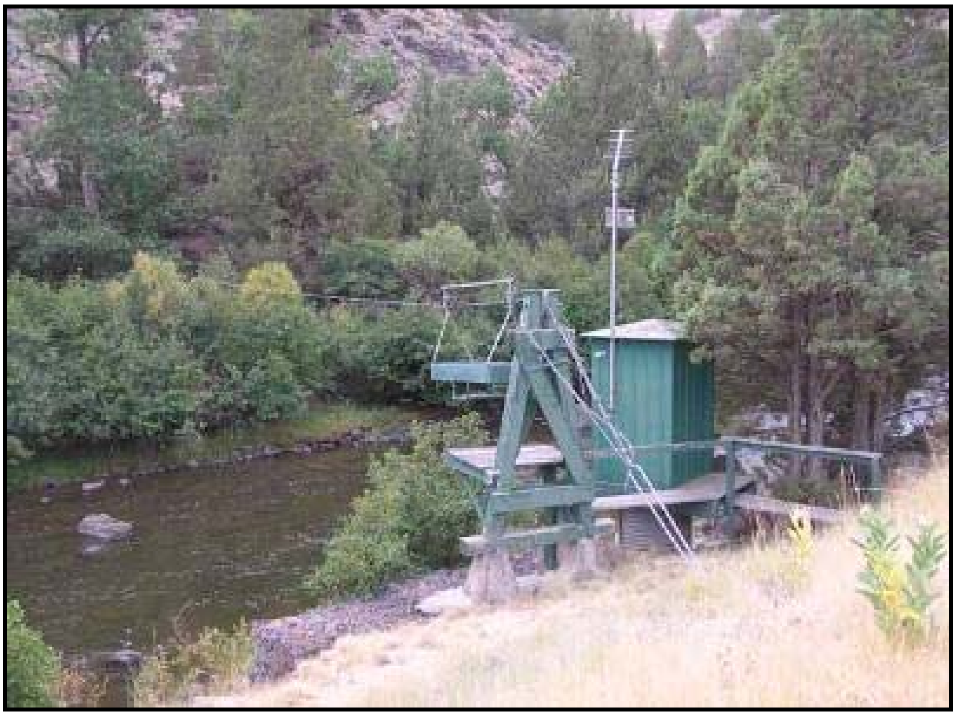
Masters Thesis
TVVR 08/5001-73

Analysis of the rainfall-runoff pattern of a catchment with limited data to estimate the runoff potential

Case study: The Mefou Sub basin in Cameroon



BY

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January 2008

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Avdelningen för Teknisk Vattenresurslära
ISRN LUTVDG/TVVR-08/5001-73
ISSN-1101-9824

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International Masters Thesis

By

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1 Picture on cover page: Stage measurement station on a stream.

Report TVVR-08/5001-73
International Masters of Science (WATERLU) Thesis project

ABSTRACT

Water resources management in a catchment requires the quantification of the water potential. This is usually achieved by the estimation of the hydrological and meteorological characteristics of the basin using observed data to carry out statistical estimates or for use in hydrological models. Hydrological and meteorological data for the Mefou sub basin in Cameroon were collected to analyse the rainfall-runoff pattern and estimate the potential runoff volume from the sub basin. The data included daily series of rainfall, runoff, temperature and evapotranspiration for some periods in which data was available for ten meteorological stations and one hydrological station within or near to the catchment. Data was available for only one rainfall station at Yaoundé and one runoff station at Nsimalen directly located within the sub basin. The rainfall station had data for seven years from 1976 to 1982 while the runoff station had data for five years from 1976 to 1977 and 1984 to 1986. However, a nearby rainfall station at Sangmelima had observed data for 13 years from 1975 to 1987 which could be used as a replacement station for Yaoundé. Simple statistical and graphical methods were used to analyse and compare the data from the Yaoundé and Sangmelima stations to determine a correlation between them in order to extend the Yaoundé data to 10 years at least. Similarly simple statistical and graphical methods were used to determine a monthly and annual relationship between the rainfall and runoff data of the Yaoundé station and the Nsimalen station. These relationships were used to extend the monthly and annual runoff to the intermediate years without data from 1978 to 1983 and 1987. It was necessary to extend this data to at least 10 years in order to increase the possibility of including both wet and dry periods of the sub basin in the hydrological estimates. The rainfall and runoff data was eventually extended to 12 years from 1976 to 1987. After extending the data the average annual runoff volume of the entire sub basin was estimated from the analysed data. This runoff was found to be within the range of previous estimates carried out in the sub basin though the volume is inadequate to satisfy the water resources requirements of the sub basin. The data was then used in the Swedish HBV rainfall-runoff model which is a semi distributed conceptual model to estimate catchment parameters, forecast the values for some years with missing data and compare results from the statistical and graphical methods. Some future climate scenarios were also simulated in the model and the results were also in line with other previous studies carried out in the bigger catchment within which the Mefou is a sub catchment. The difficulties in making hydrological and meteorological estimates in catchments with little or no data are highlighted by this project and recommendations are made towards facilitating the carrying out of satisfactory water resources studies in other sub catchments with similar limitations.

ACKNOWLEDGEMENTS

First of all I thank Professor Mat Fonteh of the University of Dschang, Cameroon and Global Water Partnership Cameroon for accepting my proposal to carry out the thesis project in association with Global Water Partnership and providing me with the direction and possibility of obtaining the data in Cameroon used in this project.

I also extend my appreciation to Mr. Banseka Hycinth of Global Water Partnership Cameroon for helping to provide the logistics possibility for the collection of data in Cameroon.

Appreciated also is the help given to me by Dr. Ntonga acting director of the National Hydrology research center of Cameroon for making it possible for me to access the data bank of the center and giving me advice on the type of data to collect.

My appreciation further goes to Mr. Ayissi of the National Hydrology research center of Cameroon for researching the data bank of the center and providing me with the available data possible.

Associate Professor Rolf Larsson who was my supervisor was very patient with me and gave me valuable advice and direction throughout the writing of this report.

Finally, I cannot forget my entire family and especially my wife and my brother Emmanuel Kefun who supported me throughout my stay in Sweden.

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LIST OF ABBREVIATIONS AND TITLES

CAMWATER: Cameroon Water Authority.

CRH: Centre de recherches hydrologiques (National Hydrology Research Center).

GWP: Global Water Partnership.

HBV: Hydrologiska Byråns Vattenbalans-avdelning (Hydrological Bureau Water balance-section).

IAHS: International Association of Hydrological Sciences.

IHMS: Integrated Hydrological Modelling System.

IRD: Institut de Recherches pour le Développement (Institute for Research and Development).

MINPLANDER: Ministry of Plan and Regional Development.

MOPEX: Model Parameterization Estimation Experiment.

PUB: Prediction in unguaged basin.

SMHI: Swedish meteorological and hydrological institute.

SANGME: Sangmelima

WHO: World Health Organisation.

YDE: Yaoundé.

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1. INTRODUCTION

1.1 General Background

The interaction between precipitation and land-surface hydrology is extremely important in relation to long term water resource planning. Integrated water resources management will be greatly facilitated by having as accurate as possible information on the amount of water resources available within different catchments. However, these potentials are not easily realized even in countries with extensive networks of gauging stations because of the lack of adequate site specific data or studies to enable design and management of water resources infrastructures. There is therefore the need to develop methods which can be used to estimate these resources. Analytical methods and simple conceptual rainfall-runoff models, which simulate the interaction between rainfall and runoff, using the water balance theory, are the most commonly used tools to estimate the potential volumes of water available within a basin. Within the framework of developing and outlining the principles of integrated water resources management in Cameroon, Global Water Partnership (GWP) Cameroon, selected the Mefou sub-basin as a pilot site on which studies will be carried out to enable the elaboration of these principles. It is in this context that it was necessary to obtain some estimation of the water resources potential of the sub-basin. In hydrological terms the Mefou sub basin is a catchment with scarce data. However, some hydro-climatic data exist for ten stations within the same climate zone as the sub basin which can be used as replacements. Data was obtained from the data bank of the National hydrology research centre (*Centre de Recherches hydrologiques*, CRH) of Cameroon.

1.2 Presentation of the Study Area

The Larger Picture

Cameroon is located in the tropics at the junction between West and Central Africa, and has a land surface area of about 475000 sq km and a population of about 18 million people according to the recent census figures from the Ministry of Planning and Regional Development (*MINPLANDER, 2006*). Four distinct geographical and topographical regions can be allocated to Cameroon. The southern region extends from the coast eastward to the Middle Congo Basin between the southern frontier and the Sanaga River. It consists of coastal plains and a dense equatorial forest plateau at an average elevation of about 300 m to 700 m above sea level. The central region extends from the Sanaga River northward to the Benue River and includes the

Adamawa Plateau; at elevations above 750 m to 1400 m. In this area the forest changes to savannah and is a transition area to the semi arid region of the Lake Chad basin. The northern region is essentially a vast savannah plain that slopes down to the Chad basin. The western part of the country is dominated by Savannah Mountains with peaks above 3000 m in the North West and forested mountains up to 4000 m in the South West where the highest peak in West Africa is located. A map of Cameroon showing the different hydrological basins is given in *Figure 1.1*.

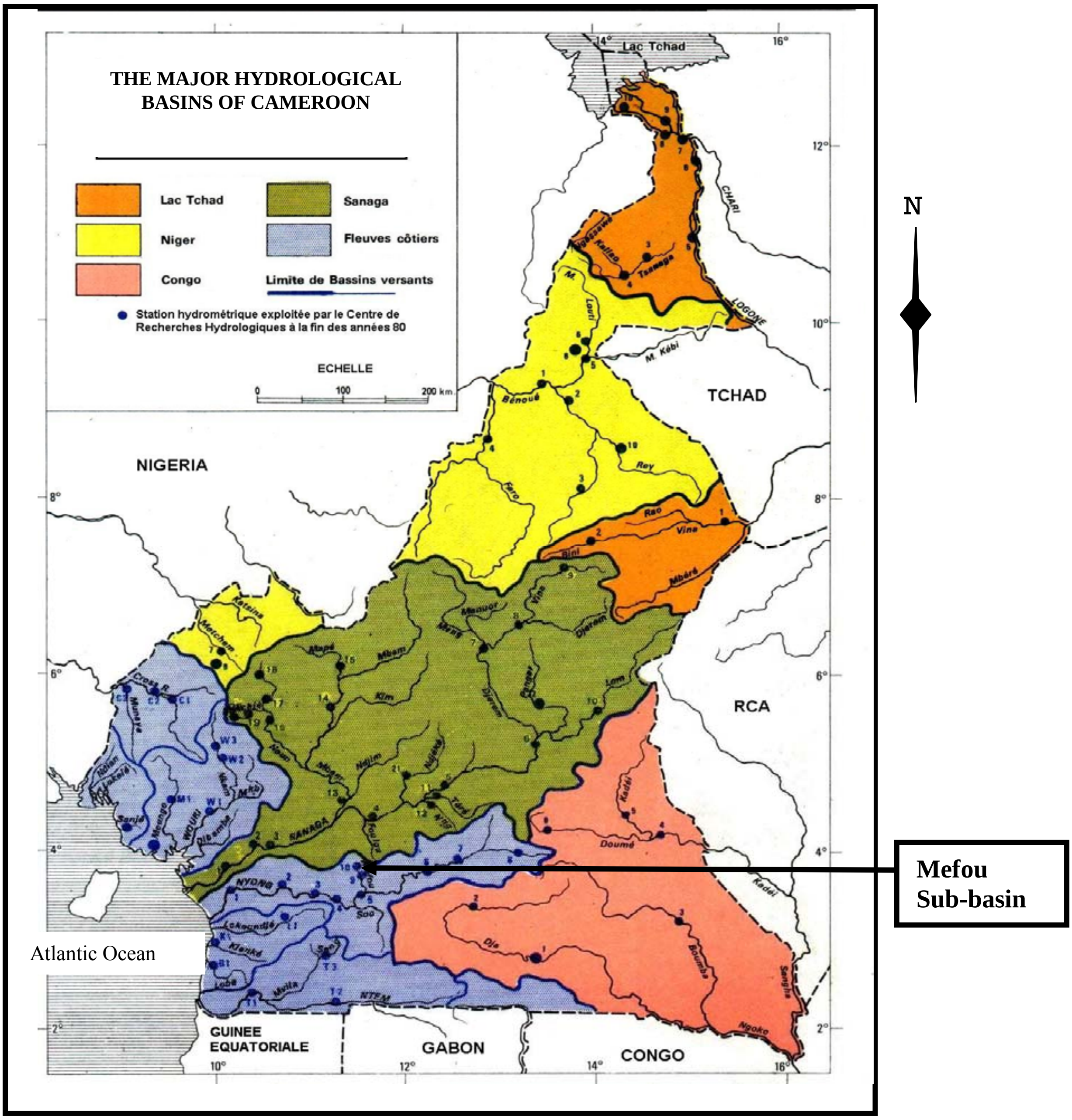

Figure 1.1: Hydrology basins of Cameroon (*source: GWP Cameroon / CRH, 2006, modified)*.

There are three main river systems in Cameroon, the Sanaga, the Niger and the Congo. The Mefou sub basin is part of the Nyong river basin located in the transition region between the southern dense equatorial forest and the central forest belt of Cameroon. The Nyong is a very important river ranking just behind the big three.

There are two distinct seasons and climatic areas with some regional variations. The climate is tropical and humid in the south and drier to the North. There are the wet and dry seasons which in general fall between the months of May to October and November to April respectively. In the southern coastal region, the average annual rainfall is about 1400 mm and maximum precipitation often measures more than 1900 mm a year (*Info guide, 2007)*. The mean temperature ranges from 24°C to 27°C. While in the southern equatorial forest region there are two distinct dry seasons from December to March and July to September with similar rainfall and temperature as the coastal region. The south western coastal region has average rainfall above 2000 mm topping to about 10000 mm in the Debundscha area at the foot of Mount Cameroon. The mean temperature ranges from 21°C to 26°C. In the extreme northern part of the country average annual rainfall measures about 400 mm to 900 mm with mean temperatures of about 30^{o}C to 32^{o}C. While in the North Western region average annual rainfall is about 1100 mm and the mean temperature ranges from 21°C to 25°C (*maps of the world, 2007*).

The Mefou Sub- Basin

Located in the Center and South provinces of Cameroon, the Mefou sub basin lies between the southern dense equatorial rainforest and the central forest region within latitudes $3^{o}33'$ to $3^{o}59'$ North and longitudes 11^{o} 22' to $11^{o}39'$ East. The surface area limits of the Mefou sub basin is shown in *Figure 1.2*. It has an estimated surface area of about 809 km^2 entirely on a plateau with rolling mountains at altitudes ranging from 700 m to 800 m reaching maximum peaks at occasional massifs of about 1300 m (*GWP documents, 2006*).

The predominant vegetation is rainforest, especially to the plateau's south. To the north, savannah takes over from the forests. Several small streams are found within the sub-basin and some drain into the Mefou and eventually into the Nyong River and the Congo River basin.

The climate is of the equatorial type with four distinct seasons including two dry seasons from December to March and from July to August and two rainy seasons from March to July and September to October. The estimated average annual rainfall is about 1600 mm with a recorded maximum just above 2000 mm and minimum about 1100 mm, average daily temperature is about 25°C and annual potential evapotranspiration is estimated to be between 1200 mm and 1300 mm.

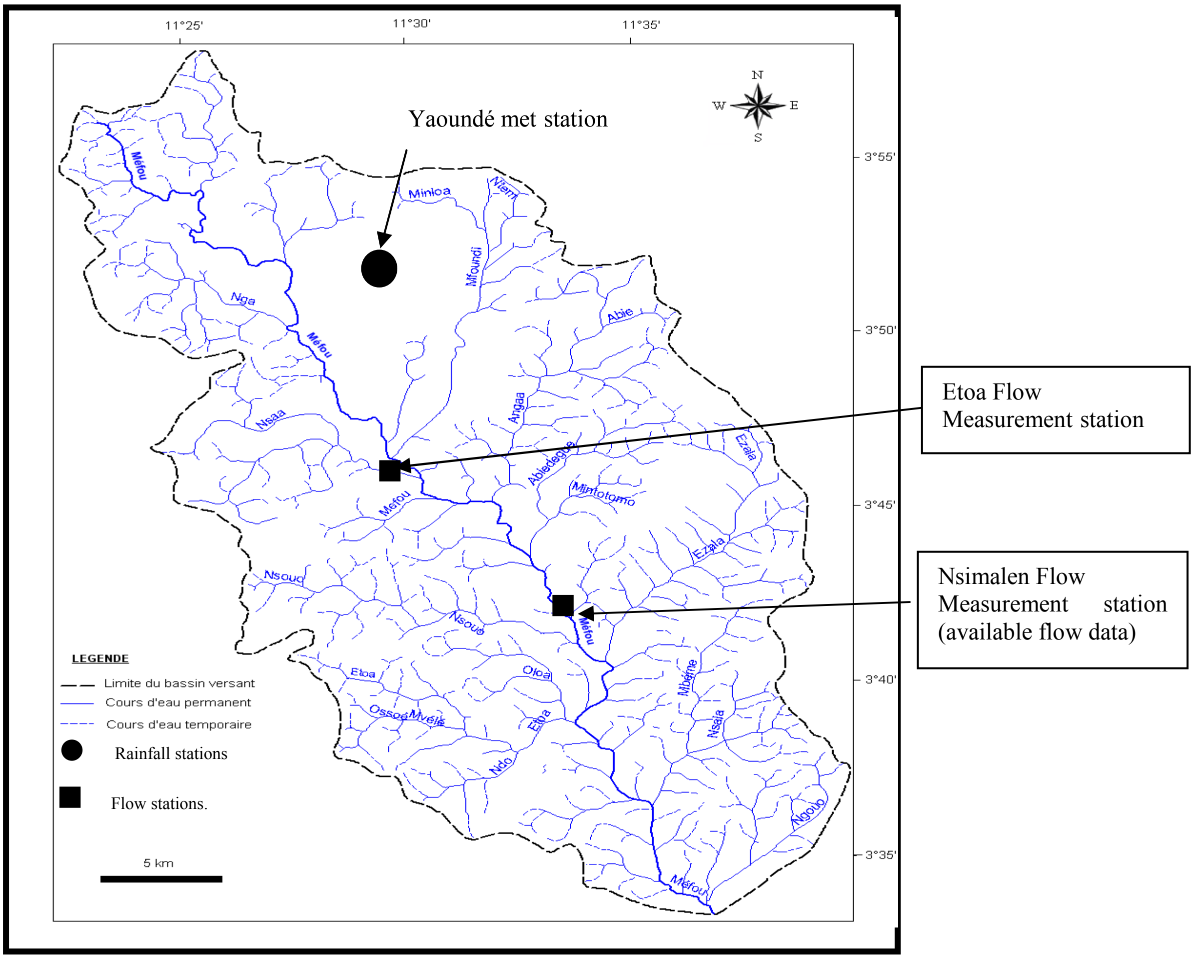

Figure 1.2: Limits of the Mefou sub-basin. (Source; *GWP Cameroon documents, 2006 modified*)

1.3 Objectives

The overall objective of this thesis project is to contribute to the development of methods for estimating the water resource potentials of sub catchments in Cameroon with scarce hydrological and meteorological data by the evaluation of available data and use of rainfall runoff models. The Mefou sub basin will be used as a case study. The focus will be on seasonal hydrological patterns and the potential runoff.

1.4 Method

The project objectives will be achieved by;

i. The collection on site of available hydrological and meteorological data for the Mefou sub basin from the National hydrological research center of Cameroon *(CRH)*), Global Water

Partnership (GWP) Cameroon, the Ministry of Water and Energy and other organisations with useful meteorology and hydrology data.

ii. Analysis of the available data using statistical and graphical methods, and information from previous studies of similar catchments in Cameroon.

iii. Simulation and calibration of a conceptual rainfall-runoff model to create a model of the rainfall and runoff pattern of the Mefou sub basin. The model will be used to estimate the hydrological parameters and characteristics of the sub basin and to estimate the water potentials of the sub basin.

iv. Estimate values for more years and prolong the available observed rainfall and runoff data.

v. Simulation of the impact of different predicted hydrological and climatic scenarios on the runoff.

1.5 Scope of the Water Resources requirements of the Mefou Sub Basin

The human aspect of the basin includes a population of over 1 500 000 inhabitants with 85% in urban areas, including part of the city of Yaoundé and 15% in semi-urban and rural areas. Some agriculture mainly subsistence farming of food crops, is practiced within the rural areas of the sub basin.

There are a few small lakes within the sub basin especially in the city of Yaoundé. However, these lakes constitute a very small proportion of the catchment area and do not have any major influence on the sub basin hydrology. It has been estimated by Global Water Partnership Cameroon(GWP) that the future water demand of the Mefou Sub basin will reach 1 600 million cubic meters per year (about 4.5 million cubic meters per day), in the next twenty years, while presently only about 300 million cubic meters is being supplied from surface and ground water sources (GWP, 2006). Clearly there will be a deficit in supply relative to the water requirements within the sub basin. This requirement can be divided into different sectors as follows, domestic demand 46%, industrial 19% and agricultural 35% (WHO, 2000). The capital of Cameroon which is entirely located in the sub basin has several industries such as the brewery and timber industries which require large quantities of water. With a population of over 1.5 million inhabitants 85% of which is urban, and a population growth rate of over 6% (*UN Habitat, 2006*) the demand of water for domestic, industrial, leisure and agricultural uses is substantial within the sub basin. A drinking water treatment plant with a capacity of about 55000 cubic meters per day was constructed on the Mefou River between 1976 and 1986. Since the daily water consumption is predicted to reach about 4.5 million cubic meters per day the situation of water supply will clearly become more serious.

2.0 LITERATURE REVIEW

The literature review will focus on the description of catchment hydrology, evaluation of catchments with scarce data and rainfall-runoff modeling of such catchment. Most of the literature was obtained from the Lund University electronic Library (ELIN), the web and hydrology text books.

2.1 Catchment Water balance

A catchment is the total geographical area contributing to runoff from a given precipitation as shown in *Figure 2.1*. It may contain flat land, slopes, forests, wetlands, lakes and rivers. Runoff as a function of time can be estimated by the evaluation of the catchment water balance over a long period or with simple as well as sophisticated models.

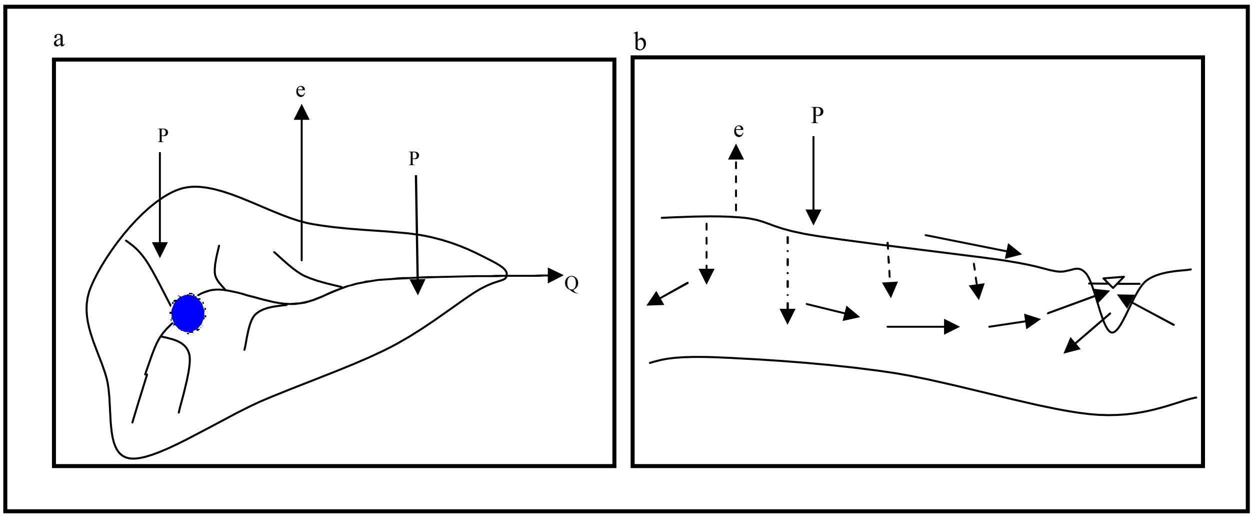

Figure 2.1: Simplified representations of catchment water balance (Source; *Bengtsson, 1997*)

According to *Bengtsson* (*1997*) in order to describe the runoff process properly, all the physical and hydrological conditions of the catchment have to be described fully using all the related scientific theories and formulae. However, the hydrological processes in a catchment of area (A) in m^2 are represented by the simple water balance theory given in *equation (2.1)*.

$$\frac{dS}{dt} = p - e - q \tag{2.1}$$

Where;

q = specific runoff = Q/A (mm/day)

Q = runoff at the outlet in m^3/s,

p = precipitation intensity in mm/day,

e = rate of evaporation in mm/day
t = time in days
S = water storage in the area expressed as volume/catchment area in mm.

Over a long period, storage change is small and runoff can be estimated as p – e. When runoff, precipitation and storages have been measured, the evaporation can also be estimated over shorter time scales or if the evaporation has been measured then the runoff volume can be estimated from the water balance theory. The specific runoff is a function of the storage level and can be defined as q= f (h). This relationship changes with water level (h) changes and seasonal variations in catchment characteristics (*Bengtsson, 1997*). The water balance equation is modified by replacing S with 'h' to give;

$$\frac{dh}{dt} = p - e - f(h) \tag{2.2}$$

This relationship represents a saturated catchment or catchment at field capacity with fast response and does not consider any of the physical variations that exist in reality. However, water storage and runoff changes with time and the relation are represented by *equation (2.3).*

$$q = f(h) = \frac{h}{T} \tag{2.3}$$

Here T is the catchment time constant usually given as 1/T implying that the smaller the T, the faster the catchment response to precipitation and the faster the runoff increases. The time constant depends on catchment size, topography and other catchment physical characteristics. The water balance relationship can be further modified by substituting p-e with the effective precipitation (P) and f (h) with h/T and the equation written as,

$$\frac{dh}{dt} = p - \frac{h}{T} \tag{2.4}$$

Analytical solutions for specific runoff (q) and water level (h) can be found from *equation (2.4).*

2.2 Hydrological estimates and predictions in catchments with limited or no data

Many rivers having important potentials for water resources development are located in catchments with very little or no data. With the growing demand on water resources throughout the world there is an increasing need to develop new approaches and methods for assessment of the water resources potentials of these sources.

The most difficult problem is to predict runoff from these catchments with scarce data since most tools for assessment of water potentials require adequate data from hydrometric and meteorological measurements (*Goswami et al, 2006*). Usually, hydrological and meteorological estimates have to be made using regionalisation techniques which assumes climatological and landscape similarities between catchments. This process is essentially about defining these similarities (*Mosley, 1981*). Even though geographic proximity is a base for regionalisation, it is insufficient on its own without considering other catchment characteristics.

Many regionalisation projects fail because of the lack of high quality data, the lack of theoretical framework for defining hydrological homogeneity, uncertainties in representation of catchment response in rainfall-runoff modelling, over simplification of the rainfall runoff processes with linear regression relationships and use of over parameterized complex models which do not have physical interpretation.

There are currently two major international projects devoted to the problems of unguaged catchments. The International Association of Hydrological sciences (IAHS), has launched a decade project for prediction in unguaged catchments (PUB) aimed at improving the possibilities of estimating runoff from catchments with limited data or no data. While the international Model Parameterization Estimation Experiment (MOPEX) started a project in 1996 aimed at the estimation of parameters of rainfall-runoff models in the absence of calibration data (*Boughton and Chiew, 2006*).

2.3 Rainfall-Runoff Models

Models are invaluable tools for resource management and distribution. Catchment modeling requires specialist input and approaches. There are several models available that can be applied to integrated water resources management of a sub basin or a catchment. They range from simple and conceptual water balance models to physically based models. Model development is usually laborious, expensive, time consuming, and often complicated depending on the complexity and depth of results expected. Models can be classified into three general classes; Simple linear models, conceptual models and physical models.

Conceptual Rainfall-Runoff model

A conceptual rainfall-runoff model can be used to analyze precipitation and runoff data for a given basin to acquire information on water movement in that basin. The focus here is on modeling with a typical conceptual model such as the Swedish HBV model (*Bergstrom, 1976, 1992*). A conceptual rainfall-runoff model uses simple continuity equations and other supplementary relationships to evaluate some of the storages in the hydrological cycle.

The HBV Model

The HBV model is a partially distributed conceptual model that combines numerical descriptions of different hydrological processes in a catchment (*Bergstrom, 1976, 1992*). The HBV model was originally developed for use in hydropower operations in Sweden and is now being used all over the world to solve resource problems over a broad range and as a standard forecasting tool to calibrate small and unregulated rivers (*HBV manual, 2006*).

In spite of its simplicity, the performance is excellent and it can be used in filling missing data, simulation of stream flow in unguaged Rivers and catchments, computation of design flood and water quality studies(*HBV manual, 2006*). The model structure is flexible and allows for sub divisions into climate zones, land use, hydro meteorological network and other features.

It consists of sub routines of snow accumulation and melt, soil moisture routine, runoff generation routine and a simple routing procedure. The model can be run separately for several sub basins and the results from each added. For a catchment with different elevation range a sub division into elevation zones can be made for the snow and soil water routines only. Different vegetation zones can also be further sub divided. In the catchment of this study there is no snow fall so only the soil routine, runoff routine and linear routing are considered.

Soil water routine

In the soil moisture routine all the soil water located between the soil surface and the groundwater level is treated as if it were in a box. Applying the water balance equation we have,

$$\frac{dh_{soil}}{dt} = p - e - f - q_{sr} \tag{2.5}$$

Where,

h_{soil} = amount of water in soil water storage (mm)

p = intensity of real precipitation (mm).
e = rate of evaporation (mm/day),
f = groundwater generation which is modeled as rate of filling of simple or double reservoir for which q = f (h), and
q_{sr} = surface runoff (mm).

The rate of evaporation depends on potential evaporation (pe) and soil water content and similarly the rate of percolation depends on rain intensity and soil water content. This implies that the rate of contribution to runoff depends on the moisture in the soil. The soil moisture routine in the *Swedish HBV-model* assumes a statistical distribution of storage capacities in a basin (*Bergström, 1976*). This is the main part of the model controlling runoff generation. Different points in a catchment are represented by similar boxes with different sizes and the runoff contribution from each point depends on when the point reaches its field capacity, which is when the box is full. Any surplus water then percolates to groundwater. The runoff gets bigger as the different boxes get full and also contribute to the runoff. The biggest runoff is attained when all the boxes are full and contribute to the runoff volume. This routine is described by *equation (2.6).*

$$f = p\left(\frac{h}{FC}\right)^{b} \tag{2.6}$$

The routine is based on the three parameters, h, FC and b. Both h represented as LP in the model and FC are related to the wilting point taken as the datum point or zero point and b or BETA in the model is a coefficient of the model which controls the contribution to the response (runoff) function with any increase in soil moisture for every millimeter of precipitation in the basin. Also, LP in the model is average soil water content for the whole area above which the potential evapotranspiration is reached and FC is the maximum value of h. LP is usually expressed as a fraction of FC (*SMHI, 2006*). Even though FC can be said to be conceptually equal to the field capacity of the soil, the value used as FC in modeling may be different from the real value (*Bengtsson, 1997*). This relationship is illustrated in *Figure 2.2*.

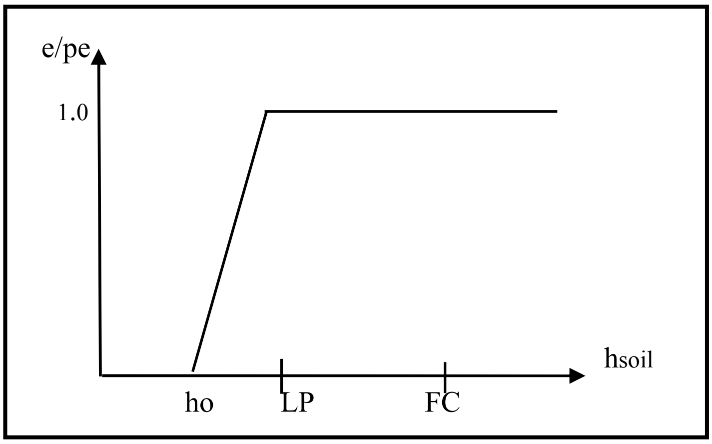

Figure 2.2: Approximate relation between evaporation and soil moisture (Source; IHMS, 2006)

Figure 2.2 shows that the ratio of real evaporation to potential evaporation (e/pe) depends on the relative soil moisture, which is the ratio of soil water content to field capacity (h/FC). In most soils the relationship is linear for soil water h < LP, the soil water content above which e = pe. The initial soil moisture content is ho.

Runoff routine

Surface runoff in a catchment may be from fast Hortonian runoff or from slow base flow or saturated soil runoff. The runoff is the difference between the rainfall intensity and the vertical hydraulic conductivity of the saturated soil. In the HBV model the runoff generation is the response when excess water from the soil moisture zone is transformed to runoff. The model also includes the effect of direct precipitation and evaporation from lakes, rivers and other wet areas (*SMHI, 2006*). Fast surface flow is represented by an upper non linear reservoir and slow base flow is represented by a lower linear reservoir. The rate of percolation, (perc), from groundwater box to deep groundwater-box can be constant or may vary depending on the amount of stored water and the runoff is the sum of both the fast runoff and the deep runoff. The three parts for soil water, groundwater and deep groundwater is supplemented with interception and routing model describing how the runoff moves between catchments.

2.4 Calibration and Parameter estimation in Rainfall-Runoff models

There are four main steps in the modeling process, which include; setting up of the model, calibration of the model, validation of the model and exploitation of the model in actual solutions. For a Rainfall- runoff model to be useful it has to be calibrated and the parameters estimated using available data series. *Hreiche et al,* (*2002*) showed that conceptual rainfall-runoff models can be applied to watersheds with scarce data by developing relationships between the model parameters and watershed characteristics. Model calibration remains the most critical and time-consuming task in the modelling process. According to *Boughton,* (*2006*) some of the problems encountered when carrying out rainfall runoff model calibration include;

- Inconsistent data in which runoff exceeds rainfall for sufficient periods of time indicating that either the rainfall or the runoff data has errors.
-Data in which the rainfall shows evidence of systematic bias, that is the rainfall may be either too big or too small and not consistent with the runoff, resulting in calibrated parameter values that are out of physically possible ranges.

-Data with random errors between rainfall and runoff such that the resulting correlation between calculated and actual monthly runoff is sufficiently poor and there is no confidence in the calibration results. Other problems involves malpractice, careless handling of input data, inadequate model set-up, insufficient calibration and validation and use of model outside of its scope. The process of calibration is a time consuming trial and error exercise in which model and catchment parameters are varied to obtain output results that best represent the catchment. The best fit to observed data is obtained by comparing the error function r^2 (*Saelthurn, 1995*) or physically looking at the resulting hydrographs to ensure they match the observed runoff hydrographs.

Error functions

The error functions are used to support interpretation of the results in single simulations. However, the best judgment of the parameter fit is often obtained by visual inspection of the graphical display of the simulations. The simulated water balance is also a very important guidance in model calibration, as are duration curves and frequency analysis of observed and simulated data. Duration curve and frequency analysis is not usually presented by the model software, but can easily be produced by spreadsheet programs using the model output. The r^2 coefficient represented in *equation (2.7)* indicates the correlation between observed and simulated flows and gives a measure of the correctness of the model (*Saelthurn, 1995*).

$$r^2 = 1 - \left[\frac{\sum (Q_{obs} - Q_{sim})^2}{\sum (Q_{obs} - Q_{obsaverage})^2} \right] \qquad (2.7)$$

Where,

Q_{obs} is the observed runoffs in m^3/s.

Q_{sim} is the simulated runoff in m^3/s.

$Q_{obsaverage}$ is the average of the observed runoff values in m^3/s.

As can be seen from *equation (2.7)*, the r^2 value is less than one. A value as high as possible is preferred and a perfect fit would give an r^2 value of 1. If the value is too low the model is incorrect and for some cases the input data may be wrong (negative r^2 value) or the model may not be suitable for application in that particular catchment. In the HBV model the error function is a compromise between the r^2 described above and the relative volume error RD (*SMHI, 2006*). RV is defined in *Equation (2.8).*

$$RV = r^2 - w\,|RD| \qquad (2.8)$$

In practice the use of r^2 alone often leads to volume error. Best results are for ‘w close to 0.1.

Use of rainfall-runoff models in Water resources management

Mathematical models have been applied for decades to obtain solutions for problems in many domains of water management (*Scholten et al, 2007*). Integrated Water Resources Management deals with complex problems involving technological, environmental, economical and societal aspects. Resource managers can use models to develop a conceptual understanding of complex natural systems, predict outcomes of high risk and high cost environmental investments, and set their priorities properly. For a model to be useful in water planning and management it should be applicable in spite of limited availability of data, and able to produce results that are acceptable in relation to observed conditions (*Olsson and Andersson, 2006).* In spite of the usefulness of models, the use of information derived from them in water resource management may be linked to two scientific dilemmas (*Olsson and Andersson, 2006*). The results from modelling are subjective and when used to predict impacts of various scenarios, the results cannot be validated until long after decisions based on them have been carried out (*Irwin, 1995; Darier et al., 1999 cited by Olsson and Andersson, 2006*).

2.5 Data requirements in hydrological estimates

The type of data used in hydrological evaluations are time series of precipitation, temperature, stream flow, vapour pressure, wind speed and estimates of long term monthly averages of potential evaporation and evapotranspiration. Unfortunately, data is often incomplete and missing or of poor quality leading sometimes to over simplification of processes. However, statistical methods of data distribution and analysis, as well as models with regionalization capabilities can be used in filling missing data and parameters between nearby homogenous catchments. In general it is estimated that in the tropics a minimum of 20 years of rainfall data is necessary to obtain any meaningful representative monthly averages, while 10 years is usually enough for other climate parameters (*Suchel, 1987 cited by Sighomnou, 2004*).

It is commonly said that, good quality data input to any water evaluation approach or any modern water balance model will give good quality results, however poor quality data will give poor quality results. The results from rainfall-runoff modelling are more dependent on the quality of the input data rather than on the model itself (*Boughton, 2006*). Conceptual rainfall-runoff models are widely used tools in hydrology because the required input data are readily available for most applications unlike other more complex, physically-based, distributed models (*Abbott et al, 1986 cited by Uhlenbrook et al, 1999*).

When applying models under the circumstances of catchments with little available data such as the Mefou sub basin the identification of parameters is always a serious problem to overcome. When confined to the above data sets, models need to be kept as simple as possible in their process representation. Too many parameters will easily lead to “identifiability problems” when estimating parameter values and questionable physical characteristics may be attributed to the catchment (*Evans and Jakeman, 1998*). Data requirements vary between models and for a model to be useful, its data requirements must be readily available (*Taylor et al, 2006*).

3.0 ANALYSIS OF AVAILABLE DATA

According to *Sighomnou, 2004*, the hydrometric and meteorological data of Cameroon is grouped into two principal data banks, which are at the Institut de Recherche pour le Développement (IRD) for 1947 to 1977 and the National hydrology research institute (Centre de Recherches Hydrologiques, CRH) from 1947 to 1987.

3.1 Presentation of Available Data

The following are the different types of data and periods of measurements available for the Mefou sub basin;

i. Daily runoff in m^3/s measured at the Nsimalen station located at about the middle of the sub basin. The available data is from 1976 to 1977 with a break and then continue from 1984 to 1987. A total of five years.

ii. Daily precipitation in mm/day measured at different stations within the basin, as well as at stations outside of the basin and downstream. The data are available for different periods at different stations ranging from 1975 to 1990. The longest continuous period is 13 years from 1975 to 1987 for the Sangmelima station and the smallest being 3 years for the Bertoua station.

iii. Daily temperature in ^oC measured at three different stations Yaoundé, Sangmelima, and Nanga Eboko from 1977 to 1983. Average monthly temperature data are available for other stations calculated from measurements made over a very long period from 1955 to 2002.

iv. Average monthly potential evapotranspiration in mm/day from 1977 to 1983 is available for the Yaoundé and Edea stations. The values are calculated by a method proposed by *L. Turc, 1961* and the *Penman method* respectively using daily evaporation measurements obtained with the PICHE Evaporimeter.

Hydrological and climate data collection in Cameroon after 1990 has been irregular and sporadic, usually limited only to the realization of particular studies or by individual organizations with particular interest. The meteorological data after 1987 is mainly available at the National meteorology center and access to them is limited with some financial cost attached. Therefore it was not possible to obtain any coherent data after 1987. A summary of the different types and periods of data available at different meteorological stations that can be used in the meteorological and hydrological estimates are given in *Appendix 1*. In spite of the inherent uncertainties in the data, the aim here is to investigate of suitable methods that can be applied using the scarce data for the estimation and evaluation of seasonal patterns and long term volumes.

3.2 Analysis of Rainfall Data

Rainfall data was collected from the CRH data bank for ten meteorological stations within the same hydro- climatic zone as the Mefou sub-basin. The period of data was selected for each station taking into consideration the availability of continuous unbroken observations in order to ensure statistic coherence to any results as *advised by Dr. Ntonga of CRH*. The periods in general range from 1975 to 1990 varying for the different stations. The availability of data from different stations within the same hydro-climatic zone is important to compare average monthly rainfalls over the same period, to evaluate the quality of the observations and also to carry out data regionalization if necessary. *Figure 3.1* shows the location of the different meteorological stations from which the available rainfall and runoff data were obtained.

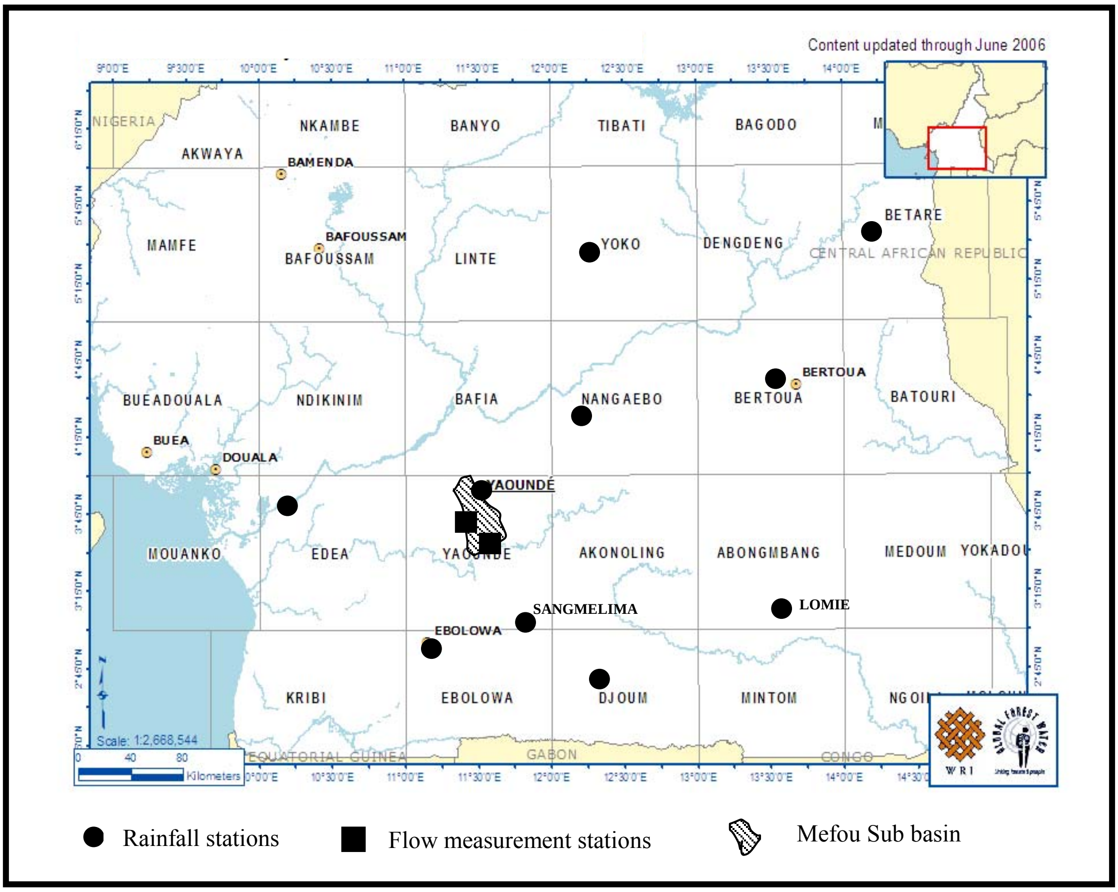

Figure 3.1: Meteorological stations where data is obtained (source of map; *(GWF), 2006 modified***)**

On closer examination of the stations details in *Appendix 1*, it is seen that the Nanga Eboko, Yoko and Betare Oya stations are located too high above the 4th parallel at 4°39′, 5°32′ and 5°36′

respectively, while the Bertoua and Betare Oya stations are too far to the East of the 12th parallel at 13°41′ and 14°05′ respectively and the Edea station is too far to the South West at 10°08′.

3.2.1 Selection of rainfall stations

The general annual average rainfall distribution of Cameroon is shown in *Figure 3.2*. The Mefou sub basin is located within the zone with average annual precipitation between 1500 mm and 1600 mm.

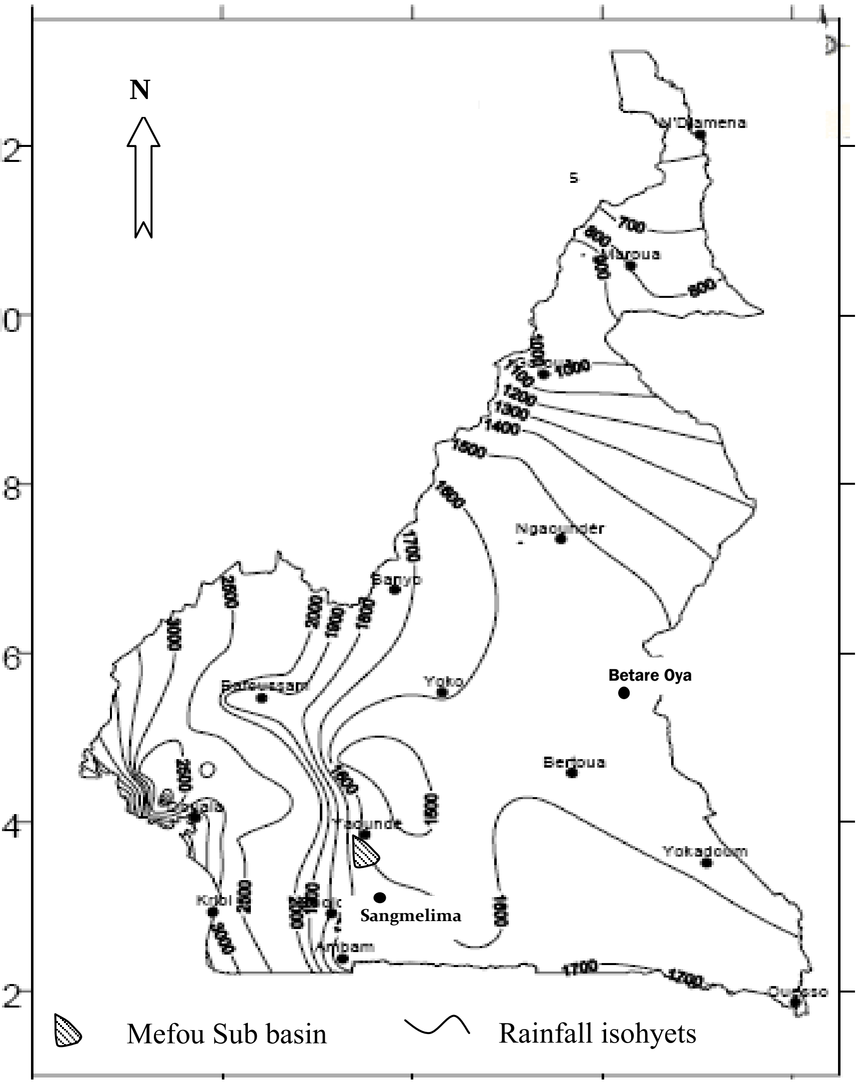

Figure 3.2: Precipitation isohyets of Cameroon. Annual rainfall in mm (source; *Sighomnou, 2004*)

As stated above, rainfall data is available for ten climate stations but not all of them are located within the Mefou sub basin. In fact only the Yaoundé meteorological station is located within the sub basin and has rainfall data from 1976 to 1982 which is seven years, while Sangmelima the station with the longest period of rainfall observations from 1975 to 1987(13 years) also corresponding to the period with available runoff data is located at about 100 km to the south of the sub basin. Another station with the most recent rainfall data series from 1981 to 1990 (10 years) that can be used for the sub basin is located at Betare Oya at about 350 km to the North East of the basin. Evaluation of the available data at the three stations for the same period showed that the annual averages range from about 1500 mm for Betare Oya, 1550 mm for Yaoundé, to 1600 mm for Sangmelima. All of these stations are located within the same climate zone with average annual rainfall between 1500 mm and 1600 mm, similar to the meteorology of the Mefou sub basin. The periods of rainfall observations at the different rainfall stations are presented as a time chart in *Table 1*.

Table 1: Periods of available rainfall data at the ten different meteorological stations

Station	**1975**	**1976**	**1977**	**1978**	**1979**	**1980**	**1981**	**1982**	**1983**	**1984**	**1985**	**1986**	**1987**	**1988**	**1989**	**1990**
Bertoua	—	—	—	—												
Nanga Eboko	—	—	—	—												
Yoko	—	—	—	—	—											
Edea	—	—	—	—	—											
Lomie	—	—	—	—	—	—										
Sangmelima	━	━	━	━	━	━	━	━	━	━	━	━	━			
Djoum		—	—	—	—	—										
Yaoundé		━	━	━	━	━	━	━								
Ebolowa			—	—	—	—										
Betare Oya							━	━	━	━	━	━	━	━	━	━

For a satisfactory calibration and validation of a rainfall-runoff model such as the HBV model which will be used in this project, data is required for at least 10 years to increase the possibility of including both wet and dry years. A comparative analysis of the available data series for Yaoundé and Sangmelima will be made to determine how the stations can be combined and used in the estimation of runoff volumes and in the model simulation.

Comparing the Yaoundé and Sangmelima stations data

The choice of stations for use in a hydrology estimates and model usually depends on the objectives of the estimates and type of model to be used. The monthly and seasonal variations are considered here as important for the sub basin runoff response.

Annual rainfall

When the annual rainfall for both stations are plotted as shown in *Figure 3.3* there is close similarity in the annual rainfall pattern for the period 1977 to 1982. However, there is a marked deviation in the 1976 record with the Sangmelima rainfall up to 668 mm higher than that of Yaoundé. Similarly, the 1984 and 1985 data have high measured rainfall values for Sangmelima. Unfortunately there is no corresponding data for the Yaoundé station for 1984 and 1985 for any comparison to be made. These years seem to be very wet years for Sangmelima.

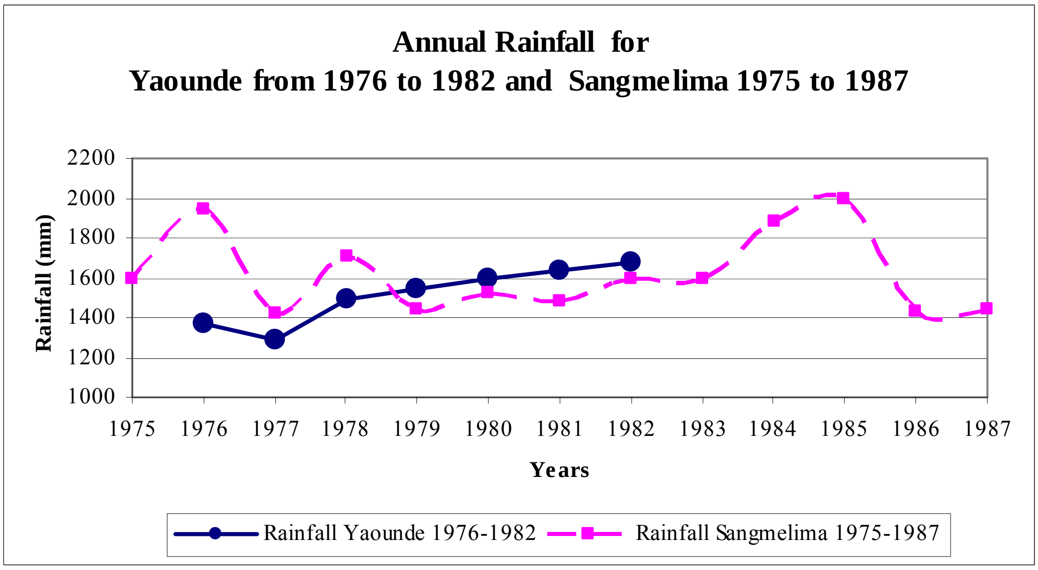

Figure 3.3: Annual rainfall for Yaoundé 1976 to 1982 and Sangmelima for 1975 to 1987

Using the annual rainfall values given in *Appendix 2,* a partial annual rainfall statistics for Yaoundé and Sangmelima stations for the period 1976 to 1982 are shown in *Table 2.*

Table 2: Annual Rainfall statistics for Yaoundé and Sangmelima from 1976 to 1982

STATION	Period	Max. Annual Rainfall(mm)	Min. Annual Rainfall(mm)	Median Annual Rainfall(mm)	Average Annual Rainfall(mm)
Yaoundé	1976 to 1982	1636	1292	1548	1500
Sangmelima	1976 to 1982	1998	1433	1508	1602

From the partial statistics analysis of the annual rainfalls for the same period for both stations a direct coefficient can be attributed as follows;

Average annual rainfall (Yaoundé) / Average annual rainfall (Sangmelima) for 1976 to 1982

= **1500/1602 = 0.94**

However looking at the graph of annual rainfall for both stations in *Figure 3.3* from 1976 to 1982 it is seen that the values are closer for six of the seven years within this period than the direct coefficient indicates. Analysis of the monthly rainfall will give a more detailed relationship in the rainfall variation at the two stations.

Monthly rainfall

The average monthly rainfalls for the period with available data are plotted for both Yaoundé and Sangmelima stations as illustrated in *Figure 3.4*. The curves show that, the average monthly rainfall variation for the Sangmelima station from 1976 to 1982 is similar to 1983 to 1987 and have similar pattern to that of Yaoundé from 1976 to 1982. All three periods show closely similar seasonal variations although the monthly averages are slightly higher for Sangmelima in general and especially for the period of 1983 to 1987. The average monthly rainfall for Yaoundé and Sangmelima are given in *Appendix 3*.

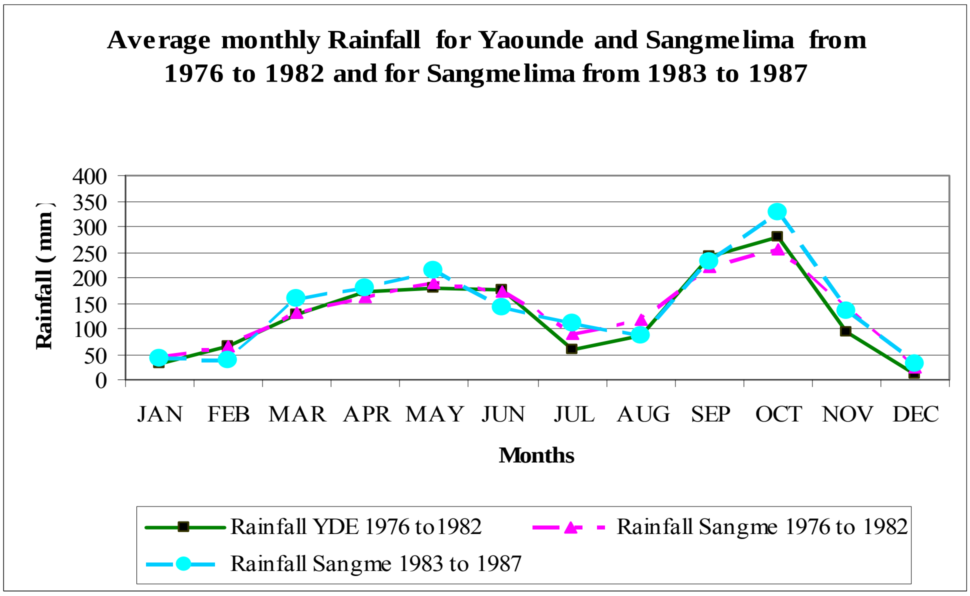

Figure 3.4: Monthly rainfalls Yaoundé and Sangmelima for 1976-1982 and 1983 to 1987

A scatter plot shown in *Figure 3.5* of monthly rainfall for both stations from 1976 to 1982 was made to determine a correlation formula for the rainfall measured at the two stations. The relationship will be used to estimate monthly values for Yaoundé using monthly rainfall of Sangmelima for 1983 to 1987.

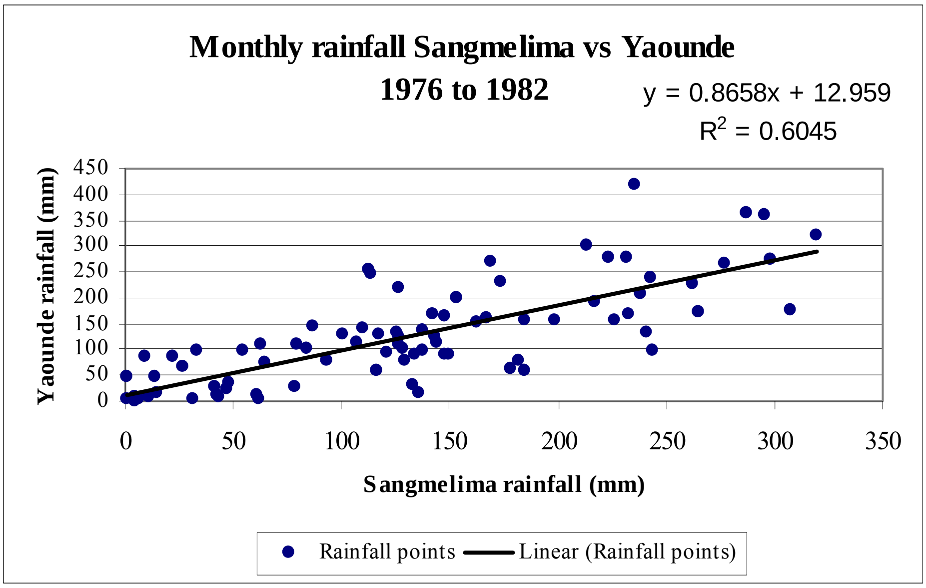

Figure 3.5: Scatter plot of monthly rainfall for Yaoundé and Sangmelima stations 1976 to 1982

The linear regression relationship for the monthly rainfall is given in *equation (3.1)*.

$$P_y = 0.87P_S + 12.96 \text{ (mm)} \qquad (3.1)$$

With coefficient of correlation $R^2 = 0.605 \rightarrow R = 0.78$

Where;

P_S = the monthly rainfall for Sangmelima in mm

P_Y = the monthly rainfall for Yaoundé in mm

Using *equation (3.1)* and the measured monthly rainfall data for Sangmelima from 1983 to 1987 monthly and annual rainfall are estimated for Yaoundé for the same period as shown in *Table 3*.

Table 3: Estimated monthly rainfall for Yaoundé 1983 to 1987

YAOUNDE: Estmated monthly rainfall 1983 to 1987												
Year	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Year**
1983	13.0	24.4	83.1	174.3	246.6	142.8	92.1	51.7	166.7	321.5	111.1	23.6	**1451.0**
1984	13.0	66.8	124.7	211.8	174.3	207.8	188.0	118.1	250.3	305.1	115.8	15.1	**1790.8**
1985	63.1	24.3	191.2	224.5	215.3	118.0	120.2	185.0	249.3	279.5	203.8	21.1	**1895.3**
1986	35.3	74.9	196.8	126.1	173.2	89.3	41.0	27.5	172.4	352.3	100.2	13.0	**1402.1**
1987	13.0	43.0	152.1	111.1	182.0	123.5	99.4	58.1	237.6	231.9	121.4	32.9	**1405.9**
Average	**27.5**	**46.7**	**149.6**	**169.6**	**198.3**	**136.3**	**108.1**	**88.1**	**215.3**	**298.1**	**130.5**	**21.2**	**1589.0**

From the estimated monthly data monthly averages over the whole period are also calculated for Yaoundé and plotted to compare with the observed monthly averages for 1976 to 1982. *Figure 3.6* shows that the average monthly rainfall pattern remains the same with some deviation for the months of February, June, July and October. However, the average over the months of June and July remain the same for both observed data 1976 to 1982 and estimated data 1983 to 1987. The rainfall for December 1983 is very high compared to the December rainfall values for other years. Similarly January 1985 and 1986 are higher than for other years. Putting together the annual rainfall over the whole period from 1976 to 1987 an average annual rainfall value of about 1537 mm is obtained for the Sub basin. This value is close to that obtained from other studies by the National hydrology research center (CRH). The average annual rainfall over an unspecified number of years was estimated by the *CRH* as 1597 mm.

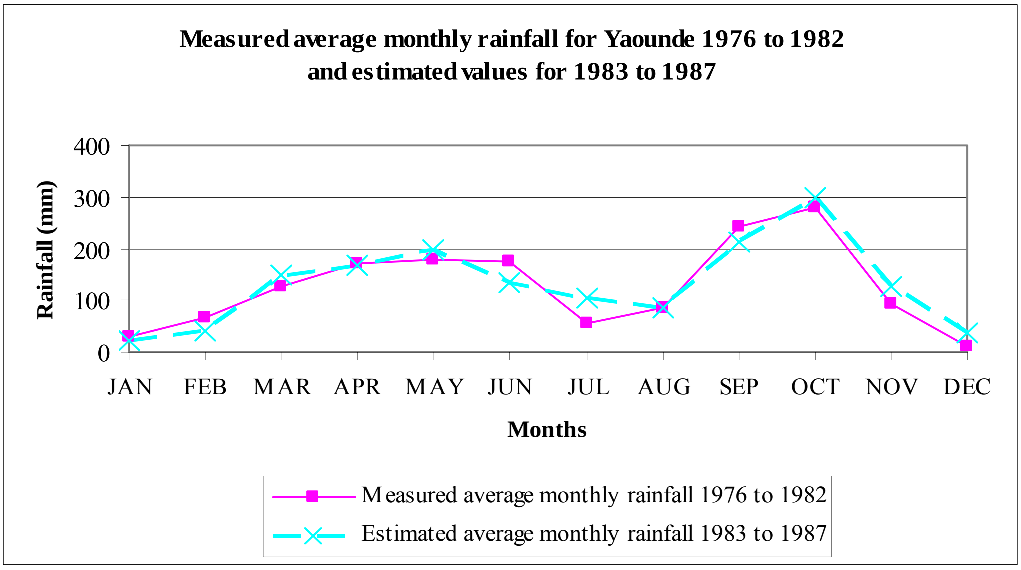

Figure 3.6: Average monthly rainfall for Yaoundé 1976 to 1982 and estimated 1983 to 1987

Since Sangmelima has the longest observation period (13 years) from 1975 to 1987, and the monthly rainfall pattern is similar to that of Yaoundé, the linear regression formula can be applied to the data, with adjustments made to the divergent months and used as replacement to that of Yaoundé station for the period 1983 to 1987 with missing data. This enables the monthly rainfall data to be extended to 12 years and to include all the years with available runoff data.

Daily rainfall

Analysis of the daily rainfall shows that over the period of 1976 to 1982 the Yaoundé station had an average of 138 wet days per year while Sangmelima had 139 wet days. A comparison was made for the actual number of rain days each month for both stations for the period of 1976 to

1982. The wet days were considered as days with rainfall measurements above 0.5 mm. It is seen that both stations have almost the same number of days per month with some minimum amount of precipitation although Sangmelima has slightly more days overall. Similarly average daily rainfall for both stations is almost the same for this period. If the rainfall for each station is distributed over the whole year the average daily rainfall is found to be 4.1 mm for Yaoundé and 4.3 mm for Sangmelima while the daily averages for the wet days are 9.9 and 10.3 respectively. The details of the daily rainfall and average daily values per rain day are given in *Table 4*. Individually and per month the daily rainfall are too varied for a simple linear regression relationship to be obtained between the two stations daily rainfall. However, a direct coefficient can be obtained from the overall daily average at both stations.

Table 4: Daily rainfall details for Yaoundé and Sangmelima from observed rainfall 1976 to 1982

	Average monthly		**Average number**		**Average daily**	
1976 -1982	**rainfall (mm)**		**of rain days**		**Rainfall(mm)per rain day**	
Month	**Yaoundé**	**Sangme**	**Yaoundé**	**Sangme**	**Yaoundé**	**Sangme**
January	18.5	9.4	4	3	4.6	3.1
February	67.1	65.3	5	7	13.4	9.3
March	125.9	129.5	12	11	10.5	11.8
April	170.7	160.4	15	14	11.4	11.5
May	179.1	190.2	18	16	10.0	11.9
June	175.0	173.1	15	12	11.7	14.4
July	57.8	88.3	6	8	9.6	11.0
August	85.2	116.0	10	9	8.5	12.9
September	241.5	219.9	21	19	11.5	11.6
October	279	255.7	22	22	12.7	11.6
November	93.9	137.0	8	14	11.7	9.8
December	6.2	20.8	2	4	3.1	5.2
Total	**1500**	**1566**	**138**	**139**		
Average daily rainfall/rain day/month					**10**	**10.3**

A coefficient between the overall daily averages is obtained as follows;

Average daily rainfall Yaoundé /Average daily rainfall Sangmelima = 10/10.3 = 0.97;

The daily rainfall values for Yaoundé for 1983 to 1987 can be estimated from the daily values of Sangmelima for the same period using the direct coefficients. Although wet days do not occur on the same days for both stations and the daily rainfall patterns show some differences, the estimated rainfall for 1983 to 1987 for Yaoundé using the data for Sangmelima for the same period can be used for long term volume calculations. With the analysis above the daily rainfall for Yaoundé can be extended to 1987 to obtain a total of 12 years of rainfall data.

3.3 Analysis of Runoff Data

The existing flow data obtained from the National hydrology research centre (*Centre de Recherches Hydrologiques (CRH)*) data bank are measurements taken at the Nsimalen hydrometric station. This station is located at about the middle of the sub basin and has a catchment area of about 425 Km^2. The model will be calibrated for the available runoff measurements at this station from 1976 to 1977 and 1984 to 1986.

Runoff measurements

The runoff values were obtained from daily stage measurements carried out at the station. The Nsimalen station had been calibrated and a rating curve for stage height with corresponding runoff was established from which a relationship for the calculation of flow in m^3/s from the daily stage measurements was derived (*CRH documents*). The rating curve for the Nsimalen station is given in *Appendix 4*. According to the National hydrology research center, this relationship which had been updated several times is valid for measurements from 1962 to when measurements were stopped.

Available Runoff data

Daily runoff data at the Nsimalen station is measured from 1976 to 1978 with a break to resume from 1984 to 1986**.** A time chart showing the period of available daily data is shown in *Table 5*.

Table 5: Period of available daily runoff data at Nsimalen measurement station

Station	**1976**	**1977**	**1978 to 1983**	**1984**	**1985**	**1986**	**1987**
Nsimalen	▬	▬	No data	▬	▬	▬	No data

The annual and monthly rainfall and runoff data for these periods will be analyzed to define a method of estimating the runoff for the period with no data. It is necessary to fill in the gap to obtain a longer period of data in order to have a reasonable comparison of both wet and dry periods within the Sub basin. The missing daily runoff can be estimated more satisfactorily by the rainfall-runoff model. The analysis starts with the monthly runoff because this can be estimated using monthly runoff coefficients for the years with observed runoff data. Daily runoff coefficients are not possible because there are days with zero rainfall while there is daily runoff for all days through out the year.

Analysis of Monthly runoff

Details of the average monthly runoffs for the available measurements are given in *Appendix 5*. The diagram given in *Figure 3.7* shows the average monthly runoff from 1976 to 1977, 1984 to 1986 and for the whole period of 1976 to 1986 from measured data at Nsimalen station without including the intermediate years of 1978 to 1983 without runoff measurements. Runoff values used in the analysis have been converted from daily values of volume per second (m3/s) to runoff heights in mm.

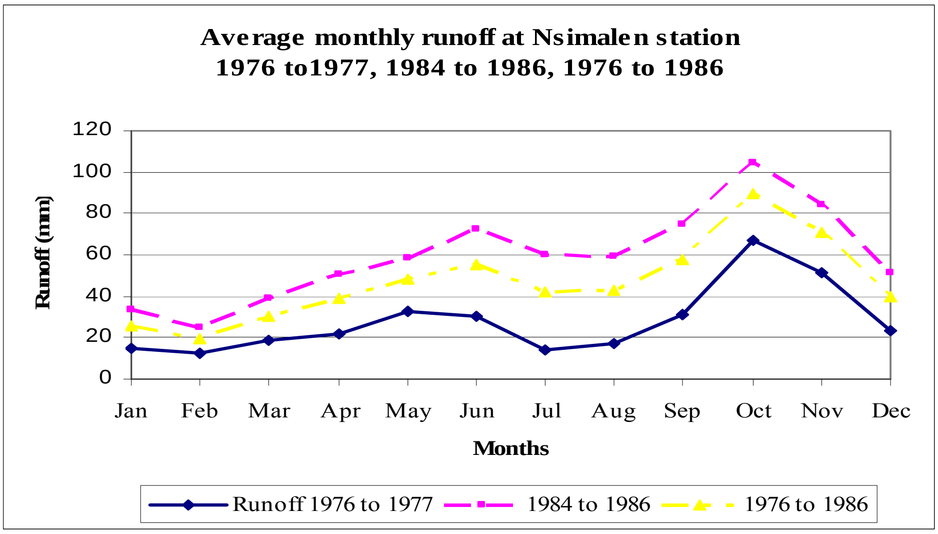

Figure 3.7: Average monthly runoff (mm) at Nsimalen 1976 to 1986 from measured data

The seasonal variation of runoff corresponds to that of rainfall for the same period. In general the Peak runoff occurs during the months of September, October and November. The runoff for May and June also correspond to the first rain season in the sub basin. *Figure 3.8* shows the monthly rainfall and runoff curves for the 1976 to 1977 period. The runoff for 1984 to 1986 is higher than that of 1976 to 1977 but corresponds to the high values of measured rainfall for the same period

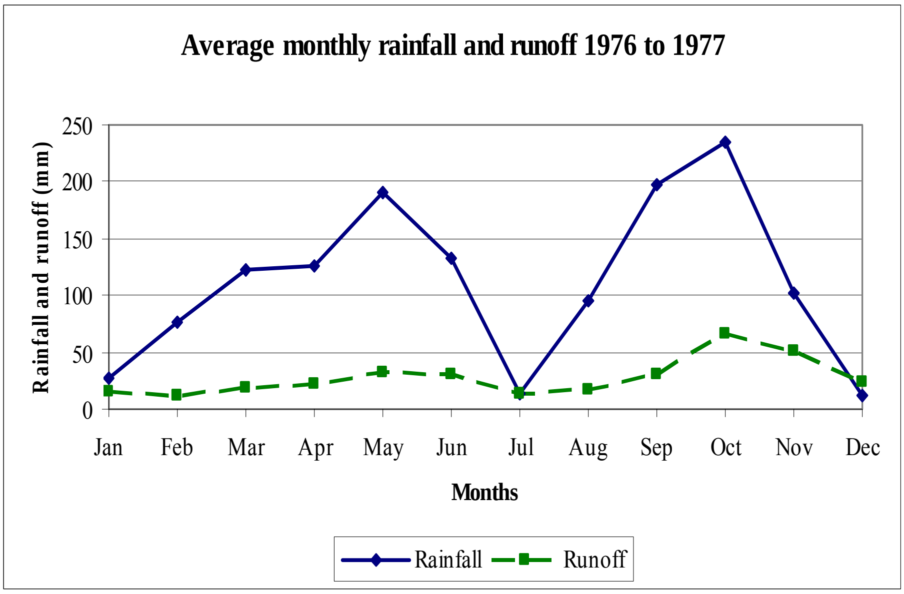

Figure 3.8: Monthly Rainfall-Runoff curves of the Mefou at Nsimalen 1976 to 1977

The average monthly rainfall and runoff curves for 1984 to 1986 were also plotted and are shown in *Figure 3.9*. The higher runoff values correspond to the higher rainfall values for this period.

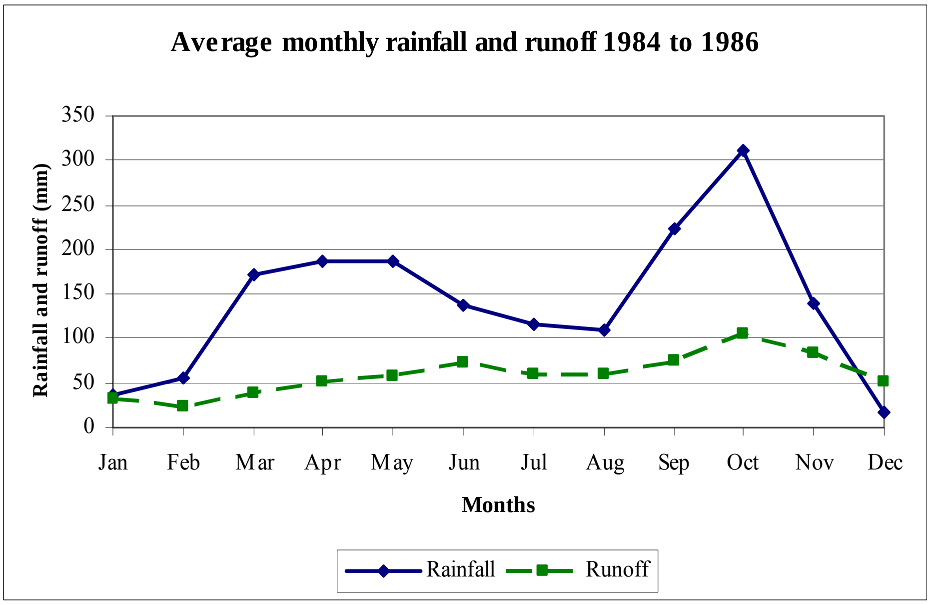

Figure 3.9: Monthly Rainfall-Runoff curves of the Mefou at Nsimalen 1984 to 1986

The monthly runoff coefficients for all the months of the five years with available flow measurements were calculated using a simple linear equation given in *equation 3.2* and plotted in *Figure 3.10*.

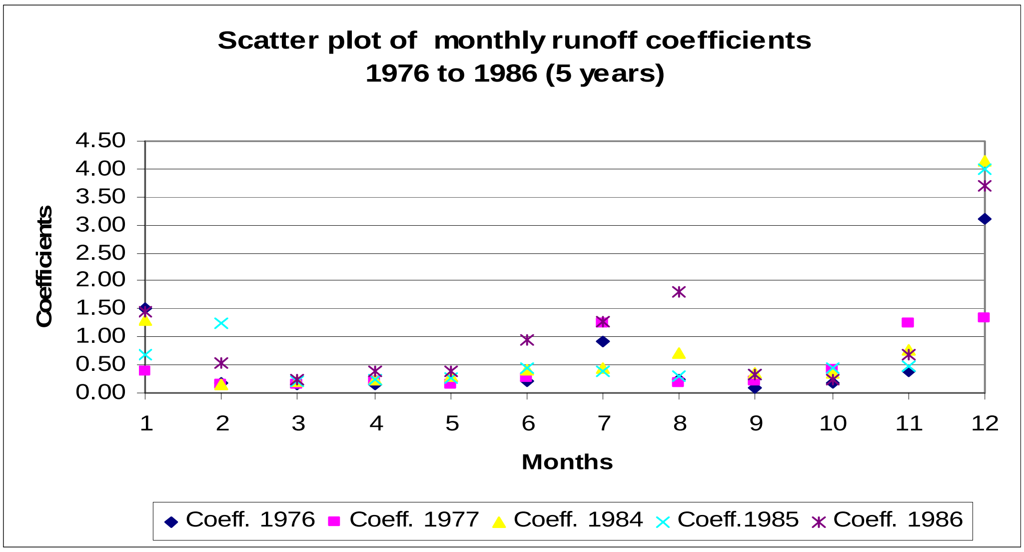

Figure 3.10: Monthly runoff coefficients for the 5 years with data between 1976 and 1986

$$Q(mm)=CP(mm) \tag{3.2}$$

Where;

Q is the monthly runoff in mm

P is the monthly rainfall in mm

C is the monthly runoff coefficient

The calculated monthly runoff coefficients for the years 1976, 1977, 1984, 1985, and 1986 are given in *Appendix* 5. Due to the wide monthly and seasonal variation in the rainfall and runoff it will be necessary for the relationship to be described differently for each month or season.

Some of the runoff coefficients for the months of January, July and December are above one meaning that the runoff is more than the rainfall. The reason for this is that, these are very dry months preceded by very wet months of September, October, and November in the situation of December, January and May, June in the situation of July. There is a runoff memory from the wet months coming to the very low rainfall months.

After investigation of several possible statistical models, the average coefficient for each month was calculated and used to estimate monthly runoff given in *Table 6* from the estimated monthly rainfall for the period of 1978 to 1983 without runoff measurements. This type of estimation has been made because it is the average runoff volume over a period of one year that is of interest and this method gave the most satisfactory results.

Table 6: Estimated monthly runoffs from measured and estimated rainfalls 1978 to 1987

	Avr.	1978		1979		1980		1981		1982		1983		1987	
		Meas.	Estim.	Meas.	Estim.	Meas.	Estim.	Meas.	Estim	Meas.	Estim.	Estim.	Estim.	Estim.	Estim.
Month	**Coeff**	**P(mm)**	**Q(mm)**	**P(mm)**	**Q(mm**	**P(mm)**	**Q(mm**	**P(mm**	**Q(mm**	**P(mm)**	**Q(mm**	**P(mm)**	**Q(mm**	**P(mm)**	**Q(mm)**
January	0.96	49	47	4	4	6	6	8	8	8	8	13	12	13	12
February	0.41	88	36	97	40	65	27	32	13	34	14	24	10	43	18
March	0.20	145	28	160	31	141	28	88	17	102	20	83	16	152	30
April	0.24	320	78	130	32	115	28	254	62	124	30	174	43	111	27
May	0.26	99	26	201	53	231	60	168	44	172	45	247	64	182	47
June	0.45	158	71	302	135	64	28	166	74	270	120	143	64	124	55
July	0.84	12	10	77	64	103	86	89	74	96	81	92	77	99	83
August	0.59	59	35	29	17	79	47	111	66	130	77	52	31	58	34
September	0.26	264	69	154	40	418	109	221	58	239	62	167	43	238	62
October	0.33	207	68	278	91	274	90	364	119	362	119	322	105	232	76
November	0.71	92	65	114	81	95	68	126	89	25	18	111	79	121	86
December	2.73	2	5	4	10	0	0	9	24	4	12	24	64	33	90
Annual P and Q		1495	**538**	1547.9	**596**	1591	**576**	1636	**649**	1567	**606**	1451	**609**	1406	**621**

***Meas. = Measured. *Estim. = Estimated.**

Using the average runoff coefficients to estimate monthly runoff values may give high values for months with high runoff coefficients such as January, July and December in a year where the rainfall for these months happen to be high. A comparison is made in *Table 7* of the measured runoff for these months and the estimated runoff using average monthly runoff coefficients. The results show that the measured and estimated values for these months give very similar overall average of 36 mm and 37 mm respectively. The study is concerned with mean monthly data, thus the use of average monthly runoff coefficients gives acceptable mean monthly runoff values.

Table 7: Measured and estimated annual runoff for January, July and December 1976 to 1987

	Measured runoff(mm)						**Estimated runoff (mm)**							
	1976	**1977**	**1984**	**1985**	**1986**	**Average**	**1978**	**1979**	**1980**	**1981**	**1982**	**1983**	**1987**	**Average**
Jan	12	18	12	41	46	**26**	47	4	6	8	8	12	12	**14**
July	14	14	85	47	48	**42**	10	64	86	74	81	77	77	**67**
Dec.	25	22	48	71	35	**40**	5	10	15	24	12	64	90	**31**
Average						**36**								**37**

Analysis of Annual runoff

The average monthly runoff coefficients obtained in *Figure 3.10* are used to estimate monthly runoffs for 1978 to 1983 and 1987. From the monthly runoffs annual values were obtained for the period as shown in *Table 6*. The measured and estimated annual rainfall and runoff as well as the runoff coefficients for all the periods are given in *Table 8*.

Table 8: Measured and estimated annual rainfall and runoff 1976 to 1987(12 years)

	Rainfall		Runoff		Coefficients	
	Measured	**Estimated**	**Measured**	**Estimated**	**Measured**	**Estimated**
Year	**P (mm)**	**P (mm)**	**Q (mm)**	**Q (mm)**	**Coefficients**	**Coefficients**
1976	1372		323		0.24	
1977	1292		354		0.27	
1978	1495			**506**		0.34
1979	1548			**596**		0.39
1980	1591			**591**		0.37
1981	1636			**649**		0.40
1982	1567			**606**		0.39
1983		**1451**		**609**		0.42
1984		**1791**	735		0.41	
1985		**1895**	743		0.39	
1986		**1402**	661		0.47	
1987		**1406**		**621**		0.44
Annual Average	**1500**	**1589**	**563**	**596**	**0.36**	**0.38**

The measured and estimated annual rainfall and runoff values are plotted to obtain a scatter plot of the annual rainfall and runoff of the sub basin, which is given in *Figure 3.11*.

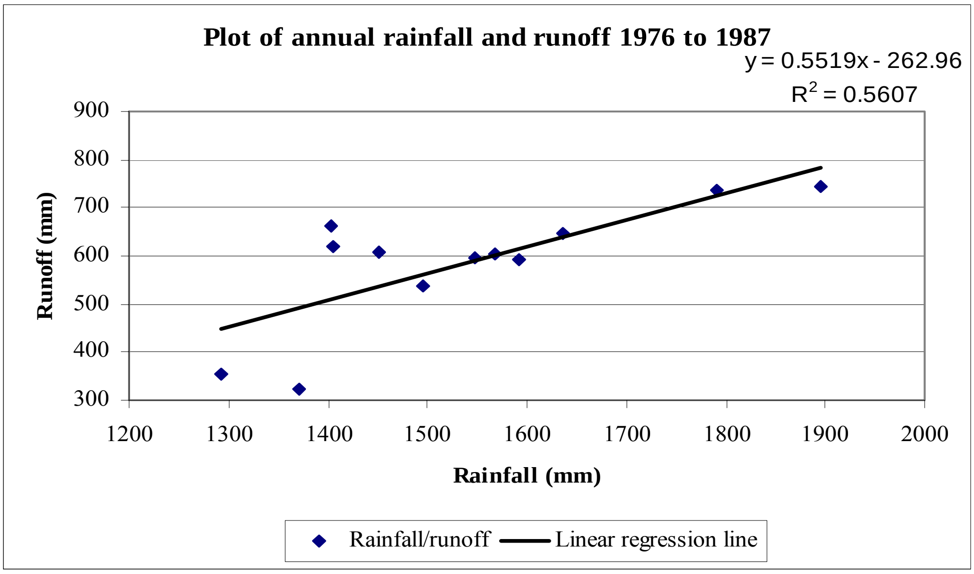

Figure 3.11: Annual Runoff and rainfall of the Mefou measured and estimated 1976 to 1987

A linear relationship is obtained for the annual rainfall and runoff as given in *equation 3.3*.

$$Q(mm) = 0.6P(mm) - 263mm \tag{3.3}$$

With correlation coefficient of $R^2 = 0.56 \rightarrow R = 0.75$

Q is the average annual runoff in mm
P is the average annual rainfall in mm.

The results of the estimated annual rainfall, runoff and annual runoff coefficients are put together with the measured values of rainfall and runoff in *Table 9* to obtain a global annual average rainfall, runoff and runoff coefficient.

Table 9: Measured and estimated annual rainfall and runoff at Nsimalen station 1976 to 1987

	Annual rainfall / runoff		
	Measured and Estimated		**Runoff**
Year	**P (mm)**	**Q (mm)**	**Coefficients**
1976	1372	323	0.24
1977	1292	354	0.27
1978	1495	**506**	0.34
1979	1548	**596**	0.39
1980	1591	**591**	0.37
1981	1636	**649**	0.40
1982	1567	**606**	0.39
1983	**1451**	**609**	0.42
1984	**1791**	735	0.41
1985	**1895**	743	0.39
1986	**1402**	661	0.47
1987	**1406**	**621**	0.44
Average P and Q	**1537**	**583**	**0.38**

The annual runoff at Nsimalen for other years can be estimated using *equation (3.3).* From the analysis the average annual rainfall and runoff for the Mefou sub basin at Nsimalen were estimated to be about **1537mm** and **583 mm** respectively with average annual runoff coefficient of **0.38** for the period 1976 to 1987. In previous estimates by the CRH, an annual average rainfall of **1597 mm** and runoff of about **441 mm** per year with runoff coefficient of about **0.28** at Nsimalen was obtained using data for an unspecified period before 1976 (*CRH archives, n.d*).

3.4 Analysis of Evapotranspiration Data

Evapotranspiration and potential evapotranspiration are amongst the most important climatic parameters that will affect the long term water balance of a catchment. There are several methods of measuring evaporation and calculation of evapotranspiration. Evapotranspiration is the measure of the amount of water vapor that leaves the land surface including transpiration from vegetation to the atmosphere and calculation of evapotranspiration is usually complicated and laborious. The evapotranspiration of a given area depends on the meteorological and atmospheric conditions and is usually presented as potential evapotranspiration. The potential evapotranspiration is the estimated maximum amount of evapotranspiration that can occur in a given area. Monthly values for evaporation and calculated evapotranspiration from 1976 to 1983 are available for Yaoundé located within the Mefou sub basin. The standard method of calculating potential evapotranspiration in Cameroon is by using *L. Turc's* method *(CRH documents).* The average monthly potential evapotranspiration have been calculated from measurements of temperature, evaporation, relative humidity and amount of sunshine. The most common method of evaporation measurement used in Cameroon is the Piche evaporimeter. It measures the amount of water lost to the atmosphere usually over a period of one day.

Calculation of Potential Evapotranspiration

The monthly potential evapotranspiration values available for Yaoundé station have been calculated using a method proposed by *L. Turc* (*CRH, documents*). This method is given as follows;

$$PET = (Ig + 50)0.40\left(\frac{t}{t+15}\right) \tag{3.4}$$

PET = the monthly potential evapotranspiration (mm /month).

Ig = the monthly global solar radiation (cal/cm^2/day) for a horizontal surface.

t = average temperature (^{o}C)

The solar radiation Ig is further given by the formula; Ig = Ig$_A$ (0.18 + 0.62 h/H).

Ig$_A$ = the energy of solar radiation (cal/cm^2/day) which will be received in the absence of atmosphere.

The values of Ig$_A$ depend only on the geographic Latitude of the area and are given in standard tables called Angot's tables.

h/H = the relationship between the duration of real insulation and the astronomic duration of the day and is given in special tables.

The average monthly potential evapotranspiration for Yaoundé calculated using equation *(3.4)* is given in *Appendix 6.* The average annual potential evapotranspiration was found to be about 1218 mm. In general, the average annual potential evapotranspiration for the Mefou sub-basin was determined to be between 1200 mm and 1300 mm (*CRH documents*). The curve of average monthly PET for Yaoundé is shown in *Figure 3.12.*

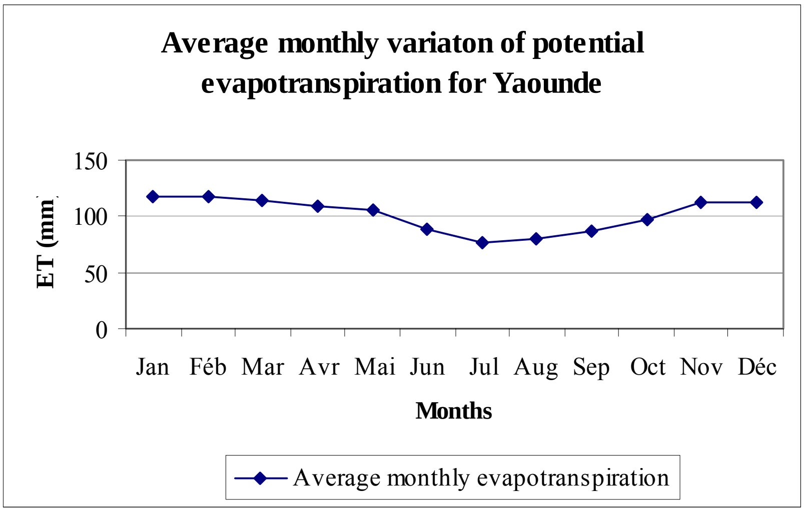

Figure 3.12: Calculated Average monthly Potential Evapotranspiration of Yaoundé 1977 to 1983

The inter-annual variability of PET is also relatively small (typically less than 0.05). For these reasons, the mean monthly areal PET is used for catchment water balance analysis and hydrological models.

3.5 Estimation of runoff volume from the data analysis

From the analysis of the available data, the rainfall and runoff data for the Mefou sub basin can be extended to 12 years using the rainfall data of the neighboring station of Sangmelima. An annual average rainfall of about 1537 mm and average annual runoff of about 585 mm is obtained for this period for the Mefou sub basin at the Nsimalen station. The average annual potential evapotranspiration of about 1218 mm will be used in the analysis and model calibration. Using the simple water balance *equation (2.1)* over a long time period storage is minimal and the catchment evapotranspiration per year can be estimated as follows;

S + ET = P-Q =1537-583= 954 mm per year.

Where, S is the average storage (mm), and ET is the average evapotranspiration (mm). The rate of recharge or infiltration can be obtained from the model. The total runoff volume for the Mefou sub basin at Nsimalen (425 km^2) and for the whole catchment (809 km^2) can be estimated from the data analysis as shown in *Table 10:*

Table 10: Estimated Monthly and annual runoff volume at Nsimalen station and whole Sub basin 1976 to 1987(12 years)

Month	Average Q(mm)	Nsimalen Area= (425 km^2) Volume(m3)	Whole catchment Area=(809 km^2) Volume(m3)
January	19	8.01E+06	1.52E+07
February	21	9.09E+06	1.73E+07
March	27	1.15E+07	2.18E+07
April	42	1.76E+07	3.36E+07
May	48	2.06E+07	3.92E+07
June	69	2.92E+07	5.56E+07
July	57	2.42E+07	4.61E+07
August	43	1.84E+07	3.50E+07
September	61	2.59E+07	4.93E+07
October	93	3.95E+07	7.52E+07
November	70	2.99E+07	5.68E+07
December	35	1.49E+07	2.83E+07
Average Q	**583**	**2.49E+08**	**4.74E+08**

The estimated annual runoff volume for the whole catchment is about **474 million cubic meters**.

3.6 Margin of error in runoff estimates

In reality it is impossible to assign a value as the margin of error in an estimated or predicted data series. However, hypothetical statistical distribution methods can be used to assign a degree of certainty known as confidence interval to an estimated data sample. One of such statistics method is the dependent pair Student t-test which assumes the zero hypotheses that the difference between the mean of two dependent data series is zero and that the data samples are normally distributed. The test is suitable when the amount of sample is small, that is less than 100 and normal distribution methods such as the Gaussian distribution cannot be applied.

The average monthly runoff for 1978 to 1983 and 1987 are estimated (dependent on) from the average monthly runoff obtained from the observed values of 1976 to 1977 and 1984 to 1986, therefore a range of likely error in the estimated series can be defined by the dependent paired t-test on the two data series. It is assumed that both sets of monthly runoff values are of the same statistics series and their mean is supposed to be the same (null hypotheses) which of course is not the case. The confidence interval is the probability that the error in the mean of the estimated average monthly runoff values will be within a certain range. In order to define the confidence interval, statistical analysis to find the mean and standard deviation of the series and the differences is made and a t-value is calculated using *Equation (3.5)*. The t-value is the parameter used to define the confidence interval. The statistical analysis of the measured and estimated average monthly runoff is given in *Table 11*.

Table 11: Statistics of measured and estimated monthly runoff 1976 to 1986 and 1978 to 1983, 1987

	1976 to 1986	**1978 to1983, 87**	
	Average	**Average**	
Month	**Qmm/month**	**Qmm/month**	**Difference.**
Jan	25.93	13.79	12.15
Feb	19.77	22.41	-2.64
Mar	30.71	24.37	6.34
Apr	39.32	42.97	-3.65
May	48.34	48.48	-0.13
Jun	55.47	78.10	-22.63
Jul	41.72	67.98	-26.26
Aug	42.72	43.70	-0.98
Sep	57.51	63.27	-5.76
Oct	89.46	95.43	-5.97
Nov	71.02	69.36	1.66
Dec	39.97	31.48	8.49
Mean	**46.83**	**50.11**	**-3.28**
SD	**18.64**	**23.96**	**10.90**

$$\text{t-value} = \frac{X_D - \mu o}{SD}\sqrt{N} = 1.04 \qquad (3.5)$$

Where;

X_D is the mean of the differences between the measured and estimated runoff values (mm)

μo is a constant to which the mean is compared (Assumed to be = 0).

SD is the standard deviation of the differences between measured and estimated values.

N is the number of samples = 12.

Statistic software known as 'GRAPHpad' is used to obtain a confidence interval of 83% to 90% that the difference in the average monthly runoff values will fall in the range of -10.38 mm to 4.21 mm.

The results for the confidence interval implies that, for the data series there is 10% to 17 % probability that any error in the estimated average monthly runoff values will be out of the range of -10.38 mm to 4.21 mm from the true value.

This does not prove that the estimated values are correct or incorrect but gives a degree of how precise the estimates were made.

4.0 RAINFALL-RUNOFF MODEL

The HBV model simulates runoff from input of daily rainfall, daily runoff, and average monthly potential evapotranspiration for a given catchment. The evapotranspiration is calculated using Thornwaites method or by normal interpolation of average monthly values. Average monthly PET values obtained from the *L. Turc* method were used in the model simulation. A detail description of the HBV model is given in *section 2.3*.

The catchment to be simulated is called a district which is sub divided into sub basins depending on existing runoff stations, water divide, topography and tributaries. The sub basins are then linked up as necessary. Water abstraction and bifurcation can also be included within the sub basins if necessary. There is also the possibility of including lakes and reservoir characteristics if available in the catchment. The sub basins can be further divided into geographical zones of field, forest, glacier, internal lakes and out lakes. Where there is no snow as in the Mefou sub basin the zones are considered as fields.

Meteorological and hydrological stations include direct stations and replacement stations with the related coefficients and weighting as related to the different sub basins. The station weights are determined by Theissen polygon method or other suitable method. The input data of daily measurements is imported from standard text files which have been formatted to the HBV standard file type including the start and end dates.

The model simulation is carried out by first creating an initial simulation state from the default initial state of the model which is taken as the first of October of the year 0001 (0001-10-01:00). This default is a typical Swedish condition which considers that at this date there is no snow and the soil moisture content is about 90% of the maximum soil moisture storage, the upper response box is empty and the content of the lower response box is 0.5 and lake level is set to the level of the out lake or reservoir. A warm up period of about one year is then simulated before calibration is started. It is advised that calibration should use data of at least 10 years in order to reflect the possible wet and dry years of the catchment.

Output variables of storage, runoff and precipitation including zonal, local and total values are selected as necessary to view the results during calibration both in the graphical presentation and spread sheet tables. The calibration is done by observing the runoff hydrograph, the cumulative volume difference and the r^2 in the log file. The aim is to obtain r^2 less than one to as close as possible to one.

After calibrating the model, validation is carried out for any number of selected years not included in the calibration years. When the result is satisfactory short term and long term forecast of hydrological and meteorological data can be made. Statistical analysis can also be done on the input data to obtain daily, weekly, monthly and yearly statistics, to determine missing data and homogeneity of data between stations.

4.1 Model set up

Sub basin set up

For the simulation, the sub basin is divided into two sub basins with their limits determined by existing flow stations, tributaries and water divides (*IHMS 5.10 manual, 2006*). Sub basin 1 has surface area of about 425 Km^2 at the Nsimalen runoff measurement station located at about the middle of the catchment. The calibration will be done for the available runoff measured at the Nsimalen station. The second sub basin 2 has area of about 384 Km^2 to the Cameroon Water Authority (CAMWATER) drinking water treatment plant at Akomnyada II, where the Mefou meets the Nyong River is included to give a complete picture of the catchment making the total area of 809 Km^2. These limits and areas have been estimated from an interactive digital map produced by *Global forestry watch and World resources Institute, 2006* and according to areas given for the sub basin at the different flow measurement stations (*CRH documents*).

Input data

As described earlier the available rainfall and runoff data for the Mefou sub basin are inadequate for a satisfactory calibration of the rainfall-runoff model. The model requires daily measurements of rainfall and runoff for at least ten years for a satisfactory calibration to include both wet and dry years. Considering that a validation period is also required one will need data for more than 10 years to set up the model. However, from the analysis of the available rainfall data carried out in *section 3*, the daily rainfall for Yaoundé which is the only station located within the sub basin was extended to 12 years using the data from a close by station at Sangmelima about 120 km South of the sub basin but with similar hydro-climatic characteristics. The runoff could only be extended by average monthly values using the coefficients between inter-annual average monthly runoff to estimate values for the years without daily runoff data. Average monthly evapotranspiration values measured at the Yaoundé station is used and distributed with constant interpolation. Thornwaites method could not be used because the values given in the model are for typical Swedish conditions. The stations are given the same weighting for all the sub basins. The model would be used to estimate the daily runoff for the period with missing data. The different stations and data type used in the model are given in *Table 12*.

Table 12: The different meteorological and hydrological stations and period used in the model

			Period		
Station	**Data**	**Type**	**Measured**	**Estimated**	**Comments**
Yaoundé	Rainfall	Daily	1976- 1982		**Main meteorological station**
Sangmelima	Rainfall	Daily		1976- 1987	**Replacement station 1983-1987 with replacement factor 0.97**
Yaoundé	Evapotranspiration	Monthly	1977- 1983		**Average monthly values calculated from daily values.**
Nsimalen	Runoff	Daily / monthly	1976-1977 1984- 1986	1978-1983, 1987	**Runoff calibration station (1978-1983 are monthly estimates)**
Yaoundé	Temperature	Daily	1976- 1983		

Parameter selections

The Swedish HBV model has about 34 parameters including runoff volume parameters, snow parameters, soil routine parameters, runoff response parameter and damping parameters. Since the sub basin is located within the tropics the snow parameters were completely eliminated reducing the parameters to 15 mainly for the runoff volume calibration, soil moisture and runoff response routines. The model was first calibrated to obtain a minimum cumulative volume difference using the parameters *rfcf, perc, fc* while observing the hydrograph fit at peak flows, then for the soil routine characteristics which include *Lp*, *alpha* , *beta and cflux* for evapotranspiration and infiltration, and the response parameters *Khq* and *K4* for base flow and peak flows affecting the hydrograph shape. The lag parameter was used to enable simulation of the fluctuation of runoff seen on the observed hydrograph. The parameters used in the calibration are given in *Table 13* with the explanation of each parameter. *Hq* is calculated using the mean of all the available runoff (HQ) and the mean of the annual maxima (MHQ) using the formula in *Table 13*.

4.2 Model calibration and validation

The rainfall and runoff data were divided in two parts from 1984 to 1986 and the other 1976 to 1977 used for calibration and validation respectively.

Calibration

An initial state was created by simulating from 01-10-1979 to 01-10-1980 before calibration was carried out from 01-01-1984 to 31-03-1986. The model was calibrated by trial and error simulation until a satisfactory result was obtained. Existing templates in the model were used to estimate catchment parameters for the Mefou sub basin.

In order to achieve rapid results, the model was first calibrated for cumulative volume error before looking for the best fit. The catchment parameters affecting volume included *rfcf, perc, fc and to a lesser extend LP. alpha*, *bet*a. Increasing '*fc*' reduces the computed runoff and reducing it has the opposite effect. Similarly reducing 'rfcf' reduces the runoff and increasing it increases the runoff. The effective calibration of the model depends largely on these two parameters *rfcf*, *fc, K4* and *Khq* and to some extend on the '*perc*'. The '*perc*' has similar effect as '*rfcf*' but to a smaller degree. After obtaining a suitable value for '*LP*' it has very little effect on the model calibration when changed.

Alpha and *beta* generally slightly reduces the computed volume and marginally increase the efficiency function r^2 and have negligible influence on the overall results after calibration has been achieved. Alpha is defined from;

$$Q = k \cdot UZ^{(alfa+1)}.$$

Where;
Q is the total outflow from the response routine (mm)
UZ is the content of the upper reservoir in the response routine (mm)
K is the recession coefficient for the upper reservoir

The cumulative volume difference obtained was about 3 mm between the computed and observed data for the 1979 to 1987 period.

The hydrograph fit was adjusted by calibrating *khq*, *K4.* These parameters generally affect the peaks after the volume is calibrated and will reduce the computed volume and r^2 when reduced and has no effect on volume when increased though r^2 is reduced. After calculating *Hq* using the formula given in *Table 13* it is not changed during calibration.

$$\text{Hq (mm)} = (\text{MQ}\cdot\text{MHQ})^{1/2}\cdot 86.4/(\text{area in km}^2) \text{ or } \text{MHQ}/2\cdot 86.4/(\text{area in km}^2)$$

Where;
MQ is the mean of all the runoff data available (mm).
MHQ is the mean of the annual peak runoff values (mm).

Some adjustments were made to the observed rainfall and runoff values which were considered to be unrealistic to obtain satisfactory results. The calibrated parameters are given in *Table 13.*

Table 13: The HBV model Parameters used in calibration and values obtained after calibration

	Parameter	**Sub Basin 1 Nsimalen**	**Parameter description**
1	Alfa	**0.4**	Used in the equation $Q = k\cdot UZ^{(alfa+1)}$.
2	Beta	**1**	Exponent in the equation for discharge from the zone of soil water.
3	Cflux	**1.62**	Capillary flow from the upper response box to the zone of soil water.
4	Fc	**42**	Maximum soil moister storage [mm].
5	Hq	**3**	Calculated as $(\text{MQ}\cdot\text{MHQ})^{1/2}\cdot 86.4/(\text{area in km}^2)$ or $\text{MHQ}/2\cdot 86.4/(\text{area in km}^2)$. Unit [mm]. Not to be calibrated.
6	K4	**0.0116**	Recession coefficient for the lower response box.
7	Khq	**0.0175**	Recession coefficient for the upper response box when the discharge is HQ.
8	Lp	**0.8**	Limit for potential evaporation.
9	Maxbas	**1.6**	Number of days (doesn't have to be an integer) in the transformation routine.
10	Pcalt	**0.1**	Factor for precipitation changing with altitude
11	Pcaltl	**800**	Highest level when *pcalt* is used. Locked to the highest forested level.
12	Pcorr	**1**	Factor for precipitation. Used when correcting non-homogenous series.
13	Perc	**2.6**	Percolation from the upper to the lower response box [mm/day].
14	Rfcf	**0.8**	Factor for precipitation as rain. Multiplied by *pcorr*. The quota *rfcf/sfcf* = max 1.5.
15	Tcalt	**0.6**	Decrease of temperature with altitude taken per 100 meter.
16	Recstep	**999**	Number of steps/days is automatically checked.

The calibration for 1984 to 1986 gave an efficiency function r^2 of 0.91. *Figure 4.1* shows the resulting runoff hydrographs for the period of calibration. The simulated hydrographs shown as **red curves** are smoother and stretched out compared to the observed runoff hydrographs shown as **green curves**, implying the model simulates a faster response which is also seen in the higher base flow and fewer peaks for the simulated runoff. This may be due to underestimation of the sub basin field capacity, lack of the proper model parameter or unsatisfactory calibration of parameters to simulate the fluctuation of runoff response or averaging by the model where there is no precipitation data.

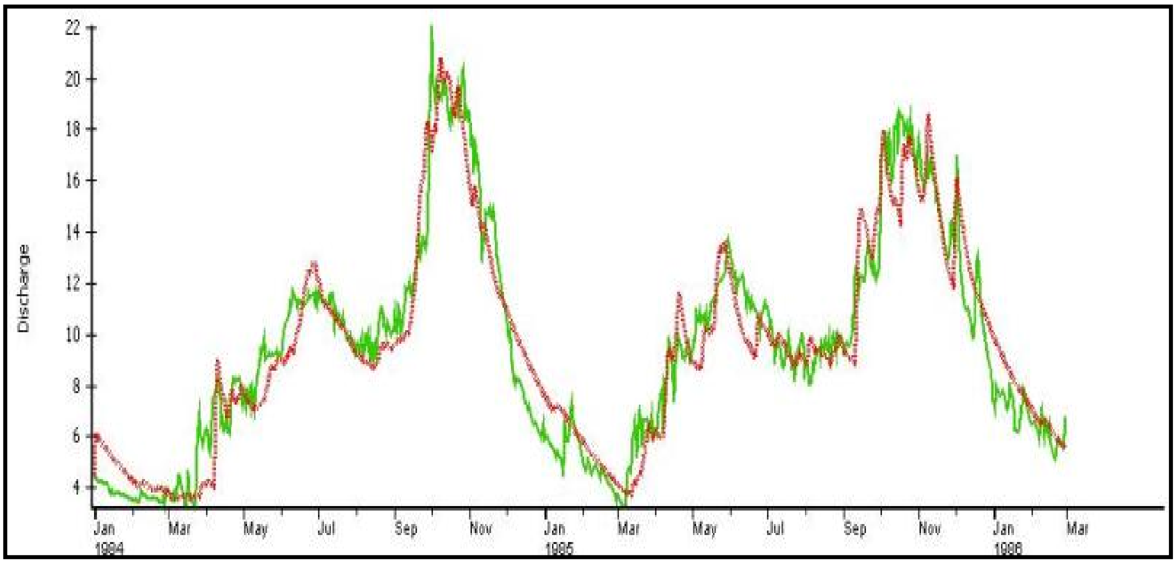

Figure 4.1: Observed and calibrated hydrographs for the Mefou at Nsimalen 1984 to 1986

Model validation

A validation process was carried out for the period 1976 to 1978 and an efficiency function r^2 of 0.77 and a cumulative volume difference of about 13 mm were obtained. Observing the resultant hydrographs it is clear that the peaks did not fit properly. *Figure 4.2* shows the hydrographs resulting from the model validation.

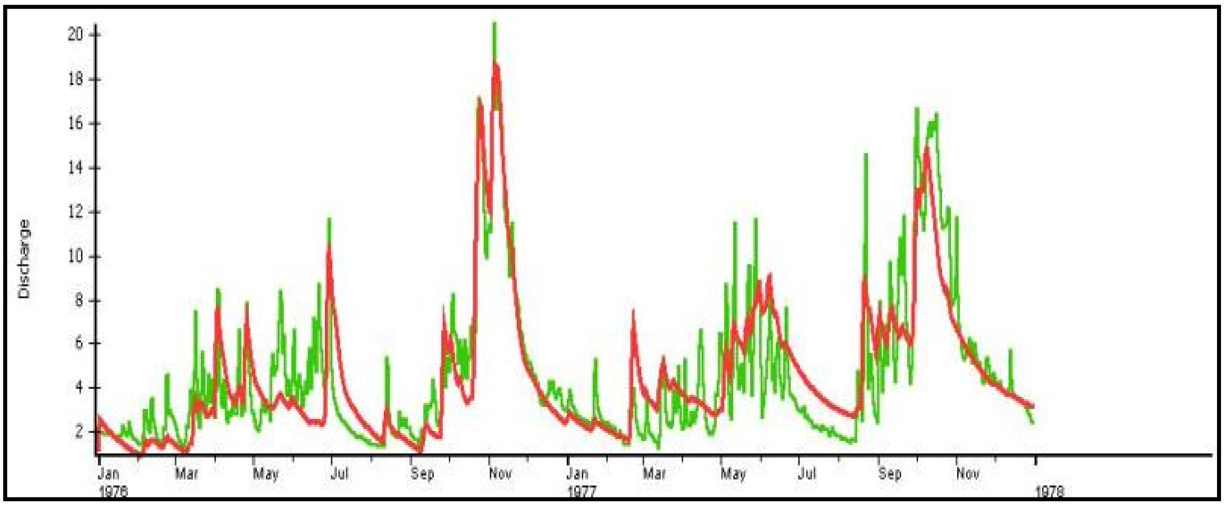

Figure 4.2: Observed and simulated hydrographs for Nsimalen after validation 1976 to 1978

4.3 Estimation of daily runoff for 1978 to 1983 and Volume calculations

After the calibration and validation of the model, it was used to forecast the daily runoff for the period 1978 to 1983. From this estimates the monthly and annual runoffs were calculated. The results of the monthly and annual estimates in the model simulation after validation are compared in *Table 14* with the estimates made in the rational method analysis of the available data.

Table 14: Measured, estimated and model computed average annual rainfall and runoff

	Rainfall		Runoff		Runoff
	Measured	Estimated	Measured	Estimated	Model simulation
Year	P (mm)	P (mm)	Q (mm)	Q (mm)	Q (mm)
1976	1372		323		**304**
1977	1292		354		**333**
1978	1495			**506**	**417**
1979	1548			**596**	**577**
1980	1591			**591**	**594**
1981	1636			**649**	**687**
1982	1567			**606**	**636**
1983		**1451**		**609**	**640**
1984		**1791**	735		**709**
1985		**1895**	743		**724**
1986		**1402**	661		**616**
1987		**1406**		621	**628**
Annual Average	**1537**		**583**		**572**

The model simulated runoff is less than the estimated runoff from the rational method. This may be because the rational method simplifies the rainfall- runoff process into a simple linear relationship while the model takes into consideration some of the catchment characteristics like potential evapotranspiration, field capacity, soil moisture storage, and ground water recharge before eventually appearing as runoff.

4.4 Simulation of different climate scenarios

In a previous study on the effect of climate change in the Central African sub region, some possible future climate scenarios were projected for the main basin of which the Mefou is a sub basin. One of the possible scenario being that there is likely to be a temperature rise of about +1.7 °C to +6.3 °C, change in PET of between + 5.7 % to 9.3% and change in rainfall of about + 0.6 % to + 1.7 % by the year 2050 (*Sighomnou, 2004*). This is not an official climate scenario but it is chosen as a possible situation and used to make a study of effects on runoff using the

HBV model. Taking the average values of these scenarios, the following values are assumed and used as climate projection for the Mefou sub basin by 2050;

Temperature = 4 °C on the current average of about 25 °C to become about 29 °C.
PET = +7.5 % which is about 8 mm increase on the present average monthly PET.
Rainfall = + 1.2 % about 19 mm increase on estimated average annual rainfall for 1976 to 1987.

The temperature was increased by 4 ^{o}C to simulate any changes in runoff volume. The average monthly evapotranspiration was increased to about 110 mm from about 102 mm calculated for normal climatic conditions and the annual total increased from 1218 mm to 1315 mm. There is about 9 % reduction in runoff volume from average annual runoff of about 572 mm to 521 mm. The ground water recharge is reduced but the infiltration rate is increased. This range of temperature change can only occur with extreme climate change. A comparison of the simulated average runoffs with temperature increase and normal temperature is shown in *Table 15*.

Table 15: Simulated average annual runoff with normal climate and climate change scenarios

	Real climate	**Climate change 4°C**
	Model simulation	**Model simulation**
Year	Q (mm)	Q (mm)
1976	**304**	**280**
1977	**333**	**308**
1978	**417**	**382**
1979	**577**	**529**
1980	**594**	**537**
1981	**687**	**624**
1982	**636**	**620**
1983	**640**	**595**
1984	**709**	**574**
1985	**724**	**659**
1986	**616**	**562**
1987	**628**	**581**
Average	572	521

5.0 RESULTS AND DISCUSSION

5.1 Results from Data Analysis

Simplified statistics and graphical methods used to analyse the monthly, daily and annual rainfall for Yaoundé and the nearby station of Sangmelima for the period of 1976 to 1982 established the similarities between the rainfall values from the two stations and enabled the rainfall data for Yaoundé to be estimated from 1983 to 1987 using data for this period from the Sangmelima station. The daily and monthly rainfall for both stations in spite of some differences showed similar statistical characteristics which made it possible for a direct ratio to be obtained between the daily rainfalls and a simple linear relationship for the monthly rainfall between both stations. Thus the rainfall series for Yaoundé was extended to 12 years from 1976 to 1987.

The daily rainfall coefficient of 0.97 obtained in the analysis was used to estimate the daily rainfall for 1983 to 1986 that was used in the model simulation, while the monthly linear regression correlation was used to calculate the monthly rainfall values for 1983 to 1987 which was used to estimate the monthly runoff for these years.

The period of 1976 to 1987 include both wet and dry periods of the Mefou sub basin and the results from the data can be assumed to reflect the general climatic and hydrological characteristics of the sub basin. An average annual rainfall of **1537 mm** for Yaoundé was estimated for the period. Other studies by the National hydrology research center using rainfall series before 1976, estimated an average annual rainfall of **1597 mm** (*CRH, archives, n.d*) for the Mefou Sub basin.

A similar rainfall analysis can be made with the Betare Oya station which has rainfall data up to 1991 and establish a relationship with Yaoundé to extend the rainfall to 1991. The same procedure can be applied to extend rainfall data using measurements from other nearby stations if available with later period of data and reasonable similarities can be established.

The average monthly and annual runoff for the Mefou Sub basin at the Nsimalen station for 1978 to 1983 and 1987 were estimated by analysis of the available rainfall and runoff data from 1976 to 1986 and applying a linear regression relationship between the rainfall and runoff.

The rainfall-runoff variation of the Mefou sub basin through a typical year can be described by grouping the months as follows; April to June, July to September, October to December and

January to March. The runoff coefficients lie between 0.2 and 0.6 for 44 out of the 60 months of rainfall and runoff data, that is about 64 percent of months with observed rainfall and runoff data. The months of January, July, August, November and December have the highest runoff coefficients with runoff for some years reaching above 1.5 times the rainfall for January, July and August, 1.8 times the rainfall for August and up to 3.5 times the rainfall for December. The widely varying coefficients make it difficult to attribute any standard coefficient for each month. The biggest coefficients are for the months of December August and January in order of magnitude.

High runoff coefficients for January, August and December can be explained by the fact that by these months the soil is saturated by the heavy rains of April to June in the case of August, while the high runoff coefficient for December which is a very dry month is as a result of the full contribution from the saturated soil due to the high rainfall of September to November. While the runoff reduces during January when the dry season is hottest and very little or no precipitation occurs. The minimum runoff occurs at the end of February and into March and the beginning of April when the soil has become very dry and the rate of infiltration and ground water recharge is highest.

The first real rainfall occurs towards the end of April and continues through May to June when the runoff begins to increase rapidly. The runoff eventually drops in August after the previous month of low rainfall in July. The soil becomes saturated again with the heavy rains which start towards the end of August through October and November. These variations are consistent with the four different seasons (two distinct wet seasons and two dry seasons) of the region in which the sub basin is located.

The average monthly runoff was used to estimate the annual runoff height of **583 mm** with an average annual runoff coefficient of about **0.38.** A total runoff water volume of **474 million cubic meters** was estimated for the whole basin. Other previous studies carried out in the sub basin by the National hydrology Institute, estimated the annual runoff at the Nsimalen station as **441 mm per year** and average runoff coefficient of about **0.28** (*CRH, archives, n.d*). However, it is indicated that data for a longer period from 1964 to 1976 was used in the estimation but details of the methods used are not available.

The average annual potential evapotranspiration of about **1218 mm** means that over a sufficiently long period about 78% of the precipitation can potentially end up as evapotranspiration. Compared to rainfall, evapotranspiration has little influence on the water balance on a daily time scale.

A possible degree of precision in the runoff analysis was determined by calculating the confidence interval using the student t-test distribution and the results gave a confidence interval of 83% to 90% that the error in the estimated average monthly runoff values will be between the ranges of -10.38 mm to 4.21 mm. The *precision* of the interval is given by its width (-10.8 and 4.21). Wide intervals do not provide very precise information about the location of the true data mean. While short intervals provide precise information about the location of the data mean. The interval obtained in the data analysis is statistically acceptable in the analysis of small amount of data as in the situation of the Mefou sub basin. The statistical test makes it possible to state a degree of precision, in the estimation of the data but cannot actually prove or disprove the estimated values.

5.2 Results from the Rainfall-runoff model

The available data though general of good quality was however lacking for several years and difficult to use in the HBV Rainfall- runoff model. The lack of continuous daily runoff data for at least ten years was a handicap in the model calibration. However after a long and difficult process of calibration and data adjustments using two years of data from 1984 to 1986, the model was calibrated to an r^2 value of 0,91 which is within the acceptable range for the model. In spite of this high value, the hydrograph fit was not the best. The simulated hydrograph showed a fast and smooth response to precipitation while the observed values were showing significant daily fluctuations.

Catchment parameters *Fc* (Maximum moisture content), *perc* (percolation within the soil from the upper fast flow layer to the lower slow flow layer), and *maxbas* (the number of days required for transformation of soil and ground water to runoff), were estimated though these may be different from the real values on the field.

The runoff volume was also estimated and was found to have an average cumulative volume error difference during calibration and after validation of about 12 mm from the observed volume. The computed total average annual runoff volume was found to be about **572 mm** about 11 mm less than the value obtained by the data analysis method.

The model was also found to be very sensitive to the parameters *Fc, rcfc, perc*, and *Khq* and the damping and lag parameter *maxbas*. Other parameters affected the model simulation rather slowly.

An assumed climate scenario of increased temperature and consequently evapotranspiration was simulated in the model. Simulation of the chosen climate scenario showed a reduction of runoff volume to be about 9 % by 2050. Other studies carried out on similar climate scenarios showed a reduction of about 8 % in runoff volume. However, these scenarios were theoretical values obtained by analysing and comparing three climate models (*Sighomnou, 2004*) which are also subject to the uncertainties of any model simulation.

The estimated runoff volume from both methods as well as from previous studies show that the potential runoff of the Mefou sub basin can only provide about 30 % of the projected quantity of 1600 billion cubic meters estimated as future demand within the sub basin by the year 2050. *Figure 5.1* shows a chart comparing the different annual water resources situation of the Mefou sub basin.

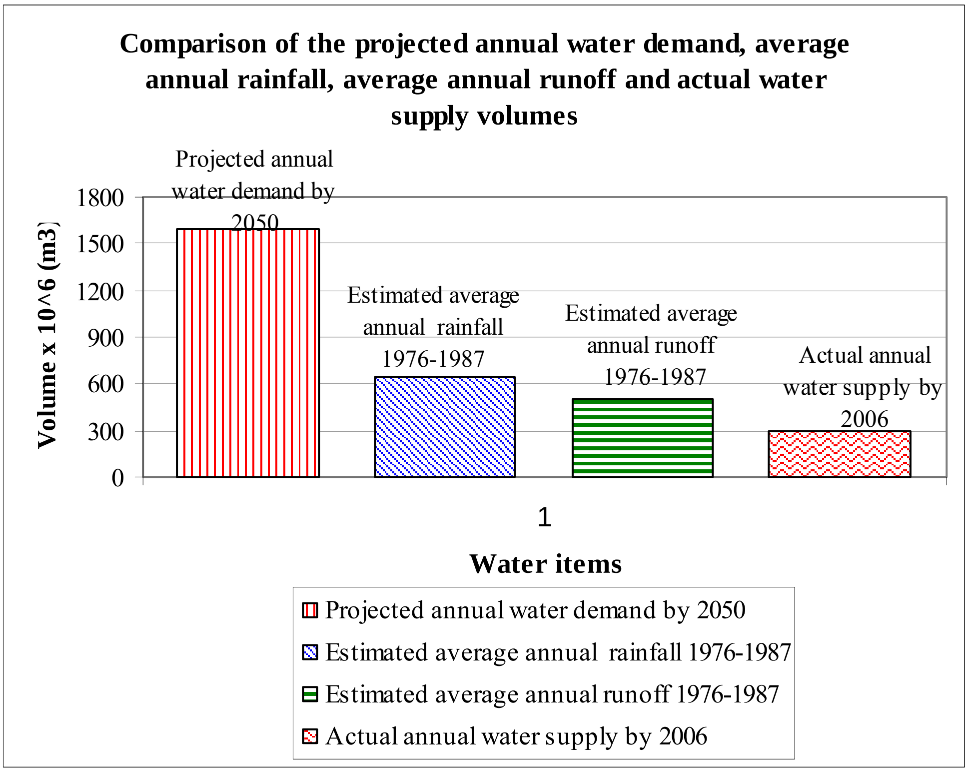

Figure 5.1: Chart comparing the annual water resources situation of the Mefou sub basin

The values used in making the comparison include the estimated runoff values obtained from the analysis of data from 1976 to 1987. The projected water demand by the year 2050 and the actual water supply is obtained from the 2006 water supply statistics for the sub basin (CRH *documents, 2006*).

The projected long term water demand of the Mefou sub basin cannot be met only from the available surface runoff and ground water recharge. Other external sources and possibly deep ground water abstraction will have to be studied for use in the sub basin.

5.3 Limitations and assumptions in the project

In spite of the results obtained in this project the limitations and assumptions that have been made in the data analysis and rainfall runoff model cannot be ignored.

Data analysis

Data homogeneity has been assumed for the Sangmelima and Yaoundé stations in order to obtain a linear relationship. It is assumed that the catchment is uniform without any variation of catchment characteristics through out.

The data analysis assumes a linear relationship between rainfall series, runoff series and rainfall-runoff.

This rational method provides a global estimate of the runoff coefficients from the linear relationship between runoff and rainfall which simplifies the reality of the rainfall-runoff process but is satisfactory for global volume estimations.

Looking at the calculated monthly runoff coefficients and the linear correlation coefficient obtained it can be seen that there is no clear cut direct correlation between the rainfall and runoff in the catchment. In reality, runoff depends on other catchment physical characteristics, type of rain storm, seasonal variations, land use and human activities.

Errors in data measurements have been ignored, however, there are always human and structural problems encountered in the field during observations of daily data.

The amount of years with available data is assumed to be adequate to analyse and obtain a satisfactory reflection of the hydrological and meteorological characteristics of the sub basin. In reality this number of years may be too few.

Rainfall-runoff model

The following limitations can be attributed to the rainfall-runoff model used in this project;
The model can only perform with the available data input and will give satisfactory results only if the data is of good quality.

The peak flows in the simulated curves are lower and less frequent than the observed peaks. The simulated curves also show fewer fluctuations than the observed hydrographs. This could be that there are some physical processes and parameters which the model could not simulate.

The calibration did not include enough years to simulate all the climatic conditions of the sub basin and data adjustment had to be made in order to obtain a satisfactory calibration. In the process some parameters could have been exaggerated or underestimated to obtain the required best fit results. It is possible to obtain good r^2 values while using wrong input parameters and data.

Changes in the physical characteristics of the catchment and human activities within the sub basin were not considered in the model simulation. The catchment was considered to be homogenous with the same characteristics within the entire area.

Lakes and reservoirs within the catchment were assumed to be negligible and did not affect the hydrological conditions of the sub basin.

The concepts of rainfall-runoff modeling are complex and to obtain a satisfactory and useful model good reliable data and a lot of time is required. The calibration as well as the validation can be affected by extreme values and special weather conditions. A model can never be perfect but can obtain a good position to predict future situations. Further studies and investigations have to be applied to a model result before being adopted for practical use.

5.4 Conclusions and Recommendations

The rational method using statistics and linear regression relationships give satisfactory and reasonable average rainfall and runoff values implying that this method can be used for hydrological estimations in catchments with scarce or partial data such as the Mefou Sub basin in spite of the limitations. The difficulties of such hydrological estimates have been highlighted in this project.

The Model simulation gave close values to the rational method. The HBV model is robust enough to perform satisfactorily in a catchment such as the Mefou and can therefore be used as a complimentary tool in hydrological estimates in similar basins.

Hydrological and meteorological measurements of good quality and adequate series length are important and absolutely necessary to monitor and propose solutions to the water resources problems of every catchment. It is impossible to be certain of any estimation using scarce or partially available data.

The total runoff of the Mefou Sub basin estimated from the runoff measurements made at the Nsimalen station and rainfall measurements at the Yaoundé and Sangmelima stations is insufficient to meet the long term water requirements of the Sub basin therefore supplementary sources have to be exploited to satisfy the long term demand.

Further studies have to be carried out on the ground water potential and other sources to be used as alternatives to supplement the water demand of the Sub basin.

It will be a good idea for other stochastic or neural modelling techniques to be applied in the sub basin and the results compared with that obtained in this study.

The government should make all the necessary effort to install and fund the minimum number of hydrological and meteorological measurement stations in all sub basins and minor water courses of Cameroon in order to be able to carry out satisfactory estimates of the water resources of different sub basins.

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Appendix 1: Summary of stations, available data and periods of measurement

STATION	FLOW Q(m^3/s)	Yrs	PREC. P(mm)	Yrs	TEMP. T(^{o}C)	EVAP. (mm/day)	ALT (m)	LAT.	LONG
YAOUNDE	1976-1977 1984-1986	5	1976-1982	7	1977-1983	Avg. 1955-2002	760	3°31'	11°30'
NANGAEBOKO			1975-1978	4	1977-1983		624	4°39'	12°22'
SANGMELIMA			1975-1987	13	1977-1983		713	2°56'	11°59'
YOKO			1975-1979	5			1031	5°32'	12°19'
LOMIE			1975-1980	6					
EBOLOWA			1977-1980	4			609	2°55'	11°09'
EDEA			1975-1979	5		1977-1983	32	3°48'	10^{o}08'
DJOUM			1976-1980	5			684	2°40'	12^{o}41'
BETARE OYA			1981-1990	10			805	5°36'	14°05'
BERTOUA			1975-1977	3			668	4°35'	13°41'

Appendix 2: Available annual rainfall for Yaoundé, Sangmelima and Betare Oya 1976 to 1990

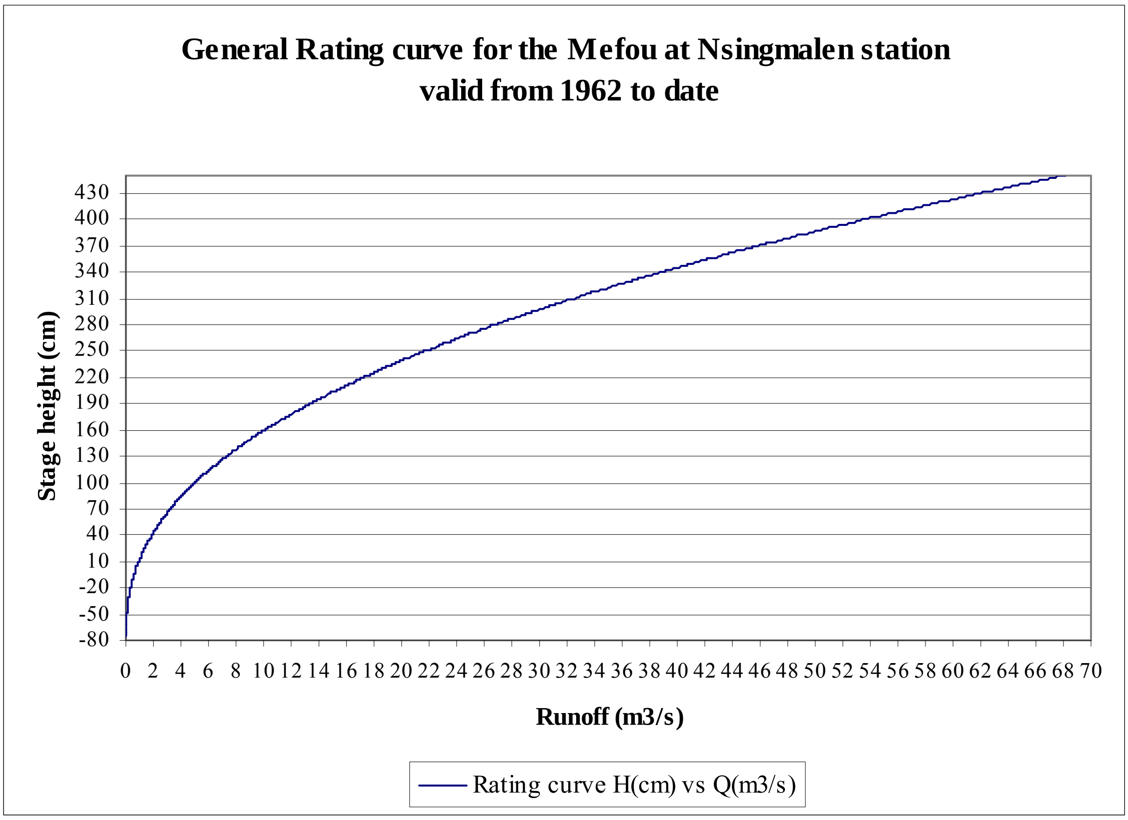
	Yaounde	Sangmelima	Betare Oya
Year	**P (mm)**	**P (mm)**	**P (mm)**
1975		1598.9	
1976	1371.8	1997.9	
1977	1291.7	1275.2	
1978	1494.7	1762.4	
1979	1547.9	1445.2	
1980	1591	1521	
1981	1635.5	1483.3	1544.1
1982	1567.2	**1507.5**	1817.8
1983		1489.07	1299
1984		1879.6	1491.2
1985		1999.8	1908.6
1986		1432.8	1223.2
1987		1437.2	1472
1988			1991.6
1989			1222.4
1990			1518.9
Annual Averag	**1500.0**	**1602.3**	**1548.9**

Appendix 3: Monthly Rainfall for Sangmelima and Yaoundé from available observed data

Sangmelima:		**Total monthly and average monthly Rainfall 1975 to 1987**									**(mm)**		
Year	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Year**
1975	20.8	90.4	158.8	137.1	207.4	125.3	143.5	6.8	161.9	270.8	251.4	24.7	**1598.9**
1976	4.6	129.3	137.2	184.3	240.8	198.5	135.3	184.8	233	231.8	307.4	10.9	**1997.9**
1977	13.9	64.2	126.5	137.9	113.3	79.1	42.6	125.3	262.3	216.7	78.9	14.5	**1275.2**
1978	0.8	22.1	86.9	319.7	243.5	226.4	60.5	115.9	276.8	237.9	133.8	38.1	**1762.4**
1979	31.6	33.6	167.6	117.4	153.7	213.4	93.6	41.6	162.9	223.7	144	62.1	**1445.2**
1980	0.5	27.2	110.3	106.8	173.2	177.8	84.3	181.5	235.2	298.2	121.2	4.8	**1521**
1981	5	132.7	149.8	112.9	142.5	147.5	147.3	62.7	126.6	286.8	126.4	43.1	**1483.3**
1982	9.1	48.2	128	143.6	264.6	168.8	54.2	100.2	242.5	295.1	47.1	6.1	**1507.5**
1983	0	13.2	80.6	185.5	268.6	149.2	91	44.5	176.7	354.7	112.8	12.3	**1489.1**
1984	0	61.9	128.4	228.5	185.4	224	201.2	120.9	272.8	335.8	118.2	2.5	**1879.6**
1985	57.6	13	204.9	243.2	232.6	120.7	123.3	197.7	271.7	306.4	219.3	9.4	**1999.8**
1986	25.7	71.2	211.3	130.1	184.2	87.7	32.2	16.7	183.3	390.1	100.3	0	**1432.8**
1987	0	34.5	159.9	112.8	194.3	127.1	99.3	51.9	258.2	251.6	124.7	22.9	**1437.2**
Average	**12.4**	**54.3**	**141.0**	**168.6**	**199.7**	**160.0**	**93.6**	**103.6**	**225.2**	**285.7**	**136.2**	**18.9**	**1602.3**

YAOUNDE	**Total monthly and average monthly Rainfall 1976 to 1982**									**(mm)**			
Year	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**	**Year**
1976	7.9	79.1	137.4	155.9	133.6	155.2	15.6	57.6	167.3	276.5	177.8	7.9	**1371.8**
1977	47.1	75.5	108.3	96.1	248.4	109.6	11.6	131.5	227.5	191.8	27.8	16.5	**1291.7**
1978	48.5	88	144.7	320.3	98.8	158.3	12.2	58.8	264.3	207.2	91.6	2	**1494.7**
1979	3.8	96.6	160.1	129.9	201.4	302.2	76.7	29	153.5	277.5	113.6	3.6	**1547.9**
1980	5.8	65	140.9	115	231.3	63.6	103.2	79	418.1	273.9	95.2	0	**1591**
1981	8.2	31.5	88.4	253.5	168.4	166.1	88.9	110.7	220.9	364	126	8.9	**1635.5**
1982	8.4	34	101.8	124.4	171.9	270.2	96.4	129.6	238.9	361.9	25.4	4.3	**1567.2**
Average	**18.5**	**67.1**	**125.9**	**170.7**	**179.1**	**175.0**	**57.8**	**85.2**	**241.5**	**279.0**	**93.9**	**6.2**	**1500.0**

Appendix 4: Rating curve for Nsimalen runoff measurement station



Rating curve for Mefou at Nsimalen runoff measurement station (source; *CRH, data*)

The relationship for runoff calculation is expressed as shown in *equation (20)* below;

$Q=Q_0*(H-H_0)^{n}$

Measured depth from the datum level varies from -80.0 to 450.0 cm → H_0 = -80.0 cm, and

Q_0= 18.61H*10^{-06}, n= 2.40909

Where;

Ho = the initial stage height (cm) which is the constant water level in the measurement weir.

Qo = an estimated runoff constant.

H = the measured stage height (cm)

n = runoff calibration parameter.

Appendix 5: Monthly runoff and runoff coefficients for the Mefou Sub basin 1976-87

Total monthlyrunoff (m3/s) at Nsimalen flow measurement station 1976 to 1986.(5 years)

Year	Jan	Feb	Mar	Apr	May	Jun	JUL	Aug	Sep	Oct	Nov	Dec
1976	58	68	96	121	128	165	71	65	87	259	349	121
1977	90	59	84	98	193	139	71	107	224	398	171	107
1984	60	47	132	242	263	410	416	405	443	527	432	237
1985	202	126	202	276	283	253	231	260	399	594	481	347
1986	227	191	241	234	321	403	237	214	264	423	326	171

Average daily runoff (m3/s) at Nsimalen flow measurement station 1976 to 1986.(5 years)

Year	Jan	Feb	Mar	Apr	May	Jun	JUL	Aug	Sep	Oct	Nov	Dec
1976	1.88	2.34	3.11	4.04	4.14	5.50	2.28	2.10	2.90	8.35	11.62	3.89
1977	2.91	2.11	2.72	3.27	6.23	4.63	2.29	3.44	7.46	12.84	5.70	3.45
1984	1.95	1.62	4.24	8.07	8.50	13.66	13.42	13.05	14.77	17.00	14.40	7.63
1985	6.51	4.51	6.52	9.20	9.13	8.43	7.45	8.40	13.32	19.15	16.02	11.21
1986	7.33	6.81	7.77	7.78	10.36	13.44	7.66	6.90	8.80	13.64	10.85	5.53

Total monthly runoff (mm) at Nsimalen flow measurement station 1976 to 1986.(5 years)

Year	Jan	Feb	Mar	Apr	May	Jun	JUL	Aug	Sep	Oct	Nov	Dec
1976	11.9	12.9	19.6	23.9	26.1	32.4	14.4	13.2	17.1	52.6	68.6	24.5
1977	18.3	12.0	17.2	19.9	39.3	28.2	14.4	21.7	45.5	80.9	34.7	21.7
1984	12.3	9.5	26.8	49.2	53.6	83.3	84.6	82.3	90.1	107.1	87.8	48.1
1985	41.0	25.7	41.1	56.1	57.5	51.4	47.0	53.0	81.2	120.7	97.7	70.6
1986	46.2	38.8	49.0	47.5	65.3	81.9	48.3	43.5	53.7	86.0	66.2	34.9

Monthly rainfall-runoff coefficients of the Mefou sub basin for 1976 to 1986 (5 years)

Year	Jan	Feb	Mar	Apr	May	Jun	JUL	Aug	Sep	Oct	Nov	Dec
1976	1.50	0.16	0.14	0.15	0.20	0.21	0.92	0.23	0.10	0.19	0.39	3.11
1977	0.39	0.16	0.16	0.21	0.16	0.26	1.24	0.16	0.20	0.42	1.25	1.32
1984	1.30	0.15	0.22	0.23	0.31	0.40	0.45	0.71	0.36	0.35	0.77	4.14
1985	0.68	1.23	0.22	0.25	0.27	0.44	0.40	0.29	0.33	0.43	0.48	3.99
1986	1.44	0.54	0.25	0.38	0.38	0.95	1.28	1.80	0.31	0.24	0.68	3.70
Average	**1.06**	**0.45**	**0.20**	**0.25**	**0.26**	**0.45**	**0.86**	**0.64**	**0.26**	**0.33**	**0.71**	**3.25**
Wgted avera	**0.76**	**0.32**	**0.22**	**0.25**	**0.36**	**0.66**	**0.75**	**0.45**	**0.29**	**0.52**	**1.98**	**2.16**

Appendix 6: Average monthly potential evapotranspiration (mm) at Yaoundé and Edea meteorology stations

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Yaoundé	117	117	114	109	106	89	77	80	87	97	112	113	**1218**
Edea	122	127	123	121	114	108	83	86	98	109	113	119	**1323**