also applicable to the humid tropical regions. With the standard methods available for evaporation and evapotranspiration computation, Allen et al. (1998) deduced that the seasonally humid and dry regions of the tropics have, on average, 25-50% and 0-25% more evapotranspiration than the humid and sub humid regions of the temperate regions, respectively, because the radiation influence is higher. However in an earlier study, Ringeoet et al. (1961) noted that the pan evaporation method employed in the tropics may underestimate the evapotranspiration of a forested catchment by as much as 20 to 30 per cent. In West Africa, Hayward and Oguntinyinbo (1987) observed anomalies in readings of evaporimeters and explained that because tank evaporimeters e.g. the US class A-pans and Piche evaporimeters can lose water by dirt and objects in the tanks and could also lose water by wind splash as a result of soil-pan temperature gradients or by consumption by birds and animals. This observation is important because most evaporation measurement in Ghana (MSD, 2004), and from developing countries within Africa in general (Schulze, 1995), is from evaporation pans.

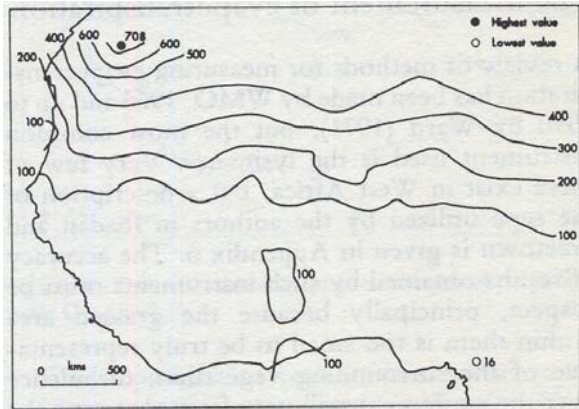


Figure 2.7 Mean Evaporation in March [mm] (Source: Hayward and Oguntinyinbo, 1987)

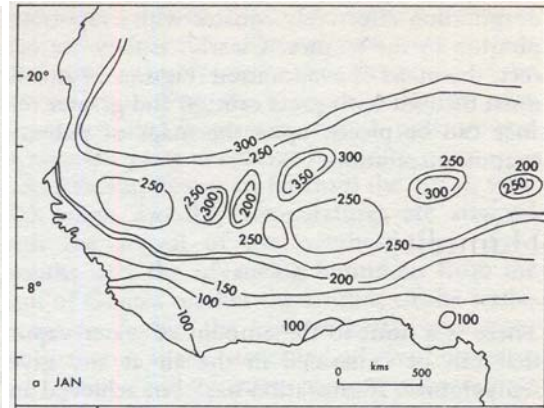


Figure 2.10 Potential Evapotranspiration in January [mm] (Source: Hayward and Oguntinyinbo, 1987)

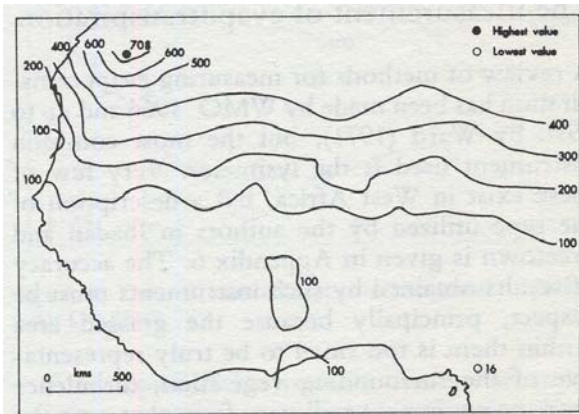


Figure 2.8 Mean evaporation in August [mm] (Source: Hayward and Oguntinyinbo, 1987)

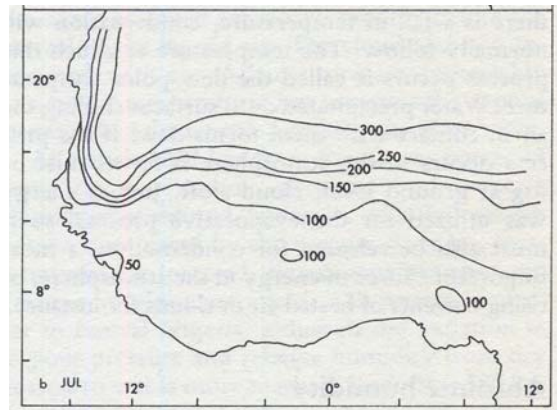


Figure 2.11 Potential Evapotranspiration in July [mm] (Source: Hayward and Oguntinyinbo, 1987)

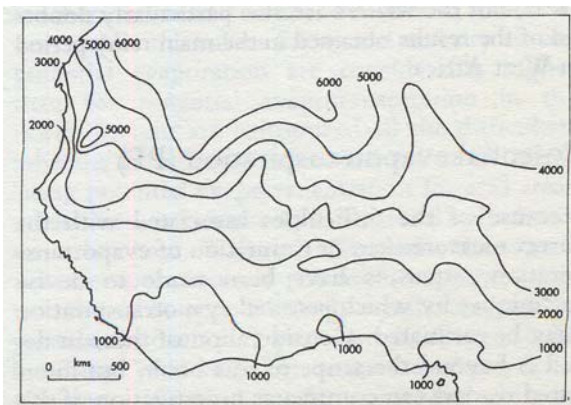


Fig 2.9 Mean annual potential Evapotranspiration [mm] (Source Hayward and Oguntinyinbo, 1987)

2.3.3 Runoff

Runoff in this context is defined by National Oceanic and Atmospheric Administration (NOAA) (2005) as "the part of precipitation that flows toward the streams on the surface of the ground or within the ground. Runoff is composed of baseflow and surface runoff".

Hortonian or infiltration excess overland flow seems to be the dominant process through which rainfall is redistributed over the landscape of the West African humid and dry region (Van Giesen et al., 2000). Van Giesen et al. (2000) noted that during the often spectacular rainstorms in the region of West Africa, rainfall intensity exceeds infiltration capacity and surface runoff is seen to occur everywhere.

Hayward and Oguntinyinbo (1987) reported unsurprisingly that annual runoff is greatest in areas with the highest rainfall and the lowest evapotranspiration, so that both the volume of the runoff and the percentage of the rainfall that becomes runoff tend to increase from the north to the south (Ayibotele, 1993). They noted that West African rivers experience marked seasonal alternation of high and low flows, although there is a considerable difference between the regimes in the north of the region where runoff is concentrated into a few floods in August and September, and those of the south where the runoff is spread more evenly. Most of the rivers in West Africa, they noted, have extremely low dry season discharges but observed that in the heavily wooded areas of the south where the dry season is short, the flow of even small streams is often permanent.

Water is most abundant between August and October, when 40 to 70% of the annual runoff is discharged (Ayibotele, 1993). Ayibotele (1993) further noted that, in the humid and dry parts of the region, five to six months account for 80% of the annual runoff.

2.3.4 Infiltration

GWP-WATAC (2000) noted that infiltration within West Africa is always poor because the precipitation intensity exceeds the infiltration rate (Van Giesen et al, 2000), which is exacerbated by the state of the soil surface, in particular by soil crusts which develop even on very sandy soils in the region.

2.3.5 Groundwater

Hayward and Oguntinyinbo (1987) reported that two main lithologies control the distribution of underground water in West Africa: rocks of the Basement Complex and the sedimentary rocks of the continental shields. Very extensive regions of West Africa are underlain by the crystalline basement rocks of the continental shield which are not very productive aquifers, so that the water from these sources is of only local significance.

Borehole and well yields from the region's aquifers are generally low and range from 0.3 to 3 m³/h but can reach 10m³/h. In some areas, yields as high as 45m³/h have been observed (GWP-WATAC, 2000).

2.4 Study Area

2.4.1 Ghana an Overview

The Republic of Ghana is located on the West Coast of Africa (Figure 2.1), between latitudes 4° 44' N and 11°11' N and 3° 11' W and 1°11'E. It has a total land area of 23.85 million ha and is bordered by Togo on the east, La Côte D'Ivoire on the west, Burkina Faso on the north and the Gulf of Guinea of the Atlantic Ocean to the south which forms a coastline 550 km long. Ghana has a population of 18.4 million with a growth rate of 2.5 percent per annum and a mean population density of 77 persons / km² (Ghana Census 2000). The population distribution varies across the 10 administrative regions of the country with 68 percent and 32 percent of the population living in the rural and urban areas respectively. About 52 percent of the labour force is engaged in agriculture, 29 percent in services and 19 percent in industry. Approximately, 39

percent of the farm labour force is women. Agriculture contributes 54 percent of Ghana's GDP and accounts for over 40 percent of export earnings while at the same time providing over 90 percent of the food needs of the country. Ghana's agriculture is predominantly smallholder, traditional and rain-fed (SRID, 2003).

The drainage network of Ghana is divided into three main systems (WARM, 1998):

- The Volta river system is the largest drainage system in Ghana. The Black Volta, White Volta and the Oti rivers flow from Burkina Faso southwards to Ghana to form the Lower Volta. This river system catchment accounts for about three quarters of the total land area of Ghana, and has been dammed at Akosombo and at Kpong for hydropower power generation. Behind the Akosombo dam, one of the largest manmade lakes in Africa has been created, with a surface area of 8 500 km² and a capacity of 148 km³.
- The southwestern river system drains about one-fifth of the total land area of Ghana. The system comprises the Bia, Tano, Ankobra and Pra rivers.
- A number of coastal rivers drain the southeastern part of the country. Together, they account for 5% of the land area of the country and the Densu Basin falls in this category.

The mean annual runoffs from the 3 major river basins within the country are respectively: 24175x10⁶m³, 13125x10⁶m³ and 2110x10⁶m³ and they contribute 61.3, 33.3 and 5.4% respectively of the actual runoff from Ghana (WARM, 1998).

2.4.2 Densu Basin: Location, Socio-economic, Drainage and Relief

The Densu River is a typical rain forest zone river and forms part of the coastal river basins of Ghana, taking its source from the Atwiredu Range of hills of the Eastern Region (a recognized administrative region) of Ghana. It lies between

latitude 5°30'N and 6°20'N and longitudes 0°10'W to 0°35'W. The relief of the basin can be grouped into four types namely;

- Steeply dissected and mountainous lands with slopes greater than 30%
- Hilly land with slopes of between 16-30%,
- Rolling land with slopes of between 8-16% and
- Coastal plain where slopes are generally 0-2 and 2-8%

The rolling land form forms the greater part of the area with the coastal plain form being the smallest (Adu and Asiama, 1992).

The basin lies within the jurisdiction of 10 district assemblies (local governing authorities). It has a population density of between 150 to 200 persons per square kilometre which is above the national average of 77 persons per square kilometre with the main occupation being agriculture which is engaged in by some 38.9% of the economically active population (Nii Consult, 2001)..

The hydrological map of the basin is shown in Figure 1.4 From a source at an elevation of about 760m (2500ft) above sea level, the river flows generally southwards until it reaches the Weija reservoir (created by a dam at Weija).

During its journey downstream, especially from Nsawam, the water quality of the Densu River is impacted upon significantly by anthropogenic influences (including settlements, agricultural and industrial activities) (OTUI, 1996). The Densu drains a total of 2564km² to the coast and traverses a total distance of about 116km before it reaches the sea at the Gulf of Guinea through a small delta west of Accra.

The river discharge is seasonal and follows the rainfall trend. The dry season flows which occurs from November to February are very low i.e. 0-0.74m³/s, with no flow conditions occurring upstream at Koforidua. The high flows occur during the months of June to September with the highest flows in June. Flows at Manhia range between 2.2m³/s-5.7m³/s (Nii Consult, 2001).

2.4.3 Hydrometeorology and Vegetation

The Densu Basin has two rainy seasons and two dry seasons and is characterized by prevailing high temperatures and marked variations in the duration, intensity and seasonal distribution of rainfall (WARM 1998). Temperatures are uniformly high throughout the year, with mean monthly temperature ranging from 24°C in August to 31°C in March and April. The mean annual rainfall is 1190 mm, ranging from 1700mm in the wet interior to 800mm near the coast. The major rainy season is, in general, from March to July attaining its rainfall peak in July, and the minor season occurs in September and October. Of the dry seasons, the December to February season is the most severe with negligible rainfall and high temperatures.

The vegetation of the Densu Basin (Figures 2.12-2.14) originally comprised a moist semi-deciduous forest to the north, graduating through a small belt of transitional zone to savannah vegetation of thickets and grassland to the south (as it approaches the sea). Currently, true forest can only be found in the forest reserves around the upper sections of the headwaters north west of Koforidua (OTUI, 1996). Figure 2.12 is a photograph taken by European Space Agency (ESA) (ESA, 2005) of the Volta Lake and its surroundings which also captures the vegetation within the Densu Basin. The image clearly illustrates the divide between the verdantly forested "Ashanti" region in the southeast of the country and the sparser lowland savannah and plains to the north.

The original forests have been replaced in most places by secondary forest (Figure 2.13) and derived-savannah due to exploitation by man for timber, commercial farming, food crop cultivation (Figure 2.14) and fuel wood. There has therefore been a gradual change in the vegetative cover.

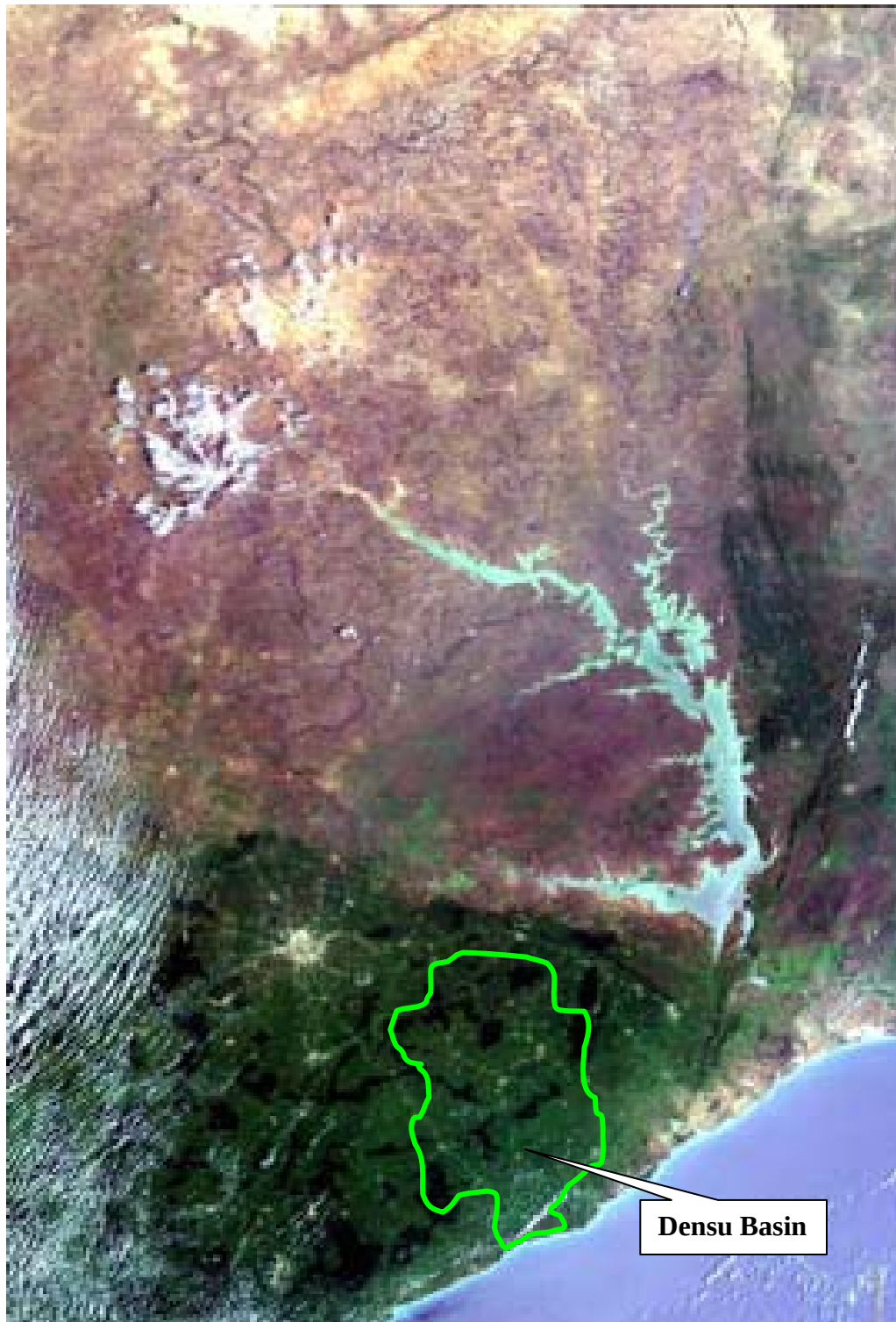


Figure 2.12 Map showing the vegetation of the Densu Basin and surrounding areas. (Courtesy [ESA - Observing the Earth - Lake Volta, Ghana](http://www.esa.int/esaEO/SEM6MXEM4E_index_0.html) http://www.esa.int/esaEO/SEM6MXEM4E_index_0.html)



Figure 2.13. Secondary forest in the Basin



Figure. 2.14. A typical land use: Cassava plantation in the Densu basin

2.4.4 Soils, geology and groundwater occurrence

The main soil type in the basin is the forest ochrosols which cover some 96% of the basin, whereas in the remaining portions in the southern part it is covered with savannah ochrosols and savannah lithosols (OTUI, 1996).

The basin is underlain for about 95% of the area by granites and gneisses of the middle Pre-Cambrian (OTUI, 1996 & Adu and Asiamah, 1992). At the source of the river Densu, the basin is composed of metamorphosed lava, phyllites, schists, tuffs and greywacke. Towards the coast, it is underlain by quartzites, shales and phyllites of the Togo series. Ground or subsurface water accumulates mainly due to infiltration of precipitation and surface water (Darko, 2002). The extent, thickness and physical character of the weathered layer vary from one area to another depending on factors such as climatic conditions (temperature, amount, intensity and distribution of rainfall), topography, lithology, the degree of fracturing and vegetation cover. During the wet seasons the water table generally rises supplying water to a number of shallow wells (Darko, 2002).

2.4.5 Description of Densu Catchment in hydrological process terms

The Densu River takes its source from the Atewa Range near Kibi, which has an elevation of about 760m (2500ft) above sea level, and travels downstream for about 116km until it reaches the sea (Gulf of Guinea) through a small delta at Sakumo. The hydrological flow processes of the basin are shown in Figure 2.15. Rainfall which occurs mainly in the rainy season is the main flow input into this basin. Runoff is experienced when the soils of the catchment reach their field capacities. The outputs from this basin are mainly the evapotranspiration and surface water abstractions.

Currently, true forest can only be found in the forest reserves around the upper sections of the headwaters. The original forests have been replaced in most

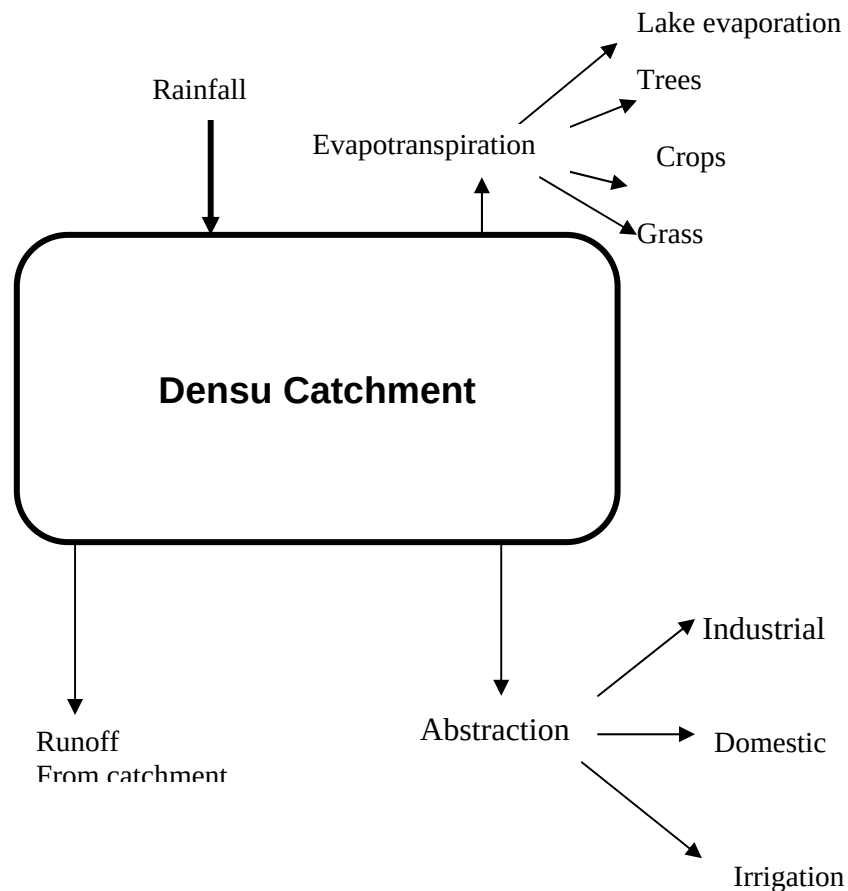


Figure 2.15 Schematic diagram of the hydrological processes in the Densu Catchment

places by secondary forest and derived-savanna due to exploitation by man for timber, commercial farming, food crops cultivation and fuelwood. There has therefore been a gradual removal of the vegetative cover. As a result of the landscape in the headwater part of the basin (hilly and mountainous) precipitation feeds into narrow streams that rapidly descend a steep gradient resulting in high surface runoff in this part of the catchment. Interception losses are higher than in the lower sections because of the generally closed canopy and high vegetation density. As a result actual evapotranspiration is higher in this section of the basin.

The upper reaches feed into a middle reach creating a "mainstem" of the river where vegetation is less dense than the headwater part thereby producing

relatively lower interception losses. However, in the middle section of the catchment, the basin varies from higher altitude (175m) to just about 3m near Weija where in between these heights, its gradient over a considerable section of the river is virtually flat (0.0056; i.e. a fall of only about 9m in the 16 km run of the river course upstream of Weija) (OTUI, 1996). Floodplains, lakes and swamps characteristically are found around the slow flowing river mainstem.

Below the mainstem is the lower reach between Weija and the sea where the river meets the ocean. In the lower reach saline and fresh water mix, silt settles, and a delta forms. The vegetation gradually turns from mostly derived-savannah (due to exploitation by man) into predominantly highly productive estuaries, mangrove forests, wetlands, coral reefs, tidal marshes and mud flats (Marchand and Tornstra, 1986).

3. Catchment Hydrology Modelling and Model Selection

3.1 Introduction

Hydrological catchment models are hypotheses of the dynamic water balance at the catchment scale and have become useful tools in water resources planning and management, providing a capability to analyze quantity and quality of streamflow from routinely measured climate data and catchment characteristics (e.g. landuse, soils and slope), for reservoir system operations, groundwater development and protection, surface water and groundwater conjunctive use management, water distribution systems, water use and a range of water resources activities (Wooldridge et al, 2001 & Wurbs, 1998) as discussed in Chapter 1.

Considering only the application to the tropics, hydrological models have been applied in humid tropical and humid sub-tropical catchments in Queensland, New South Wales, Victoria and Tasmania in Australia (Sumner et al., 1997, Boughton and Droop., 2003), sub tropical Western Sierra Madre in Northern Mexico (Descroix et al., 2002); Marite forest catchment in South Africa (Jewitt & Schulze, 1999), Hagafiro forest catchment in Tanzania (Liden and Harlin, 2000), tropical Niger basins (Conway & Mahe, 2005) and in south western Ghana (Darko 2002).

This Chapter describes the modelling approaches in general catchment hydrology, the criteria adopted for selecting an appropriate hydrological model for use in the data poor Densu river basin of Ghana, and a review of some short listed hydrological models from which the final selection was made.

3.1.1 Modelling Approaches in Catchment Hydrology

In recent decades the science of computer simulation of groundwater and surface water resources systems has passed from being of academic interest only to a practical engineering procedure (Viessman & Lewis, 2003). Increasing

computer speed and the development of new mathematical representations of physical processes are making the use of hydrological modelling tools to solve hydrological problems commonplace. Computer models have been used to simulate the behaviour of catchment systems since 1960's, for example, the Stanford Watershed Model (Crawford and Linsley, 1966; cited by Zoppu, 2001).

Viessman & Lewis (2003) observed that hydrological models vary in many ways: time step, spatial scale, whether the model simulates single events or on a continuous basis, and how different hydrological components are computed. Singh (1995) and Singh & Woolhiser (2002) state that catchment models can be classified (Figures 3.1-3.3) according to different criteria that may encompass (a) process description, (b) time scale, (c) space scale (d) technique of solution (e) land use e.g. agricultural, urban, coastal and (f) model use e.g. planning models, management models and prediction models.

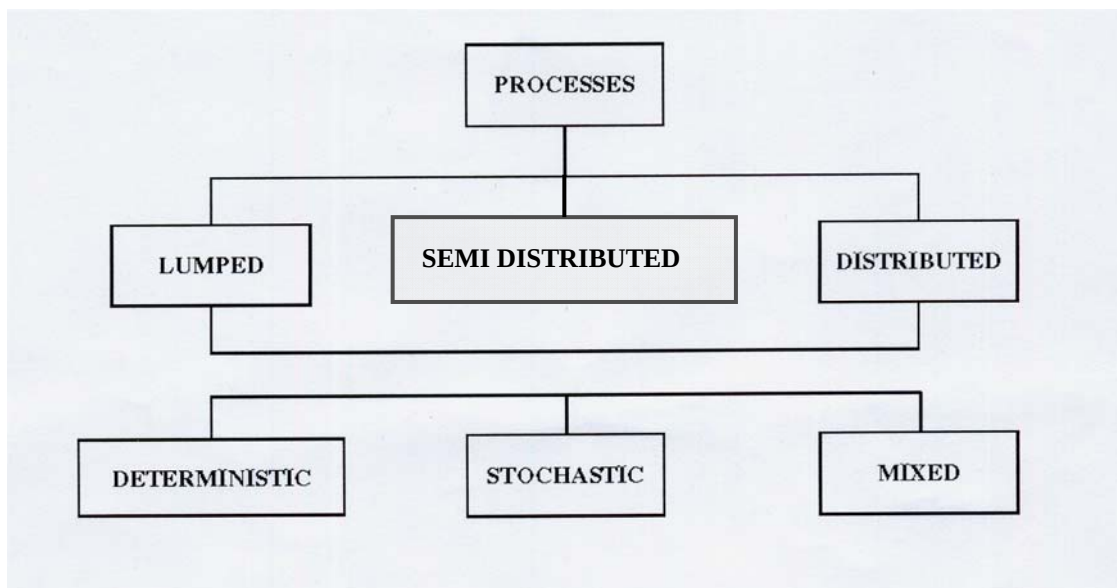


Figure 3.1 Classification of models based on process description (Source: Singh, 1995)

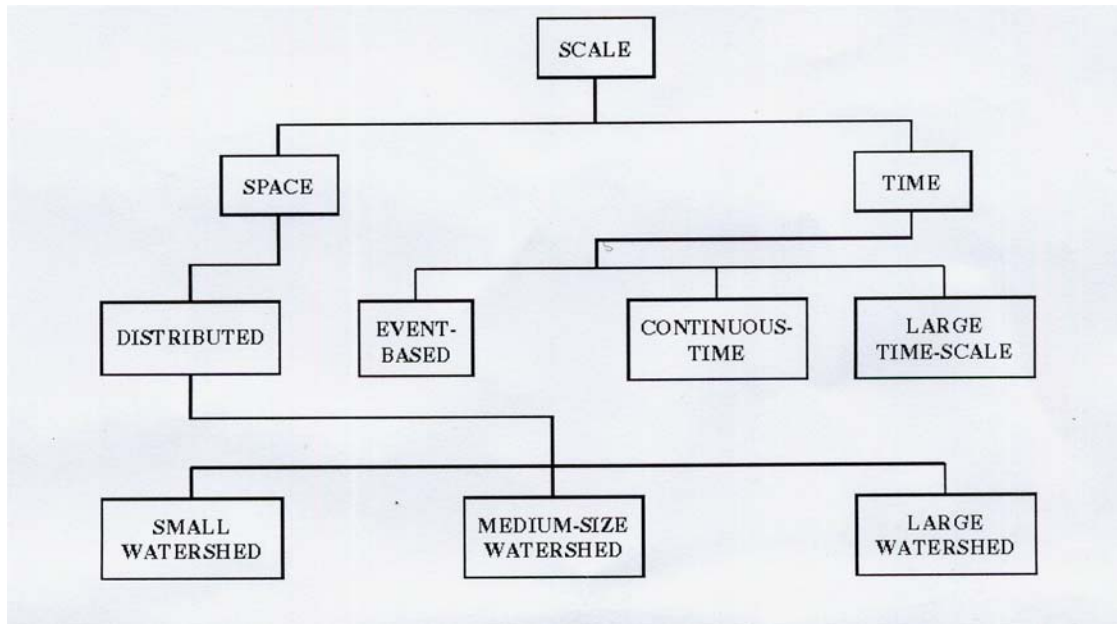


Figure 3.2. Classification of models based on space and time scales (Source: Singh, 1995)

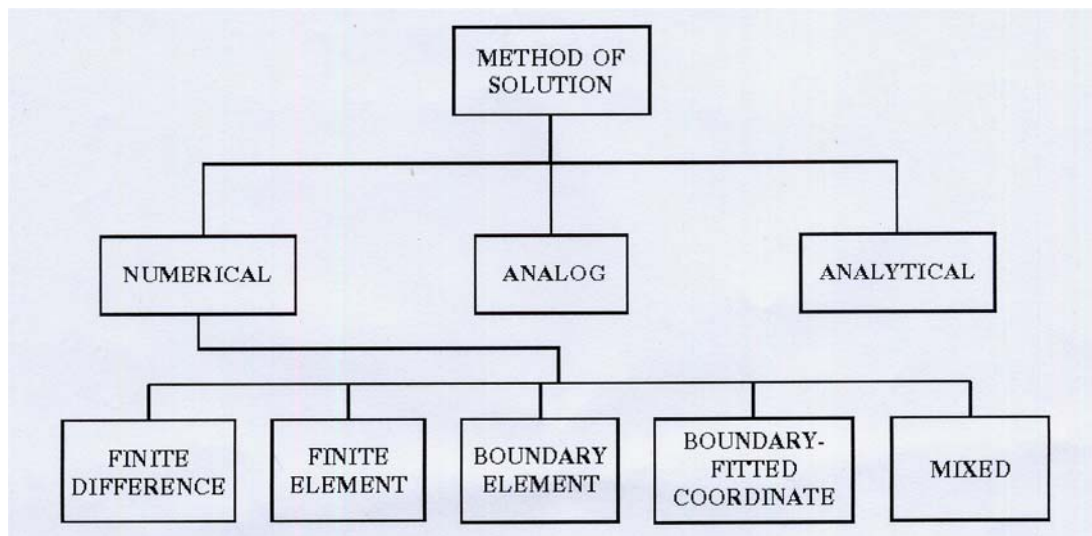


Figure 3.3 Classification of models base on solution technique.

In describing process based classification Singh (1995) illustrated a model as having five components (Figure 3.4) which include (1) system (catchment) geometry, (2) inputs, (3) governing laws, (4) initial and boundary conditions, and (5) outputs. Depending on the type of model, these components are variously combined. The processes include all of the hydrologic processes that contribute to the system (catchment) output. Based on the description of those

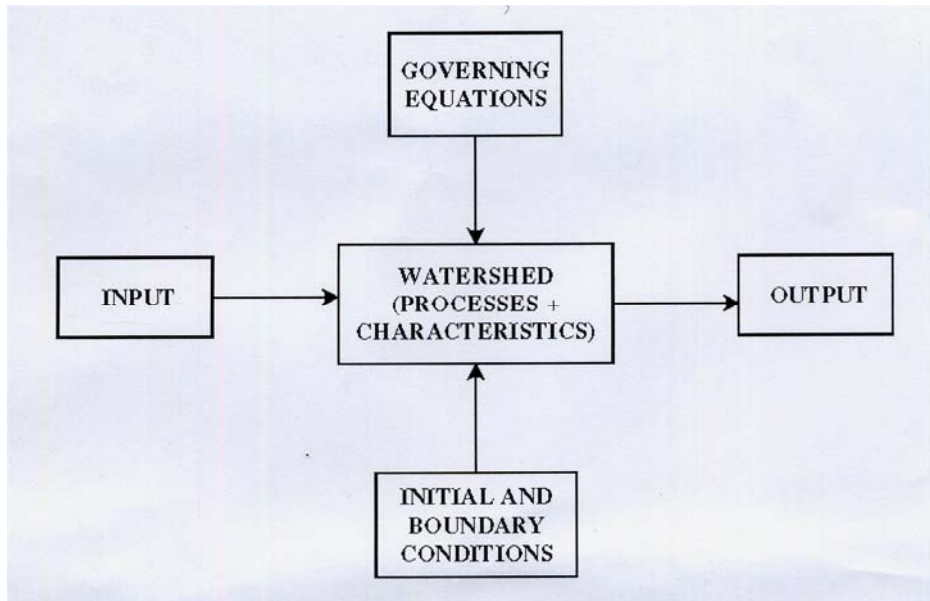


Figure 3.4. Model Components (source; Singh 1995)

processes, in conjunction with the system (catchment) characteristics, Singh (1995) and Viessman & Lewis (2003) noted that models can be described as lumped or distributed, deterministic or stochastic or mixed. Similarly Clark (1973) and Viessman & Lewis (2003) observed that if any of the variables in the model are regarded as having a probability distribution, the model is classified as a stochastic model; otherwise the model is deterministic. According to Singh & Woolhiser (2002) a deterministic model will always produce identical results for the same input parameters whereas a stochastic model will always produce a different model response where one or more variables are selected at random from a distribution. Both stochastic and deterministic models may be further classified into either conceptual/physical or empirical, depending on whether the model is based on physical laws or not (Viessman & Lewis, 2003). Further explaining, Singh (1995) and Singh & Woolhiser (2002) noted that if all of the components of a model are deterministic, the watershed model is deterministic. If all the components of the model are stochastic, the model is fully stochastic, and if only some components are stochastic then the model is quasi-stochastic. Singh & Woolhiser (2002) concluded by saying that a vast majority of the models are deterministic, and virtually no model is fully stochastic. Further they noted that, in some cases, only some parts of the model are described by the

laws of probability, and other parts are fully deterministic and observing that in such cases it is then fair to characterize them as quasi deterministic or quasi-stochastic.

A lumped model (Table 3.1) is expressed by ordinary differential equations (ODE) taking no account of the spatial variability of processes, inputs, boundary conditions and system (catchment) geometric characteristics (Singh, 1995). Singh (1995) observed that, in most lumped models, some processes are described by differential equations based on simplified hydraulic laws, and other processes are expressed by empirical algebraic equations.

Table 3.1 Lumped and distributed models (source: Singh 1995)

Input	System Characteristics	Component Processes	Governing Equations	Output	Model Type
Lumped	Lumped	Lumped	¹ ODE	Lumped	Lumped
Lumped	Lumped	Distributed	² PDE	Distributed	Distributed
Distributed	Distributed	Distributed	PDE	Distributed	Distributed
Distributed	Lumped	Distributed	PDE	Distributed	Distributed

¹ODE=Ordinary Differential Equation; ²PDE=Partial Differential Equation

Examples of lumped models are; Runoff Routing Model-RORB (Laurenson and Mein, 1995), Streamflow Synthesis and Reservoir Regulation model-SSARR (Speers, 1995), Tank model (Sugawara, 1995).

Distributed models according to Singh (1995) in Table 3.1 take explicit account of spatial variability of process, input boundary conditions, and/or system (catchment) characteristics. However, noting that, in practice, a lack of data (field or experimental (laboratory)) prevents such a general formulation of distributed models. He further noted that in a majority of cases, the system (catchment) characteristics are lumped, many of the processes are lumped, the

input is lumped, and even some of the boundary conditions are lumped, but some of the processes that are directly linked to the output are fully distributed; rather they are quasi-distributed at best. Examples of distributed models are Systeme Hydrologic European-SHE (Bathurst et al., 1995) and Storm Water Management model-SWMM (Huber, 1995) amongst others (Singh & Woolhiser, 2002).

Regarding time steps, models may use one time interval for input and internal computations and a second time interval for the output and calibration of the model (Singh, 1995). Models typically use computational time steps ranging from hourly to monthly which often is a function of the process representation and the models' intended use. Event based models are short-term models used for simulating a few or individual storm events, whereas continuous models simulate a catchment's behaviour over a longer period of time, involving daily to seasonal predictions, and form the basis of planning models for water resources (Singh, 1995).

The spatial scale according to Singh (1995) & Singh and Woolhiser (2002) can be used as a criterion to classify models into small-catchment ($\leq 100 \text{ km}^2$), medium-size catchment ($100\text{-}1,000 \text{ km}^2$) and large catchment ($> 1000 \text{ km}^2$) models, noting that this classification is arbitrary and experimental rather than conceptual and is governed by data availability rather than physical meaning and that the essential import is the concept of homogeneity and averaging of the hydrological processes.

Space and time affect model accuracy the most (Deliman et al., 1999). When models are applied over too large an area, many parameters (e.g. soils and landuse) are lumped or averaged for the area which neglects the small-scale heterogeneities that are found in the real world and this affects the prediction of runoff quality and quantity. Deliman et al. (1999) further observed that when the time step is too long, many physically based models do not operate properly in

terms of accuracy, and the benefits of using distributed rather than lumped parameters are lost.

However, despite the wide range of model types available, Singh & Woolhiser (2002) observed that frequently, the type of a model to be used or selected is dictated by the availability of data.

3.2. Selection Criteria for choice of model

Hydrological models can be data intensive tools requiring much input data (Singh & Woolhiser, 2002; & Viessman & Lewis, 2003) which often does not exist or are not available in full (Singh & Woolhiser, 2002). However, a simple empirical model might only require rainfall, temperature and streamflow data. Therefore to select a model to accomplish the objectives of this research (Chapter 1) in the Densu river basin, the following selection criteria set were formulated against which models could be assessed for suitability.

- It must be a non-urban model that can simulate agricultural/rural areas because the Densu basin can be classified as agricultural (Chapter 2 Section 2.4)
- The model should be one that can be applied over a range of catchment sizes from medium to large catchments/basins (say 50km² up to 2600km²) so that the Densu, and other smaller catchments within the sub region of West Africa, if found appropriate, could be modeled (i.e. catchment scale model)
- Its spatial discretization should be semi distributed to enable both modelling in the lumped and semi-distributed modes.
- It should be able to simulate baseflow which is an important component of the flow in perennial rivers in tropical catchments such as the Densu.
- The minimum input data requirements for the model must be easily available i.e. meet the data gathered from a data-poor catchment such as the Densu Basin.

- Should be able to output daily values to enable daily analysis to be undertaken for events such as peaks
- It should incorporate tools that would allow for effects of landuse to enable assessment of the impacts of land use changes on water resources.,
- Its temporal scale should be long term and continuous and not event based
- The model must be readily and freely available, both for research and for future use in Ghana.
- Its process representation should be largely conceptual and/or mechanistic, to enable predictions of the hydrological consequences of future change within the catchment.

3.3 Review of appropriate models

Many hydrological models were reviewed based on information in published literature (journals, textbooks, technical reports and models user's manuals) and on websites (e.g. University of Kassel, 2003).

It is not practicable to be able to review all models which have been developed over the past decades, so this review of models is in no way all-inclusive but represents a wide selection of available models. Table 3.2 was constructed to assist with the model selection and shows models assessed according to the set criteria. Empirical black box rainfall-runoff models like the Simple Linear Model (Nash and Folley, 1982), Linear Perturbation Model (Narsh and Barsi, 1983), Linearly Gain Factor Model (Ahsan and O'Connor, (1994) and Artificial Neural Network Models (Shamseldin, et. al, 1997) were not studied as they are unable to give robust predictions of future change i.e. when going outside their range of calibration. Other models were considered inappropriate due to their spatial discretization (e.g. lumped models such as IHACRES- Post and Jakerman, (1999); HSPF and SSAR; Singh & Woolhiser (2002), scale e.g. field based models such as CREAMS- Chemicals, Runoff and Erosion from Agricultural Management Systems (Foster et al., 1980); temporal resolution e.g. event based models such as KINEROS, RORB, AGNPS; and HEC-HMS

Table 3.2: Models screening against criteria

Model	Non urban	Scale:	Spatial Discritization	Models Base flow	Min Data	Output Daily Values	Incorporate Land use tools	Time Modelling Scale	Accessibility	Processes Representation
	NU	Large Scale model	D/SD					Continuous		Co/Ph
ACRU	√	√	√	√	√	√	√	√	√	√
AGNPS	√	-	√	-		√	√	X	√	√
ANSWERS 2000	√	√	√	√	√	√	√	√	√	√
AWBM2002/97	√	√	√	√	√	√	√	√	√	√
DR3	X	-	-	-	-	-	√	-	X	-
HEC-HMS	X	-	√	-	-	-	-	√	√	√
HSPF	√	-	X	√	-	-	-	√	√	√
KINEROS	√	-	√	√	-	-	-	X	√	-
RORB	√	-	-	-	-	-	-	X	√	-
SSARR	√	-	X	-	-	-	-	√	√	√
STORM	X	-	-	-	-	-	-	-	√	-
SWAT	√	√	√	√	√	√	√	√	√	√
SWATCATCH	√	-	√	√	-	-	X	-	√	√
SWMM	X	-	√	-	-	-	-	-	√	√
SWRRB	√	√	√	√	√	√	√	√	√	√

Where X = does not meet criteria, √ =meet criteria, (-) = information not considered as one or more criteria has failed for that model.

NU =Non Urban; D = Distributed, SD = Semi Distributed; Co = Conceptual; Ph = Physical
 ACRU The Agricultural Catchments Research Unit Model Schulze (1995)
 AGNPS AGricultural NonPoint Source Borah & Bera (2003)
 ANSWERS Areal Nonpoint Sources Watershed Environment Response Simulation Model Bouraoui & Dillaha (2000)
 AWBM2002/97 AWBM Catchment Water Balance Model Boughton (2002)
 DR3 Distributed Routing Rainfall-Runoff Model Singh & Woolhiser (2002)
 HEC-HMS Hydrologic Engineering Centre-Hydrologic Modelling System Young et al. (1995) and Borah &Bera (2003)
 HSPF HSPF (Hydrological Simulation Program (FORTRAN) Singh & Woolhiser (2002)
 IHACRES Identification of Hydrographs And Components from Rainfall Evapotranspiration and Streamflow data Ye et al. 1997
 KINEROS Kinematic Runoff and Erosion Model Woolsher et al. (1990),
 RORB Rainfall Routing Model Lawrenson and Mein (1995)
 SSARR Streamflow Synthesis and Reservoir Regulation Speers (1995)
 STORM Storage, Treatment, Overflow Runoff Model Singh & Woolhiser (2002)
 SWAT Soil Water Assessment tools Arnold et al (1998)
 SWMM Storm Water Management Model Huber (1995)
 SWRRB Simulator for Water Resources in Rural Basins Williams (1995)

(Young et al, 1995, Borah and Bera, 2003), urban stormwater models e.g. models such as STORM, SWMM, and DR3 (Singh & Woolhiser, 2002) or because of requirements for large amounts of data (e.g. MIKE SHE–Bouraoui & Dillaha, 2000 and Borah and Bera, 2003).

Based upon the results of this screening assessment against the selection criteria, five models were selected for further review because they appeared to fulfill all of the attributes needed for the study. These were the;

- Australian Water Balance Model-2002 (AWBM-2002)
- Simulator for Water Resources in Rural Basins (SWRRB)
- Areal Nonpoint Sources Watershed Environment Response Simulation Model (ANSWERS 2000)
- Soil Water Assessment Tool (SWAT) and
- Agricultural Catchments Research Unit Model (ACRU)

3.3.1 Australian Water Balance Model-2002 (AWBM-2002)

During further screening for this model it was discovered that the AWBM-2002 (Australian Water Balance Model) theory manual (Boughton, 2002) was unavailable from the model's website for detailed process analysis to be undertaken. Communication with the author of the AWBM calibration and operation manual ⁶Boughton, W., informed the writer⁷ that the theory manual was under development and yet to be published. This therefore ruled out the use of AWBM because, even though by the description of AWBM-2002 in Boughton (2002, 2003) in the calibration and operating manual the model fulfils the minimum criteria for the choice of a model for this study, details of methods and detailed data requirements used to compute the various processes e.g.

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⁷ Email dated 25th April 2003.

evapotranspiration, infiltration, runoff routing, surface runoff computation and crop growth were not described adequately enough in the manuals.

3.3.2 ANSWERS-2000 Model

ANSWERS (Areal Nonpoint Source Watershed Environmental Response Simulation)-2000 is a non-point source planning model (Bouraoui and Dillaha 2000) which is an improvement on the ANSWERS model which was an event based model (Bouraoui and Dillaha, 1996). It is a distributed parameter model (Conolly et al., 1997) for long term daily simulation of infiltration, run-off, drainage, evapotranspiration, groundwater recharge and nitrogen transport and transformation in an agricultural watershed. A physically based approach is taken for interception, infiltration, surface retention, drainage, overland flow, channel flow, subsurface flow and sediment detachment/transport. According to Baraoui and Dillaha (1996), ANSWERS-2000 was intended for use without calibration and intended for use on an ungauged catchment where no data are available for calibration and data availability is extremely difficult. They advised that this model should not be used for absolute predictive purposes.

Time steps in the model are daily for days without rain, and 30 seconds during days for which precipitation occurs (Bora and Bera, 2003). The climatic data and other input files such as topography, soils data and landuse, according to Cohen and Dabral (2001) are created with the use of a graphical user interface called Questions which uses Visual Basic modules.

The watershed is discretized into blocks of 30x30 m² (Braud et al, 1999) or can be discretized into volume units of one hectare in area (Bouraoui, et., al 1997), which are characterized by homogeneous topographic, soil hydrodynamic and crop characteristics, by use of a Digital Elevation Model (DEM). Digital elevation models are useful and popular tools from which topographic parameters can be quickly and efficiently extracted for various hydrologic applications (Armstrong and Martz, 2003). They also noted that DEMs coupled with automated methods for extracting topographic information provide a powerful means of

parameterizing hydrologic models over a wide range of scales. However, they noted that choosing appropriate DEM scales for particular hydrologic modelling applications is limited by a lack of understanding of the effects of scale and grid resolution on land-surface representation. The model simulates the infiltration processes using the Green and Ampt (1911) approach, with parameters derived from pedotransfer functions given by Rawls and Brakensiek (1989) (cited by Bouraoui et al., 1997) based on soil textural characteristics, whilst Manning's equation is used as the stage-discharge equation for routing both overland and channel flow.

Evapotranspiration is partitioned into evaporation and transpiration by the Ritchie's approach requiring daily solar radiation and albedo data, with a USDA crop database used to infer the development of root zone and Leaf Area Index during the crop cycle. Plant growth is represented by a varying Leaf Area Index (LAI) and root zone. For each crop cover, tabulated values of the LAI (Knisel, 1980) are used as input to the model. Ground water interaction processes use the single-soil layer, linear release coefficient model algorithm (Cohen and Debral, 2001). The model has been coupled with a GIS system (GRASS) (Bouraoui and Dillaha, 2000 and Bouraoui et al., 1997).

ANSWERS 2000 has been used mainly to simulate non point source (NPS) pollution according to Bouraoui and Dillaha (1996, 1997, and 2000), Cohen and Debral (2001) and Boarah and Bera (2003). Bouraoui and Dillaha (1996) used it for runoff and sediment transport computation in small and large catchment areas in coastal plain Watskinsville, Georgia and Owi Run catchments in Fauquire County, Virginia in USA respectively. In the coastal plain Watskinsville catchment, the model predicted the cumulative runoff within 3 to 35% of measured whereas in the Owi with about 30% forest area, the predicted cumulative runoff was found to be within 7% of the measured value without calibration. Overall the sediment transport was found to be predicted within 12% to 65% of measured values in both catchments. On the other hand Cohen and Debral (2001) concluded that ANSWERS 2000 is not well suited for sandy

soils and for flat lands (catchments having an average slope of less than 1%) because they reported that the “hydrology component of the model doesn’t know how to drive the water out to the watershed outlet when the slopes are less than 1%”.

Some of the strengths of ANSWERS 2000 include:

- Its use of physical relationships for runoff computation which allow the model to be applied without a great deal of calibration (Bouraoui and Dillaha, 1998 and Dabral and Cohen, 2001).
- Links to a GIS to facilitate analysis of output simulations and view data produced by the model
- Spatial variation in and throughout the catchment and the location of important runoff sources can be represented.
- Although ANSWERS 2000 requires lots of input data, use of pedotransfer functions are provided to derive soil data; and parameters for a range of crops are given in data tables (Bouraoui and Dillaha, 1996). This allows for some maneuverability in cases where the data in this regard are not readily available.

However, for the study at hand some of the disadvantages that will be encountered are:

1. In the absence of measured soil property data, the model relies on the use of pedotransfer functions or Model Parameter Estimation Routines (MPER’s) which were developed with US soil data for the computation of infiltration. Holman and Hollis (2001) showed that the SWATCATCH model performed better with soil data (soil water retention and hydraulic conductivity data) that had been derived from MPERs developed using local data rather than regional or continental data. As the detailed local soil property data needed to solve the equations for infiltration will be difficult to acquire the use of US-based MPER’s represents a weakness of the ANSWERS 2000 model for this study.

2. The definition of the catchment boundaries and sub catchments, and the routing of flows through the catchment depend on the use of a digital elevation model. A global coverage of public domain DEM datasets is available from the United States Geological Survey (USGS) but the best available resolution, at a nominal 1km x 1km (HYDRO1k Home Page, 2003) would not be appropriate for this task as the ANSWERS 2000 has been used for grid sizes of 30mx30m up to 1ha in area (Bouraoui and Dillaha (1996, 1997). More detailed resolution digital elevation data are generally unavailable or expensive to acquire in West Africa which limits the applicability of models which depend upon them. Based on a modelling study to predict solute transport in soil media, Inskeep et al. (1996) concluded that model predictions based on input data sets with low spatial resolution (100x100 and 200x200) may not accurately reflect transport processes occurring in situ. Also according to Chaubey et al. (2005) the minimum recommended grid sizes for DEM to give good flow measurement should be 100m to 200m square in a study with SWAT model.

3.3.3 SWAT Model

SWAT (Soil Water Assessment Tool) is a model developed by the United States Department for Agriculture, Agricultural Research Service (USDA-ARS) and it is a river basin scale model developed to quantify the impact of land management practices in large, complex catchments (Neitsch et al., 2001). Processes represented include surface runoff, percolation, evapotranspiration, erosion, nutrient and pesticide loading, crop growth and irrigation, groundwater flow, channel transmission losses, pond and reservoir storage and channel routing (Neitsch et al., 2001).

The model according to Neitsch et al. (2001) partitions a watershed into sub-watersheds and organizes input information for each sub-catchment into the following categories: climate, hydrologic response units (HRUs), ponds/wetlands, groundwater, and the main reach draining each sub-catchment. Hydrology of the catchment is separated into two major divisions: (a) the land phase and (b) the routing phase of the hydrologic cycle. The

amounts of water, sediment, nutrient and pesticide loadings to the main channel from each sub-catchment are controlled by the land phase of the hydrologic cycle. The routing phase of the hydrologic cycle determines the movement of water, sediment and other pollutants from the channel network to the watershed outlet. All model calculations are done on a daily time scale. However, the watershed response output can be obtained at a daily to annual time scale. Aggregation of input data can be facilitated using a GIS interface (either Geographic Resources Analysis Support System (GRASS) or ArcView) available with the model. The ArcView interface developed for the SWAT model requires land use/land cover, soils and DEM data as spatial inputs (Di Luzio et al., 2002) and can be used to prepare input files.

Surface runoff or overland flow is computed using the SCS curve number or the Green & Ampt infiltration method with peak runoff computed using a modification of the rational method (Neitch et. al. 2001). Time of concentration for both channels and overland flow is estimated using the Manning's equation. Percolation and lateral subsurface flow are computed together and are based on storage routing and kinematic routing. Groundwater flow is simulated based on a shallow aquifer model with evaporation, pumping, seepage and discharge being included (Neitch et. al. 2001 and Borah and Bera, 2003). For infiltration, if the Curve Number method is used to calculate surface runoff it is not possible to directly model infiltration because the model is operating on a daily time step. In that case infiltration to the soil profile is calculated as the difference between the amount of rainfall and the amount of surface runoff. For direct estimation of infiltration the Green and Ampt (1911) method is used. Potential evapotranspiration can be estimated using the Hargreaves, Priestley-Taylor or Penman Montieth methods (Neitch et. al., 2001). Runoff routing is by means of the Muskingum routing method. Plant growth is computed using the heat unit theory and it is based on daily accumulated heat units and potential biomass (Arnold et al., 1995 and Neitch, 2001) Other features of SWAT include a weather generator for long-term simulations (Arnold et al., 1995 and Neitch, 2001).

The SWAT model has become widely accepted as an effective tool to predict the effects of watershed management on runoff, sediment, nutrients and pesticide yields (Arnold et al., 1993, 1998; Arnold & Fohrer, 2005; Jayakrishnan et al., 2005). However, Jayakrishnan et al. (2005) noted that the use of SWAT model in African catchments was non-existent and tried modelling an African catchment (Sonde River basin of 3050km²) in the mountainous region of Western Kenya near the equator. The SWAT model was calibrated for monthly streamflow for the study period. However, the Nash and Sutcliffe efficiency for the calibration ranged between -0.72 and 0.10 revealing large variation between the simulated and the observed data during individual months. Poor input data are blamed for this result.

The SWAT model has been used extensively in many countries for watershed modelling and can be used under a wide range of different environmental conditions (Arnold & Fohrer, 2005).

Some of the advantages of SWAT include,

- Ready application to catchments of varying scale and complexity;
- Links to GIS, including the public domain GRASS;
- Its use of Penman-Monteith to compute evapotranspiration which has been recommended by FAO (FAO, 1998), together with other methods including Hargreaves-Samani and Priestley-Taylor (Deliman et al., 1999);
- Its representation of the major processes describing the catchment water balance;
- Significant effort has been given to providing default values or guidance as to input parameter values;
- It has been widely used in a range of regions (Arnold et al., 1993, 1998, and Jayakrishnan et al., 2005).

However, the main disadvantages noted of SWAT with regard to this study relate to its:

1. Complexity and data requirements especially with regard to the crop growth database (i.e. parameters controlling optimal leaf area development). This crop growth data will prove difficult to acquire for a large and dynamic basin (like the Densu) in which there is changing land use in a data-poor region.
2. The reliance on digital elevation models (DEM) to delineate catchment boundaries and sub catchments is a disadvantage for the wider use of the model in the Tropics. Chaubey (2005) studied the effect of DEM data resolution (30 x 30 m, 100 x 100 m, 150 x 150 m, 200 x 200 m, 300 x 300 m, 500x500 m and 1000 x 1000 m) on predictions of watershed characteristics and water quality from the SWAT model in the Moores Creek catchment in USA. Results of this study showed that DEM resolution affects the watershed delineation, stream network and sub-basin classification in the SWAT model. A decrease in DEM resolution resulted in decreased stream flow and NO₃-N load predictions. Results indicated that the DEM minimum data resolution ranged from 100 to 200 m to achieve less than 10% error in SWAT output for flow, NO₃-N and total P predictions.
3. Applicability of MPER's, as discussed with respect to ANSWERS 2000, is applicable to SWAT also as it has been developed in the USA.

3.3.4 Simulator for Water Resources in Rural Basins

The Simulator for Water Resources in Rural Basins (SWRRB) model was developed by the United States Department of Agriculture, Agricultural Research Service, (USDA-ARS) to simulate hydrology, sedimentation, and nutrient and pesticide transport in large, complex rural watersheds (Arnold et al., 1990; Arnold, et al., 1987). It was developed by modifying the field scale CREAMS (Chemicals, Runoff and Erosion from Agricultural Management Systems) daily model for large, complex basins. Major additions to the CREAMS model included allowing simultaneous computations for several sub watersheds within a large basin and adding components to simulate weather, return flow, pond and reservoir storage, crop growth, transmission losses, groundwater, and sediment routing. SWRRB operates on a daily time step and is capable of simulations up to 100 years or more and allows basins to be

divided according to land use, soils, and topography (University of Kassel, SWRRB-2003).

The model operates on a continuous time-scale and allows for subdivision of basins to account for differences in soils, land use, rainfall, etc. It can predict the effect of management decisions on water, sediment, and pesticide yield with reasonable accuracy for ungauged rural basins throughout the United States (Arnold and Williams 1994).

Processes considered in the model include surface runoff, return flow, percolation, evapotranspiration, transmission losses, pond and reservoir storage, sedimentation, and crop growth. The hydrology component of the model is based on a daily water balance. Surface runoff is based on the US SCS curve number method as a function of daily soil moisture content and peak runoff rate can be estimated by either the rational formula or SCS TR55 method. Percolation is computed using a storage-routing technique with a crack flow model to predict flow through each soil layer (Deliman et al., 1999). Once water has percolated past the root zone, it is considered groundwater, and may appear as return flow (or baseflow) in downstream basins. Return flow is calculated as a function of soil water content and return flow time. Return flow travel times can be calculated from soil hydraulic properties or user-inputs. Lateral subsurface flow is computed for each soil layer using a kinematic storage model starting at the top layer and progressing downward. Soil evaporation may be computed using the Hargreaves–Samani method or the Priestley Taylor method. Evapotranspiration is estimated using Ritchie's ET model and requires the leaf area index depending on the stage of crop growth. Transmission losses in the stream channel are calculated as a function of channel dimensions, flow duration, and effective hydraulic conductivity of the channel bed. Pond storage is based on a water balance equation that accounts for inflow, outflow, evaporation, and seepage. The reservoir water balance component is similar to the pond component except that it allows flow from the principal and emergency spillways. Daily basin outflow is computed by

summing the sub-basin outflow (Arnold and Williams, 1994). Since SWRRB places a limit on the number of sub-basins within a watershed, some lumping of input parameters is necessary (University of Kassel, 2003).

SWRRB has been used and validated in a variety of settings, including being used to study urbanization, pond irrigation and water rights (Arnold and Williams, 1994). According to Neitsch et al. (2001) watershed division in SWRRB was limited to ten sub-basins and the model routed water and sediment transported out of the sub-basins directly to the watershed outlet. These limitations led to the development of a model called ROTO (Routing Outputs to Outlet) (Arnold et al., 1995), which took output from multiple SWRRB runs and routed the flows through channels and reservoirs. ROTO provided a reach routing approach and overcame the SWRRB sub-basin limitation by “linking” multiple SWRRB runs together. Although this approach was effective, the input and output of multiple SWRRB files was cumbersome and required considerable computer storage (Arnold et al., 1995). In addition, all SWRRB runs had to be made independently and then input to ROTO for the channel and reservoir routing. To overcome the awkwardness of this arrangement, SWRRB and ROTO were merged into a single model, SWAT. While allowing simulations of very extensive areas, SWAT retained all the features which made SWRRB such a valuable simulation model (Neitsch et al., 2001). Further, it was noted (Neitsch et al., 2001) that support assistance for use of this model had been stopped in favour of SWAT.

Based on the fact that SWAT retains all the features of SWRRB and that SWAT has been short listed, SWRRB has not been considered further in this study.

3.3.5 ACRU Model

The ACRU (Agricultural Catchments Research Unit) model was developed at the Agricultural Engineering Department of the University of Natal in Pietermaritzburg, South Africa (Jewitt and Schulze, 1999, Everson, 2001) as a simple decision making tool for agrohydrological problems (Schulze, 1995). The ACRU model is described by the developers as a multi-purpose and multi-level

integrated physical conceptual model (e.g. can be used for water resources assessment, design flood estimation, irrigation water demand and supply, crop yield and primary production modelling, assessments of impacts of land use changes on water resources, assessments of hydrological impacts of wetlands, groundwater modelling and for climate change impact modelling which integrates the various water budgeting and runoff producing components of the terrestrial hydrological system with risk analysis (Shulze, 1995 & and Jewitt, et al., 2004). Examples of these applications are given below.

Model input includes information on catchment characteristics such as location, area and altitude, daily rainfall, potential Evaporation (A-pan), data on soils, vegetation/land cover, irrigation (including scheduling) and reservoir dimensions. Inputs are entered into ACRU by way of an expert system type program-interface called the menu-builder, which leads the user interactively through alternative decision paths.

Processes considered in the model include surface runoff, return flow, infiltration, evapotranspiration, pond and reservoir storage, crop growth and groundwater. The hydrology component of the model is based on a daily water balance. A modified United States curve number method is used for computing daily surface flow where the potential maximum retention of the curve number is replaced by a soil water deficit or the use of the Green and Ampt (1911) infiltration method. ACRU considers reference potential evaporation instead of evapotranspiration using the methods Penman, A-Pan, Hargreaves, Linacre, Blaney and Criddle and Thornthwaite. The model has three choices; the Storage Indication method, Muskingum and Muskingum Cunge methods for river runoff routing. Modelling of vegetation and land use processes in ACRU may be grouped functionally into above-ground factors (canopy interception losses, consumptive water use by plants and shading of the soil); surface factors (which focus on soil protection by the plant/litter cover against erosion); and below-ground factors (which are concerned with plant root distribution, root water uptake and the onset of plant stress). Evaporation, crop coefficients, leaf

area index (LAI) and Von Hoyningen-Huene (1983) equations have been employed in ACRU to compute crop growth and interception losses (Schulze, 1995, Chapter 6).

Soil input decision support offers two levels of accuracy, depending on the data available to the user; at the lower level, when soil information is very limited, only soil texture and depth need be provided, with relevant hydrological soil properties being estimated from default decision support tables developed for soils from Southern Africa and from vertical percentages of clay content in the soil profiles, while at the higher level, porosity, field capacity, wilting point and drainage response rates, as well as textures and depth, are required.

ACRU makes use of a "cell"-type discretisation to subdivide the catchment, where each cell may be regarded as a sub catchment of the main catchment. Cell boundaries are defined by the user, using large scale orthophotos or topographical maps. If the effect of land use changes on outflow from a catchment is to be investigated, then the cell boundaries should be so defined as to obtain a high degree of homogeneity of land use or vegetation type. However, this may then often be achieved at the expense of, say, homogeneity of soil type. Likewise, if the cell, or sub catchment, outlet is selected at a point where hydrological information is required, e.g. at the inflow or outflow of a reservoir, then this information is likely to be obtained at the expense of (say) vegetation homogeneity, because in such a case the sub catchment boundary would be defined uniquely by the selection of the location of the sub catchment's outlet, irrespective of its soil and vegetation characteristics.

The ACRU agro-hydrological modelling system has been used extensively in South Africa (Everson, 2001). Examples of its use include land use change in Luvuhu catchment in South Africa (Jewitt et al., 2004) for the application of Geographic Information Systems (GIS) in the analysis of nutrient loadings from an agro-rural catchment in Southern Africa (Mtetwa et al., 2003); for climate change studies in South Africa (New, 2002); water balance (Everson, 2001); for

water resource assessments in South Africa (Schultz et al., 1990); for irrigation supply (Dent, 1998) and for flood studies in Mozambique and Zimbabwe (Smithers et al., 2001). For forest hydrology (Jewitt & Schulze, 1999; Herpertz, 1994; Gillham & Haynes, 2001; Tarboton & Schulze, 1992; Smitters & Schulze, 1997; Kienzle et al., 1997; DeClerk, 1999; Tarboton & Cluer, 1991; Smithers, 1991; Smithers & Caldecott, 1993; and Jewitt, & Schulze, 1993) all in southern Africa.

Some of the advantages of ACRU for this study include

- Ready application to catchments of varying scale and complexity
- Its adoption of the use of the A-pan as the reference potential evaporation which is the mostly common used method in West Africa and Ghana.
- Additional alternative methods to compute potential reference evaporation when data other than the Apan are available.
- The process of delineating cell boundaries is based on a manual technique rather than relying on a DEM.

A disadvantage of ACRU with respect to this study is that the model has been used mainly in Southern Africa within mostly semi arid environments.

3.3.6 Comparison of the ANSWERS2000, SWAT and ACRU models

From a review of the literature and a consideration of the processes used in each of the models (Table 3.3), the following comparisons are made:

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Table 3.3 Comparison of SWAT, ANSWERS 2000 and ACRU Hydrological Models processes

Model	Catchment Delineation	Evapotranspiration/ Reference Potential evaporation	River runoff routing	Runoff estimation Methods/Infiltration	Subsurface/Groundwater Estimation	Reservoir Processes	Land use changes processes
SWAT	Use of Digital Elevation Models (DEM's)	Evapotranspiration 1. Penman Monteith 2. Priestley Taylor method 3. Hargreaves method	1. Muskingum 2. Variable storage routing	SCS Curve Number method for runoff OR Green & Ampt Infiltration Method	Lateral subsurface flow using kinematic storage model and ground water flow using empirical relations (Bora and Bera, 2003)	Four outflow methods: i.e. 1. Measured daily outflow 2. Measured monthly outflow 3. Average annual release rate 4. Target release for	Incorporate tools that facilitate the study of various land uses.
ACRU	Cell type delineation by manually inputting information on subcatchments into model	Reference Potential Evaporation 1. A Pan method 2. Penman method 3. Hargreaves Method 4. Linacre Method 5. Blainey and Criddle method 6. Thornthwaite method	1. Muskingum Method 2. Muskingum Cunge	1. Modified US SCS equation method for runoff OR Green and Ampt Method for Infiltration	ACRU applies two response coefficients to baseflow generation. 1. drainage rate from the bottom subsoil horizon to intermediate groundwater/groundwater store. 2. Coefficient of baseflow realease of intermediate/groundwataer store into the stream.	Storage Indication Method	Model incorporates a Dynamic input option system (i.e. Decision support system) to facilitate land use studies.
ANSWERS 2000	Use of Digital Elevation Models	Evapotranspiration 1. Ritchie Method (1972) 2. Priestley Taylor Method	Mannings type Method	Manning's Method or Green and Ampt	Subsurface flow defined by tile drainage coefficient and ground water flow determined by the Darcy gravity flow method		Incorporates land use assessment tools

For runoff volume computation all three models can use the Green and Ampt (1911) infiltration model, in addition SWAT employs the method of US Soil Conservation Service (SCS) Curve Number method whilst ACRU uses a modified US SCS equation (Schulze 1995). The ANSWERS 2000 model which employs the Green and Ampt infiltration method requires 30 second time steps on days with rain and daily steps on days without rain. Such resolution of 30 seconds time step on rainy days is unavailable since rainfall data collected for this study does not have the intensity factor as they have been collected with rain gauges and not rain recorders.

On catchment delineation, ANSWERS 2000 and SWAT both require DEMs of good resolution for effective catchment delineation. Resolutions of 30 m x 30 m for ANSWERS 2000 and for SWAT not bigger than 200 m x 200 m would be unavailable. Thus the manual delineation employed by ACRU is the most preferred.

When the processes of evaporation and transpiration were considered in these models, SWAT computed evapotranspiration using methods such as Penman Montieth, Priestley Taylor and Hargreaves whilst ANSWERS 2000 uses Ritchies method. ACRU on the other hand considered reference potential evaporation using the Penman, A Pan, Hargreaves, Linacre, Blainey and Criddle and Thornthwaite methods; eleven methods in all depending on the type of data, i.e. daily or monthly input data, temperature or radiation data. The use of the Ritchie method by ANSWERS 2000 requires the Leaf Area Index (LAI) data based on the stage of the crop development. These data are unavailable for this study. In the case of SWAT, the use of Apan data does not feature in the user manual (Neitsch et al., 2001) and therefore uncertainty exists on using Apan data. In ACRU the accurate estimation of daily reference potential evaporation (E_r) is viewed as vital in the ACRU model, particularly when simulations are performed in regions such as southern Africa, where an estimated 91% of mean annual precipitation (MAP) is returned to the atmosphere by total evaporation (Whitmore, 1971), as against a global average

of 65-70% (Ward, 1975; cited by Schulze, 1995). With regards particularly to the A-pan as a reference crop evaporation, Schulze (1995) emphasised the fact that:

- the Penman and Penman-Monteith equations are de facto accepted standard methods for E_r ;
- that crop water use is related more closely to solar radiation than to A-pan evaporation (Turner and Wiersma, 1964), and;
- that the A-pan has been shown to overestimate crop reference evaporation by up to 30% (van Zyl et al., 1989).

However, its incorporation in the ACRU model according to the developers (Schulze, 1995) is because of the following reasons:

1. The Class Apan is universally the most common evaporation pan in usage, having been adopted as the standard evaporation pan since the International Geophysical year of 1957/8.
2. When operated properly it is accepted as a reasonably reliable, simple, inexpensive integrator of atmospheric evaporative demand over a time period and used commonly as a reference for potential evaporation (Green, 1998).
3. In Southern Africa, where the ACRU model has been used most frequently, crop coefficients relating consumptive water use of the plant/soil continuum under different growth stages to a reference evaporation, have been tried and tested most widely against the Apan.
4. Mathematically elegant physically based methods of estimating E_r , such as the universally accepted Penman based methods (e.g. Penman 1948) make high demands on input data, including net radiation, wind and vapour pressure deficits. These data are not yet readily available in many stations in Southern Africa. On the other hand, there is often at least a rudimentary network of Apans in Southern Africa (e.g. over 750 Apans exist in Southern Africa) (Schulze and Maharaj, 1991).

The data situation with regard to evapotranspiration enumerated above also applies to western Africa and the Densu (WARM, 1998). However, Schulze (1995) recommends that physically based equations such as Penman's should be used in ACRU where relevant data are available, and at those locations should, in fact, generally be used in preference to A-pan data for E_r .

3.3.7 Model Selected.

From the preceding Sections and considering the criteria developed, the ACRU model has been selected for this research. The reasons are that in an economically poor region like West Africa there are two potentially important pragmatic advantages of ACRU for its wider future use in the region:

1. That amongst the models reviewed, it has the lowest computing requirements. ACRU can run on a PC that has no chance of running SWAT or ANSWERS 2000.
2. That in addition to not requiring a DEM, it does not require digital versions of all of its spatial datasets- if ANSWERS 2000 and SWAT were to be chosen, then all of the soil maps and landuse maps would need to be digitized and projected- there is an expense in doing this, as well as logistical difficulties.

In addition, other reasons for selecting ACRU are:

3. Rainfall data for ANSWERS 2000 is required at a 30 second time step. Although there are rainfall generators or disaggregators that might allow the derivation of such rainfall input data such as Weather Generators (WGEN) Richardson and Wright (1984), and US Climate Generator (USCLIMATE) (Harmel et al., 2000), the widespread availability of parameterization data and expertise is unlikely in West Africa;
4. The complexity and data requirement in relation to crop growth in SWAT are in excess of what are available to this study.
5. In Ghana, the usual means of collecting evaporation data is with the A Pan which only ACRU uses. ACRU has more options to consider from the methods that can be used to compute reference potential evaporation if one method is not appropriate in terms of data availability.

However, other weather variables for some of the other methods are discussed in Chapter 4.

6. In southern Africa where to date the ACRU model has been used most frequently, crop coefficients, relating consumptive water use of the plant/soil continuum under different growth stages to a reference evaporation, have been tried and tested most widely against the A-pan. It has been used in forested catchments e.g. Marite sub catchments in Southern Africa (Jewitt and Schulze, 1999) with annual rainfall between 900-1400mm which is similar to that for the Densu Basin. The Marite sub catchments lies within latitude 24°49'S-24° 52'S and longitudes 31°00'E-31°02'E and lies in the humid tropics zone defined by McGregor and Nieuwolt. (1998). According to Jewitt and Schultz (1999) the Nash and Sutcliffe coefficient for the simulation was 0.61 which is good. As ACRU has been successfully applied to a Tropical catchment it suggests the ACRU model could be used in the Densu basin.

3.4 Description of the Model Selected, ACRU

3.4.1 Model Configuration and computing requirement

The ACRU modelling system is made up of a number of discrete, but interlinked, components. As shown in Figure 3.5 the ACRU model requires an input MENU file (ACRU input utilities and decision support system), a file to indicate to the model which variables are to be stored for subsequent output and analysis; a file containing hydrometeorological data and an optional "dynamic" file. A suite of independent programs, the ACRU input utilities, have been written to assist in the preparation of the input data and information files. Similarly, the ACRU Output Utilities are used to obtain output from the model and to perform statistical analysis.

ACRU, which is written in FORTRAN 77, consists of a modularly structured main program which calls over 150 subroutines. ACRU was originally

developed in a mainframe environment, but has been updated on a DOS based PC.

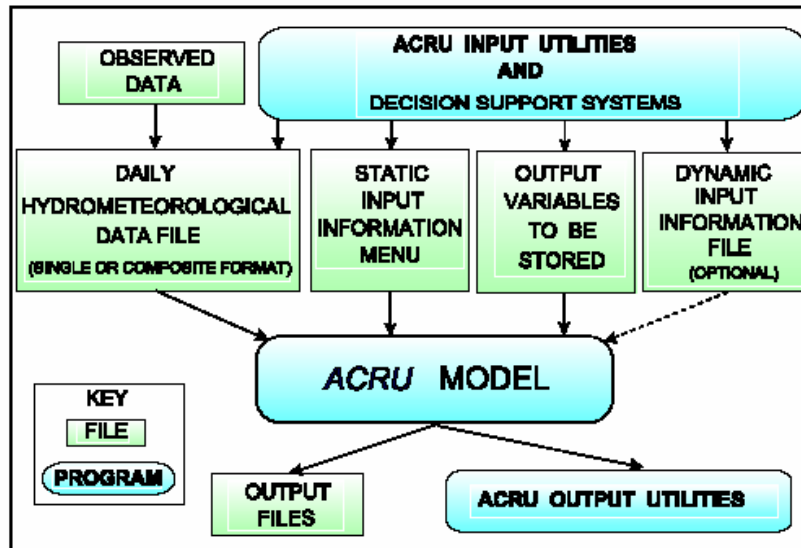


Figure 3.5 Components and linkages of ACRU modelling system (Shulze, 1995)

An optional Arc View interface has since been incorporated into the modelling system to facilitate representation of the catchment, extraction of input parameters, model runs and viewing of the results.

3.4.2 Model Theory

The ACRU manual (Schulze, 1995) has detailed information on the ACRU Modelling system. However, a summary is given in this Section.

The ACRU model has the following properties:

1. It is a physical conceptual model, i.e. it is conceptual in that it conceives of a system in which important processes and couplings are idealised, and physical to the degree that physical processes (Figure 3.6) are represented explicitly. See Annex A for a commentary on Figure 3.6.
2. ACRU is not a parameter fitting or optimising model and variables (rather than optimised parameters) are estimated from physical characteristics of the catchment.

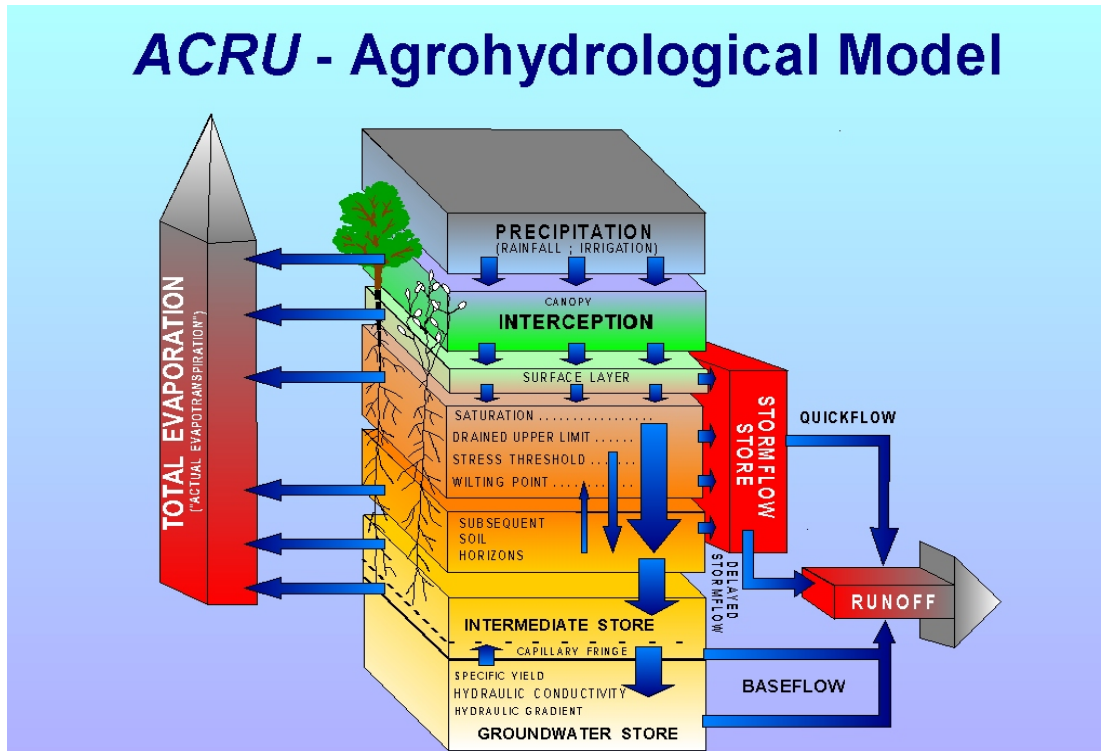


Figure 3.6 ACRU Agro-hydrological Model showing processes (from Schulze, 1995)

3. The model uses daily time steps and thus daily rainfall input, thereby making optimal use of available data. Certain more cyclic, conservative and less sensitive variables (e.g. temperature, reference potential evaporation), for which values may have to be input at monthly level (if daily values are not available), are transformed internally in ACRU to daily values by Fourier Analysis without any calibration. The appropriateness of these Fourier analysis and synthetic disaggregation methods with regard to tropical conditions are yet to be determined.
4. The ACRU model revolves around daily multi-layer soil water budgeting. It has been structured to be highly sensitive to climate and to land cover/use changes on the soil water and runoff regimes, and its water budget is responsive to supplementary watering by irrigation, to changes in tillage practices or to the onset and degree of plant stress.

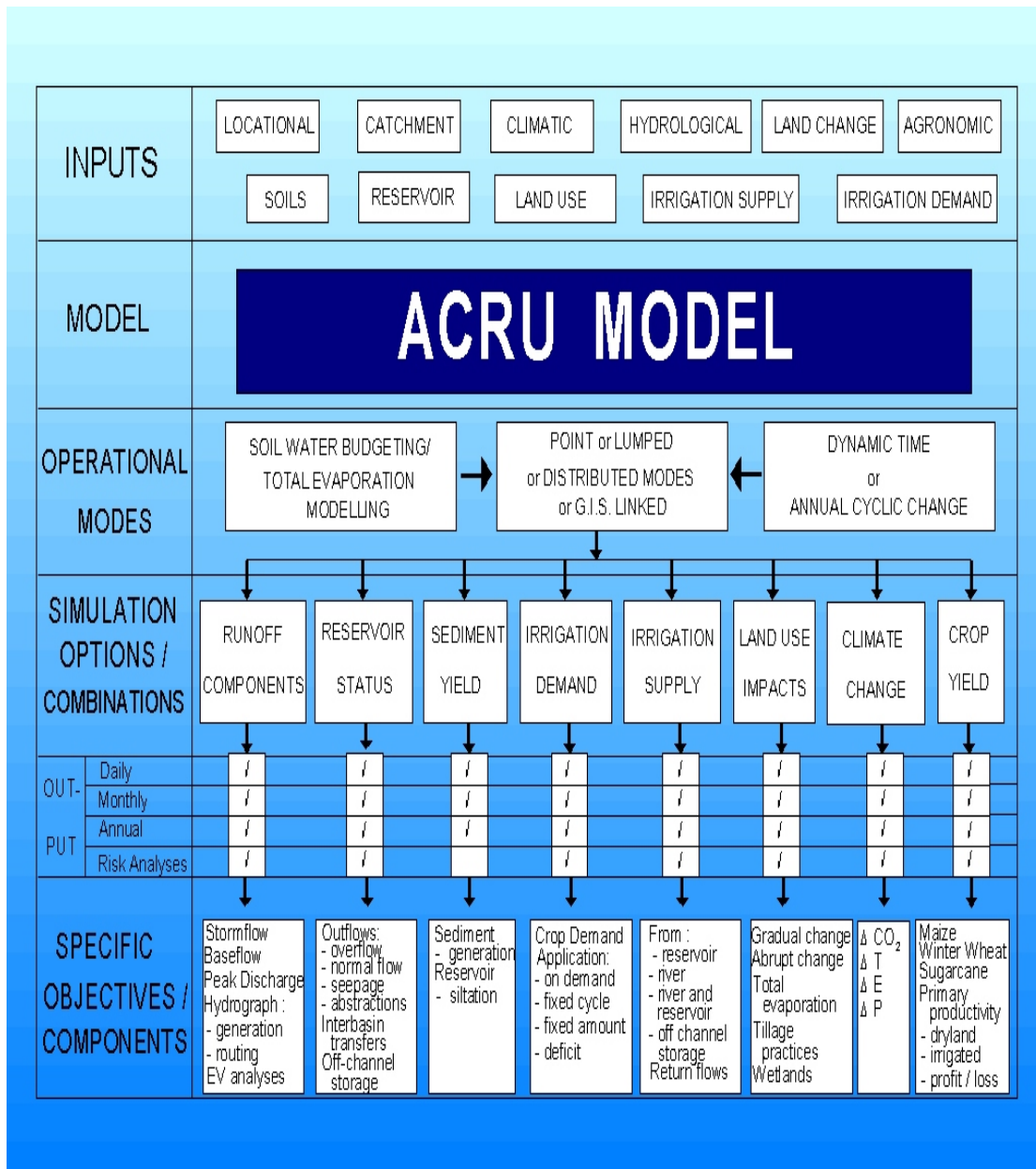


Figure 3.7 The options of ACRU model (from Schulze, 1995).

- ACRU has been designed as a multi-level model, with either multiple options (Figure 3.7) or alternative pathways (or a hierarchy of pathways) available in many of its routines, depending on the level of available input data available or the detail of output required. Thus, for example, reference potential evaporation, interception losses, values of soil water retention constants, maximum (i.e. "potential") and total evaporation ("actual evapotranspiration"), leaf area index, components of the peak discharge

estimation, hydrograph routing, reservoir storage : area relationships or the length of phenological periods in crop growth, all may be estimated by various methods according to the level of input data at hand or the relative accuracy of simulation required.

6. ACRU can operate as a field or as a lumped small (30km²) catchment model. However, for large (4000km²) catchments or in areas of complex land uses and soils ACRU can operate as a semi-distributed cell-type model. In semi-distributed mode, individual sub catchments (ideally not exceeding 30 km²) are identified, discretized and flows can take place from "exterior" through "interior" cells according to a predetermined scheme, with each sub catchment able to generate individually requested outputs which may be different to those of other sub catchments or with different levels of input/information.
7. The model includes a dynamic input option to facilitate modelling the hydrological response to climate or land use or management changes in a time series, be they long term/gradual changes (e.g. forest growth, urbanisation, expansion of irrigation project or climate trends), or abrupt changes (e.g. clear felling, fire impacts, construction of a dam, development of an irrigation project, or introduction of new land management strategies such as tillage practices), or changes of an intra-annual nature (e.g. crops with non-annual cycles, such as sugarcane). A dynamic input file is then accessed each year with the new variable inputs to be used from that year onwards, e.g. crop coefficients, root mass distributions, planting dates or soils properties (for new tillage practices).
8. ACRU operates in conjunction with the interactive ACRU Utilities, which are a suite of software tools to aid in the preparation of input information (e.g. the ACRU Menubuilder) and output information (e.g. the ACRU Outputbuilder). The ACRU Menubuilder prompts the user with unambiguous questions, leading the user into inputting, for example, complex distributed catchment information easily. The Menubuilder contains alternative decision paths with pre-programmed Decision Support Systems. Furthermore, the

Menubuilder includes a help facility, built-in default values as well as warning and error messages.

9. ACRU operates on a daily time step and since rainfall is the driving input variable of the model, the minimum daily data requirement should include a period of daily rainfall data. In addition, the model requires some compulsory and other optional information (Figure 3.8).

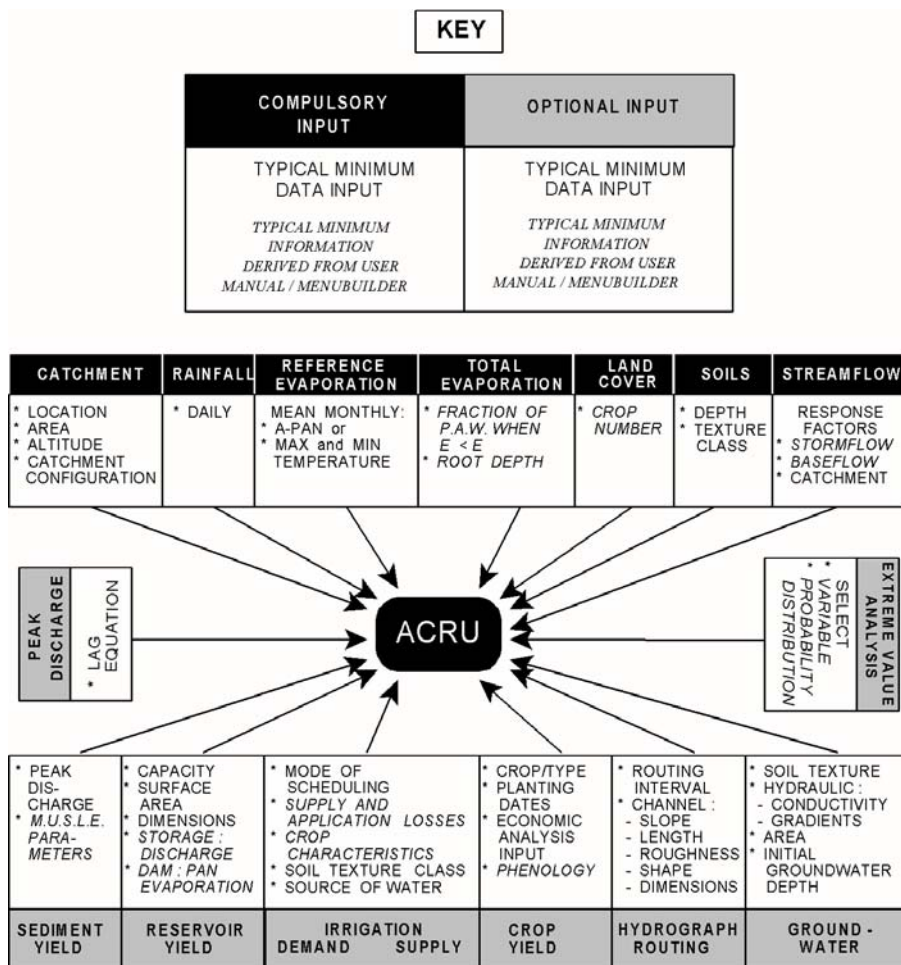


Figure. 3.8 Data requirements for the ACRU model (from Schulze, 1995)

3.4.2.1 Canopy Storage

Important to hydrological modelling is the canopy storage or interception loss, i.e. the portion of the precipitation which, after interception, does not reach the ground because it is retained by the aerial portion of the vegetation, to be either absorbed by it or returned to the atmosphere by evaporation. Interception loss may be viewed as the difference between gross and net precipitation (Schulze, 1995). On a day with rainfall, the net precipitation available for subsequent

addition to the soil water budget or for eventual stormflow (the water which is generated on or near the surface of a (sub) catchment from a rainfall event, to contribute to flow in the streams within that (sub) catchment) generation, is calculated from the difference between gross precipitation and the canopy interception losses for the day. On a day following a day with rainfall, the remaining potential evaporation, after the wet canopy evaporation has been completed, is then available for the transpiration process from the dry canopy and soil water evaporation.

The Von Hoyningen-Huene (1983) approach is employed as the estimator of canopy or interception loss in ACRU (Shulze, 1995).

3.4.2.2 Infiltration

Infiltration is the process whereby rainfall or irrigated water enters the soil profile. Redistribution is the process which occurs once infiltration has terminated and may be defined as the process whereby water moves through the unsaturated soil profile, either towards the surface by soil water evaporation and/or transpiration induced capillary action, or downwards by gravity toward the groundwater store. The Green and Ampt method calculates infiltration (sub daily) as a function of the redistribution rates for different soil horizons only if curve number (CN) method is not used.

3.4.2.3 Evapotranspiration

The combination of two separate processes whereby water is lost on the one hand from the soil surface by evaporation and on the other hand from the crop by transpiration is referred to as evapotranspiration. ACRU is described as a multi-layer soil water budgeting model and that most rainfall is transformed into evaporation either through the soil or through the plant (evapotranspiration). In ACRU evaporation takes place from previously intercepted water as well as simultaneously from the various soil horizons, in which case it is either split into separate components of soil water evaporation (from the topsoil horizon only) and plant transpiration (from all horizons in the root zone), or combined, as

total evaporation. Evaporative demand on the plant is estimated, inter alia, according to atmospheric demand (through a reference potential evaporation) and the plant's stage of growth. The roots absorb soil water in proportion to the distributions of root mass density of the respective horizons, except when conditions of low soil water content prevail, in which case the relatively wetter horizons provide higher proportions of soil water to the plant in order to obviate plant stress as long as possible. In ACRU the reference potential evaporation is the evaporation from the United States evaporation class Apan i.e. E_{apan}

During hydrological modelling in ACRU, vegetation (natural vegetative cover) and land use (implying anthropogenic influence through building roads, cropping, including plantations, as well as agricultural practices such as irrigation and/or tillage operations) processes may be grouped functionally into

1. *above-ground* factors, implying
 - canopy interception losses
 - consumptive water use by plants and
 - shading of the soil, into
 - evaporation of water from the soil surface and
 - evaporation of water from plant tissue (transpiration)
2. *surface* factors, which focus on
 - protection by the plant/litter cover against erosion, and
3. *below-ground* factors, concerned with
 - plant root distribution
 - root water uptake and
 - the onset of plant stress.

To estimate vegetation water use the concepts of crop coefficient, maximum evaporation and reference potential evaporation are used and leaf area index (LAI) where available is also employed. This LAI approach uses the Von Hoyningen-Huene (1983) method in Shulze (1995) to account for the basic physical processes of evaporation and empirically derived crop coefficients to account for specific vegetation conditions.

Total evaporation, E , may equal or be less than the maximum evaporation, E_m , also termed "potential evapotranspiration". On a given day, E can be reduced to less than E_m either when soil water has been depleted below a critical threshold value (when plant stress sets in) or when there is an excess of water in the soil profile. Actual soil water evaporation, E_s , is computed from the topsoil horizon. E_s for the day can either be occurring at maximum (or "stage one") rate (E_{sm}) if a minimum threshold of soil water resides in the topsoil horizon, or below the maximum rate once soil water content has dried to a "stage two" level, in which case E_s declines very rapidly with time.

Actual plant transpiration (E_t) is calculated next, initially for the topsoil horizon, then from the subsoil horizon where transpiration is determined based on whether there is soil water deficiency or soil water excess. More details on the various E_t processes, which include soil water stress being induced either from a soil water deficiency or excess, are given in Chapter 7 of ACRU Theory Manual (Shulze, 1995).

3.4.2.4 Surface runoff

In the ACRU model, runoff is generated as stormflow dependent upon the magnitude of daily rainfall in relation to dynamic soil water budgeting. The generated streamflow in a (sub) catchment comprises baseflow and stormflow, with the stormflow component consisting of quickflow response, i.e. stormflow released into the stream on the day of the rainfall event, and a delayed stormflow response, i.e. in essence a surrogate for post-storm interflow. The generation of stormflow in ACRU is based on the premise that, after initial abstractions (through interception, depression storage and infiltration before runoff commences), the runoff produced is a function of the magnitude of the rainfall and the soil water deficit from a critical response depth of the soil. The soil water deficit antecedent to a rainfall event is simulated by ACRU's multi-layer soil water budgeting routines on a daily basis. A modified United States SCS curve number method is used for computing the daily stormflow where the

potential maximum retention of the curve number is replaced by a soil water deficit.

The ACRU model utilises the United States Department of Agriculture's Soil Conservation Service (SCS) unit hydrograph concepts in order to compute the peak discharge from the generated daily stormflow volume. For realistic total storm hydrographs, standard unit hydrograph convolution procedures should be used to superimpose the single unit hydrographs in specified time steps according to the temporal distribution of effective rainfall within a day. However, when using a daily model and in the assumed absence of recording rainfall data or, alternatively, in the absence of a realistic synthetic rainfall distribution over time for a particular event, a uniform rainfall distribution is assumed. In ACRU, when the hydrograph routing option is not invoked, a single rather than an incremental unit hydrograph is used for peak discharge computation.

3.4.2.5 Baseflow

Baseflow consists of water from previous rainfall events that has percolated through the soil horizons into the intermediate and groundwater zones and then contributes as a delayed flow to the streams within a (sub) catchment. ACRU applies two response coefficients to baseflow generation. The first relates the drainage rate of water out of the bottom subsoil horizon store, when its soil water content exceeds the drained upper limit, into the intermediate/groundwater store. This response rate is slower for heavy textured than for light textured soil.

The second response coefficient concerns baseflow release of water from the intermediate/groundwater store into the stream. This coefficient depends intrinsically on factors such as geology, catchment area and slope. If, on a given day, no contribution is made to the baseflow store by drainage, then baseflow releases are calculated as the product of the previous day's groundwater store and a user specified coefficient of baseflow (second response coefficient). The baseflow store's magnitude is then reset.

3.4.2.6 River Runoff Routing

In ACRU, the assumption that stormflow generated on a particular day passes to the catchment outlet on the same day is considered valid for small (30km²) catchments, but not necessarily true of larger catchments. When the ACRU model is applied in the semi distributed mode on larger catchments, the option to invoke the hydrograph routing options in order to reflect the translation and attenuation of the hydrograph taking place through river reaches and reservoirs encountered en route to the catchment outlet is available. Three methods used for routing in ACRU model are the Storage indication method, the Muskingum method and the Muskingum Cunge methods.

3.4.2.6 Next Step

Having reviewed models to find an appropriate one to use for the PhD, the ACRU model was found to be the most appropriate when the models were judged against a set of selection criteria. With the relevant processes of the ACRU model already described the next step is to identify the appropriate data required for a successful hydrological modelling. In the next chapter the data availability, analysis and the model setup required are presented.

4. Data Availability, Analysis and Model Setup

This Chapter presents the data available together with their analysis for their suitability for the intended research. Finally how the model is set up for the modelling of the Densu Basin discussed in Chapters 2 and 3 is also presented.

4.1 Data Availability

In Chapter 3, the ACRU Agrohydrological model was selected which requires the following minimum data requirements:

- Weather (daily or monthly):
 - o observed rainfall and,
 - o minimum and maximum temperatures or;
 - o A pan evaporation (see Chapter 3.4.2.3).
- Other data required include:
 - o soil data, including field capacities, permanent wilting points, porosities of soil horizons, depth of soils and redistribution rates for both top and bottom soil horizons.
 - o landuse data, and model parameters such as fraction of the catchment occupied by impervious areas which are not adjacent to a watercourse (e.g. house roofs discharging onto lawn) (DSIMP) and surface storage capacity (i.e. depression storage, or initial abstraction) of impervious surface, which needs to be filled before stormflow commences (STOIMP).

The available hydrometeorological data for this study are shown in Table 4.1. These represent the data which could be accessed from data archives of meteorological data collecting agencies. It is likely that additional hardcopy data for some other periods and time frames exist, but logistical constraints due to poor filing, archiving and accessibility meant that they proved impossible to trace.

From the data availability (Table 4.1) and considering the minimum data requirements for the ACRU model, the period 1968-1972 was selected for the modelling exercise because the minimum data requirements could be found in this period. Beyond this period the streamflow data availability is variable because of irregular collection of observed data although the data for 1973-1974 are better than the remaining years and further analysis would be undertaken in this period to see how the model fares. Other data available for

Table 4.1 Data Availability for the study

		1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991
Rainfall (Daily)	Accra																																
	Koforidua																																
	Nsawam																																
Stream Flows (Daily)	Accra																																
	Koforidua																																
	Nsawam																																
Temp Min/Max (Monthly Means)	Accra																																
	Koforidua																																
	Nsawam																																
Sunshine Duration (Monthly Means)	Accra																																
	Koforidua																																
	Nsawam																																
Wind Speed (Monthly means)	Accra																																
	Koforidua																																
	Nsawam																																
Pan Evaporation Monthly Means	Accra																																
	Koforidua																																
	Nsawam																																
Rel Hum (Mon Means)	Accra																																
	Koforidua																																
	Nsawam																																

this PhD thesis are the soils of the area which were derived from local soil maps and from global data sets, landuse data from landuse maps and crop data. These data are described and analysed in detail in the following Sections.

4.2 Data Analysis

4.2.1 Rainfall

Daily rainfall data for the Densu catchment are available for over 50 years for two stations, Nsawam and Koforidua, which are still operating. Other stations

(see Table 4.2) had some data however; Nsawam and Koforidua were chosen because they were the most readily available and had longer duration. As explained in Section 4.1, these represent the data which could be accessed from archives. The data from the remaining rainfall stations at Aburi, Adeiso, Bunso, Kibi, Oyoko, Suhum and Tafo were unavailable due to poor filing and archiving from the meteorological data collecting agencies.

Table 4.2: Rainfall stations in the Densu Basin

Station	Period of Data	No of Years	Station	Period of Data	No of Years
Asuboi	1955 – 1971	16	Nsawam	1928 – date	>70
Aburi	1936 – 1971	35	Oyoko	1949 – 1971	30
Adeiso	1953 – 1971	18	Suhum	1939 – 1976	37
Bunso	1928 – 1978	50	Tafo	1939 – 1998	59
Kibi	1926 – 1978	52	Accra	1965.— date	>33
Koforidua	1953 – date	>45			

Prior to using these data in the modelling, a data screening procedure consisting of three principal steps (Dahmen and Hall, 1990) was followed:

- Initial screening of the data for accuracy and verifying totals for the hydrological year or seasons. This was done by tabulating daily totals and visual examination to detect whether the observations have been consistently or accidentally credited to the wrong day, whether they show gross errors (e.g. from weekly readings instead of daily ones) or whether they contain misplaced decimal points (Dahmen and Hall, 1990). Also noting 'no observation' instead of 'observation =0' and missing data.
- Plotting these totals (Figure 4.1) according to the annual time step and detecting any trends or discontinuities by visual examination (Dahmen and Hall, 1990).
- Testing the time series for the absence of a trend with Spearman's Rank Correlation coefficient, R_{sp} method (equation 4.1) and testing the trend for the Null hypothesis, $H_o: R_{sp} = 0$ (there is no trend) against the

alternate hypothesis, $H_1: R_{sp} < > 0$ (there is a trend) using the t_t statistic test for trend given in equation 4.3.

$$R_{sp} = 1 - \frac{6 \sum_{i=1}^n D_i^2}{n(n^2 - 1)} \quad \text{-----} \quad 4.1$$

where n is the total number of years used, i is the chronological order number and D is the difference between rankings: where D is shown in equation 4.2.

$$D_i = kx_i - ky_i \quad \text{-----} \quad 4.2$$

where kx_i is the rank of the variable x , which is the chronological order number of the observations; y_i is the series of observations and ky_i is its transformation.

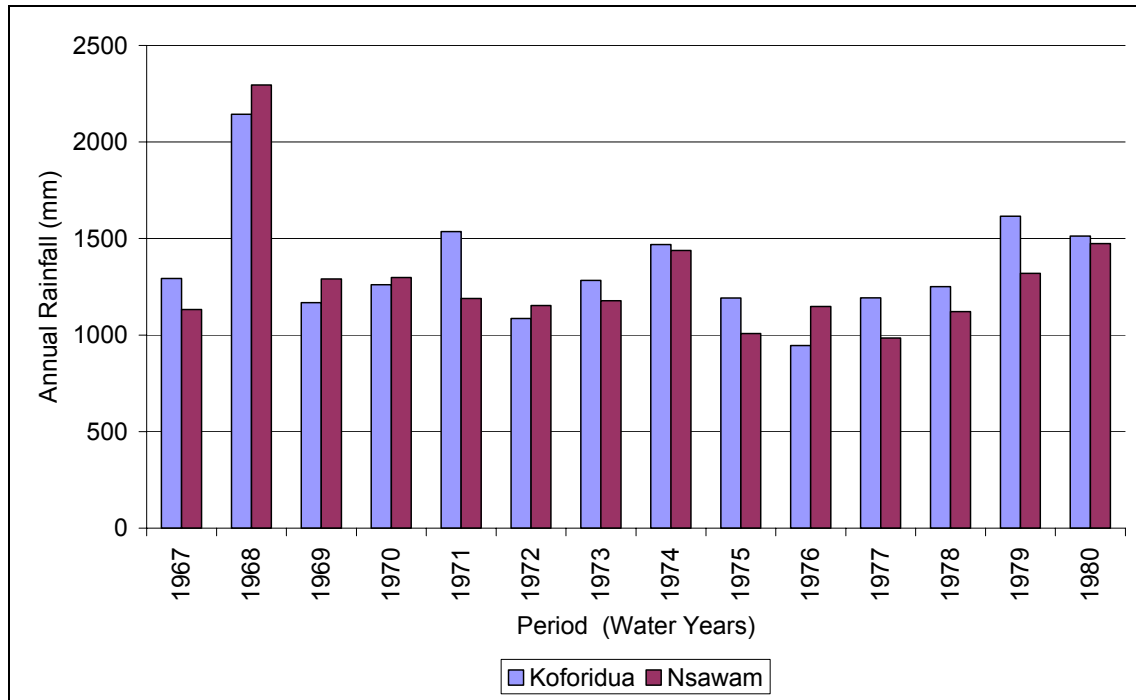


Figure 4.1: Annual rainfall distribution at Koforidua and Nsawam

$$t_t = Rsp \frac{(n-2)^{0.5}}{(1-Rs_p^2)^{0.5}} \quad \text{-----} \quad 4.3$$

where t_t has the student's t -distribution with $v=n-2$ degrees of freedom. At a 5% significance level, the H_0 is accepted if t_t (equation 4.4) is not contained in the critical region (the 5% level of significance for $n-2$ degrees of freedom).

In order words, the time series has no trend if

$$t\{v, 2.5\% \} < t_t < t\{v, 97.5\% \}. \quad \text{-----} \quad 4.4$$

The visual representation did not show any obvious annual anomalies for the period 1967-1972 which is the intended modelling period. The stationarity test could not be done for this period because the annual data series was less than 10 years. However since data for rainfall extends beyond 1972, the trend test up to 1980 was undertaken to check the period for stationarity because this period might be needed during the landuse analysis study which is part of the objectives of this PhD study.

If the time series does have a trend, the data cannot be used directly for frequency analysis or modelling (Dahmen and Hall 1990). Thus for this test the annual water year totals were used because according to Dahmen and Hall, (1990) it is 'perfectly acceptable and most convenient' if it is done annually and with the water years. Subjecting the two rainfall stations Nsawam and Koforidua to the above test using DATSCR software (DATSCR, 1990) i.e. Spearmans Rank correlation for the period 1967-1980 (period > 10yrs for meaningful analysis) water years (March to February of following year), gives the following output statistics:

Koforidua: Mean for the period is 1353.5 mm
 StDev; 293.01mm
 Spearman $t = -0.145$ making equation 4.1
 $2.5\% < (P=44.4\%) < 97.5\%$

Nsawam: Mean for the period is 1214.0
 StDev = 450.35mm
 Spearman $t = -0.531$ making equation 4.1
 $2.5\% < (P = 30.2\%) < 97.5\%$.

Following from above it is concluded that the individual stations, Nsawam and Koforidua fulfilled the condition (Equation 4.4) above and that there is no trend and the variance and mean are stable. Therefore the annual time series are stationary as given by Dahmen and Hall (1990) for this data screening method.

4.2.2 Evaporation

The availability of Evaporation data, like the previously described data, was found to be limited and only available at the Koforidua and Accra stations. The evaporation information available was the pan evaporation using the USA class

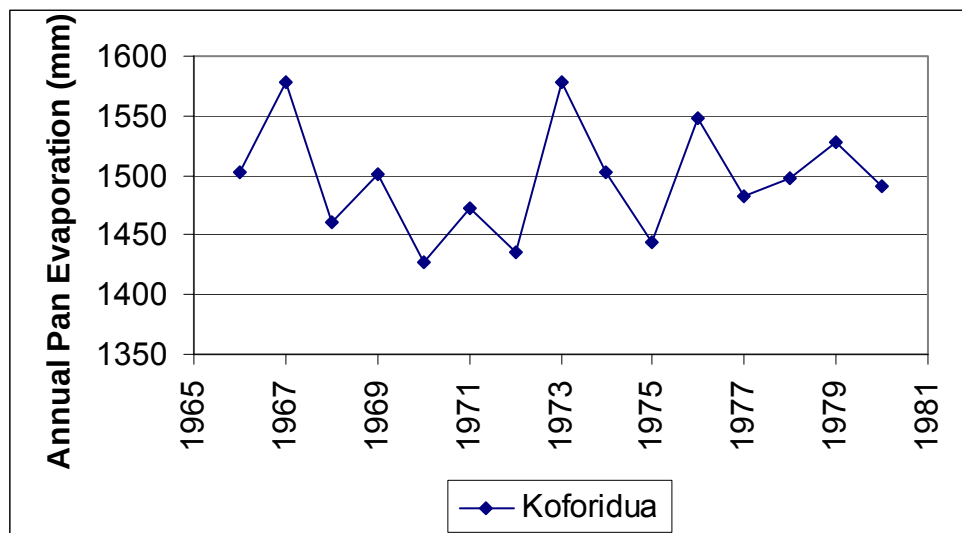


Figure 4.2 Annual A pan Evaporation for the Koforidua station.

A pan. The Class 'A' evaporation pan is a 1.21m (4ft.) diameter circular pan filled with water, from which the daily rate of evaporation from the pan is determined from the change in water level (adjusted for rainfall) (Doorenbos, 1976). Monthly means together with daily data were collected with the monthly

means more common than the daily data. The daily data were available only for the periods, September-December of 1967 and for January to December of 1971 with data for the remaining periods available as monthly means. Figure 4.2 shows the computed annual pan evaporation for the Koforidua station.

The annual mean pan evaporation for the period 1966-1980 (Figure 4.2) is 1525mm with standard deviation of 57.7mm. For this period, the trend analysis according to Dahmen and Hall (1990) gives a Spearman t of -0.575 resulting in the condition (equation 4.4) giving a $2.5\% < (P=28.8\%) < 97.5\%$ making the series stationary and without trend. A plot of monthly mean (Figure 4.3) of A-pan evaporation at Koforidua shows that February to April have the highest evaporation rates with July and August having the lowest. They range between 3 - 5 mm/day as monthly means rendering average daily evaporation rate for the station as 4.1mm.

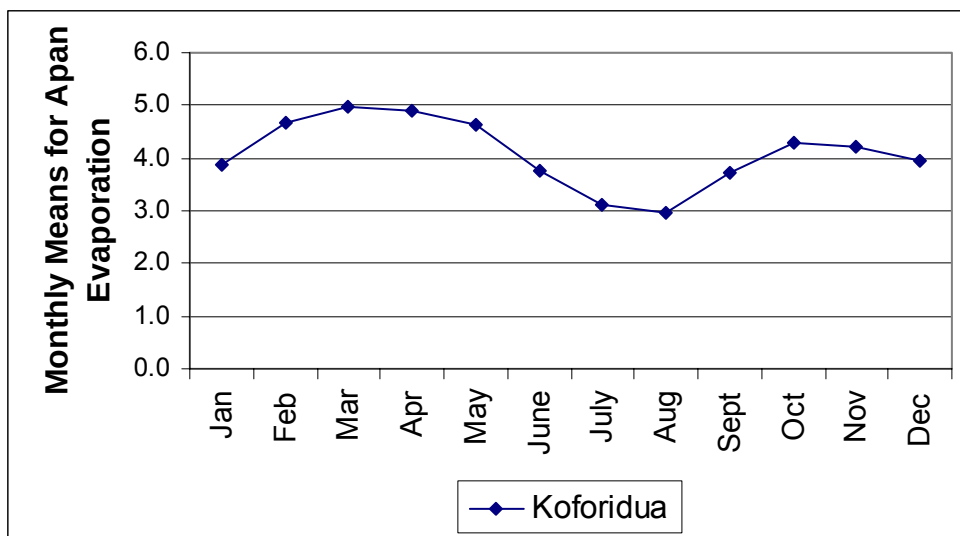


Figure 4.3: Monthly means of Apan Evaporation at Koforidua in mm/day.

Hess (1996) noted in a study in UK that pan evaporation without the use of a pan coefficient may be 25% to 100% greater than E_{To} (the evapotranspiration rate from a reference surface, not short of water where the reference surface is a hypothetical grass reference crop with specific characteristics; (Allen et al., 1998)) depending on the location of the pan and the weather conditions.

However, published tables by Allen et al. (1998) suggest that for the tropics with mean daily temperatures between 20°C and 30°C and wind speed $<2\text{ms}^{-1}$, the ratio of ET_0 to pan evaporation would be ≈ 0.85 (representing the value of the pan coefficient K_p). The average monthly mean reference crop evapotranspiration (for grass) for the station can be calculated from

$$ET_0 = K_p E_{pan} \dots\dots\dots 4.5$$

where ET_0 is reference evapotranspiration (mm/day), K_p is pan coefficient, and E_{pan} is pan evaporation (mm/day).

Using equation 4.5 and the data shown in Figure. 4.3 gives a mean monthly ET_0 of 3.5 mm/day, ranging from 2.6- 4.3mm/day. These ET_0 values compare favourably with the range of 3-5 mm/day given by Allen et. al. (1998) for humid and sub-humid tropics with mean temperature between 20°C and 30°C.

4.2.3 Streamflow

According to OTUI (1996) data collection on river stage and flow of the Densu catchment is the responsibility of the Architectural and Engineering Services Corporation (AESC) Hydro division of Ghana, now the Hydro Division of the Ministry of Works and Housing. They are assisted in the collection of flow data for the catchment, through various projects, by the Water Resources Research Institute (WRRI) of the Council for Scientific and Industrial Research (CSIR), now the Water Research institute (WRI-CSIR). Flow stations within the basin have included Manhia, Nsawam, Pakro and Akwadum. Manhia was found, during a hydrological review in 1985 (OTUI, 1996), to have been seriously affected by backwater effects from the Weija Dam, which is located downstream of the flow station. The gauging site was therefore abandoned in 1985. A recommendation from the hydrological review to re-locate the Nsawam station was effected in 1986. However, because of crude construction (OTUI, 1996), this site, which was constructed about 50m away from the original Nsawam flow gauging station, was destroyed within a year of establishment, and has since

not been repaired. As a consequence, there is effectively no additional flow data collected since 1985. At Pakro, even though the original station was not abandoned until 1985, earlier stage level data were not processed for streamflow data and are therefore not available. Akwadum and Koforidua had stage level data but there are no rating curves for them, so that the data could not be used for modelling but could be used semi-quantitatively to look at timings of events, and onset of rainy season.

So, from the foregoing streamflow data were only available for Manhia (refer to Figure 5.13) from 1967-1980, with gaps of whole months and years within this period, and Nsawam (refer to Figure 5.15) from 1967 to 1975 with gaps. Attempts were made during this PhD study to collect new flow data for the study, as promised by the constituted Densu Basin Management Board. However, the flow data which was collected for the period 2001/2002 at two new gauging stations within the basin at Ashalaja (catchment area 2111.46km²) and at Pakro "New" (catchment area 1342.77km²) were destroyed in a fire that engulfed the offices of the collecting agencies (personal communication, with Hydrologist Water Resources Commission; Mr Odame Ababio, 2003). As at October 2004, rating curves for the period 2003 and beyond had still not been established for these two new gauging stations and therefore gauge height for Ashalaja for the periods 02/12/02-18/07/03 and 01/09/03-17/09/03 and Pakro "New" for the period 01/03/03-30/09/03 were unable to be used for this study as hoped.

The quality of the streamflow data could not be assessed using the trend analysis and test of stationarity because of insufficient length of data (Dahmen and Hall, 1990). The computed mean discharge at Manhia was 18.17m³/s for the period and annual flows for the 1968-1972 water years are shown in Figure 4.4. It appears that 1968 has a very high annual average rate as compared to the rest of the years, owing to the unusual high rainfall in that year (Figure 4.1).

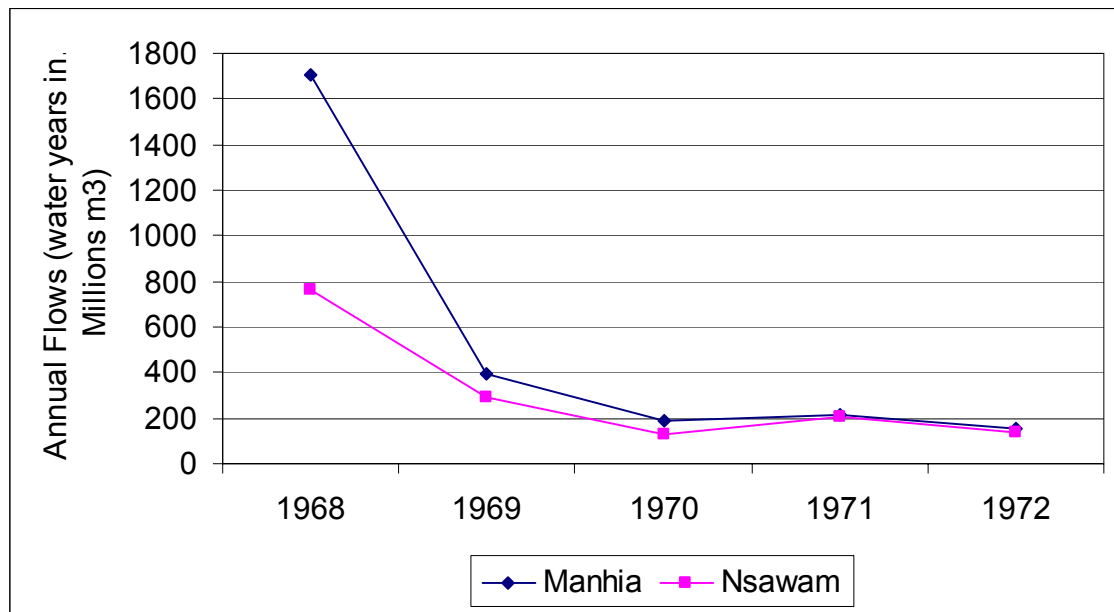


Figure 4.4: Annual Streamflow data for Manhia and Nsawam

4.2.4 Landuse Data

Landuse and management data for the study area have been obtained from the Remote Sensing Application Unit, now the Centre for Remote Sensing & GIS (CERGIS), of the Department of Geography of University of Ghana, landuse maps of the area (WRI, 2002 and Nii Consult, 2001), written information on vegetation and relief of the area (Benneh et al., 1990) and from personal communication with researchers that have worked or lived in the area. The WinDIAS 2.0 colour image analysis system and software developed by Delta T Devices (<http://www.delta-t.co.uk/>) were used to calculate the proportions of the land uses in the basin from the areas portrayed (Figure 4.5) on the paper landuse map of WRI (2002).

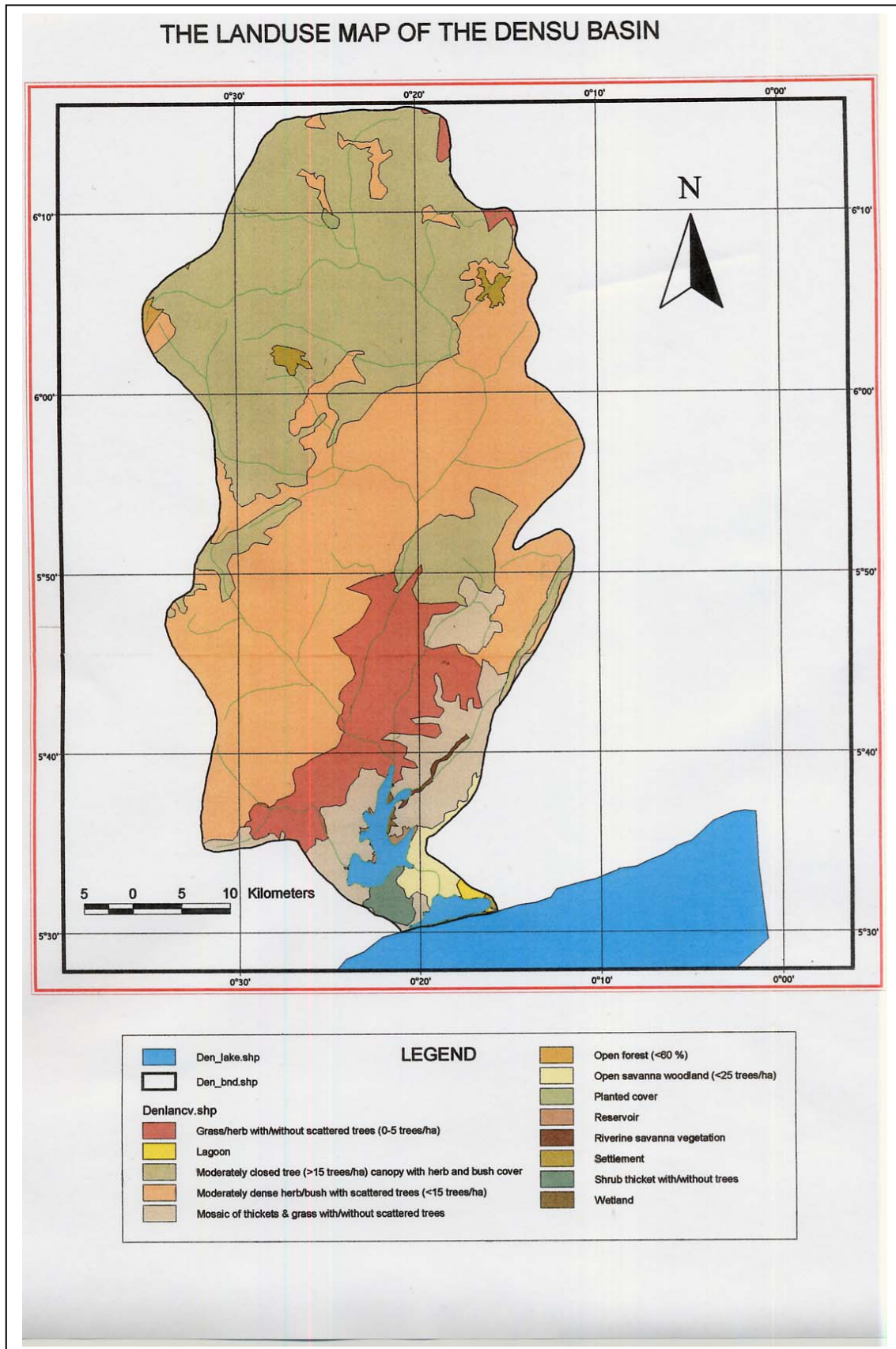


Figure 4.5 Land Use map of Densu Basin (Year 1990) (Courtesy WRI-Ghana, 2002)

The following landuse parameters were needed for each landuse type used in ACRU: Vegetation interception loss (VEGINT); monthly fraction of effective root system in A horizon (ROOTA), monthly Crop coefficients (CAY) for the pervious land cover of a catchment/subcatchment (i.e. the fraction of water “consumed” by a plant under conditions of maximum evaporation in relation to that evaporated by an A-pan in a given period) and a monthly Coefficient of initial abstraction (COIAM).

The Densu Basin has been described in OTUI (1996) and Nii Consult (2001) as having vegetation comprising of moist semi deciduous forest from the north and graduating through a small belt of transitional zone to savannah vegetation of thickets and grassland to the south. With this knowledge the basin was categorized with the help of the paper landuse map of the basin (Figure 4.5), knowledge of the area (many visits to the basin) and figures for land use parameters deduced with the assistance of land use tables developed for ACRU with the background knowledge that ACRU has been used in forest regions (Jewitt and Schulze, 1999) and in similar climatic weather conditions. The various initial uncalibrated landuse parameters for the basin are shown in Tables 4.3 – 4.7 based on the classification in Figure 4.5. In Figures 4.6 and 4.7, typical land use types observed in the Densu Basin are shown.

Table 4.3 Moderately closed tree (>15/trees/ha) canopy with herb and bush cover – initial model parameters

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
VEGINT(mm.rainday ⁻¹)	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
ROOTA (m)	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
CAY	0.8	0.8	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.8	0.8
COIAM	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35

Table 4.4** Land use parameters for moderately dense herb/bush with scattered trees (<15 trees/ha)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
VEGINT (mm.rainday ⁻¹)	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0
ROOTA (m)	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
CAY	0.8	0.8	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.8	0.8
COIAM	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35

Table 4.5 Land use parameters for Grass/herb with/without scattered trees (0-5 tree/ha)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
VEGINT (mm.rainday ⁻¹)	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
ROOTA (m)	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
CAY	0.7	0.7	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.7	0.7
COIAM	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2

Table 4.6 Land use parameters for Mosaic of thickets & grass with/without scattered trees

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
VEGINT (mm.rainday ⁻¹)	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
ROOTA (m)	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
CAY	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
COIAM	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1

Table 4.7 Landuse parameters for Settlement

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
VEGINT (mm.rainday ⁻¹)	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8
ROOTA (m)	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8
CAY	0.7	0.7	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.7	0.7
COIAM	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2

* Same values as for the moderately closed tree except that tree counts are <15 trees/ha as against moderately closed >15trees/ha



Figure 4.6 Land Use types for the Mosaic of thickets & grass with/without scattered trees, (Source: Water Research Institute, CSIR, Ghana)



Figure 4.7: Typical land use types showing the (a & b) moderately dense herb/bush with scattered (<15 trees/ha) trees and (c & d) the moderately closed tree (>15/trees/ha) canopy with herb and bush cover – (Source: Water Research Institute, CSIR Ghana)

4.2.5 Soil Data

Soil data with key physical properties were derived from, or estimated, using Adu and Asiana (1992) who studied the soils of the basin and regression equations by Hutson (1984) and Shulze et al., (1985). Complementary large scale datasets were also evaluated, including soil water holding capacities from Bouwman et al. (1993) and Batjes (1997). The soils information needed for this study as demanded by ACRU (Shulze, 1995) are:

- depths of each soil horizon
- Field Capacities (FC) and permanent wilting points (PWP)
- the porosities of the soil horizons
- surface properties (e.g. crusting & cracking) which affect infiltration rate, i.e. water entry rate into the soil
- the proportion of clay, sand and silt within the soil horizons, as they relate to the redistribution rates of water and
- soil redistribution rates

The soil map (Annex B) of the area including the Densu Basin taken from Adu and Asiama (1992) together with soil information derived from soil profiles within the Densu basin and an adjacent basin (Ayensu) were used to generate the depths of the various horizons, the textural classes and the vertical clay content of the soils. Within the catchment of the Densu Basin, Adu and Asiama (1992) depict eight soil series (Table 4.8) with their corresponding Food and Agriculture Organization (FAO) soil classifications (FAO, 1988). Table 4.8 also shows the percentage that each soil series occupies in the basin, with a description of the soil texture and average depths of the A and B horizons.

To compute the field capacity (FC) and permanent wilting points (PWP), porosity, and redistribution rates of the soils in this catchment pedo transfer functions were used. As cautioned by De Vos et al. (2005), published pedo transfer functions (PTF's) show large differences in performance and should be used with care when applied in environments other than the ones in which they were calibrated. However, Nemes et al. (2001) did note that many simulation models require water retention and hydraulic conductivity data which are difficult and time consuming to measure. They noted that one way of overcoming this is through the development of PTF's from easily measured data. Pachepsky and Rawls (1999) did note that PTF's have been used in a wide range of studies,

Table 4.8: Soil class percentages and texture of Densu soils (Derived from Adu and Asiamah 1992)

Profile	Local Soil Series	FAO (1988) Classification	Percent Area (%)	Depth of Horizons		Typical Soil Texture
				A (cm)	B (cm)	
1a	Adawso	Haplic Lixisols	52.6	41	41-142	LS, SC
1b	Nsawam	Haplic Lixisols	9.7	25	25-142	SL, SC
1c	Koforidua/Nta	Ferric Luvisol	13.2	25	25-123	SC, MSC
1d	Nta-Offin	Gleyic Arenosol	5.4	25	25-127	LS, S
2b	Atewa	Rodic Nitisol	1.8	25	25-226	SL-SCL
2c	Kokoku	Dystic Nitisol	6.2	15	15-183	SCL, SC
3a	Mamfe/Oyarifa	Rodic Nitisol	7.1	31	31-229	SC, CL
4b	Densu/Chichewere	Eutric Vertisols	4.0	54	54-130	SL, L, CL

Where S=Sandy or Sand, C=Clay/Clayey, L=Loam/Loamy, M=Medium

e.g. to assess water yields (Vertessy et al., 1993) and evapotranspiration losses (Famiglietti and Wood, 1994) and have been used to estimate volumetric soil water content at -33kPa (Θ_{33}) and -1500kPa (Θ_{1500}) on a wide range of soils.

Following from the above and in the absence of the necessary measured soil data for input into ACRU, the pedo transfer functions developed from Southern African data were employed with the knowledge that the model has been applied in a region where similarities with the Densu basin occurs in climate and rainfall patterns (Jewitt and Schulze, 1999); and soils (University of Minnesota, 2005 and University of Köln, 2005) where Luvisols and Arenosols which are found in the Densu basin are also found in the South African region as shown in Figures 4.8 and 4.9.

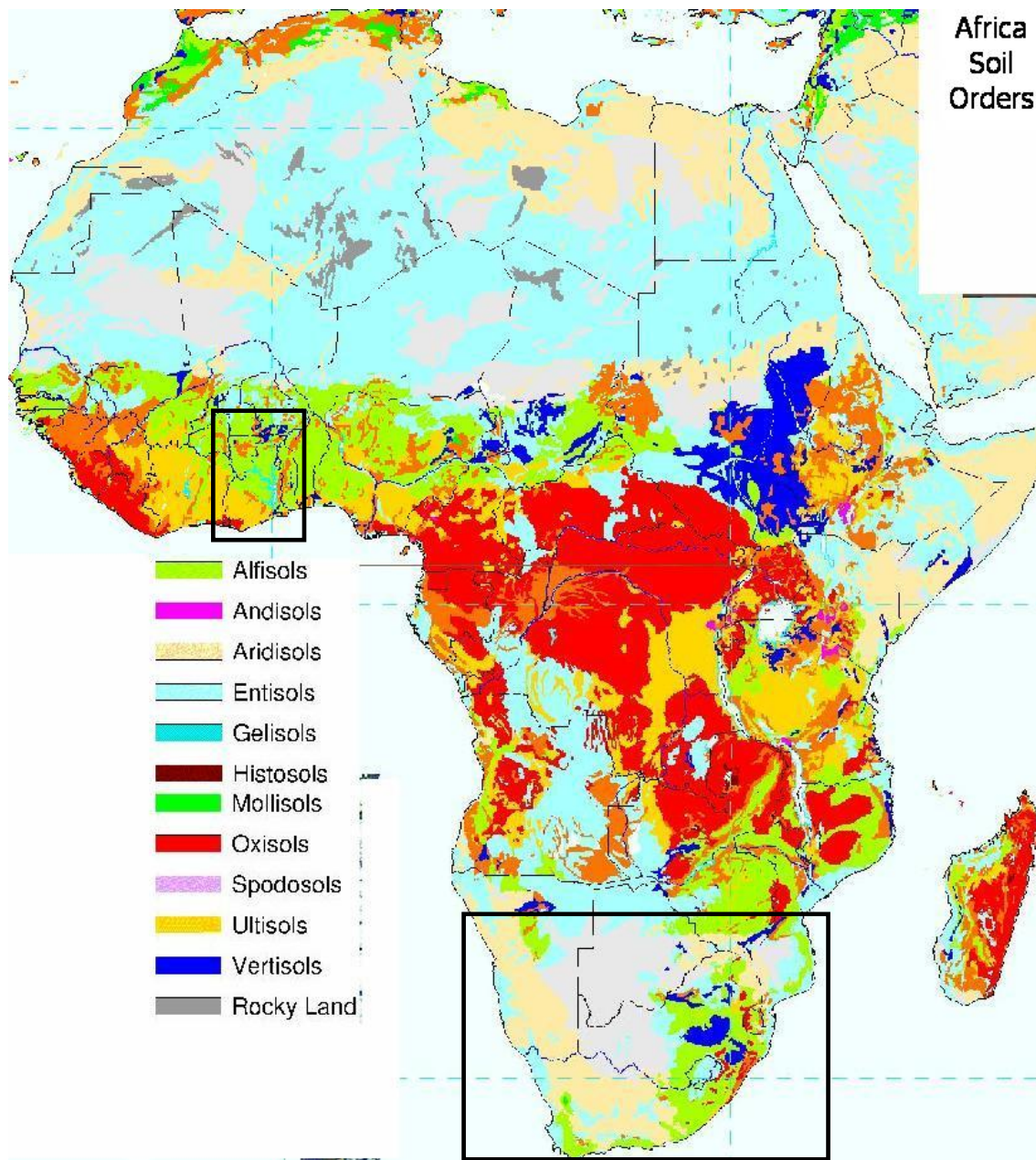


Figure 4.8. Soils of Ghana compared to soils of Southern Africa (Source: [University of Minnesota \(2005\)](#))

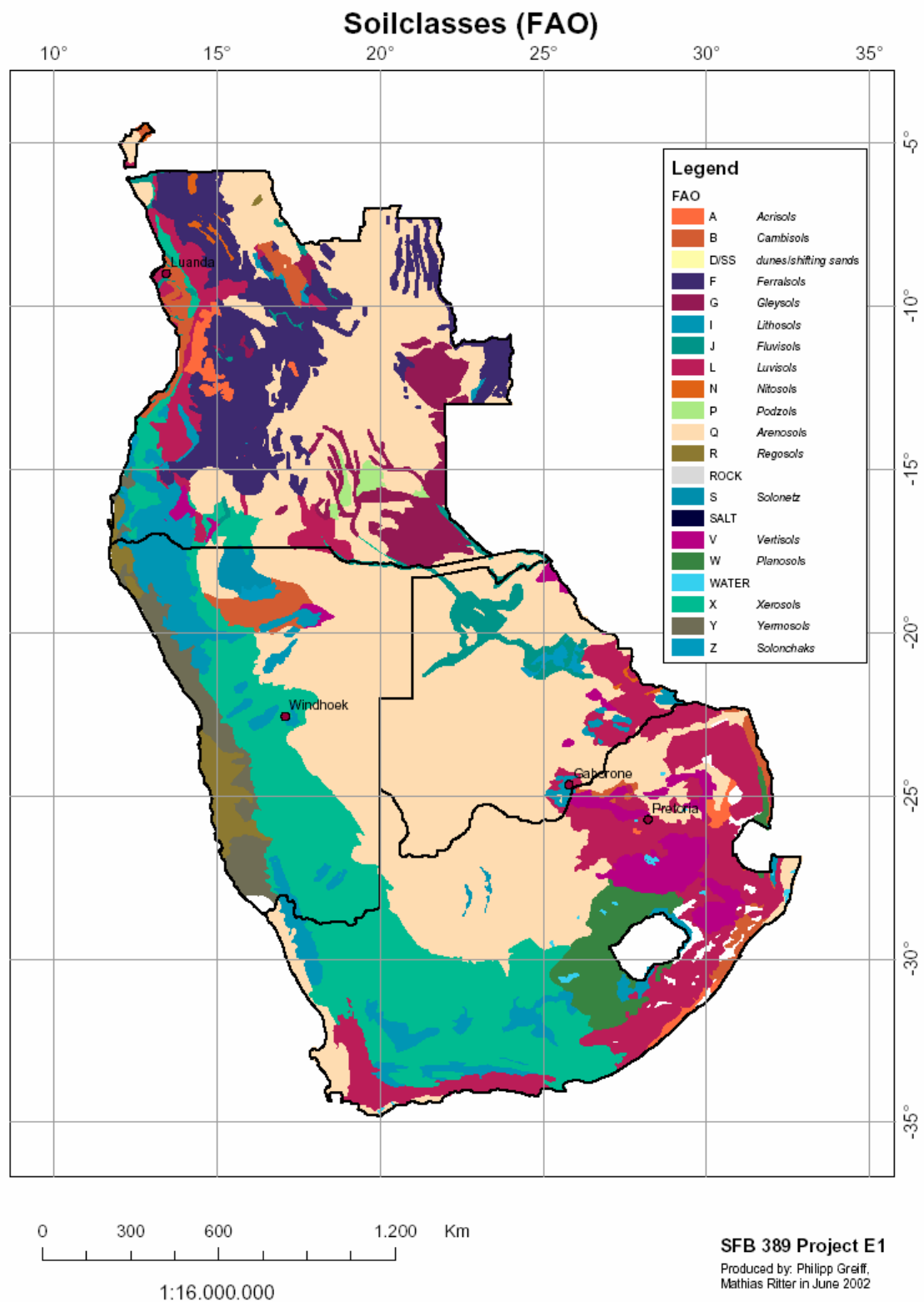


Figure 4.9. Soils of Southern Africa (source: University of Köln 2005)

In the ACRU Manual Shulze (1995) discusses three methods to generate the required ACRU input parameters where the parameters are not available. The three methods are:

1. regression equations, when laboratory analyses of the soil are available developed for Southern Africa (Shulze et al., 1985) that require percentage clay content, silt content, the bulk density of soil and percentage organic matter (OM). This method was not used because percentages of OM for the soils of the Densu were unavailable.
2. a regression equation with the percentage clay as the independent variable, when only clay percentage data are available. MacVicar et al. (1977) and Hutson (1984) noted that clay content is a primary characteristic used in soil classification. According to Shulze et al. (1985) and Hutson (1984) the percentage of clay and its vertical distribution within a soil profile is a major determinant of the soil water content at critical retention constants and gives good results in the absence of actual measured data. This assertion is also corroborated by Pachepsky & Rawls (1999) and Rawls et al. (1991). However, this method was not used because the exact clay contents of the soil horizons were not explicitly known.
3. a model showing the trend in vertical clay content is identified from five models and based on the range of clay content in the horizon when soil form and series information are available. This method by Shulze et al. (1985) and Hutson (1984) is explained further below as this was the method chosen because even though all the methods are based on regression equations developed for Southern Africa, the data requirement of this third method was the only one that could be met. This is because the input could be derived from the soil map of the basin and the horizons of the soil profiles.

For this third method (when soil form and series information are available) five models of relative vertical distribution of clay content, rather than the actual percentage of clay present in the various horizons, (Figure 4.10) for Southern Africa evolved by Shulze et al. (1985) were employed.

- Model 1 displays an increase in the percentage of clay with depth down the soil profile
- Model 2 has clay content remaining constant with depth
- Model 3 shows an abrupt transition to an increased clay content at a given depth,
- Model 4 reveals an indented clay content distribution with depth and
- Model 5 represents the mirror image of Model 3 with the transition displaying an abrupt decrease in clay percentage

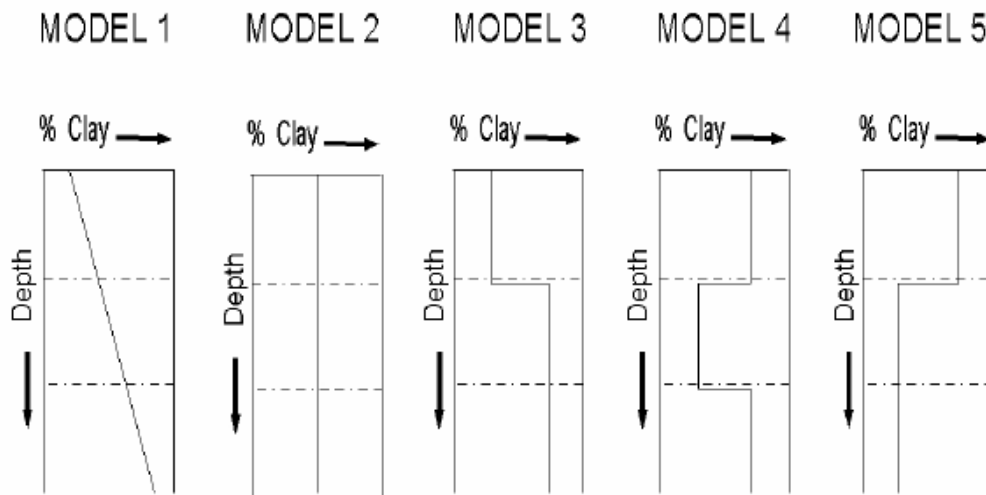


Figure 4.10 Vertical clay distribution models for southern Africa in Shulze (1995)

Analysis of the percentage clay contents in Table 4.9 for soil profiles with horizon data i.e. 1a, 2c, 4b and an Eutric Vertisol soil (in the adjacent Ayensu Basin) classification (Table 4.9) were undertaken and assigned models which were closest to their trends. The analysis suggested that the vertical clay trends for the soils of the Densu basin can be mainly grouped into three of the models; Model 1 (profile 2c),

Table 4.9 Vertical clay percentage distribution in Densu Soils (Adu & Asiama, 1992)

Soil Horizons	Haplic Lixisols (1a)		Haplic Lixisols (1b)		Ferric Luvisols (1c)		Gleyic Arenosol (1d)		Ferric Luvisols (2c)		Rodric Nitisol (3a)		Eutric Vertisols (4b)		Euric Vertisols	
	Depth	% Clay	Depth	% Clay	Depth	% Clay	Depth	% Clay	Depth	% Clay	Depth	% Clay	Depth	% Clay	Depth	% Clay
A ₁₁	0-10	0-5	-	-	-	-	-	-	0-5	14.0	-	-	0-8	15.3	0-10	53.7
A ₁₂	10-18	0-8	-	0-20	-	37-40	-	0-20	5-15	15.8	-	0-20	8-23	23.0	-	-
A ₁₃	18-41	15-35	-	-	-	-	-	-	-	-	-	-	23-54	27.0	-	-
B ₂₁	41-66	15-35	-	-	-	37-55	-	-	15-23	24.0	-	-	-	-	10-26	73.0
B ₂₂	66-91	-	-	-	-	15-37	-	-	23-43	41.0	-	-	-	>30	26-54	73.0
B ₂₃	97-117	-	-	-	-	28-40	-	-	43-71	50.8	-	20-35	-	-	54-92	75.8
B ₂₄	117-142	-	-	-	-	-	-	-	74-183	57.0	-	-	-	-	92-130	77.0

Where “-“ means horizon does not exist

3a, 4b and Eutric Vertisols), Model 3 (profile 1a) and Model 4 (profile 1c). Although soil class 1c looks like model 4; values for Model 4 were not available (Table 4.10) and therefore the soil was assigned to Model 2.

To each of the clay distribution models, standard classes of clay content of the B₂ horizon (because the vertical clay content value is attributed to this horizon) were noted such that typically (i.e. except for model 3, cf. Shulze et al., 1985) clay classes were

- a = 0-6% clay
- b = 6-15% clay
- c = 15-35% clay
- d = 35-55% clay
- e = >55% clay

Therefore with the clay content of a subsoil known, the soil parameters namely Permanent Wilting Points (PWP₁ and PWP₂), the Field Capacities (FC₁, FC₂), which are the field capacities respectively and effective porosity for the top and

sub soil horizons and the redistribution rates ABRESP (Fraction of “saturated” soil water to be redistributed daily from the topsoil (A horizon) into the subsoil (B horizon) when the topsoil is above its drained upper limit) and BFRESP (Fraction of “saturated” soil water to be redistributed daily from the subsoil to the intermediate/groundwater store when the subsoil is above its drained upper limit) were read from Tables 4.10 and 4.11.

Table 4:10 Estimates of soil water content at permanent Wilting point and drained upper limit by clay distribution model and class (after Shulze et al., 1985)

Vertical Distribution Model/Profile	Clay	Permanent Wilting Point (m ³ /m ³)		Drained Upper Limit (m ³ /m ³)	
		Topsoil PWP ₁	Subsoil PWP ₂	Topsoil FC ₁	Subsoil FC ₂
1a		.064	.065	.158	.171
b		.083	.091	.180	.201
c		.112(.127)	.158(.221)	.213	.277
d		.173(.226)	.226(.320)	.282	.354
e		.231(.320)	.265(.383)	.348	.398
2a		.067	.062	.162	.168
b		.089	.084	.187	.193
c		.138(.169)	.133(.169)	.242	.248
d		.202(.273)	.197(.273)	.315	.321
e		.250(.352)	.250(.352)	.370	.376
3a		.067	.084	.162	.193
b		.067(.054)	.110(.132)	.162	.222
c		.067(.054)	.142(.185)	.162	.259
e		.089(.091)	.133(.169)	.187	.248
5a		.067	.057	.162	.156
b		.089	.068	.178	.175
c		.138	.092	.242	.202
d		.202	.124	.315	.239

Where bracketed are unstable soils with vertic, prisma- pedo- and gleycutanic horizons

Table 4.11 Typical Values of Soil hydrological input parameters for different textural classes (from Shulze, 1995)

Soil Texture Class	Horizon	Typical Percentages of				Bulk Density (Mg.m ⁻³)	Total Porosity (m ³ .m ⁻³)	Effective Porosity (m ³ .m ⁻³)	Saturated Hydraulic Conductivity (mm.h ⁻¹)	Redistribution Fraction ABRESP & BFRESP (day ⁻¹)
		Clay	Silt	Sand	Organic Carbon					
	Topsoil (tilled)	50	37	13	0.38	1.22	.470	-	0.6	.25
	Subsoil					1.20	.549* .538^	.536		
						1.37	.482	.470		
Loam	Topsoil (untilled)	18	25	57	0.52	1.26	.512	-	13	.50
	Topsoil (tilled)					1.09	.589* .524^	.512		
	Subsoil					1.42	.440	.464		
Sand	Topsoil (untilled)	3	4	93	0.71	1.32	.446	-	210	.80
	Topsoil (tilled)					1.17	.559 .503^	.452		
	Subsoil					1.50	.440	.430		
Loamy Sand	Topsoil (tilled)	7	7	86	0.61	1.31	.452	-	61	.70
	Subsoil					1.16	.562* .505^	.457		
						1.51	.477	.432		
Sandy Loam	Topsoil (untilled)	10	15	75	0.71	1.26	.486	-	26	.70
	Topsoil (tilled)					1.11	.582* .524^	.505		
	Subsoil					1.46	.466	.448		
Silty Loam	Topsoil (untilled)	18	55	27	0.58	1.13	.530	-	6.8	.65
	Topsoil (tilled)					1.01	.619* .575^	.527		
	Subsoil					1.34	.500	.495		
Sandy Clay Loam	Topsoil (untilled)	27	8	65	0.19	1.35	.435	-	4.3	.45
	Topsoil (tilled)					1.25	.523* .500^	.486		
	Subsoil					1.58	.456	.393		
Clay Loam	Tropical (untilled)	32	22	46	0.10	1.22	.489	-	2.3	.50
	Topsoil (tilled)					1.12	.544* .528^	.497		
	Subsoil					1.41	.473	.451		
Silty Clay Loam	Topsoil (untilled)	33	46	21	0.13	1.25	.489	-	1.5	.35
	Topsoil (tilled)					1.21	.544* .528^	.509		
	Subsoil					1.40	.473	.469		
Sandy Clay	Topsoil (untilled)	40	5	55	0.38	1.35	.393	-	1.2	.40
	Topsoil (tilled)					1.25	.529* .492^	.430		
	Subsoil					1.53	.428	.423		
Silty Clay	Topsoil (untilled)	50	37	13	0.38	1.23	.476	-	0.9	.35
	Topsoil (tilled)					1.20	.547* .536^	.531		
	Subsoil					1.38	.480	.476		

* Freshly Tilled ^ End of season value

from the topsoil (A horizon) to the subsoil (B horizon) when the topsoil is above its drained upper limit and BFRESP is also the fraction of “saturated” soil water to be redistributed daily from the subsoil (B horizon) to the intermediate/groundwater store when the subsoil is above its drained upper limit. Catchment-average values for all these soil parameters were determined for the lumped-mode simulation, weighted (Table 4.12) according to the areas each soil type occupied in the Densu Basin. Taking the difference between PWP’s and the FC’s water limits for the respective soil horizons gives the average available water contents for the topsoil ($FC_1 - PWP_1$) to be 92mm.m^{-1} whilst for the subsoil ($FC_2 - PWP_2$) gives 94mm.m^{-1} . This compares favourably with the figure of $\leq 90\text{mm.m}^{-1}$ from both Bouwman et al. (1993) and Batjes (1997) for available water content for the soils in the region of the Densu Basin. In the semi distributed mode set up, the area weightings for each sub-catchment were changed according to the proportions of each soil type within each sub-catchment and optimum values set before calibration.

Table 4.12: Establishing the Area Weighting of soils in the Densu lumped mode

Subsoil Units = 8

before area weighting											
DEPAHO	DEPBHO	PWP ₁	PWP ₂	FC ₁	FC ₂	P01	P02	ABRESP	BFRESP	%	K
.41	1.42	.067	.142	.167	.259	.486	.428	.70	.40	52.60	1
.25	1.23	.202	.197	.315	.321	.393	.456	.40	.45	13.20	2
.31	2.29	.083	.226	.180	.354	.486	.473	.70	.50	7.10	3
.30	1.42	.083	.226	.180	.354	.486	.428	.70	.40	9.70	4
.54	1.30	.112	.158	.213	.227	.435	.473	.45	.35	4.00	5
.25	2.26	.173	.226	.282	.354	.476	.480	.35	.35	1.80	6
.25	1.27	.083	.091	.180	.201	.452	.440	.70	.80	5.40	7
.15	1.83	.083	.226	.180	.354	.435	.428	.45	.40	6.20	8
after area weighting											
.35	1.48	.093	.168	.194	.286	.467	.438	.63	.43	100.00	1

where DEPAHO and DEPBHO are the depths of the A and B horizons respectively, % the weighted percentage of each soil type and K is the number assigned to each different soil type

4.2.6 Water Abstractions

Water abstraction from this catchment is mainly for water supply to households and small scale industries, surface water abstraction by inhabitants for small scale irrigation and some industrial use in Koforidua and Nsawam (OTUI, 1996). Irrigation is practised mainly outside the Manhia catchment area and in the

Weija catchment (Figures 1.4 & 4.15) where the main reservoir is situated. Within the Manhia catchment, agriculture is mainly rainfed with minimal direct abstraction for irrigation (OTUI, 1996). Groundwater abstraction projections according to WARM (1998) for the whole basin including Weija in 2000 was expected to be 370,000m³/year (1014m³/day). OTUI (1996) estimated total household consumption which included small scale irrigation and small scale industries from the various water supply Agencies within the basins to be as follows:

- Koforidua sub-catchment: 9230m³/day for Koforidua and surrounding areas;
- Nsawam sub-catchment: 3790m³/day for Nsawam and surrounding areas;
- Akwadum sub-catchment 180m³/day for Akwadum and surrounding areas;
- Apedwa sub-catchment 360m³/day and surrounding areas.

For the lumped modelling, abstraction was assumed to be the sum of all the abstractions noted above, however, for the semi distributed modelling the abstractions were assumed to be the sum of all those abstractions that fall within the supposed catchment. For this catchment, the groundwater abstraction was assumed to be negligible because according to GWP-TAC (2000) borehole and well yields from the regions aquifers are generally low (Section 2.3.5).and from OTUI (1996) the annual groundwater yield for the catchment is not big.

4.3 Other Hydrometeorological Data

These data were also collected to further describe the basin since the evapotranspiration methods employed in the ACRU model are numerous. If any other evapotranspiration method is selected such data are useful for modelling using ACRU model.

4.3.1 Temperature

Daily maximum and minimum temperature data have been measured at Koforidua, within the catchment, and at the nearby Accra Station ($\approx 31\text{km}$ south east of Nsawam and $\approx 20\text{km}$ to the closest streamflow station within the catchment at Manhia), which falls outside the catchment. However, the data collected for Koforidua and Accra had a combination of daily or monthly mean temperatures where they are available with the monthly means being more common. The daily values were for the period Jan-Dec 1967, Jan-April 1969 and Jan-May 1971 with the rest as monthly means, Figure 4.11 shows the average monthly means for the maximum and minimum temperature for the period 1965-1980 for the Koforidua station. It is seen that they remain uniformly high during the day and also uniformly moderately high at around 20°C and 23°C in the night as seen from the minimum temperatures.

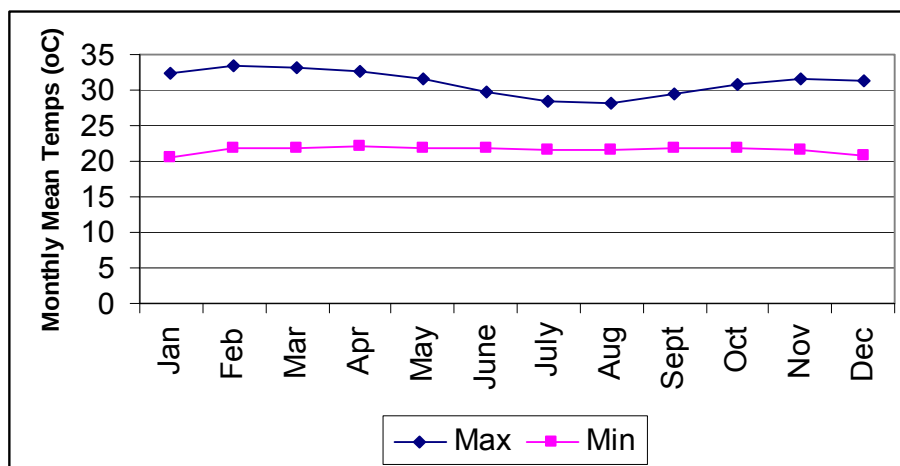


Figure 4.11 Monthly Mean Temperatures for Koforidua (1965-1980)

From the Figure, it is apparent that November through to April are the hottest ($31^{\circ}\text{C} - 34^{\circ}\text{C}$) months in this catchment, which corresponds to the dry season (November to February). The rainy seasons are cooler.

4.3.2 Sunshine Duration

Daily and monthly sunshine duration data are available for Koforidua and Accra, although monthly means are most common. Koforidua had daily data for

March–July, 1968 and March–April, 1972 whilst Accra had daily data for the whole period. Figure 4.12 shows mean monthly sunshine duration for Koforidua and Accra 1967-1980.

It could be seen that the period with low solar radiation (as given by sunshine hours) is May to September which normally is the rainy season period with the month of August recording the lowest solar radiation on average. A maximum of over eight (8) hours sunshine per day is attained on average in November.

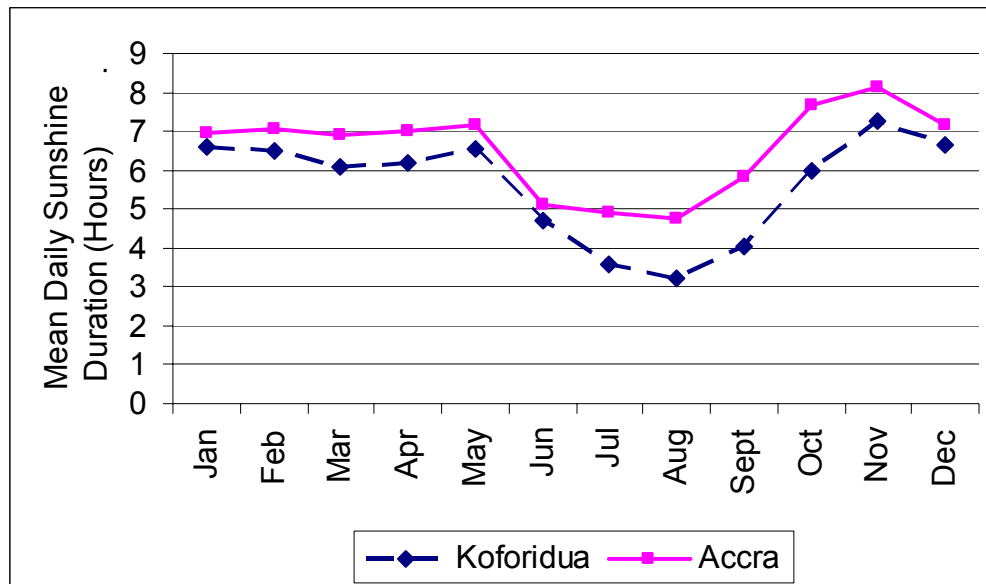


Figure 4.12 Sunshine Duration data for Koforidua and Accra (1967-1980)

4.3.3 Wind Speeds

Wind speed data are also available for the Koforidua and Accra Stations. The data available included both daily and monthly means and covered the period 1970 -1978. The average monthly wind speed is given in Figure 4.13. It is seen that the months of June through to September are the windiest with highest of nearly 1.8 knots in August for the Koforidua station.

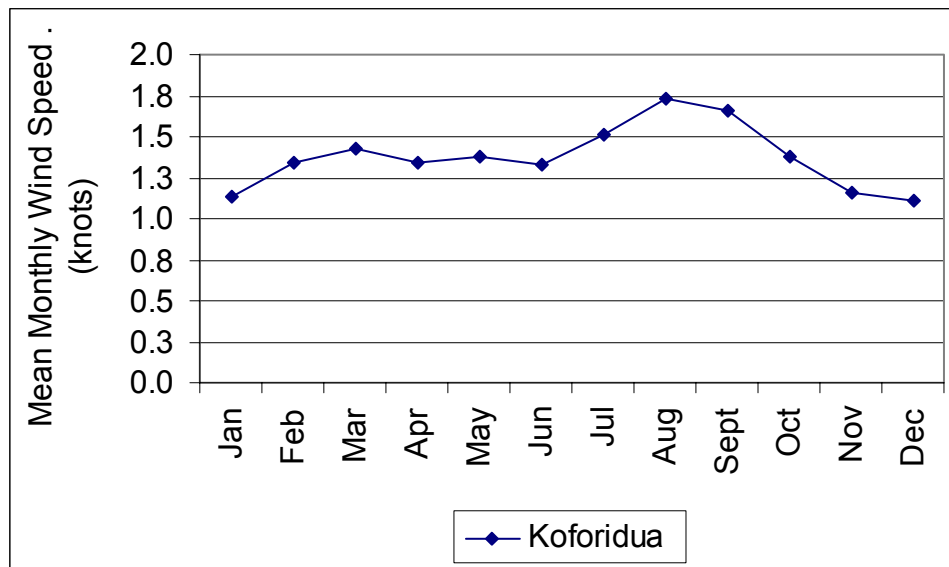


Figure 4.13 Wind speed data at Koforidua

4.3.4 Relative Humidity

Relative humidity data were compiled for the Koforidua station for the study from data available (Table 4.1). These data are usually collected at 06hrs and 15hrs, and the average for the day is calculated from the two readings. Typically mean monthly relative humidity is low i.e. 75% in January and gradually rises to a peak in June (over 85%) and then gradually falls again till January.

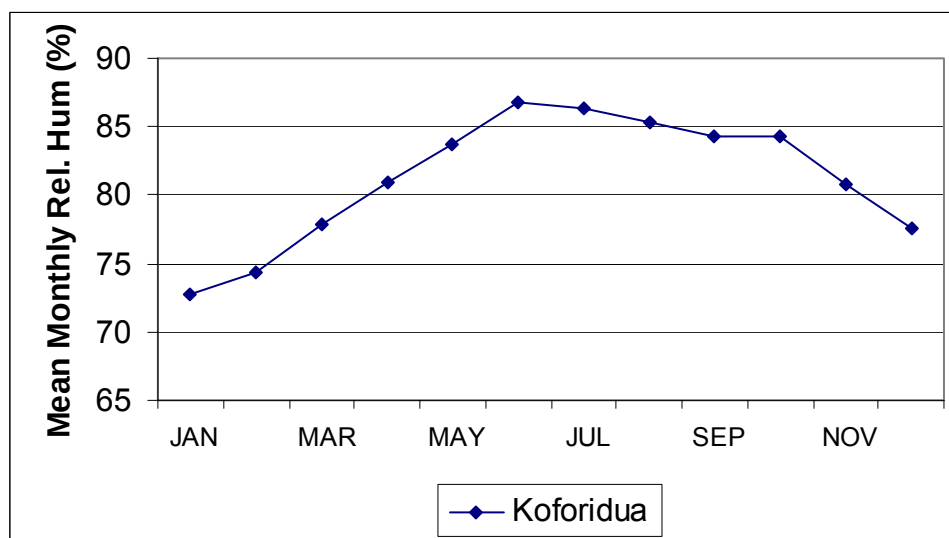


Figure 4.14: Mean monthly Relative Humidity for Koforidua.

4.4 Other Parameters

The ACRU model is described as a physical based model and therefore the model parameters were chosen with the knowledge of the area taking into consideration the maximum and minimum data range given for these parameters by the model developers.

Parameters such as the fraction of the plant available water of a soil horizon at which total evaporation is assumed to drop below the maximum evaporation during drying of soil to detect onset of plant stress (CONST); the variable to specify that wet canopy evaporation should be simulated at an enhanced rate which occurs under forest conditions, and to inform ACRU that a dynamic file generator has to be used (FOREST) are some of the additional model parameters. Others are the fraction of the catchment occupied by impervious areas which are not adjacent to a watercourse (e.g. house roofs discharging onto lawn) (DISIMP), Fraction of the catchment occupied by adjunct impervious areas, i.e., areas joined (connected) directly to a watercourse, from which precipitation contributes directly to quickflow (ADJIMP) and, surface storage capacity (i.e. depression storage, or initial abstraction) of impervious surface, which needs to be filled before stormflow commences (STOIMP)

CONST was taken as 0.4 which is the default value which according to Schulze (1995) is a typical value for ACRU.

FOREST could be = 0	wet canopy evaporation at potential rate (for short vegetation)
= 1	enhanced wet canopy evaporation if forest covers >50 % of (sub) catchment
= 2	Timber yield model is selected.

ADJIMP. The concept of "adjunct" impervious areas takes into account the hydrological effects of urbanised areas with stormwater drainage, large rock outcrops as well as the permanently saturated areas around the channel

network. Precipitation falling on this portion of the catchment is assumed to become part of streamflow immediately as a component of same-day quickflow and is not subject to other stormflow generating factors and catchment lags. The value for this parameter was estimated from the knowledge of the area (i.e urbanised at Koforidua and Nsawam, very rocky in the headwater parts of the catchment) and from the topographic sheets by estimating the areas that these would occupy in each sub-basin.

DISIMP. The concept of disjunct (or "disconnected") impervious areas is used, for example in an urban situation which has no stormflow sewers, where precipitation falling onto impervious roofs or roads, runs off and re-infiltrates into surrounding pervious areas. The effect is to elevate the soil moisture content of those pervious areas, with subsequent higher stormflows potentially being simulated from them. This parameter was estimated in the same manner as the ADJIMP for the urban areas.

STOIMP. The default value for ACRU of 1mm was chosen which Shulze (1995) put as a typical value.

The respective parameter values are shown in Table 4.13

Table 4.13 Table of initial model parameters:

	CONST	FOREST	DISIMP	ADJIMP	STOIMP (mm)
Moderately closed tree (>15/trees/ha) canopy with herb and bush cover	0.4	1	0.020	0.03	1
Moderately dense herb/bush with scattered trees (<15 trees/ha)	0.4	1	0.030	0.02	1
Grass/herb with/without scattered trees (0-5 tree/ha)	0.4	0	0.015	0.02	1
Settlement	0.4	0	0.015	0.02	1
Mosaic of thickets & grass with/without scattered trees	0.4	0	0.015	0.02	1

4.5 Setting up the ACRU Model for the Densu Basin

4.5.1 Delineation of Catchment

The delineation of the catchment area was done by consulting 1:50,000 scale topographic maps and existing maps of the catchment prepared by the Water Research Institute of the Council for Scientific and Industrial Research of Ghana. The latter was amended to incorporate the sub-catchments for the intended lumped mode and semi-distributed mode modelling. To divide the catchment into sub-basins for the semi-distributed mode (Figure 4.15) the streamflow gauging stations were used as the outlets of the Nsawam sub-

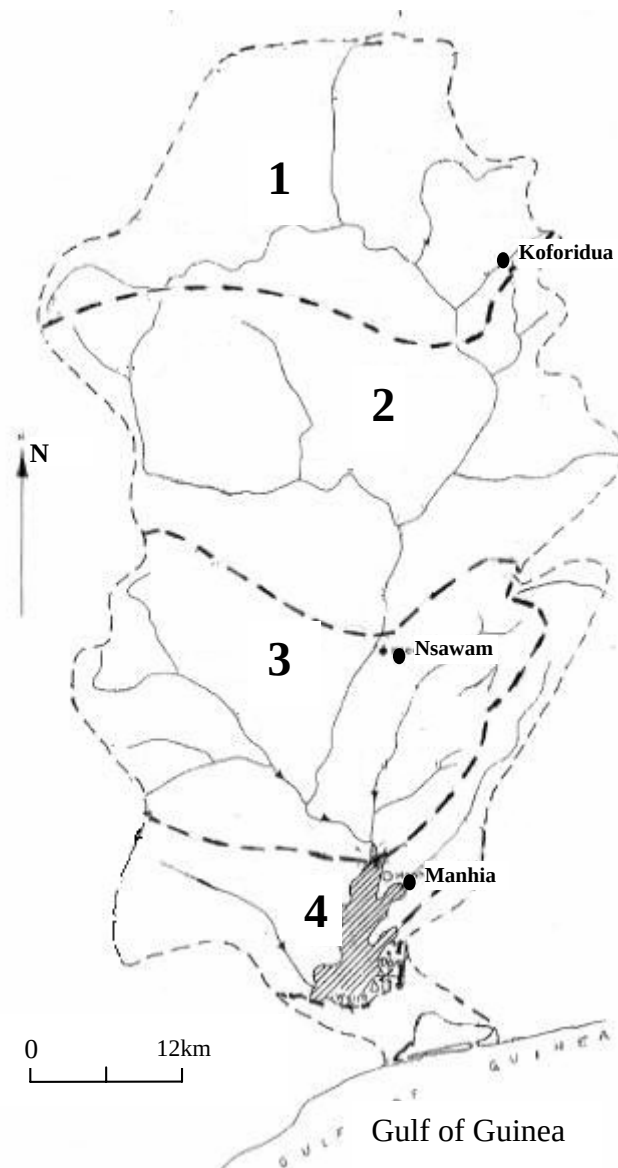


Figure 4.15 Sub-catchments of the Densu Basin

catchment (2) and Manhia sub-catchment (3), which were drawn by tracing the catchment areas on the topographic sheets. Sub-catchment (1) was delineated with the outlet as the weir at Koforidua. This subcatchment was included because in the anticipated landuse study, the changing landuse of this sub-catchment would be of interest. Sub-catchment (4) i.e. the Weija catchment is the downstream catchment beyond the Manhia (3) sub-catchment and therefore downstream of the Manhia gauging station.

4.5.2 Preparation of input data and running the model

The computed daily hydrological data for the catchment was input in the required format, called a composite format. This approach was adopted because it was more user friendly than the single format type which has only two columns making the input data set very long and cumbersome; and because again they cater for a wide selection of daily input data. The composite format is specified as having a record length of 118 columns and have a Fortran 77 fixed format, viz:

1. Station identity (A8)
2. Year (I2)
3. Month (I2)
4. Day (I2)
5. Observed rainfall in mm (F5.1, 1X)
6. Maximum temperature in °C (F5.1, 1X)
7. Minimum temperature in °C (F5.1, 1X)
8. A-pan evaporation equivalent in mm (F5.1, 1X)
9. Observed streamflow in mm (F7.3)
10. Observed streamflow quality flag (A1)
11. Observed soil water content in the A-horizon in mm (F5.1, 1X)
12. Observed soil water content in the B-horizon in mm (F5.1, 1X)
13. Total evaporation from a lysimeter in mm (F5.1, 1X)
14. Irrigation application in mm or $\text{m}^3.\text{s}^{-1}$ (F5.1, 1X)
15. Observed stormflow in mm (F7.3)
16. Observed peak discharge in $\text{m}^3.\text{s}^{-1}$ (F5.2, 1X)

17. Modified USLE cover factor, dimensionless decimal factor (F5.3, 1X)
18. Leaf Area Index, dimensionless (F5.1, 1X)
19. Incoming radiation flux density in $\text{MJ.m}^{-2}.\text{day}^{-1}$ (F5.2, 1X)
20. Relative humidity in % (F5.2, 1X)
21. Sunshine duration in hours and fractions (F5.2, 1X)
22. Windrun in km.day^{-1} (F5.2, 1X).

This format uses one line for each day of data.

The soils and landuse parameters discussed above were then incorporated, by using the menu builder facility, into the model and weighting undertaken where appropriate. Others like water abstraction were then incorporated. For the lumped mode, the outlet of the catchment is taken at Manhia which is the end of sub-catchment 3. For the Semi-distributed modelling the demarcations are as shown in the Figure 4.15 above and the input data respectively compiled for each of the sub-catchments (in this case 4 in all).

Having satisfied the input requirements, the model was successfully test run in the lumped mode.

5. Hydrological Modelling of the Densu Basin

A successfully calibrated predictive rainfall-runoff model with low data requirements is very desirable, but particularly so in the river basins of developing countries like Ghana for which data availability (chapter 4) is a major constraint. However, before such models can be efficiently applied, their performance needs testing, which includes a careful and detailed sensitivity analysis to help with the efficient calibration of the model and then the model validated (Bathurst, 1986; Schulze, 1992). This chapter will report on the various activities carried out to achieve a good hydrological representation of the Densu Basin with the selected catchment model. This includes a sensitivity analysis and results of the calibration-validation exercise using the model in both lumped and semi-distributed modes.

5.1 Modelling in the Lumped Mode

Lumped models as explained in chapter 3 assume that all characteristics are constant across the catchment. Since it is relatively simpler to apply models in a lumped rather than in a semi distributive mode, the lumped version of ACRU was initially investigated so that the model could be understood well before modelling in the semi-distributed mode.

The Densu River catchment at the Manhia (2100km²) flow gauging station was considered as the outflow point in the lumped mode. Daily area-averaged hydrometeorological parameter values for the basin (ref. chapter 4) namely, rainfall, pan evaporation, streamflow, maximum and minimum air temperatures, relative humidity, wind runs and sunshine hours of the entire basin, together with soil and vegetation parameters, were computed and used. The daily rainfall data for Nsawam and Koforidua, having been found to be stationary, having no trend and stable variance and mean, were used to estimate the areal rainfall for the basin. For the lumped mode simulation for Manhia, the Thiessen (1911) polygon area-weighting method gave the Nsawam station a weight of 0.497 and Koforidua of 0.503. Thus the areal rainfall was calculated with these weights.

In the semi distributed modelling mode, the weightings were similarly established for sub-catchment 1 (Koforidua rainfall station had a Thiessen weight of 1 with Nsawam having no influence), catchment 2 (areal rainfall was computed with the weights 0.57 for Nsawam and 0.43 for Koforidua) and for sub-catchment 3 (the weighting of Nsawam was 1 with no influence from Koforidua)

Out of the various evapotranspiration methods available within ACURU, ACURU was run using the pan evaporation and the Hargreaves (1985) daily methods. These methods were chosen because (1) the ACURU model has been developed using the pan evaporation method (see section 3.4 in chapter 3) and (2) because Hargreaves (1994) cited by Droogers & Allen (2002) showed that in estimating reference evapotranspiration under poor data conditions the Hargreaves (1985) temperature method (Hargreaves & Samani, 1985), which requires only mean daily maximum and minimum temperature data, performed nearly ($R^2 = 0.97$) as accurately as Penman Monteith equation (defined in Allen et al., 1998) in estimating evapotranspiration ET_o on a weekly or longer time step where good data were lacking. According to Jensen et al. (1997), in Hargreaves & Allen (2003), when the Hargreaves (1985) and the Penman Monteith methods were compared to the lysimeter method, Hargreaves (1985) gave a Standard Error of Estimate (SEE) of 0.34 mm day^{-1} with $R^2 = 0.94$ for monthly estimates. The SEE for the Penman Monteith was 0.32 mm day^{-1} with $R^2 = 0.96$ for the monthly data. Similarly, Droogers & Allen (2002) also showed that the Hargreaves (1985) method for computing monthly ET_o calculation is “remarkable” in comparison to the Penman Monteith method when inaccuracy in weather measurements is common and may perform even “better” than Penman Monteith under conditions of substantial data error (Root Mean Square Error (RMSE) = 0.72 mm. d^{-1}).

5.1.1 Output Simulation

The period of consideration for this study was 1968 to 1972 because flow data are only available and reliable in this period because rating curve is applicable

to this period. Typical output of the ACRU model for streamflow simulation includes simulated streamflow, baseflow, stormflow, total actual evaporation, baseflow store and soil moisture contents for the A and B soil horizons.

5.2 Sensitivity Analysis

Atkinson et al. (2002) identified sensitivity analysis as an effective means of determining the dominant physical controls on simulated streamflow variability, as it provides insight into the operation of the model and explores its response to parameter variations. McCuen (1973) defines sensitivity “as a measure of the effect of change of one factor on another factor” and noted that in terms of hydrological modelling this definition refers to a measure of the effect of changes in model input, or model structure, on model output. Bergstrom (1991) noted that an analysis of the sensitivity of a model is a very useful tool for building confidence in its structure. McCuen (1973) observed that sensitivity analysis is useful in all phases of the modelling process because it enables the hydrological modeller to gain a better understanding of the correspondence between the model output and the physical processes being modelled whilst according to Bergstrom (1991) sensitivity analysis;

- helps keep the model simple;
- identifies variables and parameters with little/insignificant effect on results;
- identifies interactions between model components and parameters and,
- identifies the stability of results in relation to the uncertainty of the assumptions made in the model.

The following model parameters were considered for the sensitivity analysis, as Angus (1989) found the ACRU output of cumulative streamflow to be sensitive to these parameters in studies in Southern Africa:

DEPAHO: Depth (m) of the topsoil of the soil profile.

DEPBHO: Thickness (m) of the subsoil of the soil profile.

ABRESP: Fraction of “saturated” soil water to be redistributed daily from the topsoil (A horizon) into the subsoil (B horizon) when the topsoil is above its drained upper limit.

BFRESP:	Fraction of “saturated” soil water to be redistributed daily from the subsoil to the intermediate/groundwater store when the subsoil is above its drained upper limit.
CAY:	Average monthly crop coefficients, K_{cm} for the pervious land cover of a catchment/subcatchment specified month by month.
ROOTA:	Fraction of the effective root system in the topsoil horizon, specified month by month.
VEGINT:	Interception loss ($\text{mm} \cdot \text{rainday}^{-1}$) by vegetation, specified month by month.
SMMDEP:	Effective (critical) depth of soil (m) from which stormflow generation takes place.
FC1:	Soil water content ($\text{m} \cdot \text{m}^{-1}$) at drained upper limit for the topsoil.
FC2:	Soil water content ($\text{m} \cdot \text{m}^{-1}$) at drained upper limit for the subsoil.
CORPAN:	Monthly adjustment factors to be applied to evaporation pan dataset to correct for screening and systematic errors.
COIAM:	Coefficient of initial abstraction, i.e. a coefficient given month by month which is used to estimate the rainfall retained by interception, detention storage and infiltration before stormflow commences.
COFRU:	Coefficient of baseflow response. It is the fraction of water from the intermediate /groundwater store that becomes streamflow on a particular day.
PO1:	Porosity of topsoil ($\text{m}^3 \cdot \text{m}^{-3}$).
WP1:	Permanent Wilting Point of topsoil ($\text{m}^3 \cdot \text{m}^{-3}$).
WP2:	Permanent Wilting Point of Subsoil ($\text{m}^3 \cdot \text{m}^{-3}$).

The output parameters selected for the sensitivity analysis were the total simulated streamflow (because streamflow data exist) and total simulated base flow (to enable comparison of the base flow response to that of streamflow as river flow is perennial) for the period 1968-1972. Furthermore, during the assessment of impacts of future catchment changes within the basin as part of the set objectives of this PhD, the most easily measurable parameter within this

basin is the streamflow, thus making the choice of streamflow very important. Finally, the choice of these also matches Angus (1989, in Shulze, 1995) who undertook sensitivity analysis using ACRU in South Africa and therefore would provide a good basis for comparison to be undertaken and if found similar make ACRU more transportable and robust for use in tropical West Africa.

For the purposes of the sensitivity analysis all comparisons were made with reference to a simulation with what were considered (prior to calibration) to be the best basin parameters. These simulations, and the 'best estimate' parameter values used within it, are referred to as the 'base case'.

5.2.1 Methodology Applied for the Sensitivity Analysis Simulations

McCuen (1973) noted that the selection of an objective function within a sensitivity analysis, subjective as it may be, is very important and thus the objective function selected should reflect adequately the intended hydrological characteristic. In this sensitivity study the visual graphical representation and the performance bias (PBIAS) objective function (see section 5.3) were chosen because, according to Bergström (1991) they are straightforward and powerful in many applications and easy to understand. This he noted is so because when the percentage in accumulated output is plotted against percentage increase in input parameter the change is easily visible.

A single input parameter at a time was varied incrementally over a range (Table 5.1) until there was no change (output changes by less than the 10% of the

Table 5.1 Parameters tested within the sensitivity analysis, with ACRU base values and range of values tested.

	ABRESP	BFRESP	FC ₁ (m.m ⁻¹)	FC ₂ (m.m ⁻¹)	PWP1 (m ³ .m ⁻³)	PWP2 (m ³ .m ⁻³)	PO1 (m ³ .m ⁻³)	PO2 (m ³ .m ⁻³)	DEPBHO (m)
ACRU Range	0.1-0.87	0.1-0.8	-	-	-	-	-	-	-
⁸ Base Values	0.63	0.43	0.194	0.286	0.093	0.168	0.467	0.438	1.48
Sensitivity range	0.36-0.90	0.23-0.55	0.12-0.27	0.20-0.47	0.055-0.134	0.11-0.26	0.26-0.61	0.30-0.61	0.48-1.12

⁸ Base values are the best estimated parameter values for the Densu Basin before calibration.

Table 5.1 continued

	DEPAHO (m)	SMMDEP (m)	COIAM	COFRU	VEGINT (mm.rainday ⁻¹)	ROOTA
ACRU Range	-	0.20-0.40	-	0.01-0.03	-	-
Base Values	0.35	0.36	0.33	0.012	3.54	0.80
Sensitivity- Range	0.21-0.50	0.22-0.50	0.20-0.46	0.007-0.06	1.0-5.0	0.48- 1.12

input change) and the percentage change in output $\Delta O\%$ determined from equation 5.1.

$$\Delta O\% = \frac{O - O_{BASE}}{O_{BASE}} \times 100 \quad \dots\dots\dots (5.1)$$

where

O = output value from a particular change in input parameter

O_{BASE} = output from the base case

The graphs of the changes in cumulative streamflow resulting from incremental changes to input parameter values are shown in Figures 5.1 to 5.5. For good graphical representation and comparison of the many parameters, an input range -40% to +40% of the base values has been used unless otherwise stated, which includes the various recommended values given for ACRU (Table 5.1) because it is long enough to show the trends..

5.2.2 Apan Analysis

Figures 5.1(a-c) and 5.2(a-c) show the relationships observed for the various parameters of soil and vegetation when the method of Apan was employed as the reference evaporation method. The effect of the parameters ABRESP and BFRESP on cumulative streamflow and baseflow were negligible i.e. -0.05% to 0.05% change when the sensitivity was conducted with the recommended range of values given by ACRU.

It is seen from Figure 5.2a and 5.2c that the changes in FC1 give a corresponding change in cumulative streamflow of -11% to 30% over the sensitivity range and the CAY changes give a change in cumulative streamflow

ranging from -18% to 34%. This shows that streamflow is sensitive to these two parameters in comparison to the other parameters plotted in Figures 5.1-5.5. Porosity (PO1) (Figure 5.1a) of the topsoil horizon showed a corresponding change of -39% to 6% in cumulative streamflow indicating that streamflow is relatively sensitive to this parameter. However, when the levels of sensitivities for baseflow and streamflow are compared (Figure 5.3) it is seen that the effect of CAY and FC1 parameters on cumulative streamflow are relatively high (and positive) when the values were decreased from their base case values and low (and negative) as the values increase from their base case values. On the other hand porosity (PO1) is more sensitive towards baseflow when it is decreased than when it is increased from the base value.

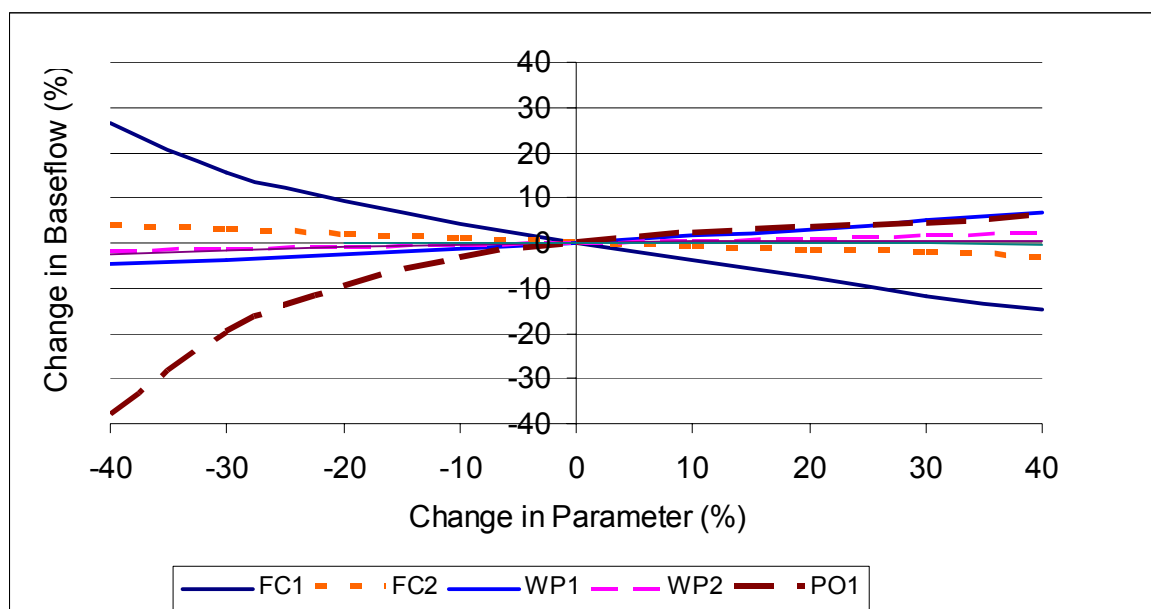


Figure 5.1a Response of cumulative baseflow to changes in soil parameters

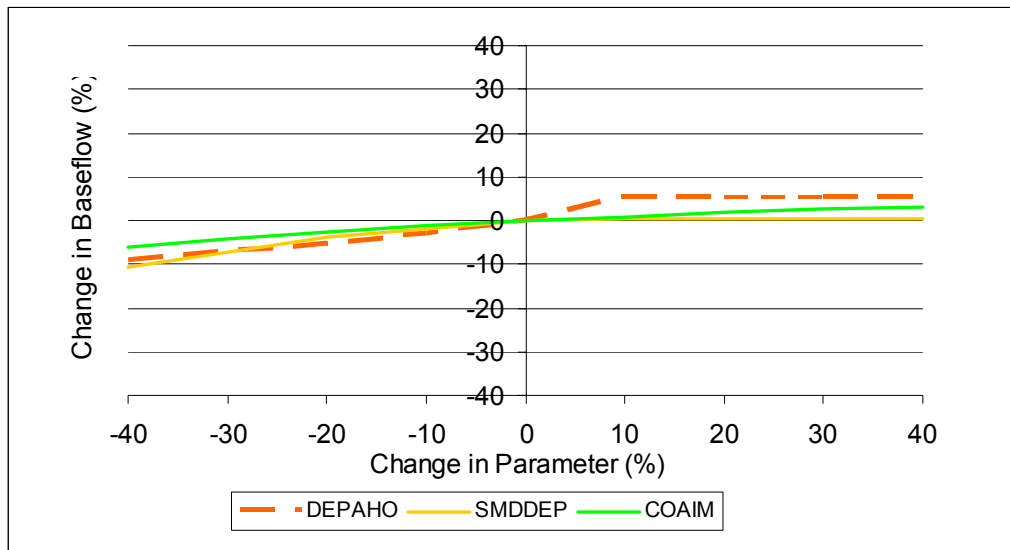


Figure 5.1b Response of cumulative baseflow to changes in soil parameters cont'd.

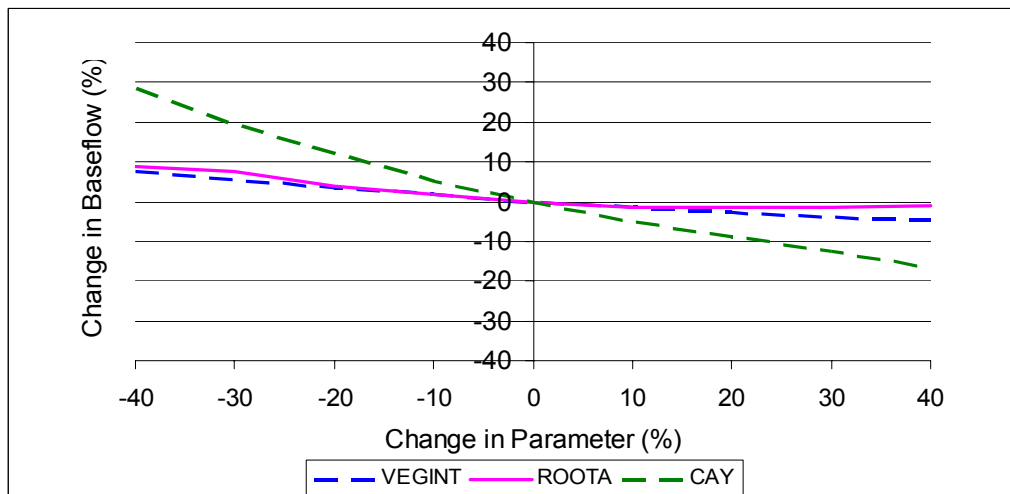


Figure 5.1c Response of cumulative baseflow to changes in crop parameters

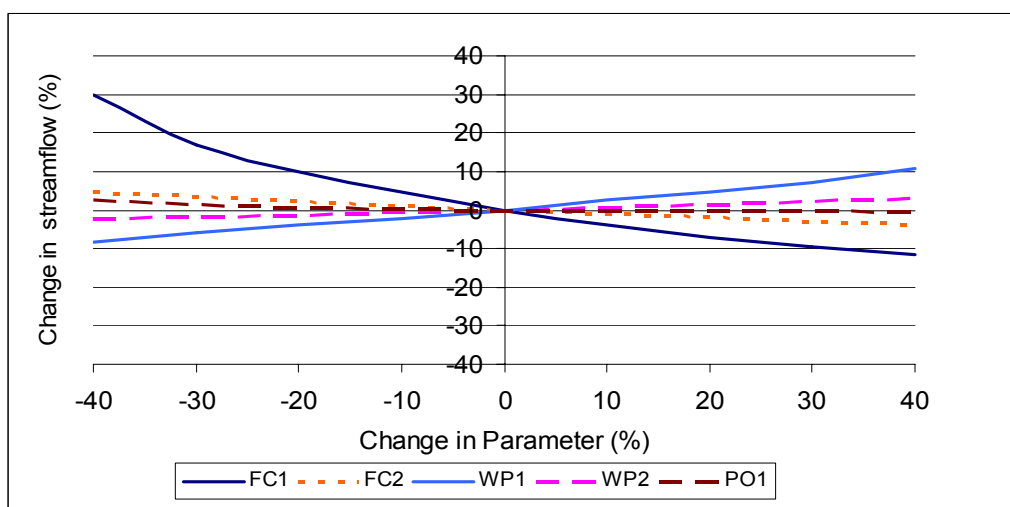


Figure 5.2a Response of cumulative streamflow to changes in soil parameters

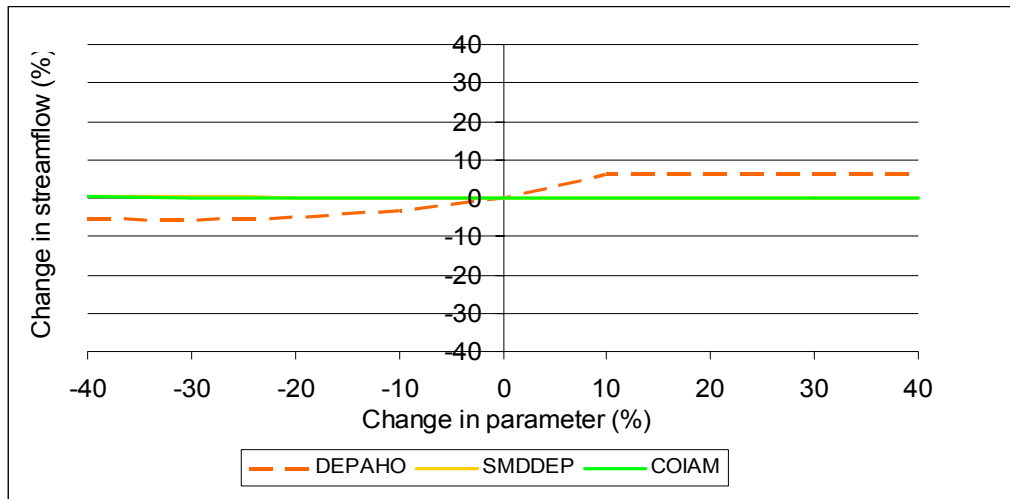


Figure 5.2b Response of cumulative streamflow to changes in soil parameters cont'd.

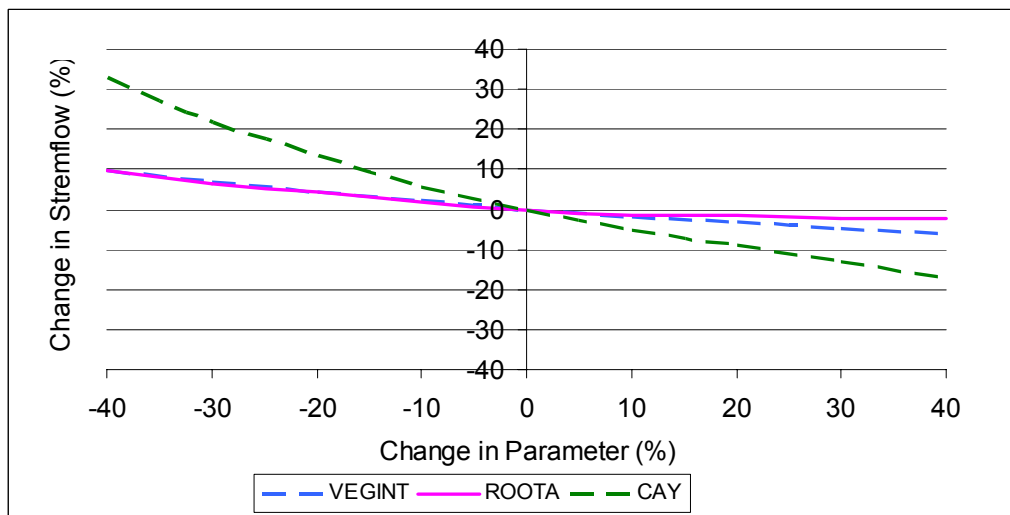


Figure 5.2c Response of cumulative streamflow to changes in crop parameters

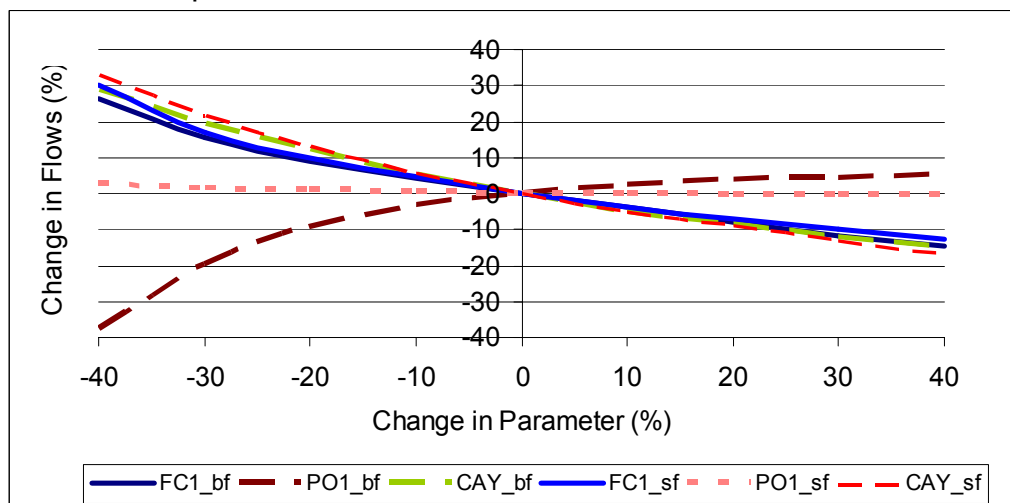


Figure 5.3 Comparison of cumulative baseflow (bf) and streamflow (sf) for the most sensitive parameters

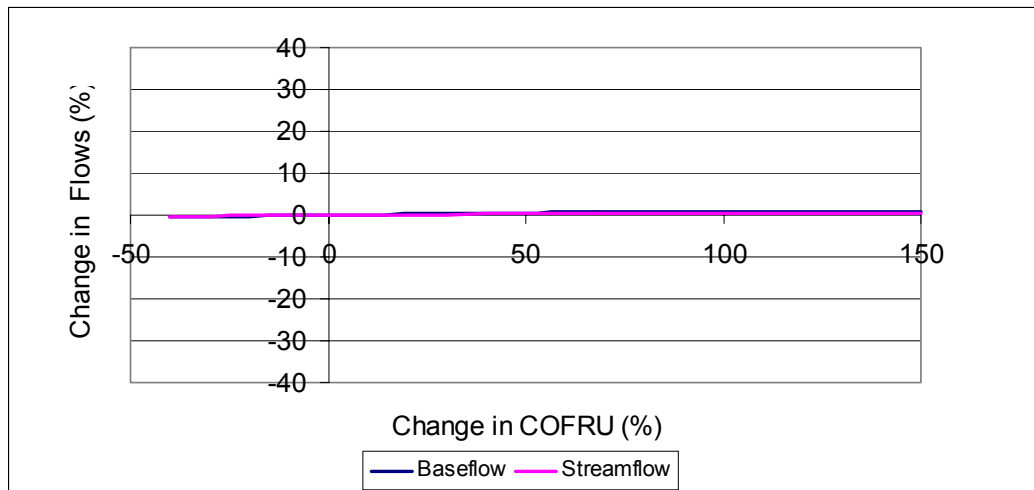


Figure 5.4. Response of cumulative baseflow and streamflow to changes in COFRU parameter

The parameter COFRU showed no influence in cumulative simulated streamflows (Figure 5.4) as per the objective function of this sensitivity analysis study. However, it was noted that it affected the shape of the hydrograph (recession section) when it is varied. This calls for examining this parameter during calibration. Although not plotted, rainfall was found to be extremely sensitive as envisaged where within the range of sensitivity, 40% increase in rainfall amount gave a corresponding increase in simulated cumulative streamflow of over 109%.

5.2.3 Sensitivities of the Apan and the Hargreaves Method

The same procedures and processes were applied to check the level of sensitivities when the reference evaporation method was changed to Hargreaves (1985) method. This was done to assess whether the choice of evapotranspiration method affects the sensitivity of parameters. It was expected that the shape of the plots would be similar, but the gradients might differ slightly, which was confirmed by the simulation (Figure 5.5). Figure 5.5 shows a comparison using the two methods for the two most sensitive parameters FC1 and CAY.

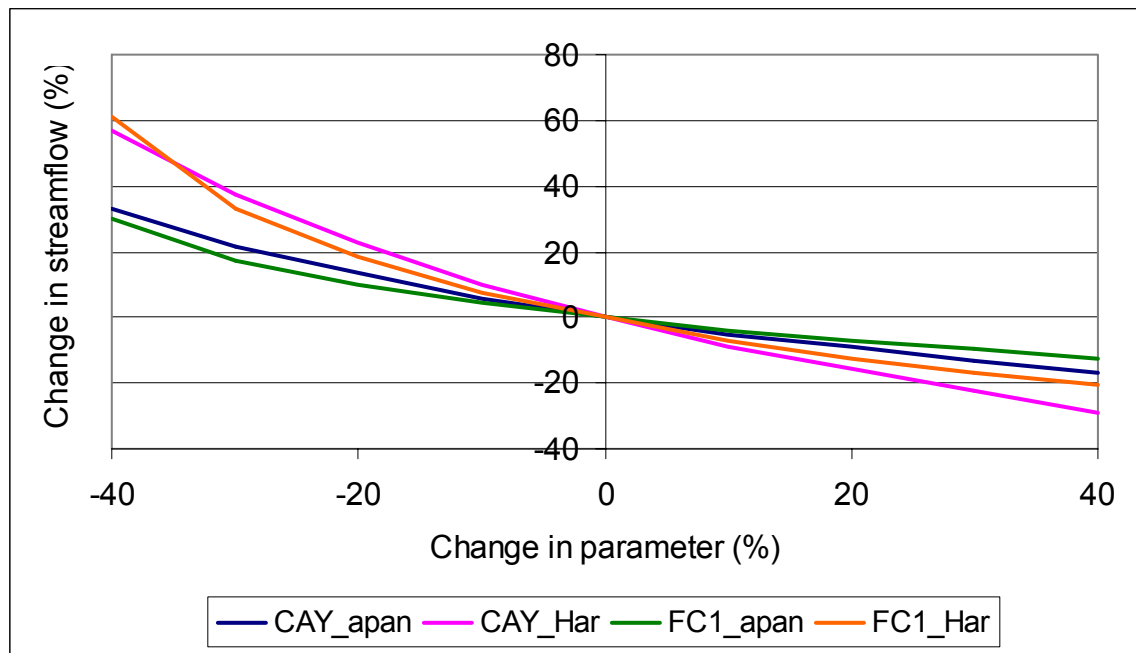


Figure 5.5 Comparison of cumulative streamflow using Apan (apan) and Hargreaves (Har) methods for the most sensitive parameters

It is observed that the Hargreaves method increases the sensitivity of cumulative simulated streamflow to changes in the crop coefficient and the field capacity of the topsoils compared to using the A-pan method.

5.2.4 Results and Conclusion

As a rule, high sensitivity of a parameter is only desirable if that parameter can be measured easily and has a very small range. Schultz (1995) suggested the following scale for parameter sensitivity in ACURU:

- *extremely sensitive* (E): the percentage change in the output ($\Delta O\%$) is more than twice that of the input parameter being tested ($\Delta I\%$), i.e. $\Delta O\% > 2(\Delta I\%)$
- *highly sensitive* (H): the output change is more than the input change, but by less than 200% , i.e. $2(\Delta I\%) > \Delta O\% > \Delta I\%$
- *moderately sensitive* (M): relative output changes less than the relative input change, but by more than 50% of the input change, i.e. $\Delta I\% > \Delta O\% > 0.5(\Delta I\%)$
- *slightly sensitive* (S): output changes by between 10% and 50% of the input change, i.e. $0.5(\Delta I\%) > \Delta O\% > 0.1(\Delta I\%)$

- *insensitive* (I): output changes by less than the 10% of the input change, i.e. $\Delta O\% \leq 0.1(\Delta I\%)$.

Considering Figures 5.1-5.5 according to the above scale, it is apparent that for cumulative streamflow and cumulative baseflow, apart from FC1 and CAY which showed moderate sensitivity, the remaining parameters were either slightly sensitive or insensitive, although PO1 is moderately sensitive over some of its range. The 38% increase in rainfall amount gave a corresponding increase in simulated cumulative streamflow of 109.6% which is over 200% that of the input parameter and is therefore extremely sensitive. This is also corroborated by Angus (1989). In Table 5.2 the Densu Basin sensitivities are compared to Angus (1989) who also tested the sensitivity levels of ACRU model parameters on cumulative flows.

Table 5.2: Comparison of Densu basin sensitivities to Angus (1989)

Parameter	Sensitivity of Parameter (Angus, 1989)		Sensitivity in the Densu Basin	
	Reduced	Increased	Reduced	Increased
FC ₁	-	-	M	S
DEPAHO	H	S	I	I
DEPBHO	H	S	I	I
ABRESP	S	S	I	I
BFRESP	S	S	I	I
CAY	H	H	M	S
ROOTA	S	S	S	I
VEGINT	S	S	S	I
SMDDEP	H	S	I	I
COIAM	M	S	I	I

From the Table of sensitivities it is apparent that the sensitivities seen in the Densu are lower than those of Angus (1989 in Schulze, 1995). It should be noted here that Angus (1989, in Schulze, 1995) undertook this sensitivity analysis at only one location i.e. Cedera in the KwaZulu Natal Midlands and further emphasised that because it was undertaken at only one location, the result can therefore not be used to represent the response of the output in ACRU in other regions. Some suggested possible reasons for the differences in sensitivities at the two locations could be the following:

1. That the two sensitivities have been conducted at two different climatic regions i.e Kwazulu Natal in the semi arid climatic region as against the Densu catchment in the tropical region.
2. DEPAHO is a soil parameter given by the depth of the A horizon of soils. Further, the SMDDEP (effective depth of the soil from which stormflow generation takes place) parameter is known to be very shallow (0.1m) in semi arid regions (Schulze 1995) which are characterised by high intensity convective rainfall, so that the response to stormflow could be high (Schulze, 1995). In the ACRU model the default value of SMDDEP is taken to be the depth of DEPAHO if it is not known, since it is always $\leq$ DEPAHO (Schulze, 1995), meaning that the smaller SMDDEP the higher the stormflow and vice versa. Since the DEPAHO of the soils of the Kwazulu Natal province in the semi arid zone as indicated by Schulze (1995) are very shallow (0.1m) and that of the Densu catchment are around 0.3m, it is apparent that the smaller DEPAHO and SMDDEP requires less rainfall to bring the soil up to field capacity so as to generate stormflows and hence be more sensitive to the soils of semi arid regions than that of the tropical Densu catchment.
3. Comparing the vegetative covers of the Kwazulu Natal province with that of the Densu catchment, the vegetation (land cover) of the semi arid Kwazulu Natal is sparser than the tropical Densu which is nearly covered throughout the year. In its simulations ACRU is sensitive to seasonal above and below-ground vegetation/land cover changes (Schulze, 1995). CAY which is a vegetation dependent parameter is more sensitive when CAY is decreased than when it is increased in the Densu (Figure 5.5). In the ACRU model typical values of the crop coefficient (CAY) have to be specified month-by-month. If there is more than one homogeneous land cover/use zone specified for the catchment, then for each "zone" the percentage area covered by the zone is also given and the land use utility facility in the model will compute an area-weighted monthly CAY. The Densu weighted CAY's were found to be higher than the Kwazulu Natal monthly values. As CAY's have a direct relationship with the stage

of growth of crops and evapotranspiration, it implies that bigger CAY's would result in higher potential evapotranspiration which may impact on the volume of streamflows depending on soil water availability. Thus with monthly CAY's lower in values in the Kwazulu Natal province than in the tropical Densu catchment it is likely that the impact of decreased CAY's on streamflows would be higher (meaning more is generated because there is less potential evapotranspiration) than that of the Densu Basin.

When the relative sensitivities of FC_1 and CAY when using the Apan and Hargreaves methods are compared in relation to cumulative streamflow, the level of sensitivities observed from use of the Hargreaves method for evapotranspiration tended to show higher sensitiveness to the input parameters than the Apan method of evapotranspiration. These slight changes in gradients were expected.

To conclude, the sensitivity analysis has demonstrated how cumulative total streamflow and baseflow respond to changes in ACRU parameters within the Densu Basin. This understanding is thus carried forward to inform the calibration where the most sensitive parameters in this basin notably CAY, VEGINT, ROOTA (the landuse parameters) and FC_1 will be calibrated. COFRU showed no influence in cumulative simulated streamflows for the sensitivity analysis however it was noted that it affected the shape of the hydrograph (recession section) when it is varied and calls for more examination during calibration.

5.3 Methodology for Calibration, Validation and Performance Evaluation

The usefulness of hydrologic models depends both on how well the model is calibrated and how well it performs during validation (Ajami et al., 2004). Calibration is the selection of model parameters to enable the model to simulate the hydrological behaviour of the study site as closely as possible (Singh, 1995)

as given by performance criteria which assess the difference between observations and model simulations. No matter how sophisticated the model structure, Gupta et al., (1999) observed that if the parameters are poorly specified (optimised), simulated streamflows can be quite different from those actually observed and suggested therefore that the calibration procedure must be conducted properly (in a systematic way) to maximise the reliability of the model.

The calibration for the current study was carried out during the period 01/03/1968 to 28/02/1970 with validation between 01/03/1970 to 31/12/1972. The period 01/01/1967-29/02/1968 was used as a warm up to help initialise the model prior to the start of the calibration period. A standard split sample calibration-validation method was used (Figure 5.6).

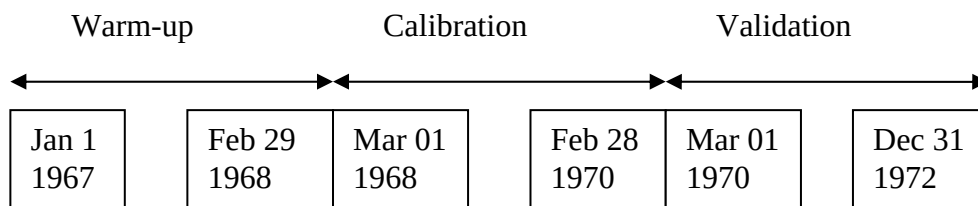


Figure 5.6 Calibration and validation calendar for ACRU modelling

The hydrological water year (referred to as the water year in this thesis) for the Densu basin is from 1st March of the said year to 28th February of the following year.

Masden (2000) noted that for modelling the rainfall-runoff process at the catchment scale, normally the only available information for evaluating the objective is the total catchment runoff. With this observation, he noted that the following objectives should be considered for proper evaluation of the calibrated model:

1. A good agreement between the average simulated and observed catchment runoff volume (i.e. a good water balance).

2. A good overall agreement of the shape of the hydrograph.
3. A good agreement of the peaks with respect to timing, rate and volume.
4. A good agreement for low flows.

However, Masden (2000) further observed that it can be difficult to achieve all of these objectives and that, in general, trade-offs exist between the different objectives, so that, for instance, one may find a set of input parameters that provide a very good simulation of peak flows but a poor simulation of low flows, and vice versa. In this PhD study, the objective to simulate the hydrological impacts of scenarios of future change and their corresponding effects on a downstream reservoir is of paramount interest. This is because the reservoir at Weija in sub-catchment 4 is a water supply point to the capital of Ghana (as explained in chapters 1 & 2) and is dependent on flows from upstream. As such the amount of flows it receives is very important as it would enrich the recommendation component to be given to the DRBMB for effective water resources management in the Basin. Thus as a result of the Masden (2002) observations, a good agreement for the observed and simulated streamflows is very important in this PhD as it would enable streamflow inflows into the Weija Reservoir to be known and assist with effective management for water supply, followed by a good agreement in the shape of the hydrographs and then the remaining elements.

The Daily Root Mean Square (DRMS), Percent Bias (PBIAS); Nash and Sutcliffe (1970) efficiency (NSE) and Performance Model Efficiency (PME) performance appraisal methods were selected due to their widespread use in appraising model performance (Gupta et al., 1999; Niel et al., 2003):

$$DRMS = \sqrt{\frac{1}{N} \sum_{t=1}^N (q_t^{sim} - q_t^{obs})^2} \text{-----(5.2)}$$

$$PBIAS = \sum_{t=1}^N (q_t^{obs} - q_t^{sim}) / \sum_{t=1}^N q_t^{obs} \times 100\% \text{-----(5.3)}$$

$$NSE = 1 - \frac{\sum_{t=1}^N (q_t^{sim} - q_t^{obs})^2}{\sum_{t=1}^N (q_t^{obs} - q_m^{obs})^2} \text{-----(5.4)}$$

$$PME = 1 - \frac{\sum_{t=1}^N (q_t^{sim} - q_t^{obs})^2}{\sum_{t=1}^N (q_t^{obs} - q_{t-1}^{obs})^2} \text{-----}(5.5)$$

where q_t^{sim} , q_t^{obs} and q_m^{obs} are respectively the daily simulated, observed and mean flow of the observed flows and N is the number of data points.

They have the ability to assess aspects of the model performance/hydrograph that are relevant to the aims and objectives i.e. the PBIAS function assesses overestimation or underestimation of streamflows and the PME statistic evaluates whether the ACRU model will be suitable for prediction when the objective to simulate the impacts of scenarios of future change is undertaken.

The Daily Root Mean Square (DRMS) and Root Mean Square (RMS) error compute the standard deviation of the model prediction error; where a smaller value indicates a better model performance, and are measured in millimetres.

The Performance Bias (PBIAS) measures the average tendency of the simulated flows to be larger or smaller than their observed counterparts; the optimal value is zero (0); positive values indicate a model bias toward underestimation, whereas negative values indicate a bias toward overestimation. Its units are in percentages.

The Nash and Sutcliffe Efficiency (NSE) measures the relative magnitude of the residual variance (“noise”) to the variance of the flows (“information”); the optimal value is 1.0 and the values should be larger than zero (0.0) to indicate “minimally acceptable” performance (Gupta et al., 1999). A value equal to zero indicates that the mean observed flow is as good as the model. Henrikson et al. (2003) categorised NSE into five classes namely; excellent, very good, good, poor and very poor and defined the limits of the classes for each of the efficiency indexes. They proposed a limit of 0.5 for a result between good and poor performance. Liden and Harlin, (2000) and Andersen et al. (2001) also state that a good simulation should have an NSE between 0.5 and 0.95.

The PME measures the relative magnitude of the residual variance (noise) to the variance of the errors obtained by the use of a simple persistence model (a model that provides a close approximation of the real behaviour (Cali et al., 2000)); the optimal value is 1.0, and values should be larger than 0.0 to indicate minimally acceptable performance. In addition to these statistical indices, the shape of the simulated hydrograph was also visually judged against the observed hydrograph.

The calibration procedure (Figure 5.7) used was a manual version of that proposed by Ajami et al. (2004), which can be broken down into the following steps:

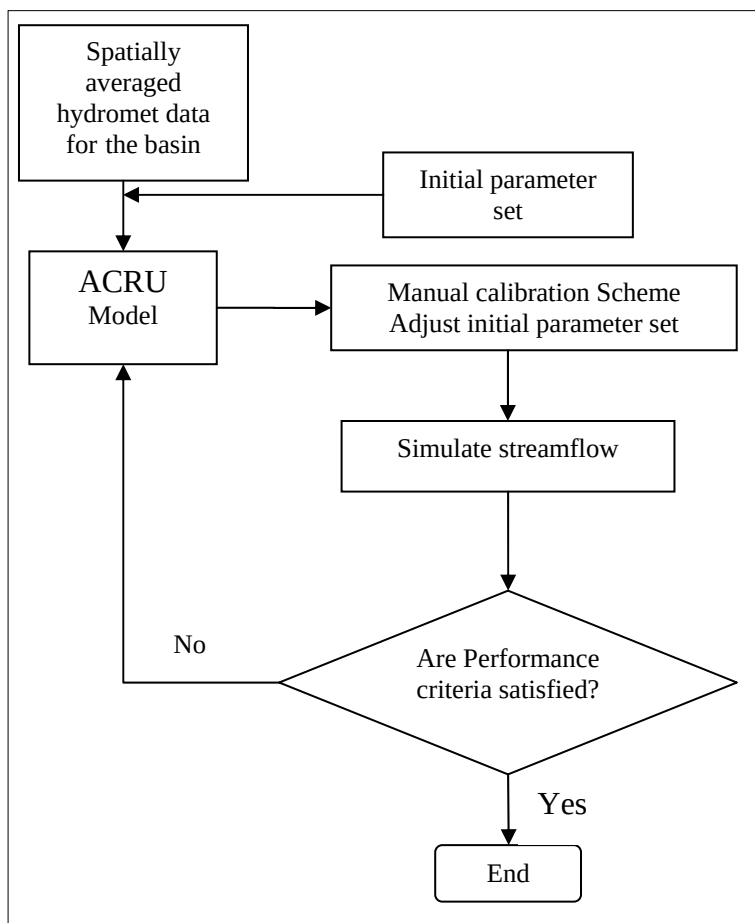


Figure 5.7 Calibration procedure adapted from Ajami et al. (2004)

- A period of observed calibration data is selected

- Initial best estimate values (base values) for input parameters are calculated from data or estimated, based on the physical meaning of those parameters, as appropriate (chapter 4);
- The model is run using these parameter values;
- The performance between the model output and the observed data is measured using a mathematical equation called an objective function;
- The objective function is compared to the chosen performance criteria to determine whether the acceptance criteria are met;
- Further calibration is done, if necessary until the objective functions gives the best acceptable value.

The manual calibration procedure followed a trial and error method in which step by step adjustment of one parameter at a time were made until the performance criteria for the simulated hydrograph were best met. This method relies on the fact that many of the hydrological models are designed so that the parameters have some conceptual relationship to the characteristics of the catchment. Therefore by adjusting certain parameters in certain directions it is expected that this will have predictable effects on the way in which the simulated outputs will change. This effect is not always attained when a large number of interacting parameters are used which can result in unpredictable effects (Singh et al., 1999, Ajami et al., 2004).

For each of the identified parameters from Section 5.2, the range between the minimum and maximum parameter values was split into three intervals, based upon the mid-points between the minimum, base case and maximum values. . The parameter values of the mid-point of these intervals were used in conjunction with the default values of insensitive parameters to preliminarily establish the intervals that best resulted in the simulated output resembling the observed output and having good appraisal statistics. With the best interval noted after running the model several times and recording outputs, incremental parameter values within this interval were input into the model one at a time, and the model run. The simulated streamflow for the calibration period

01/03/1968-28/02/1970 was analysed using the performance appraisal methods PBIAS and NSE to assess whether the parameter value change had improved the objective function value. A plot of the evolution of NSE and PBIAS statistics observed during the calibration process is shown in Figure 5.7b. The calibration was ended when the values of NSE and PBAIS had peaked and could not be improved further. The values of the parameters at this stage were then taken to be the best calibrated values.

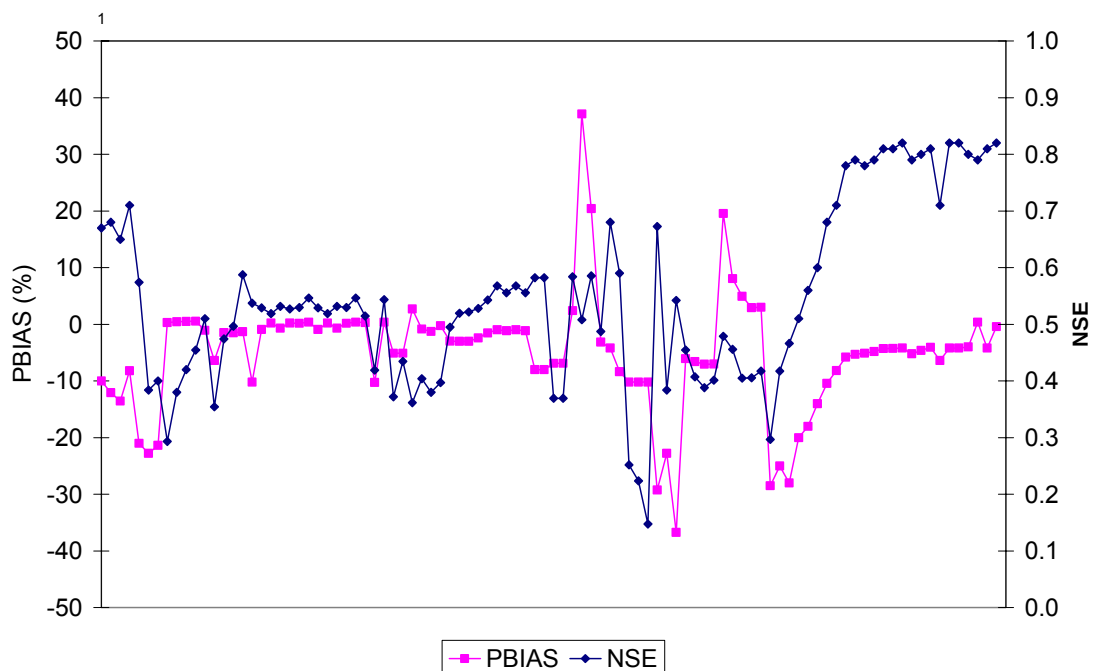


Figure 5.7b Graph of calibration appraisal statistics showing the evolution of the PBIAS and NSE through the calibration process from the base case to the final calibrated simulation.

5.4 Results of Calibration and Validation

The daily and weekly (based upon daily flows aggregated into a weekly average) simulated streamflow from the calibrated ACURU model of the Densu Basin in the lumped mode are shown, respectively, in Figures 5.8 and 5.9. The performance statistics are displayed in Tables 5.3 and 5.4 for both daily and weekly calibrated simulations. These show that the daily calibrated model satisfied the NSE criteria ≥ 0.5 , overestimated the observed streamflow by 4.20% (PBIAS), but failed the PME criteria (which should be at least 0 to pass). The DRMS was 1.01 mm.

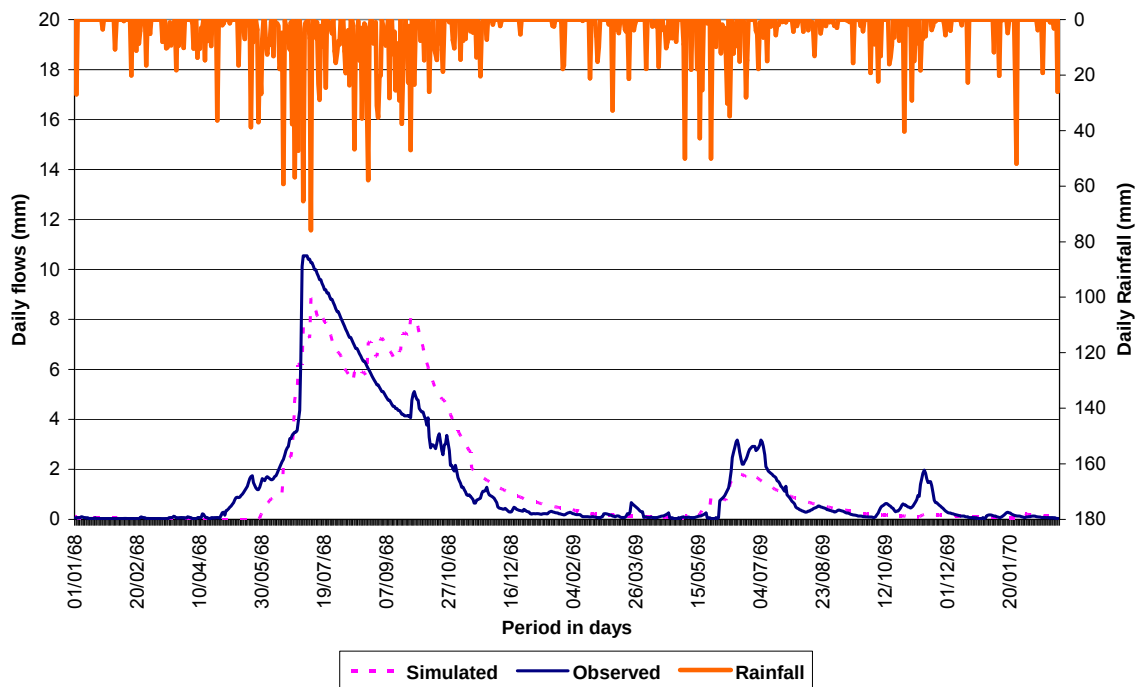


Figure 5.8 Daily calibrated simulated streamflow at Manhia in the lumped mode.

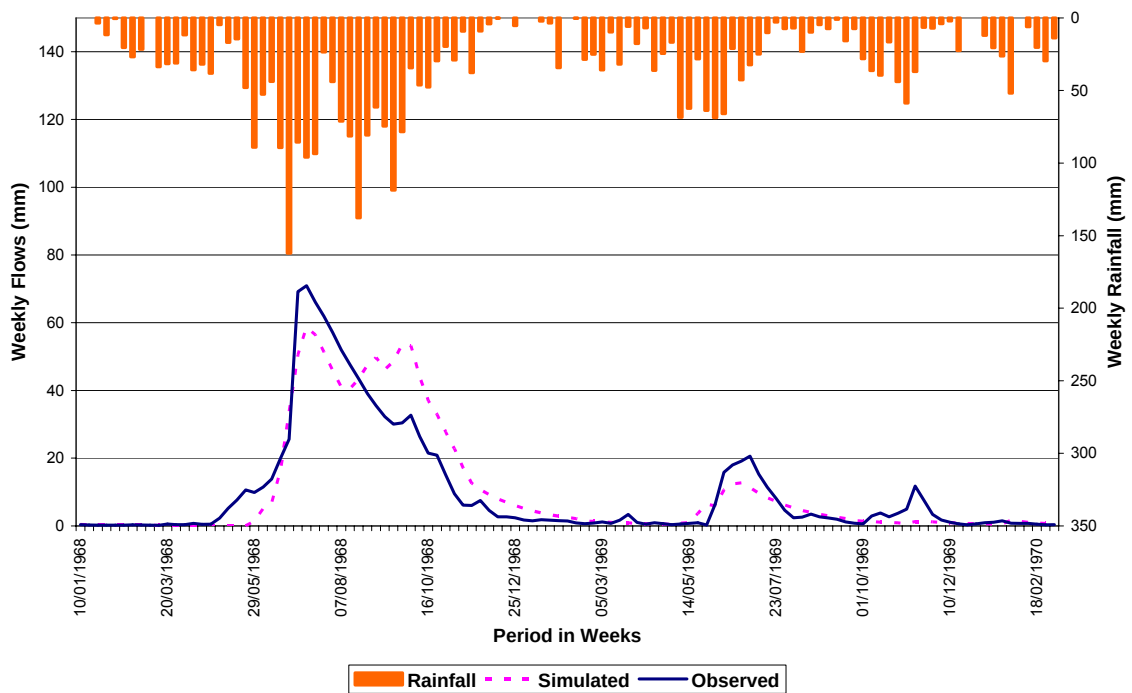


Figure 5.9 Weekly calibrated simulated streamflow for the Densu river in the lumped mode at Manhia

Table 5.3 Performance statistics for daily lumped simulations at Manhia

Daily Calibration		Daily Validation		
Period (01/03/68-28/02/1970)		Period (01/03/1970-31/12/1972)		
	All Months	All Months	Water Years ⁹	Period
	Period	Period	01/03/1971-31/12/72	01/03/1972-31/12/72
RMS (mm)	1.01	0.51	0.40	0.25
PBIAS (%)	-4.20	-69.74	-33.80	9.90
NSE	0.82	-0.51	0.28	0.58
PME	-ve	-ve	0.13	0.18

⁹ Water Year (1/03/Year to 28/02 of following year)

Table 5.4 Performance statistics for weekly lumped simulations at Manhia

Weekly Calibration		Weekly Validation		
Period (01/03/68-28/02/1970)		Period (01/03/1970-31/12/1972)		
	All Months	All Months	Water Years	Period
	Period	Period	01/03/1971-31/12/72	01/03/1972-31/12/72
RMS (mm)	6.67	3.20	1.88	1.40
PBIAS (%)	-4.35	-69.27	-13.71	9.69
NSE	0.83	-0.70	0.54	0.70
PME	-ve	-ve	0.37	0.43

The weekly calibrated streamflow had an improved NSE of 0.83 (compared to the daily simulation) which is good and a PBIAS of overestimation of 4.35%. The weekly RMS error was 6.67 mm indicating that the standard deviation of the model prediction error was high.

With the 'best' calibrated values established and the model achieving a low PBAIS and a very good NSE according to Henrikson et al. (2003) the model was run for the validation period. Figures 5.10 and 5.11 show the simulated daily streamflow and weekly streamflow for the validation period with the corresponding performance appraisal statistics shown in Tables 5.2 and 5.3 respectively.

From the performance statistics of both the daily (Table 5.3) and weekly (Table 5.4) simulations during the validation period, it is apparent that the validation period had NSEs of -0.51 (daily) and -0.70 (weekly) which were poor according to the acceptance criteria. However, the year of 1972 has very good statistics with NSE as high as 0.70 for the weekly and 0.58 for the daily. In the weekly simulations the year 1970 had an improved PME of 0.37 to 0.43 for the weekly flows for 1971 and 72 water years, respectively as against 0.13 and 0.18 for the daily flows respectively.

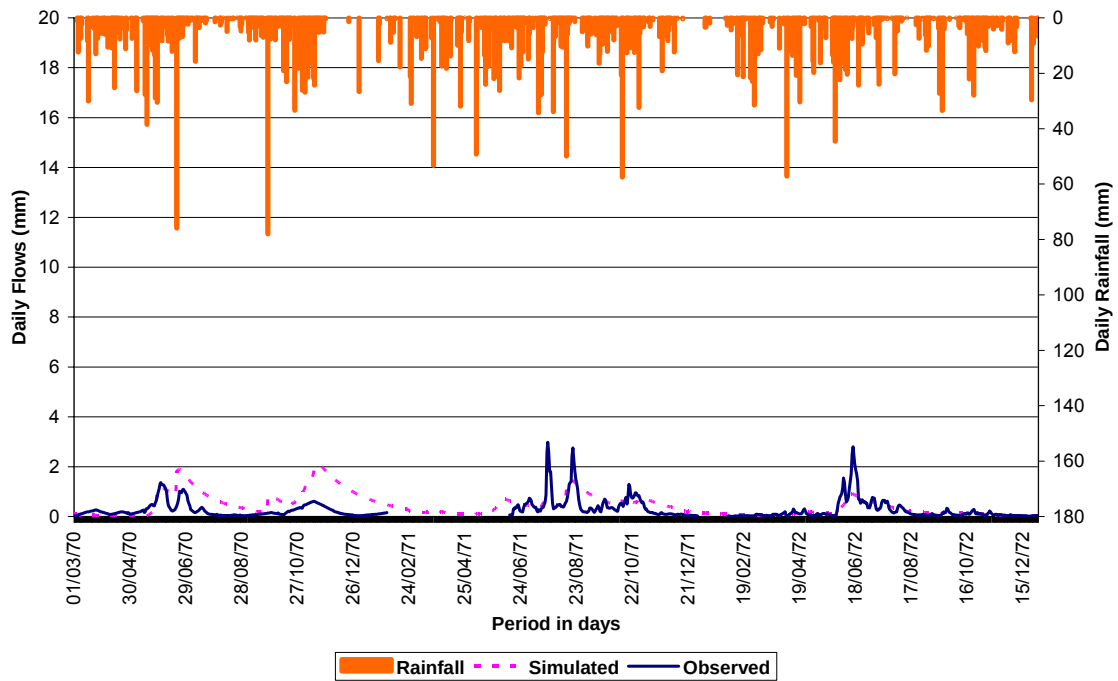


Figure 5.10 Daily simulated streamflow in the lumped mode at Manhia during the validation period

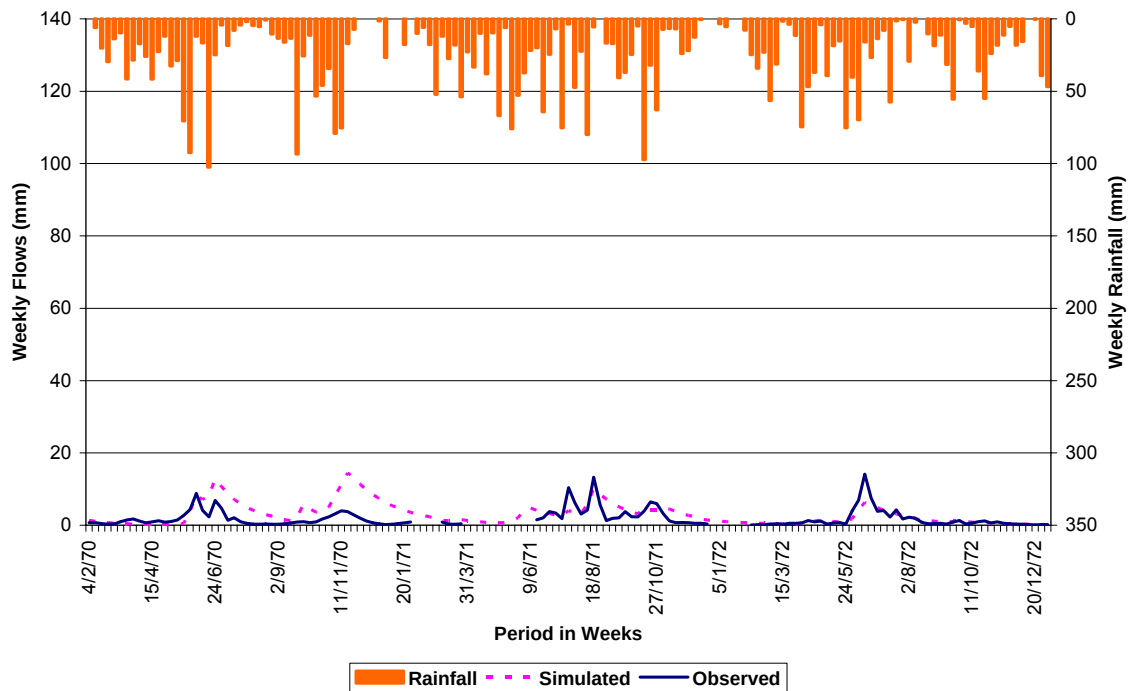


Figure 5.11 Weekly simulated streamflow for the in lumped mode at Manhia during the validation period

5.5 Water Balance for the lumped simulation

The water balance of this basin has been computed with the equation

$$P - E_a - Q_s = \Delta s$$

where P is the rainfall, E_a is the calculated actual evapotranspiration, Δs is the combined change in soil and groundwater storage and Q_s is the streamflow (Eagleson, 1978). All terms except P depend upon the soil moisture content and distribution which are generally not measured, but this problem can be overcome by assuming the system to be stationary in the mean (Everson, 2001).

The independent input variable is rainfall, which is transformed in the hydrological system into the dependent output variables of evaporation, streamflow and the change in soil and groundwater storage. The various continuous water movement processes of the hydrological cycle are lumped over finite time intervals and areas and related by the water balance equation.

The validity of the input data collected and simulated was checked by balancing the equation. Between the 1968 and 1972 water year's, Δs was calculated as the residual balance of the model output. The other input parameters E_a and Q_s were the values using the ACRU model. The mean monthly water balance for the period is shown in Table 5.4b and it indicates that the months of November and October have negative storage meaning water was being lost from storage. In Table 5.4c the difference between the simulated and observed streamflow data were compared to the observed rainfall on an annual basis and the percentage difference computed. It is shown that, but for the year 1970/71 which has relatively higher percentage (12.1%) of the difference between the observed and simulated runoff as a proportion of the mean annual rainfall for the period, the rest of the differences were below 5% which shows that the simulated values are not too far fetched from the observed. Expressing the error in streamflow as a proportion to the measured annual streamflow is shown in the last column of Table 5.4c. These errors are higher suggesting that there

Table 5.4b The mean monthly water balance output table for the lumped model at Manhia for the period 1968-1972

	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Total
Rainfall (mm)	98.8	115.7	199.9	178.2	131.8	114.9	159.9	152.9	101.2	25.1	47.0	77.0	1402.5
Actual Evapotranspiration (mm)	76.8	76.3	73.8	65.2	48.8	39.2	35.8	84.8	72.8	28.4	26.4	39.7	668.1
Simulated Streamflows (mm)	3.0	2.5	6.0	36.9	60.9	52.7	52.0	43.6	29.1	16.8	9.4	4.9	317.7
Change in Storage (ΔS) (mm)	19.0	36.9	120.1	76.2	22.1	23.0	72.1	24.4	-0.7	-20.1	11.2	32.5	416.8

Table 5.4c: Lumped annual water balance components at Manhia. P = Rainfall, E_a = Simulated actual evapotranspiration, Q_s = simulated streamflow, Q_a = observed streamflow and (ΔS) is change in storage..

Year	$P - E_a - Q_s = \Delta s$ (mm)	Q_a (mm)	$Q_s - Q_a$ (mm)	%($Q_s - Q_a$) to P	%($Q_s - Q_a$) to Q_a
1968/69	2153.2 - 612.8 - 1014.1 = 526.3	915.9	98.2	4.6	10.7
1969/70	1230.2 - 697.8 - 152.6 = 379.8	202.9	- 50.3	4.1	24.8
1970/71	1271.2 - 587.3 - 242.8 = 441.1	88.6	154.3	12.1	174.1
1971/72	1369.7 - 810.1 - 150.7 = 408.9	111.0	39.8	2.9	35.9
1972/73	1112.2 - 720.9 - 66.9 = 324.4	73.95	- 7.1	0.6	9.6

might be data problems as discussed in Chapters 6 and 7. For the five year period, the average percentage of annual rainfall that turns into streamflow for any particular year is about 16% (6.6% - 42.5%) In Table 5.4c the change in storage is positive for each of the five years, indicating that the groundwater store is ever increasing year by year for this period. Is this large positive storage indicating that the model is not in balance? However, this ever increasing groundwater storage is also observed by Ayibotele (1974) when he conducted a preliminary water balance study for the Densu Basin for the same period suggesting that this observation is not peculiar to this modelling and that there might not be any problem at all. However, this call for future further investigation into this ever increasing groundwater storage to determine whether the proceeding few years attains negative storage to enable the storage to attain equilibrium.

5.6 Modelling In Semi Distributed Mode

The Densu catchment was partitioned into four sub catchments (Figure 4.15) based upon:

- streamflow data availability; sub-catchments 2 and 3, were delineated based upon the catchments of the flow gauge stations and;
- the importance of a sub-catchment in terms of water resources abstraction; catchments 1 and 4 were delineated based on the location of Koforidua (sub-catchment 1) which is very important to this study in terms of abstraction and Weija (sub-catchment 4) which is the reservoir feeding Accra, the capital city of Ghana with water supply as discussed in chapters 1 and 2.

The sub division of the catchments is intended to improve the simulation of the hydrological impacts of scenarios of future change within the catchment by allowing more spatially realistic scenarios of land use change.

The simulated streamflows at the gauge stations are flows exclusive of the contributions of upstream sub-catchments and are as follows (Figure 4.15):

Koforidua sub-catchment	(1)	600km ²	No flow measurement
Nsawam sub-catchment	(2)	938km ²	Observed flows available
Manhia sub-Catchment	(3)	562km ²	Observed flows available
Weija sub-Catchment	(4)	464km ²	No flow measurement

Technically from the way the streamflow data has been measured as described above and the data availability for this thesis, the simulation that would be undertaken could be described as a series of three lumped sub-catchments. However because the parameter values are different in Subcatchments 1, 2 and 3, the model for the whole of catchment 3 is not lumped but can best be described as semi-distributed.

In semi-distributed models of the type embodied by ACRU the catchment is depicted as an assembly of interconnected units of area. Each such unit,

represented in the model by a cell or subcatchment, is considered to be a lumped representation of that area. The interconnected layout of cells within a hypothetical catchment can be represented by an inter-cell flow diagram (Shulze, 1995). In Figure (4.15) a lumped inter-cell flow diagram is shown depicting the sub-catchments of the Densu Basin which reflect the major stream patterns of the catchment

That is to say, the flow at the outlet of sub-catchment (2) is the sum of the flow from both sub-catchment (1) and (2), and for sub catchment (3) i.e. Manhia the observed flow equals the sum of flows from (1)+(2)+(3). The flow path is shown in Figure 5.12. Mean daily hydrometeorological parameter values for the sub-basin namely, rainfall, pan evaporation, streamflow, temperatures (maximum and minimum) were prepared. Similarly soil parameters and landuse parameters were computed on an area-average basis for each sub-catchment.

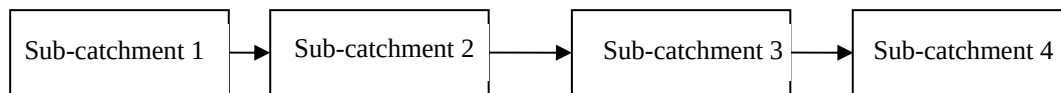


Figure 5.12 Flow path of the Densu Modelling

Sub-catchment 1+2 was modelled first, followed by sub-basin3, all with daily time steps. Sub-catchment 4 was not modelled because observed streamflow was not available.

5.6.1 Results of Semi Distributed Calibration and Validation.

To calibrate the performance of the model in the semi-distributed mode, the same performance criteria statistics (DRMS, PBIAS and NSE's and PME) for the calibration period i.e. 01/03/1970 to 31/12/1972 and calibration algorithm were used as for the lumped modelling. To calibrate sub catchment 1, the parameters of this sub-catchment were fixed with their *a priori* estimated values, since flow data were unavailable. For the calibration of sub catchment 2, similarly the parameters were fixed to their *a priori* estimated values and the model run following the algorithm of Figure 5.7 until the closest shape to the

observed streamflow hydrograph was obtained. The parameters that gave the best fit to the observed hydrograph were then taken as the calibrated values for this sub-catchment. To calibrate the subsequent sub-catchments, the parameters of upstream sub-catchments were fixed to their calibrated values and runs undertaken until optimized values gave satisfactory performance indices.

Nsawam

Initial observations in simulating in the semi distributive mode (Fig 5.13) for the daily simulation were that the shape of the initial hydrograph produced from simulating sub-catchments (1+2) was good visually in terms of patterns of peaks, onset of the rainy season and dry seasons, but that the timing of these peaks and rainy seasons were not coinciding with the observed streamflow. The daily calibrated and validation simulations are shown in Figures 5.13 and performance appraisal statistics are given in Table 5.5.

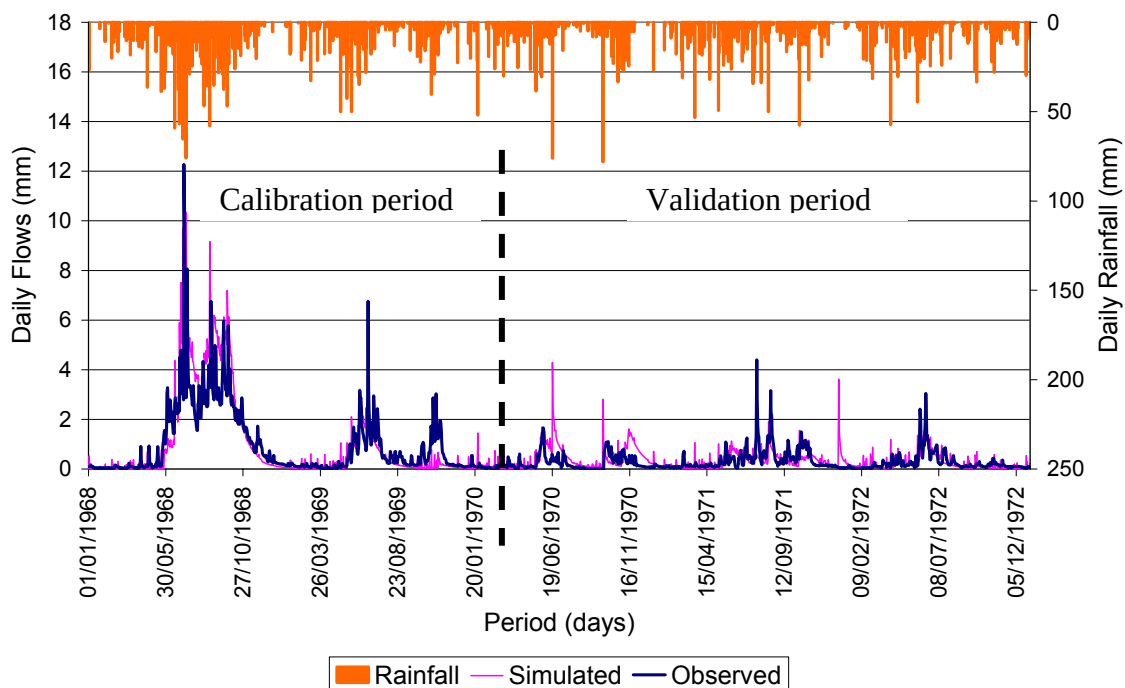


Figure 5.13 Comparison of observed and simulated daily flows for the calibration and validation periods of the semi distributed model at Nsawam.

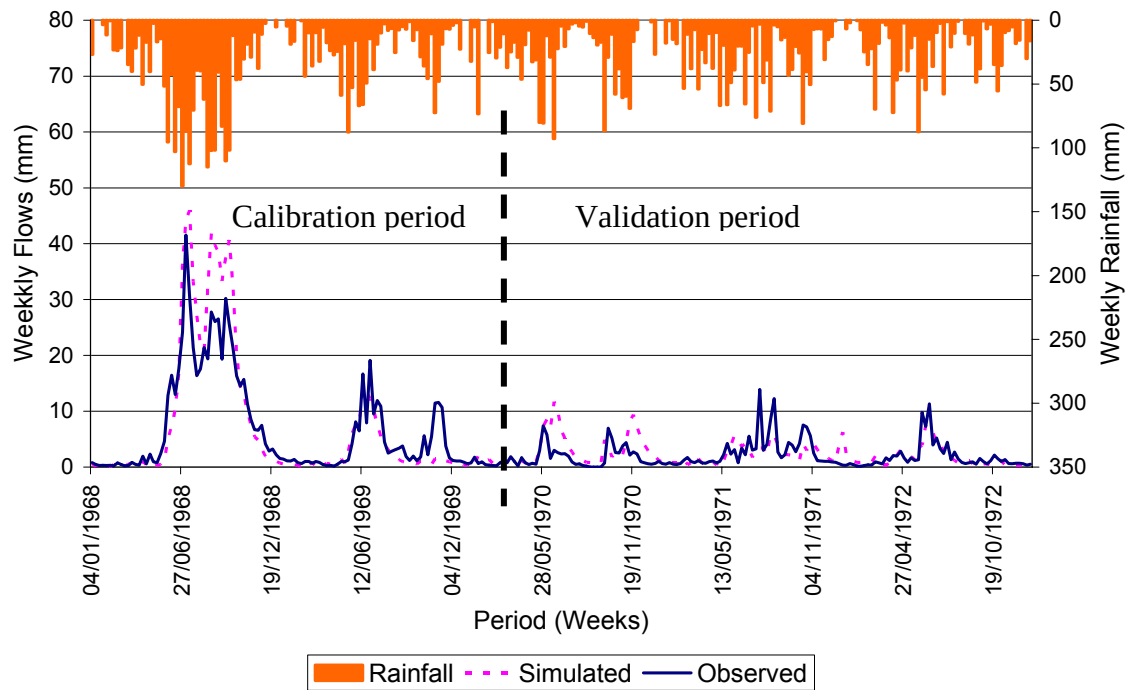


Figure 5.14 Comparison of observed and simulated weekly flows for the calibration and validation periods of the semi distributed model at Nsawam.

Table 5.5. Daily performance statistics for semi distributed modelling at Nsawam

Daily Calibration			Daily Validation				
Period (1/03/68-28/02/1970)			Period (1/03/1970-31/12/1972)				
	All Months	Dry months	All Months	Period	Period	Dry Months	Dry Months
	Period	01/11-28/02	Period	01/03/1971-31/12/72	01/03/1972-31/12/72	1970-1972	01/031971-31/12/72
RMS (mm)	0.99	0.44	0.44	0.42	0.31	0.39	0.16
PBIAS (%)	-6.38	44.89	-14.1	10.44	14.67	-121.11	-59.36
NSE	0.47	0.16	-0.30	0.07	0.35	-7.65	-10.26
PME	-ve	-ve	-ve	-ve	-ve	-ve	-ve

From the appraisal statistics, the daily NSE for the calibration was 0.47, with an overestimation of 6.38% given by the PBAIS. The performance model efficiency fell below zero. In the validation period, the daily NSE deteriorated to -0.30 but improved when the year 1970 water year was not included. The NSE for only 1972 was further improved to 0.35.

Figure 5.14 also shows the weekly calibration and validation streamflow simulations for the Nsawam catchment with Table 5.6 showing the performance appraisal statistics for the weekly simulations.

Table 5.6. Weekly performance statistics for semi distributed modelling at Nsawam Simulations

Daily Calibration			Daily Validation				
Period (1/03/68-28/02/1970)			Period (1/03/1970-31/12/1972)				
	All Months	Dry months	All Months	Water year	Water year	Dry Months	Dry Months
		01/11-28/02		01/03/1971-31/12/72	01/03/1972-31/12/72	1970-1972	01/03/1971-31/12/72
RMS (mm)	4.88	2.48	2.30	2.02	1.35	2.20	1.03
PBIAS (%)	-6.17	44.59	-15.04	10.22	14.17	-131.15	-62.83
NSE	0.68	0.28	0.06	0.40	0.66	-6.76	-8.59
PME	-ve	-ve	-ve	-ve	0.56	-ve	-ve

The performance criteria statistics RMS, PBIAS and NSE are seen to have improved for the daily aggregated into weekly simulations over that of the daily simulation for both the calibration and validation phases. As with the lumped simulation for the larger catchment at Manhia, the calibration period gave a good NSE, i.e. 0.68 (weekly). The weekly validation statistics (Table 5.6) were not as good as that for the weekly calibration period when the water year 1970 is included for both daily and weekly simulations. Omitting 1970 improved the NSE but it still did not pass the Henrikson et al. (2003) acceptance limit for this statistic making it still unacceptable. Similarly, when the dry periods are considered, i.e. Nov-Feb, the statistics for the calibration period are better than for the validation period but the results still failed to satisfy the NSE criteria given by Henrikson et al. (2003) and the PME still gave negative values. Considering the PBIAS criteria, the simulation produced an overestimation of the total streamflow in the calibration period by 6.38% (daily) and 6.17% (weekly) whilst in the validation period, it overestimated by 14% (daily) and 15% (weekly).

With the weekly simulation based on daily data showing better performance statistics than the daily streamflow, monthly (aggregated daily flows for 28 days)

simulated streamflows were derived from the daily data. Figure 5.15 show the corresponding aggregated daily into monthly streamflows with the point x-x

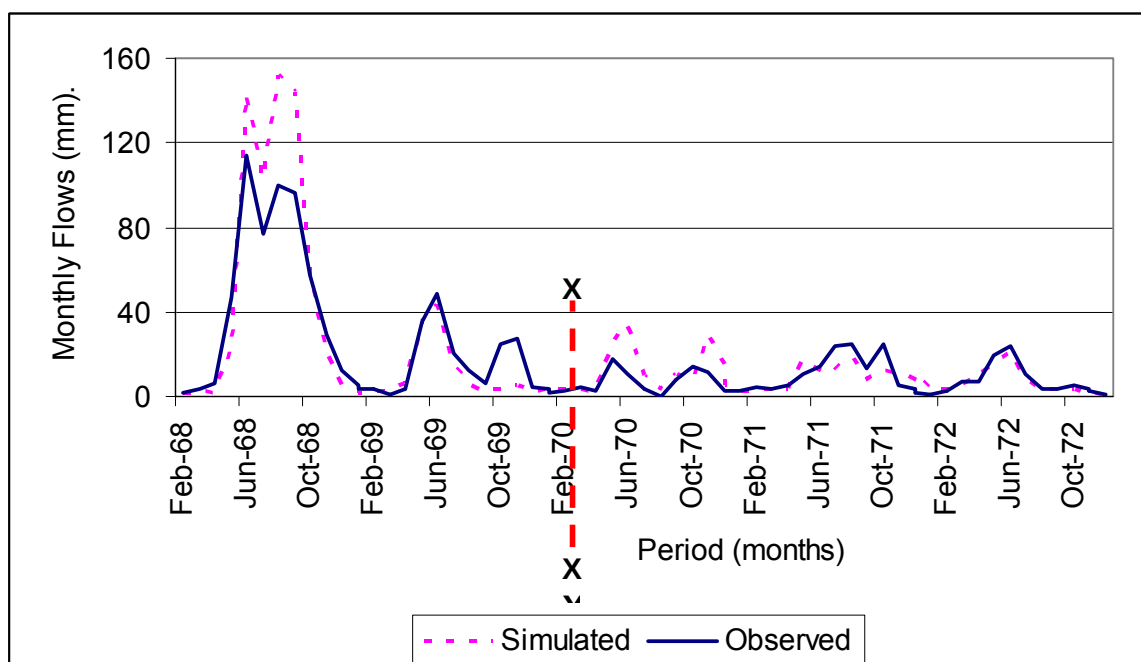


Figure 5.15 Monthly flows for semi-distributed model at Nsawam with x-x indicating the end of the calibration period and beginning of validation.

indicating the end of the calibration and beginning of the validation period. The statistics are seen in Table 5.7. The NSE improved to 0.71 from 0.68 (weekly) and slightly deteriorated from -6.17% (weekly) to -6.37% for the PBAIS. The PME statistic has improved significantly from negative (-ve) from weekly to 0.39 for the monthly passing the criteria which should at least be zero (0).

Table 5.7 Performance statistics for monthly lumped and semi-distributed simulations at Nsawam and Manhia

Monthly Calibration				Monthly Validation 25/03/1970-31/12/1972 ¹⁰					
Period (01/03/68-28/02/1970)				01/03/1970-31/12/1972			01/03/1971-31/12/1972		
	Lumped	Semi Distributed		Lumped	Semi Distributed		Lumped	Semi Distributed	
	Manhia	Nsawam	Manhia	Manhia	Nsawam	Manhia	Manhia	Nsawam	Manhia
RMS (mm)	24.88	17.56	25.86	11.55	6.90	12.40	6.11	4.97	5.22
PBIAS (%)	-4.27	-6.37	15.26	-66.97	-14.89	-58.90	-18.13	9.70	-14.20
NSE	0.86	0.71	0.80	-1.32	0.13	-1.49	0.47	0.62	0.63
PME	0.65	0.39	0.54	-1.31	0.01	-1.57	0.52	0.51	0.52

¹⁰ Excluding periods without information as seen on corresponding graphs.

Manhia

Having achieved the best calibration of the Nsawam sub catchment, the calibration of sub-catchment 3 i.e. Manhia was carried out. During this calibration, the parameters for the upstream Nsawam sub catchment were fixed and sub-catchment 3 calibrated using the same procedures as described for Nsawam (sub-catchment 2). The calibrated plot of the daily, weekly and monthly simulated streamflows are shown respectively in Figures 5.16, 5.17 and 5.18 with the corresponding appraisal statistics shown in Tables 5.8, 5.9 and 5.7. The results indicate that NSE for the daily simulated streamflow during the calibration period is 0.73 with underestimation of simulated streamflow of 170.7 mm over observed streamflow of over 15% (PBAIS) and a RMS of 1.24 mm.

For the weekly calibration, (Figure 5.17 and Table 5.9) the performance appraisal statistics gave a satisfactory NSE of 0.77 but for the whole of the validation period i.e. 01/03/1970 -31/12/1972 the NSE was unacceptable i.e. -0.96, although the validation period of 1972 gives an NSE of 0.67.

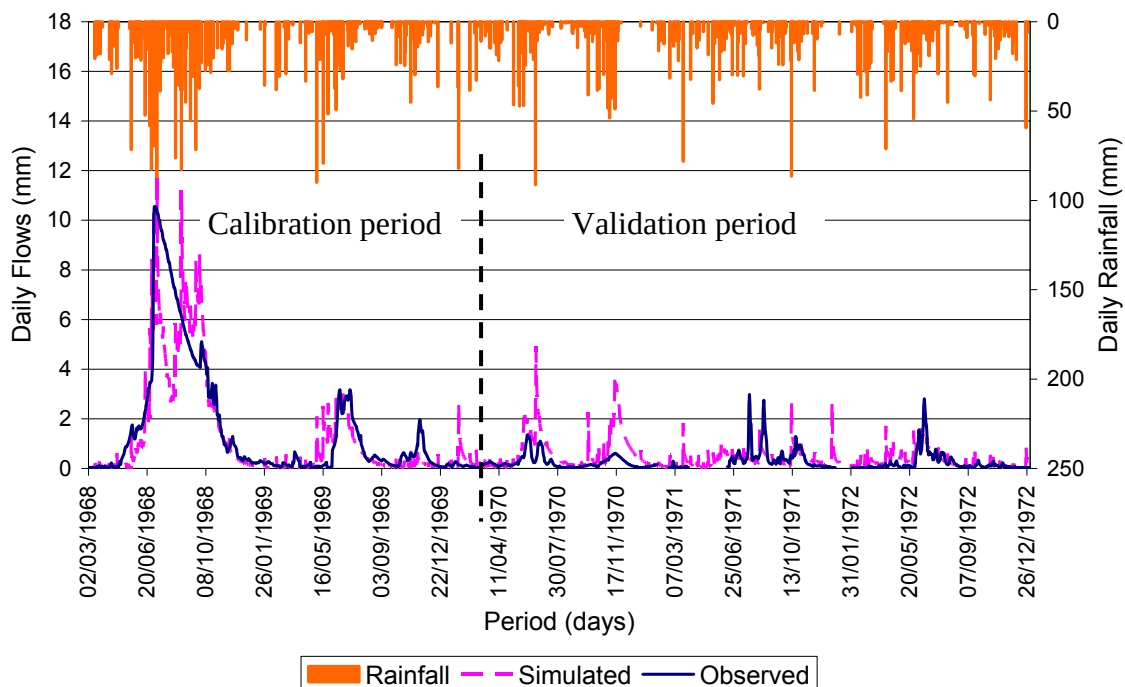


Figure 5.16 Daily streamflow simulation for calibration and validation periods at Manhia catchment in the semi distributive mode.

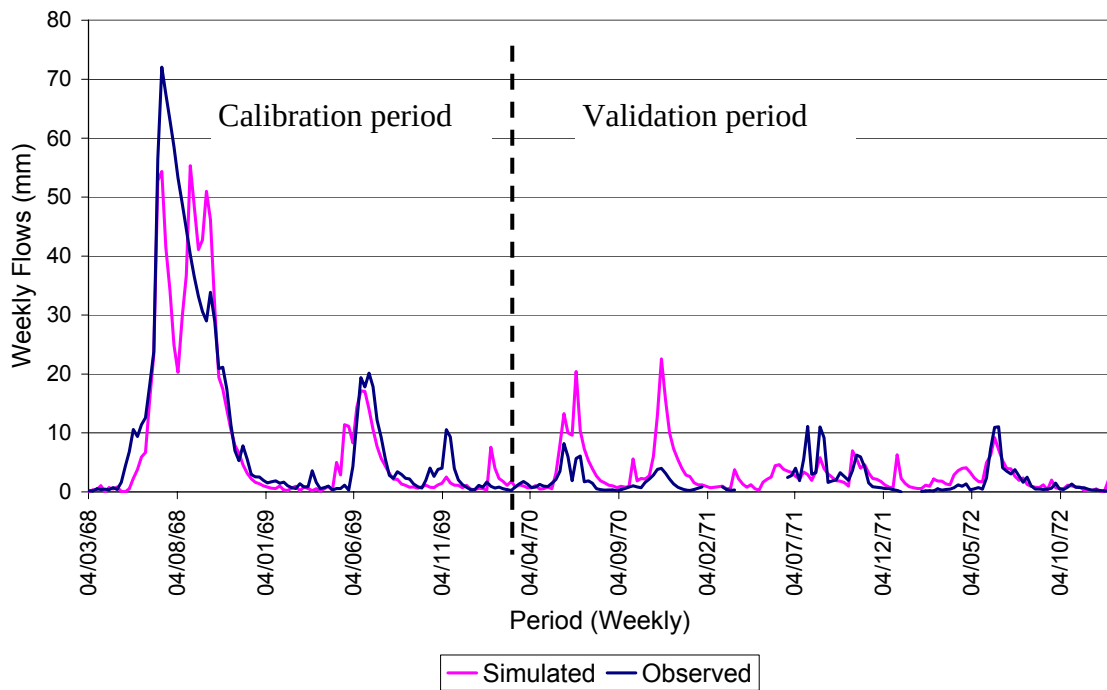


Figure 5.17 Weekly streamflow simulation for calibration and validation periods at Manhia catchment in the semi distributive mode

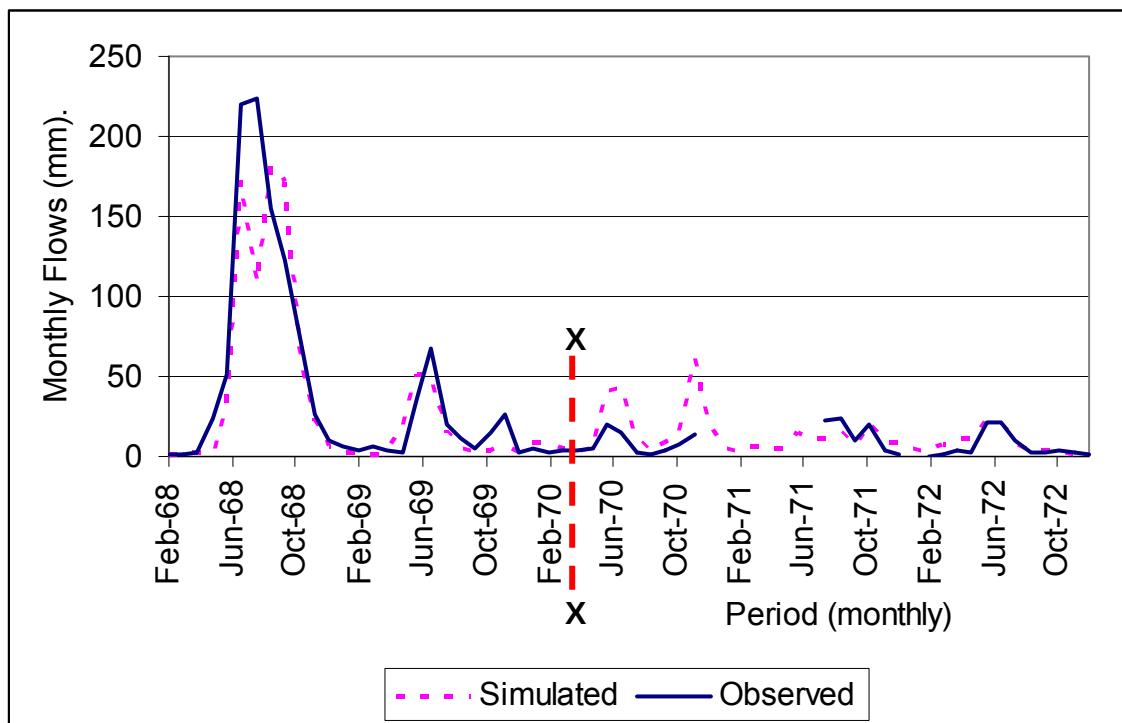


Figure 5.18 Monthly flows for Semi-distributed Manhia with point x-x indicating end of calibration and beginning of validation

Table. 5.8 Daily performance statistics for Manhia (sub basin 3) in the semi distributed mode

Daily Calibration			Daily Validation				
Period (1/03/68-28/02/1970)			Period (1/03/1970-31/12/1972)				
	All Months	Dry months	All Months	Water year	Water year	Dry Months	Dry Months
	Period	01/11-28/02	Period	1971-31/12/72	1972-31/12/72	1970-1972	1971-31/12/72
RMS (mm)	1.24	0.42	0.57	0.41	0.32	0.70	0.30
PBIAS (%)	15.26	23.99	-65.35	-14.91	-31.16	-279.76	-156.17
NSE	0.73	0.11	-1.17	0.10	0.33	-19.89	-10.60
PME	-ve	-ve	-ve	-ve	-ve	-ve	-ve

Table. 5.9 Weekly performance statistics for Manhia (sub basin 3) in the semi distributed mode

Daily Calibration			Daily Validation				
Period (1/03/68-28/02/1970)			Period (1/03/1970-31/12/1972)				
	All Months	Dry months	All Months	Water year	Water year	Dry Months	Dry Months
	Period	01/11-28/02	Period	1971-31/12/72	1972-31/12/72	1970-1972	1971-31/12/72
RMS (mm)	5.68	1.84	2.33	1.43	1.01	2.92	1.10
PBIAS (%)	15.19	23.31	-63.16	-31.58	-28.79	-290.52	-181.15
NSE	0.77	0.25	-0.96	0.39	0.67	-13.73	-2.67
PME	-ve	-ve	-ve	-ve	0.14	-ve	-ve

For the monthly calibration the NSE was 0.80 but for the validation period, it was -1.49 failing the Henrikson et al. (2003) criteria of $NSE \geq 0.5$. The PBIAS was 15.26% meaning it was underestimating as compared to the lumped mode at Manhia which was overestimating (4.27%) for the same monthly simulation.

5.7 Conclusion

The modelling of the Densu Basin using the ACRU model has been undertaken and the results shown by means of sensitivity analysis, calibration and validation. The sensitivity analysis demonstrated that cumulative total streamflow and baseflow respond to changes in ACRU parameters within the Densu Basin. The most sensitive parameter values identified in this basin are the monthly crop coefficients (CAY), Vegetation interception loss (VEGINT), Fraction of the effective root system in top soils (ROOTA) and the Drained

upper limits for the top soils (FC1). The calibrated values of these parameters are shown in Annex C for the lumped and semi distributed mode modelling. The sensitivities observed in the Densu-Basin were found to be lower than those reported by Angus (1989) which were undertaken in only one location and therefore the result of this sensitivity analysis compared to Angus (1989) is not conclusive. However, the results of this sensitivity analysis will complement the knowledge of sensitivity analysis for the tropics as Angus (1989) was undertaken for semi arid catchments.

During the modelling, the performance criteria used for appraising of the model performance were undertaken with the NSE, PBIAS, DRMS and the PME objective functions. The criteria of Henrikson et al. (2003) for NSE which was to be ≥ 0.5 to be accepted was followed and also the PME which was to be ≥ 0 (Gupta et al., 1999) was used. There was variability in the results with regard to the NSE which fared well > 0.5 for the calibration period but poorly in the validation period. The PME statistic failed for both daily and weekly simulations improving (0.4-0.65, ref. Table 5.7) for only the aggregated daily into monthly simulations for the various modes in the calibration period.

On the whole the semi distributed mode simulation statistics compared to the lumped mode did not show any significant improvement. However, from the daily, daily aggregated into weekly (weekly) and also daily aggregated into monthly (monthly) simulated flows, it is seen from the results that the latter had very good statistics comparatively with very high NSE and improved PME for the calibration period but poor NSE and failed PME for the validation periods.

To conclude, modelling the streamflows from the Densu Basin with the ACURU model from the appraisal statistics shows that the model performed better in the calibration period than the validation period. Again the statistics show that the lumped mode simulation performance was better than the semi distributed mode performance with the aggregated daily flows into monthly flows giving the 'best' results suggesting that ACURU would be more suited for long term

planning for irrigation and water supply. The next Chapter (Chapter 6) will discuss these results and try to find reasons for the variable appraisal statistics.

6. Discussion

In Chapter 5, the modelling of the Densu Basin using the ACRU model was undertaken and results of the modelling presented. Chapter 5 showed that the model was sensitive to a limited range of input parameters such as the field capacity water contents of the soils, and the monthly crop coefficients, which were calibrated during the modelling stage in both lumped and semi-distributed modes. The results showed variability in model performance based on the appraisal statistics, DRMS, NSE, PBAIS and PME. Various causes of this variability are hypothesised which could relate to:

- a) the quality of the observed river flow data against which the simulated flow data are calibrated and compared;
- b) the quality of the observed weather data e.g. rainfall and evapotranspiration;
- d) shortcomings within the numerical representation of processes within the ACRU model;
- e) shortcomings related to the incorporation of spatial variability within the lumped and semi distributed simulations;
- f) features within the Densu basin which were not considered within the simulations e.g. abstraction and discharges; effects of control structures e.g. weirs.

The purpose of this chapter is to analyse the simulated and observed riverflow data in detail, in order to identify and discuss the reasons for the variable model performance observed in both the lumped and semi distributed modelling of the Densu Basin.

6.1 Dry Season and Water Year Analyses

The analysis of the behaviour of the simulations has been principally performed on the lumped mode results because, from the results shown in Sections 5.4 & 5.5, they were not significantly different from those of the semi distributed mode.

6.1.1 Dry Season

The daily streamflow results of the lumped mode simulation for the entire modelling period were given in Chapter 5 in Figures 5.8 and 5.10 and Table 5.3 for the calibration and validation periods. In Table 6.1, analyses of the simulated results for the dry periods (defined from the beginning of November to the end of February) for the lumped mode are shown for both calibration and validation periods.

From Table 6.1 the daily RMS for the dry periods remains constant i.e. 0.64 mm for both calibration and the validation periods, while the weekly RMS differs slightly. However, the daily NSE was unacceptable for both calibration (-1.12) and validation (-10.68) periods. The ACRU model overestimated the daily streamflow during the dry periods by over 50% (PBIAS) during the calibration period and by over 330% (PBIAS) in the validation period. The PME statistic failed during both calibration and validation periods.

Table 6.1 Performance Statistics for Daily/Weekly Lumped Simulations at Manhia for the dry period

Daily Calibration			Daily Validation ¹¹			
1968-1970			1970-1972		1971-31/12/72	
01/11-28/02			01/11-28/02		01/11-28/02	
	Daily	Weekly	Daily	Weekly	Daily	Weekly
RMS (mm)	0.64	4.33	0.64	4.15	0.19	1.33
PBIAS (%)	-50.19	-48.03	--330.58	-367.17	-164.85	-193.43
NSE	-1.12	-1.35	-10.68	-13.85	-3.98	-3.13
PME	-ve	-ve	-ve	-ve	-ve	-ve

In considering the lumped mode performance in relation to the PBIAS statistics for the entire period of simulation (i.e. wet and dry seasons), Tables 5.3 and 5.4 showed that there was overestimation of 4% (48 mm) within the calibration period, but nearly 70% (188.7mm) in the validation period. However, this overestimation in the calibration period is entirely accounted for during the dry period where the PBIAS of 50% gave a total simulated streamflow of 144 mm as against 96 mm observed. In the entire validation period, the overestimation

¹¹ For period with observed data

in the simulated streamflow of PBIAS of 70% was observed. However unlike in the calibration phase where the entire overestimation is accounted for by the dry period simulation, the overestimation of PBIAS of over 330% (108.6 mm) observed in the dry period validation is less than that observed in the entire validation period.

This shows that in terms of the PBIAS in the lumped mode simulation, the overestimation of total flows during calibration is accounted for by the overestimation of baseflow during the dry periods from November to February suggesting that recharge to the groundwater store or the rate of groundwater release may be a contributory cause. However this observation is not so for the validation period suggesting that there might be other factors causing this overestimation some of which are discussed in the proceeding sections.

6.1.2 Water Year Analysis

The daily performance statistics of the simulations for the entire validation period (01/03/70-31/12/72) in Figure 5.10 and Table 5.3 are not good because they all fell outside the acceptable values given by Gupta (1999) and Henrikson (2003) but the weekly simulation had better values (Table 5.4) during the calibration period (NSE= 0.83) and the periods 01/03/71-31/12/72 and 01/03/-31/12/72. However, when the water year of 1970 was omitted from the validation period and validation undertaken for 01/03/1971-31/12/72; there is a significant improvement. Although the improvement in NSE from -0.51 to 0.28 for the daily simulation is still not acceptable according to Henrikson et al., (2003), the weekly simulation NSE is acceptable at 0.54 while the RMS error also improved from 3.20 to 1.88 mm for the weekly and the PBIAS is also better for the weekly than the daily with less overestimation.

From the validation simulation in both daily (Table 5.3) and weekly (Table 5.4) timesteps, it is apparent that the year of 1972 has very good statistics with NSE as high as 0.70 for the weekly as against 0.58 for the daily. However, the statistics for the dry periods were poor in all respects for both calibration and

validation. In the case of the PME appraisal statistic the simulation failed because they were negative (Gupta et. al. 1999) for the daily calibration simulation but was positive for two periods (01/03/1971 -31/12/1971 and 01/03/1972-31/12/1972) in the validation period. When the daily simulations were aggregated into weekly simulations the year excluding 1970 had its PME improved from 0.13 to 0.37 for the period 01/03/1971 -31/12/1972 and 0.18 to 0.43 for the period 01/03/1972-31-12/1972

6.1.3 Summary

The foregoing analysis describes the variability in the model performance in the Densu basin when using the ACUR model in the lumped mode. Very similar model performances were found with the semi-distributed modelling, with the exception of the PBIAS statistic overestimating at Manhia in the lumped mode (4.2%) and underestimating in the semi distributed mode (15.3%) also for Manhia. Comparing Figs 6.1a and b, it looks as though there is more over-estimation in the lumped mode (250mm over the entire modelling period) compared to the semi distributed (~20mm). The above preliminary analysis has identified a number of issues which will be explored in greater depth in the following sections:

- The over-estimation of flows is most obvious in the dry period (Nov – Feb) of the simulation;
- 1970 is very poorly simulated;
- semi-distributed modelling makes no difference to most of the performance statistics with the exception of PBIAS which is reduced.

This modelling exercise within the Densu basin of West Africa did show that moving from a lumped model structure to semi-distributed modelling creates more complexity in modelling and calibration, creating more uncertainty in the results. This is corroborated by Ajami et al. (2004) during a calibration of a semi distributed hydrologic model for streamflow estimation along a river system. They noted a few uncertainties in modelling results which came about because of:

- The assumptions behind the input parameters;
- The assumptions made in choosing model parameter values;
- The assumptions behind the calibration strategies (e.g. initialization of the parameters);

Ajami et al. (2004) further noted that the use of semi distributed models is better because they can provide information about flow conditions at interior points within the basin, but added that if the resulting improvement in simulation capability at the outlet in the semi-distributed mode compared to the lumped model is not significant it does not justify the adoption of the semi-distributed approach.

6.2 Temporal Analysis

To analyse the discrepancies in the simulated against the observed streamflow, a cumulative graph of the weekly simulated and observed streamflows at Mania and their difference were plotted against time (lumped mode output in Figure 6.1a and semi-distributed output in 6.1b).

It is apparent from Figure 6.1a that after an initial period of zero difference, the observed and simulated flows deviate markedly between 22/04/68 to 19/08/68 (a-b), where there was a sharp underestimation from the calibrated model.

The causes of this anomaly can be explained in several ways: 1) that the evapotranspiration could be too great, implying that the landuse parameters e.g. monthly crop coefficients CAY for the period might be too high for the period giving high AET leading to high water extraction and late recovery of the soil moisture deficit to field capacity 2) the soil parameters of the catchment could have been classified outside the optimum values because the information from the soil profiling was based on only a few points considering the size of the basin (2100km²), 3) the measured hydrometeorological data e.g. streamflow

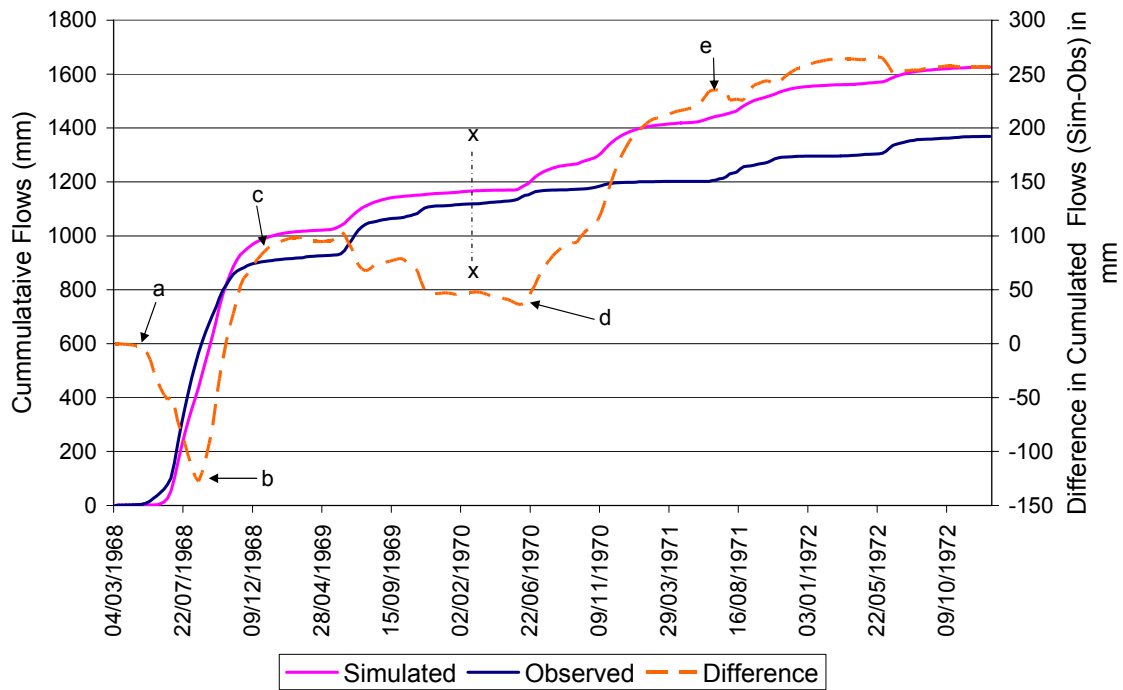


Figure 6.1a Graph of cumulative weekly observed simulated flows and cumulative difference at Manhia for lumped model (x-x marks the end of calibration and beginning of validation)

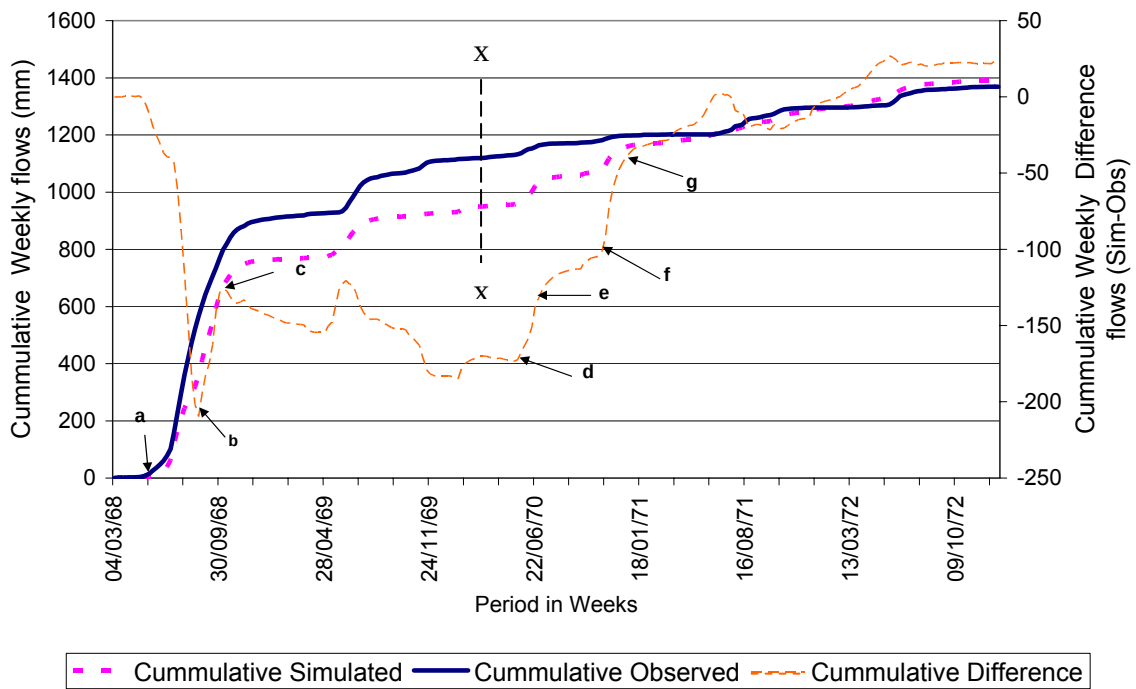


Figure 6.1b Cumulative weekly analysis at Manhia in semi distributed mode with x-x as end of calibration and beginning of validation.

data and rainfall distribution data could have errors in them (discussed later in chapter) and 4) the drainage rates chosen for this simulation may not have been fully optimized.

In ACRU ground water/base flow generation, depends on two coefficients:

1. The first relates to the drainage rate of water out of the bottom subsoil horizon store, when its soil water content exceeds the drained upper limit, into the intermediate/groundwater store. This response rate K_{BF} (BFRESP) is slower for heavy textured soils compared to light textured soils.
2. The second response coefficient concerns base flow release of water from the intermediate/groundwater store into the stream. This empirical coefficient (COFRU) depends intrinsically on factors such as geology, catchment area, slope and the size of the groundwater store.

As a result if these drainage rates are not optimised well the response could be affected. This could be that COFRU and BFRESP for the soil parameters were not fully optimized due to the manual calibration.

Following from the underestimation period (a-b) of Figure 6.1a discussed above was a sudden overestimation from 19/08/68-14/10/68 (b-c) of streamflow volume of 203 mm. This overestimation could partly be a consequence of the initial underestimation discussed above due perhaps to delays in flow reaching the catchment outlet and to the other problems already discussed above. Also could this overestimation be a result of the assumption behind lumped stormflow computation in ACRU? When using ACRU in the lumped mode, the model assumes that “stormflow (water which is generated on or near the surface of a (sub)catchment from a rainfall event, and which contributes to flow in the streams within that (sub)catchment)” passes the catchment outlet on the same day. Whilst this is likely to be a reasonable assumption for small catchments, its use in larger catchments, such as the Densu, must be questioned. Another reason could be that because the actual level of water

abstraction for irrigation and household chores are not known they have been underestimated

Another reason of this overestimation looking at Figure 5.8 for the daily simulations could be that in 1968, rainfalls were very much higher than usual (Figure 4.1), and therefore elements of the observed data might not have been as accurately measured as under more normal circumstances. To assess whether the observed streamflow data were accurate during the periods of very high flows, the streamflow data at Nsawam (upstream) and Manhia (downstream) were compared in Figure 6.2a (ring xx which is the rainy season period in 1968). This ring x-x shows that in this period there were very much higher flows measured at Manhia compared to Nsawam. The differences in streamflows between the two stations for subsequent periods in Fig 6.2a are very much less. To investigate this further, Figure 6.2b shows the double mass curve (Daymen and Hall, 1990) for the Manhia and Nsawam gauging stations for the 4 years of observed streamflows in

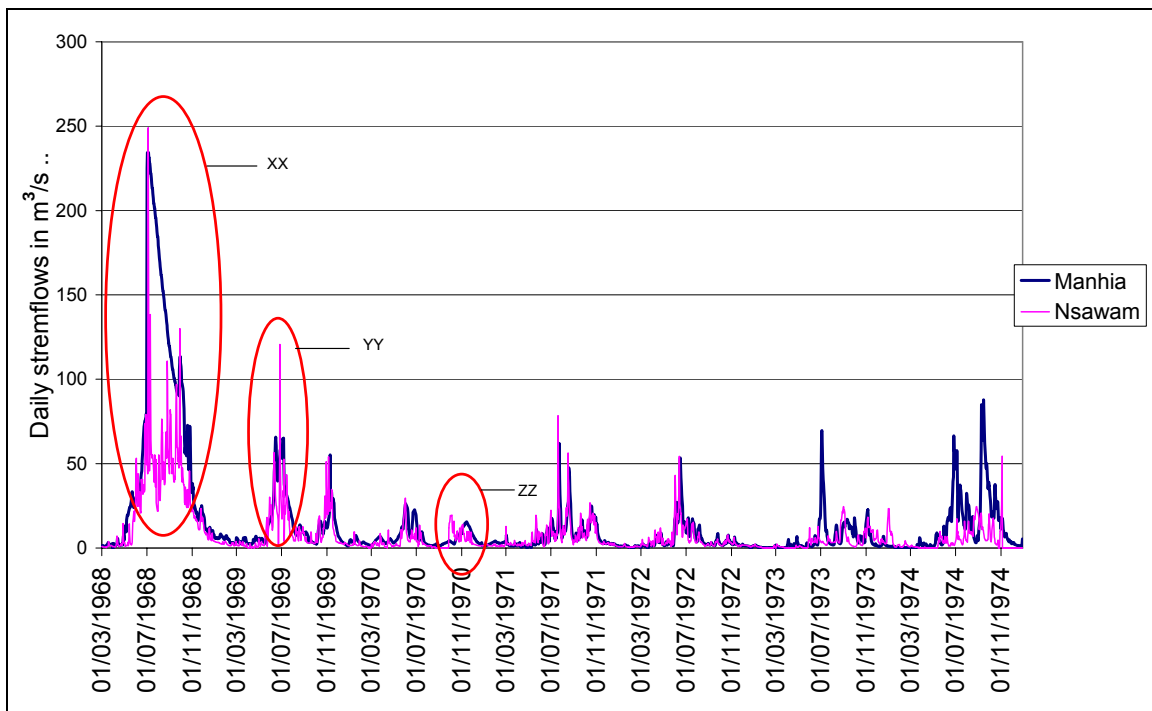


Figure 6.2a. Daily observed streamflow for Nsawam and Manhia for 1968 - 74.

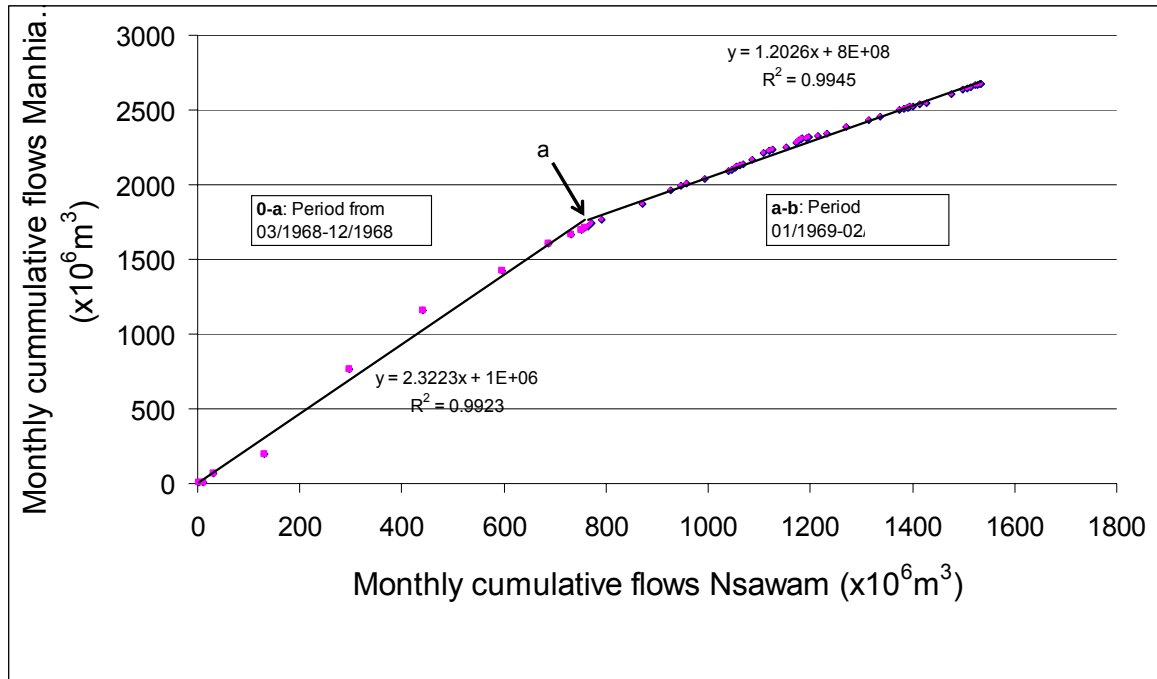


Figure 6.2b Double mass diagram for Manhia and Nsawam gauging stations

the modelling period. There is a significant change in the gradient of the line at point **a** which occurs towards the end of 1968. As such an abrupt major change in the catchment behaviour is unlikely; it suggests that there was some problem with the measurement of streamflow data at Manhia in 1968, which was a very high year on record.

To identify the cause of the measurement error, the measured river flows were compared with established rating curves for Manhia given in Ayibotele (1974). This showed that the gauge levels recorded during this period (1968 water year) fell outside the rating curve limit for accurate readings given in Ayibotele (1974). The highest gauge level for the rating curve (Ayibotele, 1974) at Manhia is 3.72m above streambed (equivalent to 62.30 cumecs and 2.73 mm.day⁻¹) and a minimum gauge reading of 0.79m water level (equivalent to 1.13 cumecs and 0.07 mm.day⁻¹). From the 1968 streamflow records and graph (Figure 6.2a) there are more than 3 months in which the recorded gauge level heights were above the highest gauge level on the rating curve of 3.72m for which

extrapolating beyond these limits is bound to introduce errors. It should be noted that there was no apparent evidence that the data had been subject to quality control measures which would have flagged up that the data was outside the range for the validated rating curve. The likely possibilities of exceeding the upper limit of the rating curve are; 1) the water level could have overtopped the banks at the weir (in which case the cross-sectional area of flow was underestimated, and therefore the actual flow was underestimated), 2) the weir was drowned out so the flow was no longer super-critical over the weir so that the flow was overestimated; 3) both (1) and (2) mentioned above occurred. A closer look at the simulated and observed streamflow plot (Figure 5.8) suggests that both scenarios were possible because the observed streamflows were higher than simulated streamflows in the first part but the simulated flows were higher than observed streamflows in the second. However, this observation of Figure 5.8 alone does not show that it is certainly scenario (3) as other issues such as baseflow simulation by ACRU, data quality in general and rainfall distribution in the basin have been questioned.

Analysis of the Nsawam data for similar problems of flows topping the gauge levels could not be established because the rating curve was not available and also the manual recorded data sheet (of flow readings) did not show any flagged event on the streamflow data sheet to indicate a problem or caution and therefore the data was used as reflecting true recordings. However, it is possible that over topping of the weir and flooding may also have happened at Nsawam. From the semi distributed simulation plot at Nsawam (Figure 5.13 and Table 5.5) in the calibration stage, overestimation of the simulated streamflow of 50 mm (PBIAS of 6.4%) was observed with an NSE of 0.47. In the same period in the dry period an underestimation of 43 mm (PBIAS 45%) was noted suggesting that the overestimation noted for this phase occurred during the wet period. In the entire validation phase, the model overestimated the streamflow by 44 mm (PBIAS of 14%) with a very poor NSE (-0.30) whilst in the dry period it also overestimated by 52 mm (PBIAS of 121%). Since Nsawam is upstream of Manhia, and the lumped simulation used streamflow data of only Manhia, the

response of ACRU at Nsawam in the semi distributed mode is independent of the flows of Nsawam meaning the supposedly “false” readings at Manhia had no direct effect on the semi-distributed modelling at Nsawam. Figure 5.16 and Table 5.8 illustrate the simulated streamflows and statistics at Manhia in the semi distributed mode. The results follow the same trend of variability in the NSE values which are poor and overestimation in the validation period but underestimation in the calibration phase.

In the 1968 rainy season the simulated flows appear to be lagged by several months – they go up late (leading to underestimation) but peaked at the right time. They then stayed high for too long (leading to overestimation). Possible reasons could be underestimation of measured streamflows due to overtopping of the weir and flooding, with another being suspect rainfall data which could have been read higher than actual.

Between the periods c-d in Figure 6.1a ACRU was simulating streamflows reasonably well, although the timings of some individual events was not right. This supposed reasonable simulation could be linked to the receding of the floods encountered earlier. However, at the end of the calibration period (section x-x in Figure 6.1a), the cumulative simulated streamflow was 1.2% higher than the observed. From point (d) 15/06/1970 till the 05/07/71 point (e) in Figure 6.1a the overestimation of simulated streamflow is 196mm. Analysis of the said period in Figure 6.2a showed some interesting features. The measured streamflow generally showed that flows at the downstream Manhia gauging station were higher than those measured upstream at Nsawam. However, in Figure 6.1a ring zz which is during the period of simulated overestimation at Manhia, the measured streamflow at Nsawam is higher than that for Manhia for the periods 25/09/70-4/11/1970; and 29/12/1970-10/1/1971 and 28/02/1971-6/6/1971. The likely reasons for the periods of unusual relative measured flows could be:

- 1) water could have been abstracted downstream of the Nsawam gauging station but before the Manhia gauging station due to low flows leading into the

dry season and in the dry season. From the knowledge of the area this is possible and the volumes could be significant especially closer to the vegetable farms and pineapple plantations in the basin when water stress sets in for the plants;

2) deliberate blockage of the river to allow water abstraction just before the Manhia gauging station or an accidental blockage- which leads to temporary impoundment upstream and lower river levels at the gauge leading to underestimation of flow.

After this period the observed and simulated flows were nearly the same until the end of the validation period bringing the total simulated flows to 256mm above the observed flows for a total overestimation of 18.7%.

In the semi-distributed modelling at Manhia the calibration phase underestimated streamflow by over 15%, while the streamflow was overestimated by over 60% in the validation period (Tables 5.8 & 5.9) whereas in the lumped simulations at Manhia (Tables 5.3 & 5.4) the ACRU model overestimated in the calibration phase by about 4% and also overestimated in the validation phase by over 60%. Over the entire four year modelling period, this resulted in the lumped model overestimating total cumulative streamflow by more than 250mm, while the semi-distributed model overestimated by only 24 mm. However, overestimation of a lumped model and underestimation of semi distributed model as witnessed in the calibration phase according to Ajami et al. (2004) is not unusual as they noted a similar observation whilst using a lumped and semi distributed models of the US NWS (National Weather Service) SAC-SMA (Sacramento Soil Moisture) when it was applied to the Illinois River Basin at Watts. They (Ajami et al., 2004) concluded that the overall performance measures, namely DRMS, PBIAS and NSE, did not show that there was any improvement when moving from the NWS lumped structure to the semi distributed structure with respect to the predictions at the basin outlet and so was this research (PBIAS moved from -4.2% overestimation to 15.25%

underestimation in the calibration phase but slightly improved (-69.7% - 65.4%) on overestimation in the daily validation).

In a recent study (Conway & Mahé, 2005) in West Africa, a conceptual water balance model was applied in a distributed manner to model monthly river flow in tributaries of the Niger River. The approach utilised global data sets of rainfall and potential evaporation time series and soil available water capacity at 0.5 degree latitude and longitude resolution. River flow data for catchments ranging in size from 631 km² to 71 510 km² for the period 1950-1989 were used to calibrate and validate the model. The results showed varying degrees of model performance during both the calibration and validation procedure. The analysis (Conway & Mahé, 2005) highlighted some interesting issues which pertained to the development and application of water balance models such as sensitivity of model performance and parameter values to input data sets, particularly the method chosen to estimate Potential Evapotranspiration. Conway & Mahé, (2005) attributed the variability in model results to failure to represent additional sources of water loss in the catchments which include percolation to deep aquifers, evaporation losses from surface waters and an overall underestimate of soil moisture storage. Also in a mountainous tropical region of Western Kenya (Sonde River basin of 3050km²) near the equator, the SWAT model was calibrated for monthly streamflow for the study period. The Nash and Sutcliffe efficiency for the calibration period fell between -0.72 and 0.10 revealing large variation between the simulated and the observed during individual months (Jayakrishnan et al., 2005). The wide variability of results was attributed to poor input data

It is interesting to know that the results of variability observed in the Densu Basin simulations using the ACRU model for tropical West Africa is similar to the findings of these research by Conway & Mahé, (2005) in Niger and Jayakrishnan et al., (2005) in Kenya and in these cases poor data was blamed for the variable modelling results.

Other general reasons for the “poor” performance, according to the appraisal statistics, are discussed below.

6.2.1 Hydrometeorological Station Distribution in the Densu Basin

In chapter 4 the data situation for the modelling was given. For rainfall, it was discussed that even though several rain gauge stations existed in the basin, due to logistics and archiving problems only two stations within the catchment at Nsawam and Koforidua, and a station outside the basin at Accra, were able to be used in this study because they were readily available. In a personal communication¹² the respondent noted that one of the biggest problems encountered during his research in a large catchment area (12000km²) in South Africa was “representative rainfall”. He reported that the area in question is characterized by short intensive thunderstorms and that, within a 200km² sub-catchment one rain station could record 70mm on a day while two others do not record anything within the same sub-catchment. Jackson (1978), as discussed in Chapter 2, also reported on this situation in tropical Tanzania.

This type of short intensive rainfall is reported to take place in most catchments in Ghana (WARM, 1998). Therefore, considering the relatively large size of the Densu basin (2100km²), it must be considered whether using only two rain gauges is adequate. Shaw (1994) noted that in convective rainfall regions, as in tropical regions including the Densu Basin, the recommended density of rainfall stations to achieve good areal estimation of rainfall for daily time step for flat areas should be 600-900 km²/gauge; in mountainous areas the density should be 100-250 km²/gauge. Following from this and considering the landscape and area of the Densu Basin, the minimum number of stations to give good areal representation should be at least 3 for the flat areas and 2 for

¹² E-mail with Cor Langhout [CorL@bks.co.za] in Dec, 2002
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the mountainous regions which represent the headwaters of the basin, bringing to 5 the minimum rain gauge stations needed in the Densu Basin. This observation by Shaw (1994) indicates that, with the number of rain gauges being less than recommended, there are probable chances that errors may be higher than usual and this could be a contributory reason for the poor daily simulations. However the errors improve slightly when the results of the simulated flows are amalgamated to weekly or monthly.

To demonstrate rainfall variability in the catchment the rainfall distribution observed for the period of modelling is shown in Table 6.2. On average, Nsawam station has 119 rain days (rainfall ≥ 0.1 mm for a day) and 246 dry days without rains whilst Koforidua has an average of 141 rain days and 224 dry days with no rains. The likely cause of difference in the rain days could be attributed to the altitude which is higher for the Koforidua station and perhaps the relative closeness of the Nsawam station to the coast. When the areal analysis is done using data from the two rain gauges, there are, on average, 179 days with no rain in the basin and 186 rain days. In Table 5.8 the daily areal rainfall variability for the basin is shown with a range of 0 to 75mm rainfall per day. Thus from the foregoing, proper distribution of

Table 6.2. Rainday analysis of the Densu Basin

Year	Nsawam Station			Koforidua Station			Areal Analysis	
	Annual Rainfall (mm)	No rains (days)	Rain days ¹³	Annual Rainfall (mm)	No rains (days)	Rain days	No rains (days)	Rains (days)
1967	1116.3	248	117	1293.2	223	143	202	164
1968	2203.5	251	114	2143.5	191	174	170	195
1969	1291.1	237	128	1167.7	227	138	163	202
1970	1297.4	242	123	1261.4	238	127	180	185
1971	1189.5	239	127	1535.8	218	148	158	208
1972	1152.9	244	121	1086.0	249	116	201	164
Mean	1375.1	246	119	1414.6	224	141	179.0	186.3

hydrometeorological data collecting instruments within a basin should be encouraged to reduce errors.

¹³ A rain day is when the days reading is greater or equal to 0.1mm rainfall.

6.2.2 Quality of Rainfall Data

Rainfall analysis of the two stations, Koforidua and Manhia (Chapter 4) showed no anomaly for the period 1967-1972 which was the modelling period after tabulating daily totals and visualizing to detect whether the observations have been consistently or accidentally credited to the wrong day, whether they show gross errors (e.g. from weekly readings instead of daily ones) or whether they contain misplaced decimal points (Daymen and Hall, 1990). These totals were then plotted (Figure 4.1) according to the annual time step and detecting any trends or discontinuities through visualization undertaken, as the period of analysis for the modelling was too short for trend analysis (Daymen and Hall, 1990). A cumulative annual rainfall and weekly totals of Nsawam and Koforidua are shown in Figures 6.3a and 6.3b.

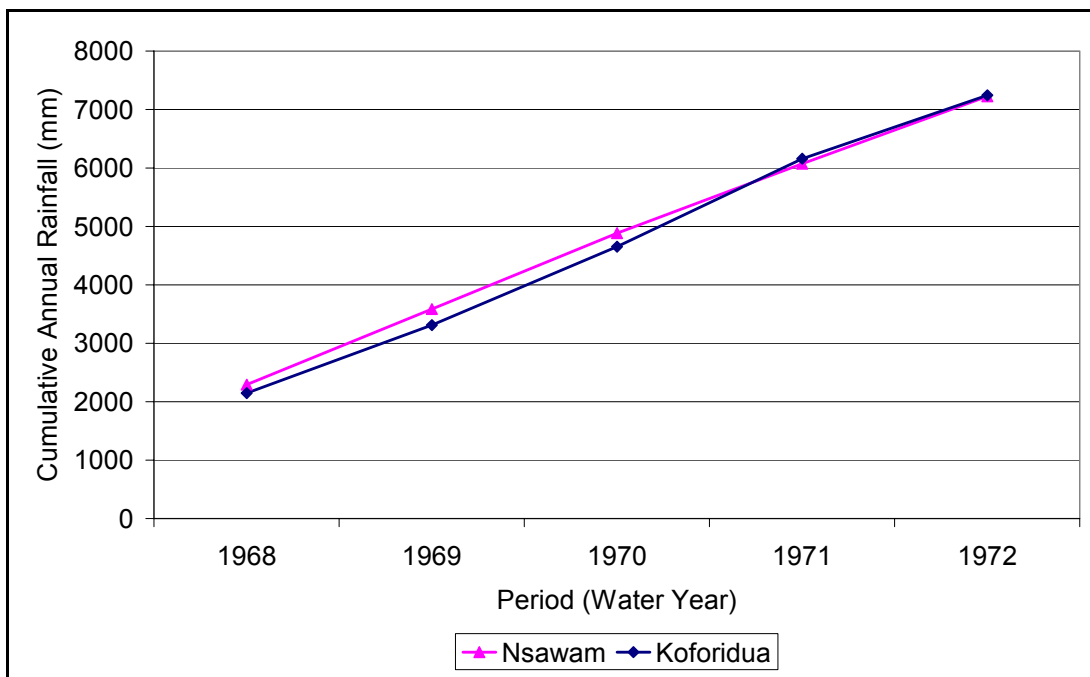


Figure 6.3a Cumulative annual rainfall at Nsawam and Koforidua

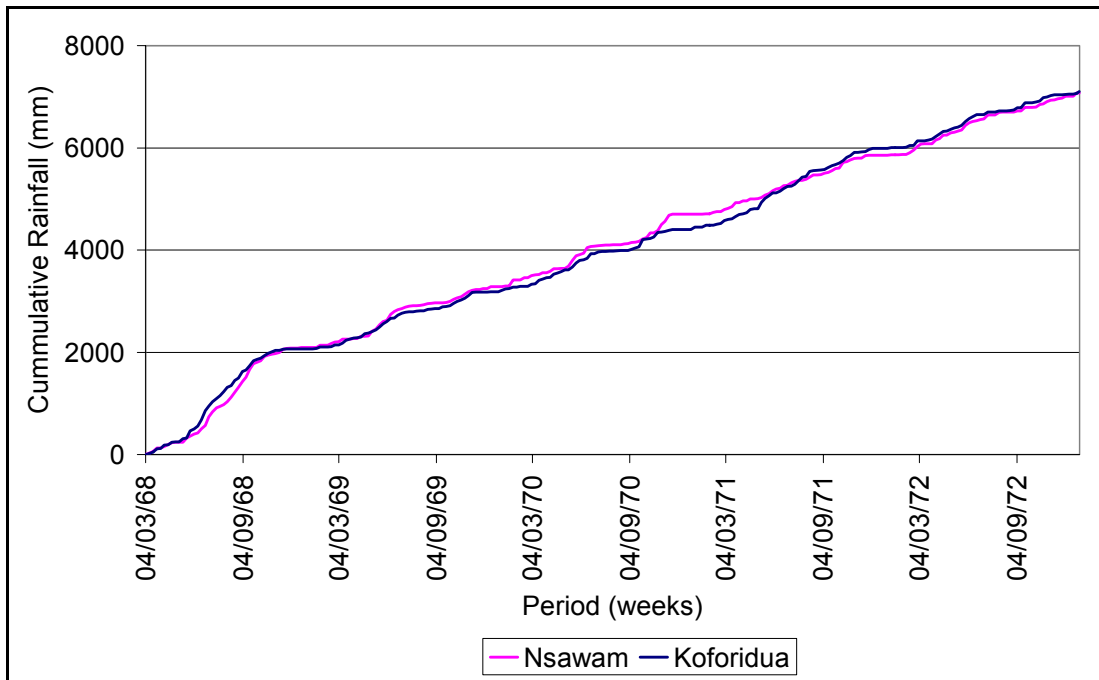


Figure 6.3b. Cumulative weekly rainfall at Nsawam and Koforidua

From the plots it is observed that the two stations have almost the same pattern of annual rainfall even though the curves occasionally cross each other. However, not much could be said about the quality of data even though from streamflow analysis (next Section 6.2.3) some concern is raised about certain rainfall recordings and for the fact that for year 1971 Koforidua seemed to have recorded much higher than usual rainfalls because it crosses the Nsawam line in the annual plot of Figure 6.3a.

6.2.3 Quality of Streamflow Data

The quality of the streamflow data during very high flows in 1968 has already been mentioned. However, the quality of the streamflow data may be further affected by the:

- method of data collection, and;
- quality of the data recording.

In a personal communication¹⁴ with an officer of the streamflow measuring organization, he explained that daily streamflow measurement was usually made by the collection of one spot measurement using staff gauges to read stage discharge heights. However, during the construction of the rating curve for the basin, Ayibotele (1974) reported that three readings taken at 06.00 hrs, 12.00 hrs and 18.00 hrs were averaged to represent daily discharges, but did not give any indication of the range of variability within readings for a given day. Spot readings taken in a day to represent a day's average flow could introduce errors as other periods of the day could have higher flows (e.g. as a result of torrential rainfalls caused by convective storms in the tropics) or lower flows (readings taken at around the peak of a runoff event) based on rainfall in the basin after or before flow measurements not captured. How daily spot streamflow measurements differ from daily averages calculated from continuous streamflow readings during a day is not certain as no literature comparing these two methods was found. However, using spot streamflow measurements within the Densu Basin to represent average daily streamflow certainly will introduce unknown errors as compared to continuous measurement, although these errors are likely to be greatest during the rainy season in days of high flow or days with runoff events.

After daily measurement of flows, the data are recorded on monthly paper log sheets. Examination of these has also highlighted possible data quality issues (Figures 6.4a and 6.4b). In hatched rectangular boxes (Figure 6.4b) on April 11 to April 14 of 1970, the readings of 20, 14, 0 and 109 cusecs inclusive of recorded streamflow looks suspicious when compared to the areal rainfall in Figure 6.4a (hatched rectangular box) because the 0 reading on the 13th looks out of place from the trend of rainfall. Similarly the subsequent day's rainfalls (i.e. 15th and 16th) were not 'high' yet the streamflow of the 16th looks exceptionally higher than would be expected.

¹⁴ Mr. Allotey, Senior Hydrologist Hydrological Services Department, Ministry of Works and Housing, Accra, Ghana (August, 2002)

Computed Areal Rainfall for Nsawam for the 1970/71 water year													
	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	JAN	FEB	
1	0.0	4.7	0.3	0.0	2.4	0.0	0.1	0.0	5.1	0.0	26.7	0.0	
2	0.0	0.8	7.5	0.1	0.0	0.0	0.1	3.4	24.3	0.0	0.0	0.0	
3	0.0	6.0	0.0	8.6	1.1	0.0	0.0	8.0	3.7	0.0	0.0	0.8	
4	1.0	0.0	0.0	0.0	0.0	0.1	5.2	3.7	0.0	0.0	0.0	8.9	
5	12.4	0.0	1.8	2.7	0.4	2.7	8.1	0.0	27.7	0.0	0.0	0.0	
6	0.0	10.7	4.4	0.6	0.8	1.7	0.1	0.0	0.0	0.0	0.0	0.0	
7	0.4	0.0	2.5	0.0	0.0	0.0	0.1	3.0	0.0	0.0	0.0	5.3	
8	7.4	0.0	23.2	0.0	0.0	0.1	1.1	3.0	21.5	0.0	0.0	0.3	
9	2.3	3.4	0.0	14.7	15.8	0.0	1.1	0.4	10.4	0.0	0.0	0.4	
10	0.0	10.9	0.0	0.0	1.0	0.0	3.7	1.3	1.8	0.0	0.0	0.0	
11	0.0	0.9	0.0	2.0	0.4	0.0	2.0	3.3	0.0	0.0	0.0	0.0	
12	0.0	3.2	0.0	0.0	2.5	5.0	8.1	19.2	0.0	0.0	0.0	0.0	
13	0.0	25.3	0.0	0.0	3.6	0.0	3.3	0.0	21.2	0.0	0.0	0.0	
14	0.0	5.8	1.1	22.7	0.0	0.0	0.3	0.9	17.7	0.0	0.0	17.8	
15	8.3	0.4	0.0	0.0	1.0	0.4	0.0	23.1	24.8	0.0	0.0	0.0	
16	30.1	5.3	9.8	0.0	0.0	0.0	1.4	3.6	0.3	0.0	0.0	0.0	
17	0.0	1.7	17.9	0.0	0.9	0.0	1.5	3.2	3.8	0.0	0.0	0.0	
18	0.0	0.0	17.1	45.6	0.0	0.5	6.5	7.9	1.9	0.0	0.0	0.0	
19	0.0	7.7	23.6	32.1	1.3	0.3	0.5	1.4	2.5	0.0	0.0	0.0	
20	3.2	0.0	4.9	2.0	2.0	0.0	7.1	0.5	5.3	0.0	0.0	0.0	
21	0.0	3.7	10.7	8.0	1.0	0.0	0.0	0.0	2.8	1.4	0.0	0.0	
22	3.8	0.0	12.3	3.6	0.0	0.0	0.0	0.0	0.1	0.0	15.5	0.0	
23	0.0	0.0	7.2	0.0	0.0	0.1	0.0	2.8	1.3	0.0	2.3	0.0	
24	13.1	0.0	11.8	4.1	0.0	0.0	7.0	33.4	5.2	0.0	0.0	0.0	
25	0.3	11.2	2.9	9.1	0.0	0.1	78.0	0.0	0.4	0.0	0.0	21.2	
26	7.4	4.3	13.4	0.1	0.0	3.2	1.3	0.0	0.0	0.0	0.0	31.0	
27	3.9	0.0	29.6	0.0	0.0	4.8	0.3	0.0	0.4	0.0	0.0	0.0	
28	0.0	0.0	4.6	0.6	0.0	2.3	7.7	18.3	0.0	0.0	0.0	1.3	
29	0.0	0.0	18.5	0.1	0.0	0.0	3.9	10.5	0.0	0.0	0.0		
30	5.7	0.0	12.2	0.0	1.5	0.0	2.4	0.0	0.0	0.0	0.0		
31	0.0		0.1		0.4	0.0		5.6		0.0	0.4		

Figure 6.4a Rainfall for subcatchment Nsawam to illustrate data anomaly (1970/71 water year) with streamflow.

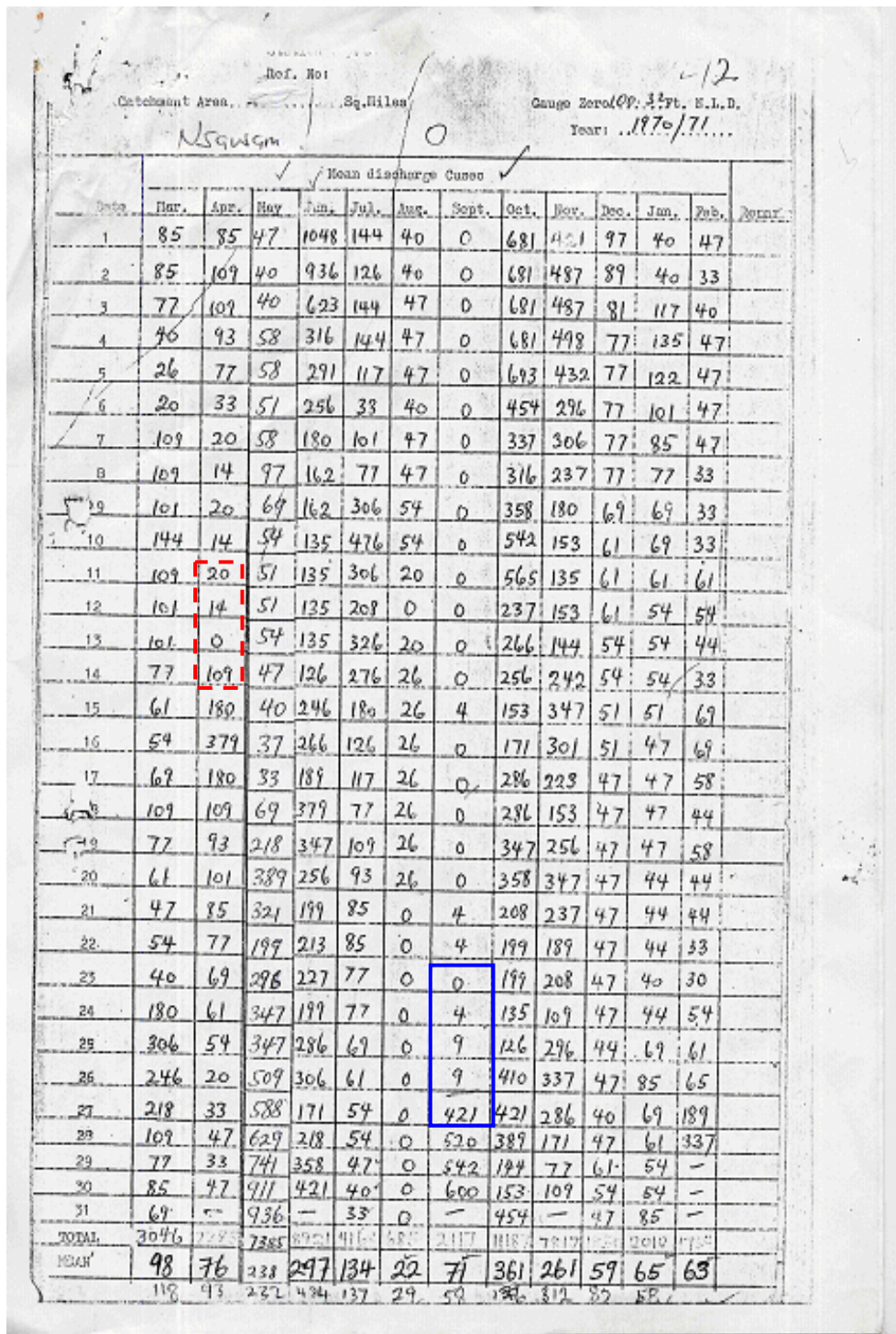


Figure 6.4b Illustrating data anomalies in the Densu River Basin

Figure 6.4b (rectangular box) illustrates a further anomaly observed in streamflow measurement for the Nsawam station in September, 1970. It is seen that for a period the readings were zero (0) m³/s (0 cusecs, day 23), then 0.11m³/s, (4 cusecs; day 24), and then suddenly jumped from 0.25m³/s (9

cusecs) on day 26 to $11.9\text{m}^3/\text{s}$ (421 cusecs) on day 27. Likely reasons for the above observation could be that it might have rained in a section of the catchment that was not captured because of low density of rain gauges; lagging or suspect data for both streamflow and rainfall. A careful look at the streamflow and rainfall data suggests that lagging (refer to Section 6.4) of two to three days is encountered in this basin.

Also, actual water abstraction data for small scale irrigation projects and industrial purposed in the basin are not known due to the fact that no water abstraction policy exists in the basin. Thus if the abstractions are underestimated, dry season simulated flows would become “bigger” than expected culminating in the overestimations that are seen in the simulations during the dry season.

6.3 Evapotranspiration

In Section 3.3.5 the methods employed by ACRU to compute evapotranspiration were detailed. For this modelling the A pan method was employed for the Densu basin as the evaporation data available was from the Apan. It should however, be noted that Schulze (1995) recommended the use of the Penman Montieth as the most favoured method if the necessary data are available. However, in an assessment to determine evaporation pan density in basins McCulloch (1965) cited by Shaw (1994) observed an evaporation loss over a 18km^2 drainage basin in Wales with a range of altitude of 460m by means of point sample (e.g. pan evaporation) and concluded that, whereas 25 rain gauges would be needed for effective rainfall analysis with error of 2%, only 3-4 hydrometeorological stations would be needed for areal evaporation estimates for the same basin. However, this source of uncertainty in evaporation is likely to be different to the rainfall. This indicates that generally the evaporation pan density could be less than the rain gauges and still give good results. McCulloch (1965) further noted that single stations can give reliable adequate information over a flat plain or plateau but cautioned that variations could occur from differing types of vegetation.

As described under Section 6.2.1 the distribution of the rainfall stations was inadequate for a basin of the size of Densu and therefore the derived areal figures for the pan evaporation could have errors. This could be another reason which could have affected the modelling of the Densu catchment.

A comparison has been performed of the values of mean monthly actual evapotranspiration (AET) for the Nsawam and Manhia sub-catchments for 1968 to 1972 simulated by the ACRU model in the semi distributed mode and the values established by Ayibotele (1974) for the same period (Figures 6.5 to 6.6) using data from the same stations. Ayibotele (1974) used the Penman (1948) method to calculate potential evapotranspiration using monthly data. To estimate actual evapotranspiration in Ayibotele (1974) a relationship between evapotranspiration under conditions of abundant water and those of inadequate water supply given by Monteith equation (Monteith, 1965) was used. These conditions were assumed by Ayibotele (1974) to be related to the frequency of wetting of the vegetation. For this actual evapotranspiration analysis (Ayibotele, 1974), the frequency of wetting is taken as the frequency of rainfall. Figures 6.7a and 6.7b compare the mean monthly data for the rainy and dry seasons for the Nsawam sub-catchment.

According to Allen et al. (1998), for two data sets to be similar and used interchangeably, the correlation coefficient R (i.e. the dependent in this study being the ACRU-simulated AET and the independent the Ayibotele (1974) AET values) should be high ($R^2 \geq 0.7$) and the regression coefficient b should be in the range $0.7 \leq b \leq 1.3$. From Figures 6.7a and 6.7b, the R^2 values fall below 0.7 for both the rainy and dry seasons. The regression coefficients b in the rainy season falls within the acceptable range, while that for the dry season falls outside. From the foregoing, according to Allen et al. (1998) the two data sets (for the modelling period) are statistically different even though the correlation between the two data sets over the combined wet and dry seasons is 0.76 for Nsawam. At Manhia, the coefficient of correlation was 0.75 for the combined

wet and dry whilst the R^2 are 0.24 and 0.46 for the wet and dry respectively, making this set of data also statistically different. At the monthly level, the ACRU model simulated higher AET values than Ayibotele (1974) in almost all the months except August, September and January (Figure 6.5b) whereas it is variable at Nsawam (Figure 6.5a). At this stage it is inconclusive to assign reasons for the difference in the two data sets apart from the mode of computation where Ayibotele (1974) AET was computed using the Penman (1948) equation and Monteith (1965) with mean monthly meteorological values as against mean monthly values for ACRU simulated. For how ACRU computes actual evapotranspiration from pan evaporation refer to Section 3.4.2.3. Whether the ACRU simulated AET is better than the Ayibotele (1974) data is subjective, however, if going by the results of the PBIAS estimations observed through simulations then the dry seasons could have lower AETs as they give the most overestimation (-48%--330%; ref to Table 6.1) Over-estimation in the dry season implies that there is too much simulated baseflow, which implies too much recharge in the wet season and/or incorrect baseflow recession constants. In that case the ACRU simulated AET's could be closer to the actual than the Ayibotele (1974) values which are lower than the ACRU simulated (Figures 6.6a & 6.6b).

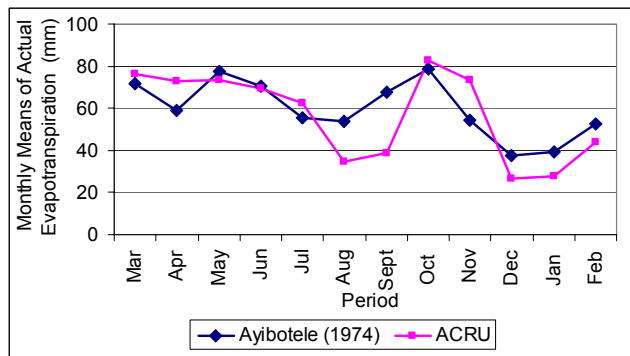


Figure 6.5a. Comparison between ACRU mean monthly AET and Ayibotele (1974) for Nsawam

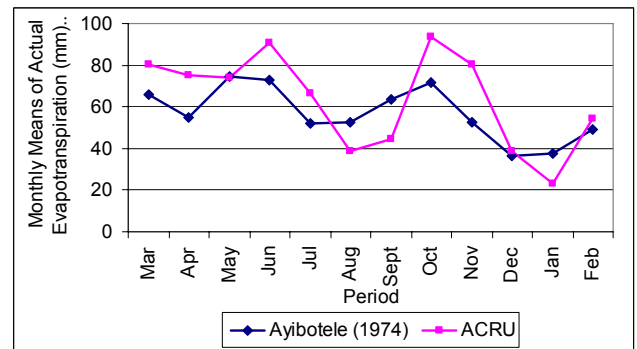


Figure 6.5b. Comparison between ACRU and Ayibotele (1974) for Manhia

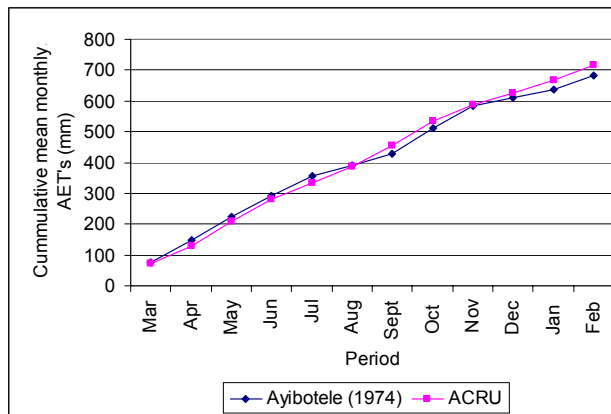


Figure 6.6a. Cumulative mean monthly AETs of ACRU Simulated AET and Ayibotele (1974) calculated AET for Nsawam

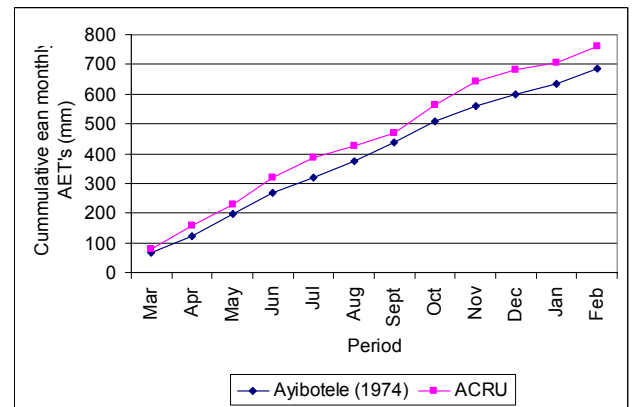


Figure 6.6b Cumulative mean monthly AETs of ACRU Simulated AET and Ayibotele (1974) calculated for Manhia

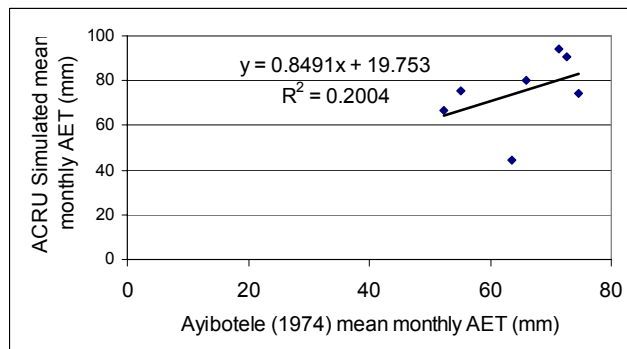


Figure 6.7a Relationship between ACRU simulated and Ayibotele (1974) mean monthly AET for the rainy season at Manhia

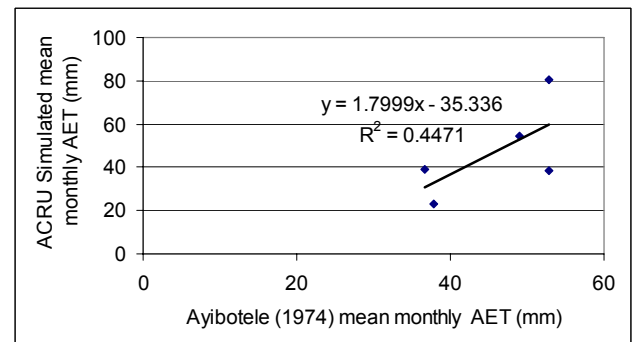


Figure 6.7b Relationship between ACRU simulated and Ayibotele (1974) mean monthly AET for the Dry season at Manhia

6.4 Streamflow Routing in ACRU

In chapter 3 Table 3.2 and Section 3.4.2 the routing mechanisms employed to generate stormflow in a catchment using the ACRU model are the Muskingum and the Muskingum Cunge methods and for reservoir processes the storage indication methods. However the assumption that stormflow generated on a particular day passes the catchment outlet on the same day is valid for small catchments up to 50km² in ACRU but is not necessary true of larger catchments (Shulze, 1995). Routing is only simulated in ACRU during semi distributed modelling in large catchments, so that the effects of routing on the flow hydrograph could not be considered during the lumped mode modelling. Considering the size of the Densu basin, this is a weakness within the process description in ACRU. Although a 2-3 day lag between rainfall and streamflow responses was suggested in Section 6.2.3, applying a lag of 1-5 days to the

lumped simulation at Manhia (Table 6.3) did not improve the modelling results in terms of the appraisal statistics used, meaning that this is unlikely to be a significant cause of the poor model performance.

In the semi-distributed modelling of the Densu, the routing option was not invoked because the required parameters BWIDTH (Bottom width of main channel [m] of the downstream sub-catchment); ZSIDE (Side slope of main channel of the downstream sub-catchment), TWIDTH (Top width of main channel [m] of the downstream sub-catchment) and DELT (Main time interval [minutes] at which all

Table 6.3. Results of lagging the simulated streamflow at Manhia in the lumped simulation

Daily Calibration							Daily Validation						
Period (1/03/68-28/02/1970)							Period (1/03/1970-31/12/1972)						
	Lag period (days)							Lag periods (days)					
	0	1	2	3	4	5		0	1	2	3	4	5
RMS	1.01	1.03	1.05	1.07	1.1	1.14		0.51	0.66	0.68	0.69	0.70	0.72
PBIAS	-4.20	-4.28	-4.28	-4.28	-4.28	-4.27		-69.74	-70.70	-72.26	-74.64	-75.41	-76.70
NSE	0.82	0.81	0.81	0.80	0.78	0.77		-0.51	-1.41	-1.66	-1.87	-2.01	-2.27
PME	-ve	-ve	-ve	-ve	-ve	-ve		-ve	-ve	-ve	-ve	-ve	-ve

hydrographs are stored internally in the model) were unavailable for this study because profiling data for the river are non existent. These parameters could have been estimated but it was felt that the assumptions required to enable these parameters to be generated would have been too subjective.

6.5 Groundwater simulation in ACRU

Many methods exist for groundwater simulation in hydrological models such as use of kinematic equations in SWAT model (Bora and Bera, 2003); by Darcy's gravity flow method in ANSWERS 2000 model (Bouraoui and Dillaha, 2000), 3-D groundwater flow equations solved using a numerical finite-difference scheme and simulated river-ground-water exchange methods for MIKE SHE model (Bora and Bora, 2003). In ACRU ground water is simulated using two drainage response coefficients i.e. a drainage rate from the bottom subsoil horizon to the

intermediate groundwater store and coefficient of baseflow release from the intermediate store into the stream (Schulze, 1995).

The earlier analysis of the delayed initial wetting up of the catchment following the 1967 dry season (in comparison to the observed) which the calibration could not correct and the generally poor simulation during the dry seasons suggests weaknesses in the recharge and baseflow generation model components. Everson (2001) and New (2002) also found some limitations of ACRU in relation to groundwater simulation.

According to Everson (2001) a limitation observed during a relatively wet year simulation was the inability of ACRU to account for lateral subsurface soil water flow during a water balance study in South Africa, where analysis of the simulated unsaturated flow from the B horizon to the groundwater zone and saturated drainage could not account for the predominance of subsurface flow found in the catchment. The soils were reported as having organic matter contents of 6-10%, and high water holding capacities but the subsoils had a very high clay content and poor infiltration leading to soil water logging and lateral interflow within the more permeable upper soil layer. These mechanisms could occur in Densu Basin because of the heterogeneity of soils within this large catchment with water holding capacities and high clay contents, between 35-55%, in the subsoils (Adu and Asiamah, 1992).

New (2002) observed two shortcomings of the ACRU model which affect baseflow simulation which are 1) the inability of the model to simulate the wetting-up of the catchments at the beginning of the wet season, which resulted in over prediction of streamflow and 2) the tendency of the ACRU model to underestimate dry season baseflow. In this modelling with ACRU for the Densu Basin, the dry season produced the most overestimation which may be as a result of reasons deduced in the earlier Sections such as “poor” input data, and weaknesses in the groundwater routine in ACRU where the delay in the initial wetting up of the catchment in 1968 (in comparison to the observed) could not

be corrected by calibration. New (2002) on the other hand attributed the shortcomings which affected baseflow mentioned above to errors in the model parameter values and inadequacies in model design/structure but did not show how these happened.

Two main lithologies control the distribution of underground water in West Africa (Hayward and Oguntinyinbo, 1987): rocks of the basement complex and the sedimentary rocks of the continental shields. Very extensive regions of West Africa are underlain by the crystalline basement rocks of the continental shield which are not very productive aquifers. Although ACRU was developed in a similar geological environment in Southern Africa where soils such as Luvisols and Arenosols (University of Minnesota, 2005 and University of Köln, 2005) which are found in the Densu basin are also found in the South African region (see Figures 4.8 and 4.9), the weaknesses reported by Everson (2001), New (2002) and this study with the baseflow generation in ACRU suggests that the simple conceptual representation of the processes governing groundwater recharge and baseflow generation may be too simplistic for the spatially discontinuous and variable minor aquifers developed within the continental shield.

6.6 Evaluation of ACRU in Wet and Dry Years

The earlier analyses have highlighted problems with model performance during the dry season and data quality during exceptionally wet years. To assess further how ACRU performed with regard to wet and dry years, annual performance appraisal statistics were related to the annual mean daily flows (Figure 6.8_{a-c}). These types of graphs according to Gupta et al. (1999) bring out trends in model performance as to whether the appraisal statistics fare better during the dry years (low annual mean daily flows) or the wetter years which have higher annual mean flows based on the daily model runs.

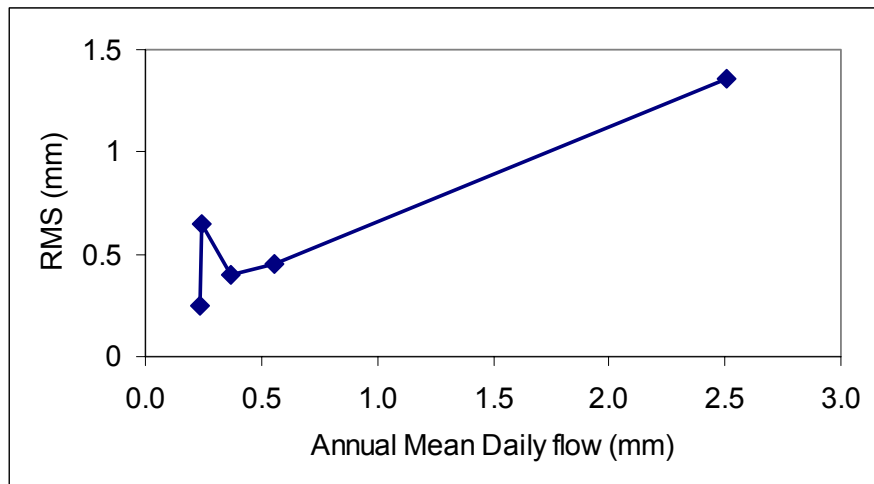


Figure 6.8a

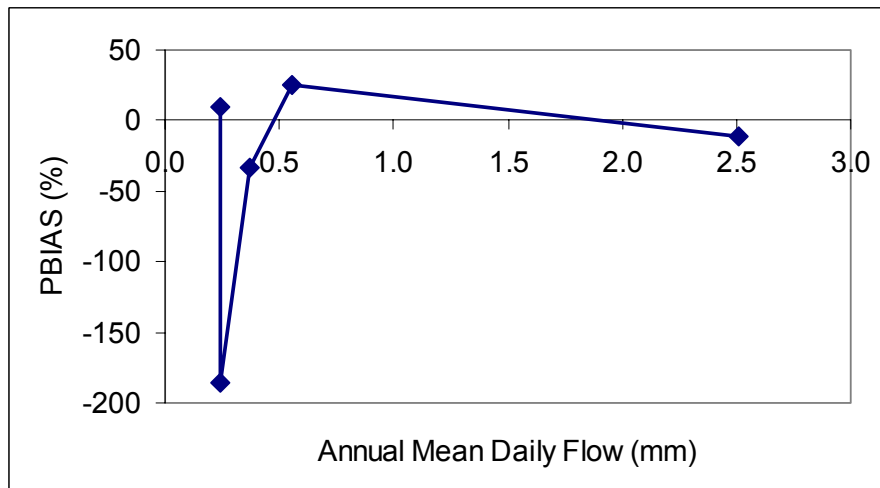


Figure 6.8b

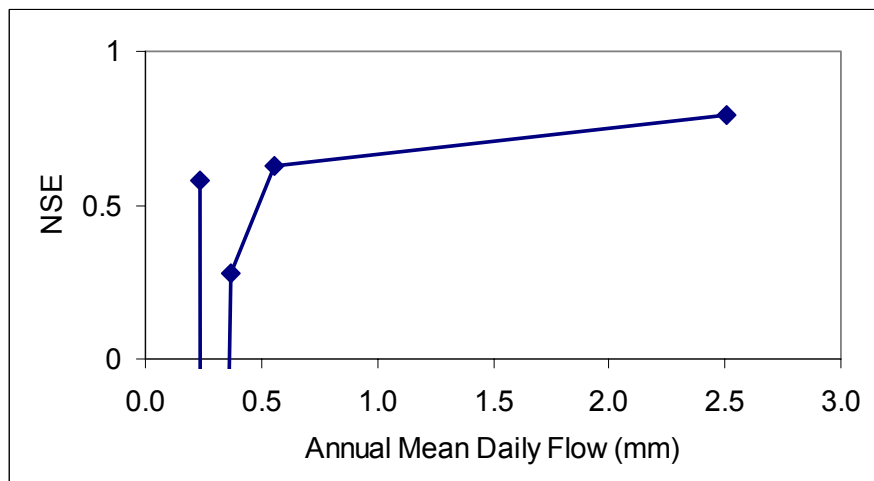


Figure 6.8c

Figures 6.8a-c, Evaluation of the calibrated ACRU model on an annual basis for five years for annual mean flows at Manhia.

The figures show that there is no apparent trend between the appraisal statistics RMS, PBIAS and NSE and the annual mean daily flow in this study for the years studied. However, this is not conclusive because of their relatively short duration of observations (only five years) and more data would be required before the variability can be properly explained.

6.7 Soil Parameters on ET

As discussed in Section 3.4.2.3, there are several relationships between soils and evapotranspiration. In ACRU evapotranspiration is considered as soil water evaporation (from the topsoil horizon only) and plant transpiration (from all horizons in the root zone). This shows that soil parameters required for evapotranspiration computation such as soil depth, field capacities, and redistribution rates should be computed accurately for correct evapotranspiration to be attained. However, as described in Section 4.2.5, soil parameters were generated because direct data were not available. As such if the generated data is not accurate the outcome of computed ET may be different from actual ET computed. Therefore problems with soil parameters could not be ruled out from the poor results seen in some of the simulations.

6.8 Manual Calibration

Hydrologic models are intended to be applicable to different watersheds and for that reason they typically have parameters that must be adjusted to make the model behaviour match the behaviour of the catchment of interest (Gupta et al., 1999, Masden, 2000, Ajami et al., 2004). No matter how sophisticated the model structure is if the parameters are poorly specified, the model simulated fluxes (e.g. streamflows) can be quite different from those actually observed (Gupta et al., 1999). Therefore the calibration procedure must be conducted carefully to maximise the reliability of the model. ACRU model is described as a multi parameter model (Schulze, 1995) and therefore has many parameters such as COFRU, COAIM, BFRESP, CONST, STOIMP and FOREST which are not directly observable and yet have to be estimated for the Densu catchment.

The technique of manual calibration involves obtaining historical records of the important hydrologic inputs and outputs for the catchment (e.g. streamflow, mean areal precipitation estimated evapotranspiration, etc.) processing the input data through the model and then adjusting the unknown parameters to obtain model–simulated outputs that match the observed watershed outputs as closely as possible.

A manual calibration (trial and error method) was used in this research (Section 5.3). The feasibility of manual methods relies on the fact that many of the hydrologic models are designed so the parameters have some conceptual relationship to the characteristics of the catchment. Therefore the modeller / hydrologist expect that adjustment of certain parameters in certain directions will have predictable effects on the way in which the simulated outputs will change. However, a large number of interacting parameters can result in unpredictable effects when multiple parameters are adjusted (Singh et al., 1999, Ajami et al., 2004). Because the model structures are highly non-linear, it is difficult to predict just how sensitive the different portions of the simulated outputs will be to parameter adjustments. In general, manual calibration procedure can be extremely time consuming and frustrating (Gupta et al., 1999) as noticed in this research. As a result of the above observations the calibrated values for the ACRU parameters may not have been optimised due to the manual calibration employed which could have caused some of the variabilities observed in the results.

6.9 Summary of Analysis

Based on the criteria of Henrikson et al. (2003), the daily ACRU simulations for the Densu are not acceptable as, although it did well in the calibration period (NSE = 0.82) it was very poor in the validation period. The model only performed well during the validation period in 1972, but with 1970 and 1971 added the performance was poor. The PME statistic was negative for most periods indicating that for most years (-ve values) the ACRU model is unable to provide, on a daily average basis, a forecast that is superior to that provided by

a simple persistence model and even for the periods that it was positive it was only 39%-54% better than the simple persistence model for the aggregated daily into monthly simulations.

As noted by Wallace and Oliver (1990), complete information on all the terms of the water balance equation is rarely available in a catchment. However having analysed the modelling results from both the lumped and semi-distributed modes within the context of the available data the strengths and weaknesses of the ACRU model are highlighted below together with a summary of the contributory factors for the poor model performance.

Strong Points of ACRU:

- The simulated streamflows generally follow the observed streamflow, showing runoff peaks in wet seasons as in the observed streamflow data;
- The model performs better in the wet seasons of the year rather than in the dry seasons;
- The aggregated daily into monthly simulations were superior over the aggregated weekly and also the daily in as far as the appraisal statistics are concerned making ACRU model more suitable for long term planning for irrigation and water supply;
- The lumped simulations performed better than the semi distributed mode simulations though not for PBIAS.

Weak Points of ACRU:

- There is overestimation in simulated flows during the rainy season which was very pronounced in 1968 (an exceptionally wet year on record);
- The model performance in the drier periods is poor where PBIAS was overestimating by over 60% for the validation period and underestimated for the calibration periods (about 23%) and nearly overestimated 300% for specific years like 1970 for the semi distributed Manhla simulations. The NSE for the period failed the NSE criteria according to Henrikson et al., (2003). The PME statistic also failed in this period.

Summary of the Causes of the Variable Model Performance in the Densu Basin

The above detailed analysis of the performance of the ACRU model and the data that was used within the model or against which the model outputs have been calibrated or compared has identified a number of causes of the variable model performance. Whilst it has not been possible to quantify the magnitude of their contribution to the model performance, recognition of the detrimental effects of the following issues is necessary:

- 1) the variable quality of the observed river flow data against which the simulated flow data are calibrated and compared:
 - a. flow data recorded outside the limits of the rating curve are not flagged;
 - b. suspect measurement readings, the causes of which could be non reading and 'cooking' data, unadherence to times for reading data and poor reading of measuring instruments;
- 2) the quality of the observed weather data e.g. rainfall and evapotranspiration;
 - a. insufficient density of raingauges and pan evaporation stations
 - b. data quality auditing not strong
- 3) shortcomings within the numerical representation of processes within the ACRU model;
 - a. groundwater processes
 - b. flow routing
- 4) shortcomings related to the incorporation of spatial variability within the lumped and semi distributed simulations
 - a. Influence of soil parameters on ET:
 - b. Influence of manual calibration.
- 5) features within the Densu basin which were not considered within the simulations above:
 - a. effects of control structures e.g. weirs
 - b. level of actual abstraction for irrigation not known.

Based on the above analysis, it is not considered appropriate to proceed further to use the ACRU model to simulate the hydrological impacts of scenarios of future catchment change in the Densu Basin until the situation of data quality and paucity within the Densu Basin is addressed in order for better simulations to be attained.

6.10 Improving Quality of Data Available for Hydrological Modelling

Within a data poor catchment such as the Densu, it has been demonstrated that the lack of availability of good quality data is not simply a function of data not having been collected. For example, the collection of significant amounts of rainfall and streamflow data has been identified during the course of this PhD, but the physical existence of the data has not been located. There is therefore an urgent need for procedures to be put in place to maximise the value of both historical data and that being currently collected. Six elements to improving the quality of data available for hydrological modelling have been identified during this research:

- 1) Instigating collection of new data.
- 2) Provision of good quality, robust data collection infrastructure
- 3) Development of data archiving / back-up systems
- 4) Making historical data available to the wider hydrological community
- 5) Ensuring that all data (new as well as existing) is subject to QC/QA procedures
- 6) Staff training to improve knowledge

Instigating collection of new data

Ayibotele (1974) noted that adequate and reliable data were generally scarce for streamflow and OTUI (1996) reported no subsequent improvement in data availability of the streamflow data. This study has also found no improvement in the collection and management of streamflow data up until the year 2002. However, new impetus has been infused by the newly formed DRBMB to collect all relevant hydrological data in the basin, such that attempts have been made

by the authorities since 2001 to improve data collection in this basin. Evidence of this is the collection of streamflow data since 2002. However, although these data were collected partly in order to inform this current study it could not be used because rating curves had not been established for the 'new' stations at Ashalaja and Pakro as at October 2004 according to the Senior Hydrologist¹⁵ at the Hydrological Services Department of the Ministry of Works and Housing in Ghana. Therefore water level heights for Ashalaja for the periods 02/12/02-18/07/03 and 01/09/03-17/09/03 and Pakro "New" for the period 01/03/03-30/09/03 were unable to be used for this study as anticipated.

While new data collection activities have been started for streamflow data, there are no ongoing activities collecting or improving the available soil and cropping data. The sensitivity analysis showed that parameter values for the field capacity water contents for the soils and crop coefficients for the vegetation showed relatively high sensitivities to cumulative streamflow meaning these are important but currently uncertain parameters to be considered when modelling with ACRU and many other hydrological models. Derivation of the necessary soil data for this study has been necessarily very subjective as most of the dataset required had to be derived from a small scale soil map of the area (Adu and Asiamah, 1992) and very limited soil profile data. Improvements in the data resources to support the important parameterisation of soil and vegetation in hydrological models are therefore needed.

Provision of good quality data collection infrastructure

From the OTUI (1996) report which reported recommendations to establish new gauging stations due to problems of backwaters and easy accessibilities, it has taken nearly 10 years for some of these new stations to be implemented at Ashalaja and Pakro 'New' in the basin. However, prior to the establishment of these two 'new stations', earlier construction of a new replacement gauging station in 1986 for the Nsawam station was undertaken based on the hydrological review cited in OTUI (1996). This station was destroyed by floods

¹⁵ Mr. Allotey

within a year of establishment due to crude construction and was therefore abandoned. As a consequence, there has been effectively no additional flow data collected since then. There is the need for good construction of structures to enable long and continuous data to be collected. In other instances, insects such as termites can destroy wooden structure platforms for mounting equipment, such as weather stations, in a short period of time. It is therefore important for more robust materials, such as concrete or insecticidally-treated wood to be used to construct such structures.

Development of data archiving / back-up systems

The aforementioned important data collection activities have been undermined by the lack of secure data archiving or back-ups. The flow data which was collected for the period 2001/2002 at the two new gauging stations within the basin at Ashalaja and at Pakro 'New' were destroyed in a fire that engulfed the offices of the collecting agencies (personal communication, with Hydrologist Water Resources Commission; Mr Odame Ababio, 2003). The lack of any secure back-up system meant that these data were lost.

Effort was put into trying to establish if the data collecting organizations in Ghana follow any established standards for the establishment of data collection stations and data collection/archiving/back-up systems, yet no concrete answer was found. For groundwater activities, personal communication¹⁶ showed that none were available, although it was said that work has commenced to instigate such standards and guidelines. For surface water data collection activities, no firm answer could be obtained suggesting that such standards are also probably not used or, if they are available, are not enforced. This issue of implementing and maintaining standards in order to improve data reliability and availability should be taken seriously to enable data to be properly collected, archived and accessed when needed.

¹⁶ Dr. P. K Darko, Senior Research Scientist, Hydrogeologist, Water Research Institute of CSIR, Ghana in September 2005

Making historical data available to the wider hydrological community

With the paucity of current or recent data available within the Densu, the extensive data that has historically been collected gains greater importance for understanding the hydrology of the Basin. Getting better value from this historical data by making it more widely available is therefore important. Ten rainfall gauging stations were identified in the Densu Basin and 1 outside. Yet for this research, only 3 stations were considered since only data from these were readily available and had longer duration records. The other records could not be accessed because they were 'lost', due to archiving and storage problems. There is therefore the need to locate historical data and transfer it into a format that can be made available to the hydrological community. Also historical data generated by other data collecting agencies such as the Research Institutions, Universities, water related non-governmental organizations (NGO's) are difficult to access as they are not readily available to the wider hydrological community. This observation has been experienced by the author in several instances whilst undertaking research in different aspect of hydrology as a researcher in Ghana. This calls for collaboration between all data generating institutions and NGO's and the recognised data collection institutions such as Meteorological Services Department of Ghana, the Hydrological Services Department of the Ministry of Works and Housing of Ghana to enable data generated to be transferred to them for proper auditing and storage.

Ensuring that all data (new as well as existing) is subject to Quality assessment (QA) procedures

Data auditing for quality assessment is paramount to provide confidence in the data and to ensure that decisions are based upon reliable information. However, from the examination of data e.g. streamflow, there appear to be no formal QA procedures to check data quality in Ghana. This calls for such procedures to be established and enforced to enable data to be 'confidently' used. This should ensure that suspect data is readily identified and flagged or

corrected soon after collection, and that erroneous data does not find its way unsuspectingly into ready use by the hydrological community.

Staff training to improve knowledge:

Staff training periodically for new developments in the area of hydrometeorology especially hydrometry and standards for data collection is very important, yet this is lacking in many of the data collecting agencies, according to conversations with some staff of these organizations. Reasons normally assigned to a lack of such training are lack of funds.

7. Conclusions and Recommendations

In this chapter conclusions are drawn from the results of the study and recommendations are presented, both for the Densu River basin and wider. The recommendations fall into two main areas: (1) guidance on how best to derive model inputs for future modellers within this data-poor sub region, based on the experience of modelling the Densu Basin, and (2) recommendations to the Densu River Basin Management Board and other river management boards in West Africa on how the results may be integrated into sustainable catchment management strategies.

Hydrological modelling in the tropical regions and especially the West African region has lagged far behind that in other geographical and climatic regions (van de Giesen et al., 2000). The recommendations from this research, together with the results of the modelling exercises undertaken, represent the important contributions made by this PhD to the knowledge of tropical hydrological modelling.

7.1 General

To achieve the sustainable development of water resources within a catchment, the concept of IWRM (Section 1.0) which is a process which promotes the coordinated development and management of water, land and related resources in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability (GWP/TAC, 2000) is advocated. Similarly activities such as improving agricultural and forestry productivity, conservation of ecosystem and habitats, and meeting the requirements of urban infrastructure and industry which may be in potential conflict with each other from time to time should be encouraged (Heathcote, 1998,). These challenges, faced in water resources management in many developing countries are a delicate balance (figure 1.2) between providing water for livelihoods and protecting water as a resource (GWP/TAC, 2000).

One approach to assisting sustainable water resource development and management within river basins is the use of mathematical modelling of watershed hydrology (Singh and Woolhiser 2002). Numerical models of groundwater and surface water resources systems have been used to simulate the behaviour of catchment systems since the 1960s (Zoppou, 2001). However, increasing computer speed and the development of new mathematical representations of physical processes has allowed the science of computer simulation to pass from being of academic interest only to a practical engineering procedure (Viessman & Lewis, 2003). The use of hydrological modelling tools to address a wide spectrum of environmental and water resources problems (Singh and Woolhiser, 2002 and Borah and Bera, 2003) is now commonplace.

The tropical regions of the world represent a huge but relatively little studied part of the globe with regard to the study of hydrology (Bonell et al., 1993; van de Giesen et al., 2000 and Giertz & Diekkruiger, 2003). The Densu Basin, a river catchment in Tropical Ghana in West Africa was selected as a typical medium-sized catchment within this region for study. Based on the problems faced in the basin, which are typical of those in the region, the objectives of the study were defined in Chapter 1.

7.2 Model Selection

The first stage in selecting a suitable model to simulate the Densu Basin (and potentially other catchments in West Africa) was the identification of a series of criteria against which to judge the multitude of available models. The criteria chosen are a mixture of hydrological, simulation and pragmatic reasons given in Section 3.2.

An initial screening review against the above criteria, based on information in the published literature (journals, textbooks, technical reports and model user's manuals) and on websites, identified three potentially suitable models (SWAT, ANSWERS-2000 and ACRU) which were reviewed in greater detail (Chapter 3).

Based on this detailed review the ACRU model was selected for modelling the Densu Basin because of the following:

1. Of the three models, ACRU is the only one not to require a DEM for model operation. Although there are global coverages of public domain DEM datasets (e.g. the United States Geological Survey's HYDRO1k dataset), the available resolution of a nominal 1km x 1km is not appropriate for ANSWERS-2000 (Bouraoui and Dillaha (1996, 1997) or SWAT (Chaubey et al., 2005). More detailed resolution digital elevation data are generally unavailable or expensive to acquire in West Africa which limits the applicability of models which depend upon them;
2. Rainfall data for ANSWERS 2000 is required at a 30 second time step. Although there are rainfall generators or disaggregators that might allow the derivation of such rainfall input data such as Weather Generators (WGEN) (Richardson and Wright, 1984), and US Climate Generator (USCLIMATE) (Harmel et al., 2000), the widespread availability of parameterization data and expertise is unlikely in West Africa;
3. The complexity and data requirement in relation to crop growth in SWAT is a disadvantage to this study because of the heterogeneous mixture of crops/vegetation in most tropical catchments which makes simulations of individual plants difficult/impractical;
4. In Ghana, the usual means of collecting evaporation data is with the A Pan. ACRU is the only model to allow the direct use of such data. ACRU has more options to consider from the methods that can be used to compute reference potential evaporation if one method is not appropriate in terms of data availability;
5. In an economically poor region like West Africa there are two important pragmatic advantages of ACRU for its wider future use in the region:
 - a. that amongst the three models reviewed, it has the lowest computing requirements. ACRU can run on a PC that would be unable to run either SWAT or ANSWERS 2000.
 - b. that ACRU does not require digital versions of all of its spatial datasets- if ANSWERS 2000 or SWAT were to be chosen, then all

of soil maps and landuse maps would need to be digitized and projected- there are significant expenses and logistical difficulties in doing this beyond this PhD.

7.3 Sensitivity Analysis

A sensitivity analysis of ACRU was undertaken which showed that the most sensitive parameter values with regard to total streamflow and total baseflow for the Densu Basin were the rainfall, monthly crop coefficients (CAY), Vegetation interception loss (VEGINT), Fraction of the effective root system in the topsoil (ROOTA) and the Drained upper limits for the topsoil (FC1). The sensitivity in the Densu Basin to the input parameters were found to be lower than those of Angus (1989) which was undertaken in single catchment in South Africa, and therefore the result of this sensitivity analysis compared to Angus et al. (1999) is not conclusive. However, the results of this sensitivity analysis aided the model calibration by identifying those parameters to focus on. Furthermore, the analysis for the Densu Basin shows how sensitive those parameters are for the Densu Basin of tropical West Africa for the ACRU model as Angus et al. (1999) was undertaken in a semi arid climate. The sensitivity analysis highlights the parameters that are important for the modelling and can therefore be used for the prioritization of future data collection / analysis activities to support hydrological modelling with ACRU.

7.4 Model Performance

During the modelling, the performance criteria used for appraising model performance were the NSE, PBIAS, DRMS and the PME objective functions. The criteria of Henrikson et al. (2003) for an acceptable NSE, ≥ 0.5 , and PME, ≥ 0 (Gupta et al., 1999) were used. There was significant temporal variability in the simulation results with regard to the NSE which was acceptable (> 0.5) for the calibration period but poor in the validation period in both daily and weekly (based on aggregated daily) simulations. The NSE for the calibration phases in daily, weekly and monthly periods were all above 0.8 in the lumped simulations

but slightly deteriorated to nearly 0.75 in the semi-distributed modes. The PME's for the daily and weekly calibrations failed (being negative) but passed the criteria in the monthly simulations to 0.65. In the validation period the NSE and PME failed (both having negative values) for all three categories of daily, weekly and monthly results. However, breaking down the validation periods into individual water years in both daily and weekly, it is realised that the year of 1972 has very good statistics with the NSE as high as 0.70 for the weekly as against 0.58 for the daily and a PME of 0.42.

The statistics for the dry seasons were poor in all respects for both calibration and validation. In the case of the PME appraisal statistic the simulation failed because they were negative (Gupta et. al. 1999) for the daily calibration simulation but was positive for two periods (01/03/1971 - 31/12/1972 and 01/03/1972 - 31-12/1972) in the validation period improving from 0.13 to 0.37 and 0.18 to 0.43 respectively when the daily simulations were aggregated into weekly simulations.

In general, there was no significant improvement in model performance between the lumped mode simulation and the semi distributed mode. However, aggregating the daily streamflow output into weekly and monthly streamflow significantly improved the performance. Overall the model performance was erratic but the results suggested that the model was more suitable for long term planning for irrigation and water supply.

The variation in the modelling results has been attributed to several causes which are:

- The low density of raingauges which are unlikely to have adequately captured the variability in rainfall within the catchment. Studies (e.g. Shaw, 1994) suggest that a catchment of the size of the Densu should have had five raingauge stations, instead of the two for which data were available;

- the use of daily spot streamflow measurement as against average daily streamflows calculated from continuous streamflow reading, is likely to have introduced errors into the streamflow data;
- significant uncertainties in the measured streamflow data at high water levels, where it was identified that flows had been determined using extrapolation beyond the established stage-discharge rating curves for the gauging stations at Manhia and Nsawam;
- the lack of routing of streamflow in the lumped simulation or allowance for a delay in river response at the catchment outlet to rainfall is a limitation of ACRU, and the unavailability of required streamflow routing parameters for the Densu River.

Although not proved in this study, the variability in some of the results could also be associated with the groundwater routines for recharge and base flow generation in ACRU; which were found by Everson (2001) to be unable to account for lateral subsurface soil water flow whilst New (2002) reported the inability of ACRU in a study in South Africa to adequately simulate the wetting-up of the catchments at the beginning of the wet season which resulted in over prediction of streamflow in the wet season and the tendency of ACRU to underestimate dry season baseflow. New (2002) attributed these inadequacies to both model design/structure and to errors in model parameters.

Although the ACRU model failed to achieve satisfactory performance statistics within the validation period, a qualitative analysis of the model output shows that the model has both strong and weak points which are:

Strong Points:

- The simulated streamflows generally follow the trend of observed streamflow, showing runoff peaks and wet/dry seasons as in the observed streamflow data;
- The model performs better in the wet season than in the dry season;

- The aggregated daily into monthly simulations were superior over the aggregated weekly and also the daily in as far as the appraisal statistics are concerned, making the ACRU model more suitable for long term planning for irrigation and water supply;
- The lumped simulations performed better than the semi-distributed mode simulations.

Weak Points:

- Much overestimation is noticed of simulated flows against observed during the rainy season. This overestimation is very pronounced in 1968 which was an exceptionally wet year on record (Meteorological Services Department of Ghana, 2004);
- The model performance in the drier periods is poor, which is the time in which water availability is most critical for the intake points of the water supply system of Koforidua.

The variability in modelling results described in a study in River Niger (Conway & Mahé, 2005), also in West Africa, interestingly shows the same performance variation observed with the modelling of the Densu Basin as discussed previously in Section 6.1. Conway & Mahé, (2005) attributed the variability in model results to failure to represent additional sources of water loss in the catchments such as percolation to deep aquifers, evaporation losses from surface waters and an overall underestimate of soil moisture storage. However, Conway & Mahé's, (2005) losses were errors across all years suggesting failure of the model to represent processes adequately whereas in this modelling of Densu catchment the errors are prominent in particular years suggesting problems with data.

From the points listed above, it is considered that reporting on the modelling for the Densu Basin at a daily time step to show, for example, individual peaks and floods is not appropriate because of the performance statistics. However, when the daily results are aggregated into monthly average flows, the improved

statistics suggest that the current data / model are suitable for less dynamic decisions making processes which use longer time interval data, like irrigation planning, and reservoirs inflow forecasting.

7.5 ACRU Model Processes

The modelling identified two process-based weaknesses in the ACRU model. Firstly, routing is only implemented in ACRU during semi distributed modelling, and so cannot be used in the lumped mode modelling. Where a move to semi-distributed modelling does not provide sufficient improvement in simulation capability at the outlet (compared to the lumped model) to justify the adoption of the semi-distributed approach (Ajami et al., 2004), as occurred in the Densu, the inability to implement routing or a delay in the arrival of a rainfall-induced runoff event at the catchment outlet, in the lumped mode in such a relatively big catchment is a model weakness.

Secondly, weaknesses in the groundwater routine in ACRU are implicated in the poor model performance in the dry season and the delay in the initial wetting up of the catchment in 1968 (in comparison to the observed) which calibration could not correct. This latter weakness was also witnessed by New (2002) who attributed this groundwater routine error to the model parameter values and inadequacies in model design/structure but did not show how these happened. Everson (2001) on the other hand saw a limitation in groundwater processes during a relatively wet year simulation where ACRU was unable to account for lateral subsurface soil water flow during a water balance study in South Africa, where analysis of the simulated unsaturated flow from the B horizon to the groundwater zone and saturated drainage could not account for the predominance of subsurface flow found in the catchment.

Two main lithologies control the distribution of underground water in West Africa (Hayward and Oguntinyinbo, 1987) which are the rocks of the basement complex and the sedimentary rocks of the continental shields. These extensive crystalline basement rocks of the continental shield are not very productive

aquifers (Hayward and Oguntinyinbo, 1987), as a result borehole and well yields from the region's aquifers are generally low ranging from 0.3 to 3 m³/h (GWP-WATAC, 2000 & Ayibotele, 1993) suggesting that the hydrogeology of the region is spatially variable.

Thus the variability in the performance of ACRU during the dry season where base flow makes up the river flow could emanate from the spatially complex groundwater processes in African geology and therefore the current conceptual approach based upon rate constants is too simplistic for the inherent complexity and that alternative algorithm or approaches need to be investigated.

7.6 Data Problems

The availability of good quality data has been a significant constraint for this research project. Some causes of variable model overestimation/underestimation and the poor performance statistics in the simulation results from this study could be associated with poor data as a result of several problems identified in relation to the data availability and quality. In a data poor region, it is vital to maximise both the value of the data being currently collected as well as the value of the historical data. Features of the current data collection or data management systems that have been identified during this research which limit their value are:

- inappropriate density of observation e.g. rainfall station network;
- mode of data collection such as spot measurements instead of continuous flow measurements for streamflows and poor construction of weirs;
- general data collection problems such as logistics and lack of inducements;
- archiving of data.

These issues are explained in the subsequent sections.

7.6.1 Density of Observation

In chapter 4 & 6 the data situation in the Densu basin for the modelling was described. Of the daily rainfall data that had been originally collected from the network of up to eleven stations in the catchment, only two stations, Nsawam and Koforidua were able to be used because data were readily available.

However, according to Shaw (1994) for tropical areas, such as Ghana, where rainfall is generated by convective means, the recommended rain gauge density for flat areas should be 1 to 600-900 km² and 1 to 100-250 km² for hilly areas to reduce areal rainfall errors to the minimum.

This shows that the two rain gauges used for this PhD, rather than the recommended five, was inadequate and it would be strongly recommended if possible to re-open old stations such as Oyoko, Asuboi, Adeiso and Aburi (Table 4.2) if abandoned to take advantage of their historical data series and also to establish new stations to improve the raingauge network in the basin.

7.6.2 Mode of Collection

The streamflow data quality was compromised by three elements in its collection. Firstly, it was found during this study, that the daily streamflow data was collected by spot flow measurements (personal communication¹⁷) at given times of the day, rather than from continuous measurement. This is particularly likely to introduce errors during days with significant flow variability e.g. rainy days in the wet season. Secondly, the construction of the weirs and the maintenance of flow gauging stations were noted to be poor as explained in Section 4.2.3. There were four gauging stations in this Basin in the 1970s, at Pakro, Akwadum, Nsawam and Manhia, with an additional private gauging station at Koforidua run by the local Water Company to monitor water flows. However, because of poor maintenance, a review in 1985 established that the Manhia flow gauging station was the only functioning station by that time. Finally, the monitoring of station performance was lacking, since it was not until

¹⁷ Mr. Allotey, Senior Hydrologist Hydrological Services Department, Ministry of Works and Housing, Accra, Ghana (August, 2002)

the review in 1985 was it established that the Manhia flow gauging station had been affected by backwater effects due to the construction of Weija reservoir since the late 1970s. Therefore although stage levels of the river Densu at this station are available, there is no valid rating curve for this period.

For a catchment of the economic importance to the country of the Densu basin, it is surprising that for a long period until 2002, there was no streamflow collection for the basin. However, with the formation of the DRBMB which was inaugurated in March 2004, a new impetus has been given to the collection of hydrometeorological data within the basin with new gauging stations established at Ashalaja (catchment area 2111.46km²) and Pakro “New” (catchment area 1342.77km²).

7.6.3 General Data Collection Problems

Data collection problems have been reported in Ghana in WARM (1998) and WRC (2000) for many of the river basins in the country including Densu. Some of the general problems identified with the poor data situation and storage enumerated below have also been observed by Manley and Askew (1993) during measurement of parameters related to the quantitative and qualitative aspects of the rainfall runoff processes in tropical catchments. Some of which are:

- Distances between monitoring stations (weather, rain gauge or flow gauging stations) in remote areas (which are dominant in developing countries) are very long because usually the population densities are low in such remote areas and maintenance of gauging stations becomes difficult because of lack of relevant logistics such as vehicles to transport recorders to and from stations and good pay;
- Readings are not taken on time (e.g. rainfall amounts should be recorded at 09.00 hours, however in some instances they are taken late or not at all in instances of manual recorders),

- The long distances between recording stations is also compounded by the lack of roads which makes travel in and out of such areas difficult, especially in the rainy season leading to instances of non collection of observed/measured data by the reader and paper rolls not changed on chart recorders.
- Problems with termites because insecticide treatment of building materials such as wood is non existent or poorly carried out. This encourages termites to eat the wooden structure and build ant mounds around e.g. wire meshes (which creates shades where they are not needed) affecting readings of say maximum and minimum temperatures
- Problems (e.g. lack of enthusiasm to work, literacy in reading instruments) with local trained personnel who are paid to look after 'their' rain gauge or staff gauge, as remuneration and technical know-how are low in such remote areas.
- Finally some technical people in the Hydrology and Meteorological organization (personal communication) also complain of a lack of adequate training (personal communication) in new developments in the area of their chosen fields and inadequate pay resulting in low morale and low output.

Other problems identified with data collection in Ghana are;

- Poor data storage when data has been acquired. Original data from the 1960s to 1990s are still stored on the original paper log sheets, instead of in electronic formats. If the paper on which the data are recorded is lost, the data are lost forever;
- Poor coordination of the transfer and processing of collected data at a centralized store. When data are collected from the remote individual stations by the locally trained people, personal observation indicates that the data are not transferred as quickly as possible to the necessary meteorological office for processing. This delay in transfer, in some instances, leads to data getting lost because of poor storage by the collector;

- Data auditing which should be done in all instances when data are collected cannot be said to be always done. As observed in this PhD, streamflow data recorded for very high flows in 1968 which fell beyond the rating curve limits were not flagged for caution. This inadvertently creates difficulties such as trying to assign reasons to certain trends in data.

7.6.4 Data Archiving

Severe limitations are apparent in the quality control and archiving procedures for data collected in the Densu catchment. During this study, data metadata (see Section 7.7.1.1) was obtained indicating several rainfall stations within the catchment for which data were supposed to exist (Table 4.2). However, locating and acquiring the data from these stations proved very difficult.

Upon requesting the data from the rainfall station where it had been collected, in instances where the data were not available at the regional office, the usual response from the rainfall station was that the data had been transferred to the regional head office of the Meteorological Services Division of Ghana, with the possibility that no-back-up was kept by the rainfall station. Following up the data at the head office usually met the response that “it has not been received” or, if it had, that the data were in a raw unprocessed form (i.e. on the original paper forms). In some instances, the archiving was so crude that, although the data had been received from the collecting stations, it could not be traced. For some cases where the paper form of data was available, quality control notes or flags are not provided as to suspicious events such as rain gauge over topping its pan or rainfall recorder failing to record because of a faulty clock or to paper running out because the paper roll had not been changed to enable the user of the data to be cautious in the interpretation of the data. Examples in this research were the provision of flow data which was based upon level data beyond the valid range for the rating curves at the Manhia gauging station.

Where good quality data has been collected and suitably archived, the long term availability of the data is potentially compromised by the lack of data back-

up facilities/practices/routines. For example, flow data collected for the period 2001/2002 at two new gauging stations within the basin at Ashalaja and Pakro “New” were destroyed in a fire that engulfed the offices of the collecting agencies. The lack of any secure back-up system meant that this data was lost forever.

7.7 Recommendations

From the conclusions identified above, recommendations are made to address the three main problem areas which were observed in this hydrological modelling using the ACRU model, namely:

1. problems with data quality,
2. generation of some model parameters, and;
3. shortcomings in the ACRU processes

7.7.1 Data Quality Recommendations

The problem with data quality could be addressed with the following recommendations:

7.7.1.1 Making Historical Data Available To The Wider Hydrological Community

Historical data on paper records and those already put into digital format but not in any standardized form should be encouraged to be converted into an agreed digital format e.g. Metadata standards. Metadata is structured information that describes, explains, locates, or otherwise makes it easier to retrieve, use, or manage an information resource. It is called “data about data” (NISO 2004, Gililand-Swetland, 2000; ANZLIC, 1996; Kildow, 1996). What metadata does is to facilitate discovery of relevant information. In addition NISO (2004) reckons that it can help organize electronic resources through links to resources based on audience and type such as static web pages with the names and locations of the resources “hardcoded”; facilitate interoperability (the ability of multiple systems with different hardware and software platforms, data structures, and interfaces to exchange data with minimal loss of content and functionality) by using defined metadata schemes, shared transfer protocols and crosswalks

between schemes allowing it to be understood by both humans and machines; provide digital identification to uniquely identify the work or object to which the metadata refers such as URL (Uniform Resource Locator) or some more persistent identifier like a PURL (Persistent URL) or DOI (Digital Object Identifier); and support archiving and preservation so that resources will survive and continue to be accessible into the future with the growing concern that digital information is fragile by adding special elements to track the lineage of a digital object (where it came from and how it has changed over time), to detail its physical characteristics, and to document its behaviour in order to emulate it on future technologies through schemes such as the National Library of Australia, the British Cedars Project (CURL Exemplars in Digital Archives) and a joint Working Group of Online Computer Library Centre (OCLC) and the Research Library Group (RLG) (NISO, 2004 & Woldai, 2004). There are softwares which could assist in transforming data into Metadata formats such as: DDI Tools (<http://www.icpsr.umich.edu/DDI/users/tools.html#a01>); Dublin Core tools (<http://dublincore.org/tools/>); GDC Metadata Tools (<http://www.nbil.gov/datainfo/metadata/tools/>) Metadata Software Tools (<http://ukoln.bath.ac.uk/metadata/software-tools/>); TEI Software (<http://www.tei-c.org/Software/index.html>)

For harmonizing metadata standards, a minimum mandatory set of metadata items is recommended by International Organization of Standardization (ISO-<http://www.iso.org/iso/en/ISOOnline.frontpage>) (Woldai, 2004). These are:

- Metadata Language Code.
- Metadata Characterset [default = “ISO 10642-2”].
- Hierarchy Level Scope [default = “Dataset”].
- Dataset Language Code, Dataset Characterset [default = “ISO 10646-2”]
- Abstract, Category Dataset Citation (Title & Date).
- Dataset Contact (Responsible Party Name/ Organization & Responsibility Type)

7.7.1.2 Development of Data Archiving / Back-Up Systems

There is an urgency for improved data archiving and back up systems because the demand for information about different measured hydrometric parameters such as rainfall, water level or streamflow is increasing in quantity and quality significantly (Schlaeger et al., 2005). However, for metadata schemes to be put in place, problems associated with data which are listed below should be addressed.

- Historical data, mostly from the pre 1990s and some onwards, which are only available in analogue paper media must be electronically input
- Inconsistencies in the production of observed/measured/collected data arising from no specific standard being followed must be corrected which is a very serious problem (Woldai, 2004). This could be done for instance by interested groups such as at national level for generic agreement between parties; branch level for agreements between say hydrometeorological institutions of their specific common application and data, internal institutional level, where interval processes are aligned through data and procedure definitions. Standardization is not an easy job (Woldai, 2004) and it requires decisions on how the application sector classifies/aligns measured/collected data of interest.
- Security of data holdings because of poor storage must be improved through electronic backups where available or “properly” catalogued in cases of manual paper recordings for ease of access;
- The current minimal data exchange/sharing between the other data generating establishments such as the NGOs and the established data collecting agencies like the National Meteorological Services Department must be improved to improve the general data situation for the whole country, since such NGO’s normally work in very remote areas.

7.7.1.3 Ensuring That All Data (new as well as existing) Is Subject To QC/QA Procedures

Screening of generated data should be encouraged for data quality assurance and quality control at all times. Software which can assist in quality assurance

are the Data Screening- DATSCR (Daymen and Hall, 1990) software for hydrological data screening including rainfall and streamflow and the WISKI (Schlaeger et al., 2005) software package which is a modern tool for hydrological data management. This software has been designed to be user friendly and simple to apply. DATSCR is DOS based but usable on a Window based client/servers and WISKI is purely Windows based. WISKI combines modern standards of data management with advanced tools to collect, edit, store and present time series data to intranet, internet and GIS. The quality flags incorporated in WISKI summarise the data quality of the data sets with standard flags, like good, suspect or missing. More detailed secondary flags inform the user about the editing process, abnormalities during calculation or modelling and are configured for the different processing methods.

For future (from today onwards) data collection and quality assurance there must be a solid data management infrastructure based on good data collection policy, a political will, guidelines and administrative arrangements for the data collection agencies, technical standards such as the International Standards Organization (ISO), fundamental datasets, and a means by which hydrological data is made accessibility to the community. This is important because information technology bridges national land disciplinary boundaries and therefore standards must be consistent with those in related fields to enable different users of data to have a common working ground to stand on. As such:

- Data collecting agencies must be resourced sufficiently to enable their scheduled activities in the area of good data collection and storage not to suffer. Researchers can bring attention, through seminars and lobbying of appropriate funding bodies, to the needs of good data collection, processing and storage.
- Where resources are available, continuous (automated) data should be taken and averaged over the day rather than spot measurements. Data are important for any meaningful research to be undertaken and therefore relevant authorities must ensure that adequate logistics are available for data to be collected at all times.

Could there be the need to place in the highest echelon of government, somebody who understands all these issues for better understanding and effective action? This is because from his study on “The Problem of Developing Metadata for Geoinformation in Africa”, Woldai (2004) concluded that such a move would be appropriate. Such a person could provide the top-down political will to require and resource the data collection Agencies to collect and appropriately manage the necessary good quality hydro-meteorological data required to support sustainable water management in these rapidly developing countries.

7.7.2 Guidance On How Best To Derive Model Inputs For Future Modellers

It is very important during model selection for the modeller to be clear about what exactly the model is required for and then to set out very clear criteria based on those requirements. Based on this study the modeller in data poor regions is advised to assemble all relevant hydrometeorological data as a prerequisite for the model selection as that has been the main constraint with this study

From the sensitivity analysis undertaken for this basin with the ACRU model, the most sensitive parameter values identified are the rainfall, monthly crop coefficients (CAY), Vegetation interception loss VEGINT; Fraction of the effective root system in top soils (ROOTA) and the Drained Upper Limits for the top soils (FC1). The high sensitivity of simulated flows to these parameters made assessing their values or credible ranges within which to calibrate important. However, these parameters are all dependent on local soils and vegetation, quantitative data on which are often lacking.

In the absence of locally available local quantitative data, reference should be made, in the case of soil data, to:

- International catalogues of published soil information e.g. WOSSAC – World Soil Survey Archive and Catalogue (<http://www.wossac.com/>) This is a site for soil survey reports and maps produced by British companies and surveyors overseas in the last 80 years in 250 countries, with a view to ensuring their enduring availability and protection.
- Online sources of regional information e.g. FAO country data (e.g. in the case of Ghana- http://www.fao.org/ag/agl/swlwpnr/reports/y_sf/z_gh/gh.htm which provide information on land resources, water resources, country overview and links to others such as social economic features and climate of a country.
- Online sources of international information e.g.
 - o FAO Gateway to Land and Water Information (<http://www.fao.org/ag/agl/swlwpnr/swlwpnr.htm>); An access point to global, regional and national reports compiled by FAO and the participating institutions worldwide and an entry point to the worldwide web of information on land, water and plant nutrition and related subjects
 - o DG Rossiter's "Compendium of On-Line Soil Survey Information" (http://www.itc.nl/personal/rossiter/research/rsrch_ss.html)
- Web-based sources of global or regional datasets e.g.
 - o World reference base for soil resources at <http://www.fao.org/ag/agl/agll/wrb/mapindex.stm>,
 - o FAO/AGL Soil resources and mapping classification portal (<http://www.fao.org/ag/agl/agll/prtsoil.stm>)

For land use/cropping/vegetation data reference should be made to:

- Online sources of regional information e.g. FAO country data (e.g. in the case of Ghana- http://www.fao.org/ag/agl/swlwpnr/reports/y_sf/z_gh/gh.htm as in soils above.

- Online sources of international information e.g. FAO Gateway to Land and Water Information (<http://www.fao.org/ag/agl/swlwpnr/swlwpnr.htm>) as in soils above;
- Online sources of satellite imagery showing landuses e.g. European Space Agency-ESA http://www.esa.int/esaEO/SEM6N6MXEM4E_index_0.html Here, some images such as landscape and vegetation on countries could be assessed.
- For crop coefficient data FAO Irrigation and Drainage paper 56 which can be electronically assessed from <http://www.fao.org/docrep/X0490E/X0490E00.htm> and Chapter 2 of the United States Department of Agriculture Soil Conservation Service's Part 623 National Engineering Handbook (available from <http://www.info.usda.gov/CED/ftp/CED/neh15-02.pdf>) can be of help as they are two main documents where useful information on crop water use and field irrigation water requirements could be found

7.7.3 Recommendations to Densu River Basin Management Board

The formation of the Densu River Basin Management Board was very timely in as much as the problems of the Densu Basin are concerned. Their mandate (Section 1.1) captures many of the issues which have been observed as problematic in the basin. Their activities include the need to create awareness and mobilize political will; banning farming in buffer zones; introducing environmental and farmer friendly systems of agricultural production (crops and livestock); desilting drains; improved hydrological data collection; control clay and sand extraction and quarrying of stone. Other activities include enforcing mandatory preparation of Environmental Impact Assessment (EIA's) for development projects; monitoring and assessing the state of natural resources, and implementing the community, small towns' and urban towns' water supply system rehabilitation in the districts are all in order.

In addition the activity that states to “monitor and assess the state of natural resources” e.g. water has highlighted the need for research in the area of water resources. This research has been able to identify some of the problems in the Densu Basin which when improved would assist with this objective of the DRBMB such as:

- a) inappropriate density of observation e.g. rainfall station network;
- b) mode of data collection such as spot measurements instead of continuous flow measurements for streamflows and poor construction of weirs;
- c) general data collection problems such as logistics and lack of inducements;
- d) poor archiving of data.

As the data situation in the basin is fraught with problems such as mentioned above, it has hampered the objective of this research “to assess the impact of land use change on the future water resources of the basin” as the period of available data was so short and the modelling results inconclusive because the Performance Model efficiency (PME) test failed in nearly all the runs and the Nash and Sutcliffe Efficiency (NSE) varied from acceptable to unacceptable levels. From the host of problems catalogued in Chapter 1, there is an urgent need for collection of hydrological data which is important to be able to assess the inflows into the Weija reservoir- a very important reservoir in as far as the water supply to Accra, the capital city of Ghana, is concerned.

As seen from the modelling performance, the modelling of the Densu Basin using the ACRU model was found not to be suitable for daily time step simulations (e.g. identifying peaks and floods) because their timings are not “good” based on the statistics. But ACRU is recommended when the monthly simulations (daily aggregated into monthly) are concerned because the results gave improved statistics. Hence from this study when water management issues such as irrigation planning and monthly flows into the Weija Dam for water supply are concerned, the ACRU model is suitable and could be used.

However, data improvement is recommended strongly, to enable better simulations to be attained for better results on these to be achieved.

So, one major recommendation in as far as this PhD and the Board is concerned is to follow strictly their objective “to facilitate the co-ordination and integration of the plans and programs of the different institutions (Meteorological Services Department, Hydrological Services Department of the Ministry of Works and housing, the District Assemblies and other data generating institutions such as the NGO’s) at the district level”, especially of data collection in the basin. Their activities must be effectively co-ordinated by the DRBMB with the IWRM principles listed below adhered to:

1) Water resources assessment:

- improve data collection networks and assessment techniques
- introduce risk management tools, for instance for floods and droughts.

2) Communication and information:

- raise awareness- a ‘water movement’ which might help motivate data collectors if they can perceive that they are doing something worthwhile (rather than just collecting numbers which disappear into a data ‘black hole’).

3) Allocation and conflict resolution:

- tools for conflict resolution: upstream versus downstream, sectors versus sector, human versus nature should be introduced

When these issues are tackled problems that might get solved are the

- Lack of institutional capacity for water management at both Government and water providers’ level might be improved with access to better understanding based on good data
- Water shortages due to low flows and dryness of streams upstream of the basin with attendant reduction in water levels of reservoirs downstream can be observed through scenario modelling.

7.7.4 Future Research

Since the modelling results of this research were not conclusive due to inadequacy of data and variability in results, it is recommended that for effective future study, the data situation should be improved. The currently available data in terms of streamflows are too old (nearly over 20 years old) to be used for any meaningful assessment of the basin in terms of future landuse effects on the flows from the catchment. Another area of recommendation in relation to the modelling would be to investigate further the groundwater processes problems of ACRU observed by Everson (2001) and New (2002) and in this research in relation to poor simulation of groundwater in certain instances. Other areas that would need further study are the data on land use change in the catchment through analysis of air photos/remote sensing images and the derivation of suitable crop/vegetation parameter sets and soil parameters.

7.7.5 Lessons Learnt

At the end of this PhD some particular lessons learnt during the research period are:

- It is very important to always first get hold of the required data (since data availability may constrain the research method used) and to follow it by performing strong quality assessment checks to ascertain that the data are of sufficiently good quality before undertaking the hydrological modelling.
- For a good research output, critical analysis of results must be undertaken to understand why such results occur and to learn from them.

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Annex A

Commentary of Figure 3.6

Soil Water Budgeting and Total Evaporation

Introduction

In Chapters 3 Section 3.3.5 and Section 3.4 which outline the considerations and philosophies upon which the *ACRU* modelling system has been described, it was stated that *ACRU* is in essence a multi-layer soil water budgeting model and that most rainfall is transformed into evaporation either through the soil or through the plant. One of *ACRU*'s major aims is, therefore, to simulate the soil water budget accurately by accounting realistically for the total evaporation processes, since these processes are the "heart" of the agrohydrological system (Kovacs, 1986).

Total evaporation, E , may equal or be less than the maximum evaporation, E_m , formerly termed "potential evapotranspiration". On a given day, E can be reduced to $< E_m$ either when soil water has been depleted below a critical threshold value (when plant stress sets in) or when there is an excess of water in the soil profile. From a multi-layered soil, E also responds to self regulatory mechanisms when certain soil horizons are relatively wetter than others. To place the entire soil water budget as represented in *ACRU* in perspective, however, the various steps and sequences of a daily soil water budget are first elucidated.

Structure of the Model

The *ACRU* agrohydrological modelling system (Shulze, 1995) is structured on a daily multi-layer soil water budgeting (Figure 3.6). Rainfall and/or irrigation not abstracted as interception by the vegetation canopy or stored on the surface are partitioned into stormflow and effective rainfall that enters the topsoil horizon.

Drainage from the topsoil to subsoil horizon takes place when soil water in the topsoil exceeds field capacity. Similarly, when the soil water in the subsoil exceeds the field capacity, drainage to the intermediate and groundwater stores occur, from which baseflow is generated. Unsaturated soil water redistribution between the two horizons occurs according to their relative soil water contents. Runoff comprises stormflow, in the form of quickflow, delayed stormflow and baseflow. Total evaporation (evapotranspiration) takes place simultaneously from previously intercepted water as well as from the soil horizons in the form of soil evaporation and plant transpiration, depending on plant growth stage, root distributions and horizon water contents. The nature of this model implies that the model is not a parameter fitting or optimizing model but parameters are replaced by variables estimated entirely from physical features of the catchment.

Sequences and Processes in Determining the Daily Soil Water Budget

The sequences and processes presented below are for a typical day with rainfall. The assumption is made that plant transpiration and soil water evaporation are treated as separate components from a two horizon soil profile. A brief description of streamflow generation processes is included to provide a more global view of the water budgeting procedures.

Step 1: Evaporation of Previously Intercepted Water

The intercepted water on the plant canopy, stored from the previous day if it had rained, is first evaporated. This occurs either at "potential" rate (E_r , according to atmospheric demand) for most short vegetation types/crops, or at an enhanced rate if the land cover is predominantly (> 50%) forest. The remaining (or residual) potential evaporation, E_{pr} , becomes available for soil water evaporation and transpiration.

Step 2: Apportionment of Maximum Evaporation to Maximum Soil Water Evaporation and Maximum Transpiration

Maximum evaporation (E_m), i.e. the product of the reference potential evaporation and the crop coefficient for the day, is then apportioned to

maximum soil water evaporation (E_{sm}) and maximum plant transpiration (E_{tm}). The apportionment depends on the stage of development of the plant, which is a function of plant biomass expressed either by LAI or by the crop coefficient.

Step 3: Apportionment of Available Maximum Transpiration to Different Soil Horizons

The maximum evaporation available for transpiration from the plant, E_{tm} , is apportioned to the different soil horizons in proportion to the root mass distributions of the respective soil layers.

Step 4: Estimation of Actual Soil Water Evaporation

Actual soil water evaporation, E_s , is computed from the topsoil horizon. E_s for the day can either be occurring at maximum (or "stage one") rate (E_{sm}) if a minimum threshold of soil water resides in the topsoil horizon, or below the maximum rate once soil water content has dried to a "stage two" level, in which case E_s declines very rapidly with time.

Step 5: Estimation of Actual Transpiration from the Plant

Actual plant transpiration (E_t) is calculated next, initially for the topsoil horizon, then from the subsoil horizon.

Step 6: Compensations for Differentially Wetted Soil Horizons

After resetting the soil water contents of the top- and subsoil horizons (θ_A and θ_B) to account for actual soil water evaporation and transpiration losses for the day, the relative soil water contents of these horizons are compared, and if one horizon is under water deficit stress and the other is not, compensations are made by the E_t from the wet layer being enhanced if the plants are in a stage of active growth.

Step 7: Interception Losses on a Day with Precipitation

On a day with rainfall, the net precipitation (P_n) available for subsequent addition to the soil water budget or for eventual stormflow generation, is calculated from the difference between gross precipitation, P_g , and the canopy interception losses for the day, I_i , i.e. $P_n = P_g - I_i$

Step 8: Generation of Quickflow from Impervious Areas

Impervious areas, whether "connected" directly to a watercourse (either by being adjacent to a stream as the permanently saturated partial area or by draining directly into a stormwater drain in urbanised areas) or whether "disconnected" (in which case they discharge their excess water onto adjacent pervious zones and alter the soil water budget there) are accounted for next.

Step 9: Stormflow Generation from a Rainfall Event

On a day with rainfall occurring, the stormflow generating routines become operational.

- The soil water deficit is determined for the critical soil depth (SMDDEP) from which stormflow response is generated. This depth is either that of the topsoil horizon (if *ACRU*'s default value is used) or some threshold input soil depth, as specified by the user. The deficit, D_{SMD} , is the difference between the soil water content at θ_{PO} , and that held by soil column of the critical depth, θ_{SMDDEP} , i.e. $D_{SMD} = \theta_{PO} - \theta_{SMDDEP}$
- Initial abstractions are computed as the product of a coefficient $COIAM$ and D_{SMD} .
- If the net rainfall (observed gross rainfall minus interception loss) is less than the estimated initial abstractions, no stormflow is generated. The net rainfall is then infiltrated into the soil and the delayed stormflow remaining from a previously generated stormflow is calculated.
- If net rainfall exceeds initial abstractions, stormflow is generated. This stormflow is added to a stormflow store remaining from previous events. Quickflow (i.e. same-day stormflow response) is then computed by applying a coefficient to the total stormflow store, subtracting the day's stormflow and then resetting the stormflow store for the following day.

Step 10: "Saturated" Drainage Processes

- Following stormflow abstractions, the soil water content of the topsoil horizon, θ_A , is reset by the addition of the effective rainfall, P_e , where $P_e = P_g - I_l - Q_s$

- Soil water content for the topsoil horizon, θ_A , is reassessed and if it is above the topsoil's drained upper limit, θ_{DULA} , a proportion of the "excess" water drains into the subsoil horizon, and θ_A is reset.
- The above is repeated for the subsoil horizon, where excess water from the topsoil horizon is added and if B is above the subsoil's field capacity, a fraction of the excess water drains to below the root zone and the subsoil horizon is reset.

Step 11: Accumulation of Soil Water under Waterlogged Conditions

Under conditions of poor drainage out of the bottom of the root zone, soil water content may accumulate to a level exceeding its porosity, i.e. θ_{POB} . In such cases the water accumulates from the bottom upwards, filling first the subsoil horizon to beyond porosity ($B > P_{OB}$), thereafter "entering" the topsoil horizon from below and wetting that. Should the topsoil's water content exceed porosity (i.e. $A > P_{OA}$), the excess water contributes directly to stormflow as a saturated overland flow.

Step 12: Redistribution of Unsaturated Soil Water

Upward and downward unsaturated soil water redistribution procedures are considered next and θ_A and θ_B stores are reset.

Step 13: Baseflow Generation

Baseflow routines become operative next.

- * If on a given day no contribution is made to the baseflow store by drainage, then baseflow releases are calculated as the product of the previous day's groundwater store and a user specified coefficient of baseflow response.
- * In computing baseflow releases, the user specified coefficient of baseflow response is adjusted (internally in the model), dependent on whether the store is relatively "full" or relatively "empty".
- * The baseflow store's magnitude is then reset.
- * If a contribution through drainage is made to the baseflow store, this is done in accordance with the amount of water available for drainage from the subsoil

horizon and its drainage coefficient. This contribution is then first added to the baseflow store before baseflow is released and the store is recalculated.

Step 16: Setting Final Values of the Water Budget

Final values of soil water storages, soil water evaporation and transpiration, stormflow, baseflow, quickflow and baseflow store amounts are stored, to be used as initial values the following day, and/or for daily/monthly/other statistical output, and/or to be used in subsequent water budget related computations such as crop yield analyses.

Annex B

Soil map of Densu Basin

Annex C

The Calibrated parameter values for the lumped and semi distributed mode modelling

Calibrated values of input parameters for ACRU modelling in Densu Basin														
			Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sept	Oct	Nov	Dec
CAY	Lumped		0.90	0.90	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.98	0.90	0.90
	Semi distributed catchments	1	0.85	0.85	0.95	0.95	0.95	1.0	1.1	1.3	1.3	1.1	1.0	0.85
		2	0.80	0.80	0.90	0.90	0.90	0.95	1.05	1.25	1.25	1.05	0.9	0.85
		3	0.80	0.80	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.80	0.80
VEGINT (mm.day ⁻¹)	Lumped		3.54	3.54	3.54	3.54	3.54	3.54	3.54	3.54	3.54	3.54	3.54	3.54
	Semi distributed catchments	1	3.0	3.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	4.0	3.0	3.0
		2	3.0	3.0	3.5	3.5	3.5	4.0	4.0	4.0	4.0	4.0	3.0	3.0
		3	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0	3.0

Parameters	Lumped		Semi-distributed		
	Base Value	Calibrated	Catchment 1	Catchment 2	Catchment 3
ABRESP	0.63	0.61	0.64	0.65	0.61
BFRESP	0.43	0.39	0.42	0.43	0.40
FC1 (m.m ⁻¹)	0.194	0.271	0.260	0.250	0.245
FC2 (m.m ⁻¹)	0.286	0.333	0.342	0.349	0.340
WP1 (m.m ⁻¹)	0.093	0.096	0.095	0.094	0.109
WP2 (m.m ⁻¹)	0.168	0.185	0.184	0.189	0.173
QFRESP	0.15	0.05	0.35	0.35	0.35
PO1 (m3.m ⁻³)	0.467	0.433	0.456	0.445	0.461
PO2 (m3.m ⁻³)	0.438	0.435	0.429	0.433	0.435
DEPAHO (m)	0.35	0.36	0.38	0.38	0.37
DEPBHO (m)	1.48	0.80	0.80	0.80	0.80
SMMDEP (m)	0.35	0.36	1.28	0.38	0.36
COIAM ¹⁸	0.29	0.33	0.40	0.38	0.25
COFRU	0.012	0.020	0.040	0.040	0.040
ROOTA (m)	0.70	0.80	0.70	0.8	0.92

¹⁸ Assumed same for all months

