Regionalization of flow duration curve for Abbay Basin using GIS technique

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Glory to ALMIGHTY GOD.

Pages

Abstract i

Table of content ii

Acknowledgements iv

List of symbols and abbreviations v

Introduction

Background 3

Abbay River and its Basin 5

Problems 8

Hydropower 8

Irrigation 9

Objective 9

Previous studies 9

Hydrological analysis and regionalization

Availability of data 10

Hydrological data 10

Metrological data 10

Identification of regions 11

Monthly rainfall patterns and classification of regions 11

Evaporation patterns 18

Flow duration curve and low flow analysis

Analysis of flow duration curve from monthly stream flow 18

Estimation of daily flow from monthly flow 24

Flow duration curve in relation to low flow analysis 29

Prediction of low flows from catchments characteristics 30

Low flow analysis 30

Estimation of low-flow characteristics for ungauged catchments

Multiple linear regression approach 32

Single linear regression approach 36

Selection of catchments characteristics 36

Prediction of low flows from catchments characteristics.

Geographic information systems 40

Water shade delineation 42

Catchments elevation 42

Station elevation 42

Stream length 42

Stream slope 42

Prediction of low flow 43

Discussion and recommendations

Discussion 56

Recommendations 57

References 58

Bibliography 60

Appendices

A Some information on hydrological stations 62

B	Some information on meteorological stations	75
C	Catchment physiographic and hydrometeorological characteristics	82

List of Symbols and Abbreviations

a,b,c	Constants in low flow regional equations,
ADF	Average daily flow (m^3/s),
AREA	Catchment area in Km^2,
b at the	Constant in regression equation, it is the value of y point where the line crosses the y-axis,
D	distances between cell sizes which is equal to 90m,
DEM	Digital Elevation Model,
d_f	The degrees of freedom,
E	Percent of exceedance in (%),
EEA	Ethiopian Engineers and Architects,
EEPCO	Ethiopian Electric and Power Cooperation,
F	The F statistic or the F-observed value,
FAO	Food and Agriculture Organization,
FDC	Flow Duration Curve,
GIS	Geographic Information System,
GLCF	Global Land Cover Facility,
i	rank,
K	Recession constant for each month,
L the in m,	Length of the main stream from the gauging site to head of the stream (or up to the divide line)
L	Multiplier constant for each month,
LENGTH	River length in m,
m	Number of sites included in the region,

m_1, m_2, m_3,…,m_n	coefficients of independent variables,
MF	Median flow,
MoWR	Ministry of Water Resources,
MW	Mega Watt,
NASA	National Aeronautics and Space Administration,
NGA	National Geospatial-Intelligence Agency,
NMSA	National Meteorological Services Agency,
$\overline{P}_j$	Mean monthly regional rainfall profile for month $_J$,
$(P_J)_k$	Mean monthly rainfall profile of the k^{th} station,
P_J the	Mean monthly rainfall of the month $_J$ in percent of annual rainfall,
PR_J	Mean monthly rainfall of the month $_J$ in mm,
$Q_{(standardized)}$	Standardized discharge dimensionless,
Q_{70}	Average low flow with 70% exeedance in m^3/s,
Q_{80}	Average low flow with 80% exeedance in m^3/s,
$Q_{avg.(data)}$	Average monthly flow given in m^3/s,
$Q_{avg.(estimated)}$	Average monthly flow estimated in m^3/s,
Q_i	Estimated daily flow of rank i in (m^3/s),
$Q_{min.(data)}$	Minimum monthly flow given in m^3/s,
$Q_{min.(estimated)}$	Minimum monthly flow estimated in m^3/s,
R	Mean annual rainfall in mm,
r^2	The coefficient of determination,
S_1,S_2,S_3…S_n	Slope between adjacent cells in %,
Se_1,se_2,...,se_n	The standard error values,

Se_b	The standard error value for the constant b,
se_y	The standard error for the y estimate,
SRTM DEM	Shuttle Radar Topographic Mission, Digital Elevation Model
ss_{reg}	The regression sum of squares,
ss_{resid}	The residual sum of squares,
$x_1, x_2, x_3, \ldots, x_n$	Catchment's characteristics,
y	Estimated y-value in m^3/s,
Y	Actual y-value in m^3/s,
y	Stream flow characteristics (low flow) in m^3/s,

Abstract

Water resource development planning is usually referred as the process to define how to utilize the available water resource to meet the desired objectives. In order to compensate for the scarcity of data for the available water resource, regionalization is found to be one of the best methods of transferring information from the gauged station to ungaged sites.

The purpose of this paper is to develop regionalized Flow Duration Curve for Abbay Basin. Based on similarity of standardized rainfall patterns eight regions were identified and Flow Duration Curves of each region are developed.

For the development of reliable flow duration curve, daily flow distribution from the mean monthly stream flow is derived. Flow Duration Curve based on the estimated daily flow is developed and an equation for each region is determined.

The regional equations were developed using regression analysis. These equations relate discharges of 70 and 80 percent of exceedance for ungauged watershed in the basin, or for short record length stations and catchment characteristics.

Estimation of low flow for ungaged sites (below 50% of exeedance) can be obtained using regional regression method and subsequently Flow Duration Curve for each regions.

For the evaluation of hydropower potential sites requires knowledge of the time availability of flow at a certain point in a river as described in Flow Duration Curve. It is also useful in other hydrologic investigations where knowing the average time

availability of flow is required, such as for irrigation projects and others.

1. Introduction

The rural and the major population of Ethiopia depend on agriculture and the source of water is from the rain. Agriculture that relies only on direct rainfall is sometimes referred to as dry land farming. In contrast irrigation is the replacement or supplementation of rainfall with water from another source in order to grow crops or plants. The water source for irrigation may be as nearby or distant body of lake such as a river spring lake, aquifer or well. Depending on the distance of the source and the seasonality of rainfall, the water may be channeled directly to the agricultural fields or stored in reservoirs for later use.

Therefore, as agricultural product is the backbone of the country's economy. The development of irrigation in Ethiopia is essential.

Out of 80 million population of Ethiopia more than 85% live in rural area and only 1% of this population has access to electricity. Today the largest use of hydropower is for electric power generation, which allows low cost energy to be used at remote distances from the watercourse.

Therefore an important sector for development in Ethiopia is hydropower. Hydropower is the harnessing energy of moving water for some useful purpose. In the absence of widespread availability of commercial electric power, hydropower can also be used for irrigation and for other industries like textile manufacture, sawmills and similar.

Most of the river basins in Ethiopia are suitable both for hydropower and irrigation developments. But hydrological and metrological stations in Ethiopia are few in number, unevenly distributed, very limited record length and large unobserved record gaps resulting in un-gaged catchments in river basins. When project development is planned for these un-gaged catchments hydrologists are facing difficult task of assessing the water availability in the source.

The research carried out for this thesis is on Abbay River and its basin located on the north-western part of Ethiopia. It has a promising future expansion and in comparison to other basins the river stands as one of the leading rivers in Ethiopia, besides its important role to the riparian countries like Sudan and Egypt.

Though Abbay is one of the major rivers in Ethiopia, this river has a very limited rain gauge coverage and limited meteorological data. In the absence of sufficient hydrological and meteorological data from the upper stream, the hydrological assessment of the Abbay River becomes more dependent on downstream measurements. Most studies of the Blue Nile typically begin near the Sudan-Ethiopia border and progress towards Khartoum (A. Mishra et.al., 2003).

The two major constraints, namely limited meteorological and hydrological data and complex methods of investigation, are applicable not only to Abbay but also throughout the basins in the country. But the important and basic development strategies such as hydropower and irrigation need hydrological and metrological data as a basis for designs and studies.

The main objective of this thesis is to develop flow duration curve from gauged river catchments and infer its result be regionalization for the ungauged catchments of similar characteristics. GIS technique is used to derive some of the catchment characteristics. The two key words of this objective are described below:

Regionalization

Regionalization is a generally understood term to explain information transfer from gauged catchments to other ungauged catchments of similar characteristics. It can also be used for gauged catchments with limited record length.
From the gauged catchments homogeneous regions are grouped into regions that are similar in terms of catchments hydrological responses. Ungauged catchments within the identified homogeneous regions can refer to the information (for this thesis, flow duration curve) obtained from the gauged catchments. This approach is suitable in conditions of limited data availability.

Flow duration curve

Flow duration curve (FDC) is a method of describing the time availability of flow at a certain point in a river. It is a plot of flow versus the percent of time that a particular flow can be expected to be exceeded. FDC is a useful tool in hydrologic analysis in general and especially useful in hydropower studies. It is also useful in other hydrologic investigations where knowing the average time availability of flow is required, such as for irrigation projects.

In the absence of sufficient meteorological and hydrological data, these methods can be an important tool for the analysis of water resources in planning the development of irrigation and hydropower of Ethiopia, especially in the construction of mini and micro hydropower and they can be applied to all other river basins of the country.

1.1. Background

The East African Rift System divides the plateaus giving rise to the existence of two drainage basins. The eastern plateau slopes to the southeast towards the Indian Ocean and the western plateau slopes to the west towards Sudan (*Admasu Gebeyehu*, 1988). Both branches of the Nile are on the western flanks of the East African Rift. The Abbay River (Figure 1.1) that joins the White Nile in Sudan drains into the Mediterranean Sea where as the other major Rivers of Ethiopia located in the Eastern Plateau drains into the Indian Ocean. Therefore, the Great Rift of Eastern Africa divides the two important drainage basins, that is, the Mediterranean and the Indian Ocean Basin and the Abbay River Basin located at the north west of Ethiopia is part of the Mediterranean drainage basins.

Geo-scientists assume that Lake Tana, also located at the north west of Ethiopia and the source of Abbay River, was first formed during the early stages of the river system development millions years ago and during the Pre-Nile phase the major Nile System captured the Abbay River and this became the dominant source of sediments. Throughout its history the Abbay River, as with the whole Nile, has been greatly influenced by tectonic setting and relative sea level.

The traditional source of the Abbay is a spring which feeds the little Abbay, a stream which flows North-East into Lake Tana. Lake Tana itself lies at an elevation of a little over 1800 m and was formed when a young lava flow blocked the river, flooding a shallow depression. Lake Tana is a natural lake with a surface area of 3150 km^2. From Lake Tana the Abbay River flows in a southwesterly direction for 35 km until it reaches Tissiasat Falls where it drops 50m.

Why should the river that tumbles out of the Ethiopian highlands and joins the White Nile at Khartoum be called the Blue Nile? It is not particularly blue. Perhaps it should be called the Summer River, because for most of the year it provides little water compared to the White Nile, but in the rainy season it is very much the dominant tributary. It is the annual flooding of the Abbay along with that Tekezze to the north which also flows out of the Ethiopian highlands that caused the Nile to rise each year in Egypt. It is erosion of the basalt lavas of the Ethiopian highlands that allow the river each year to bring a fresh varnish of black mud to its floodplain.

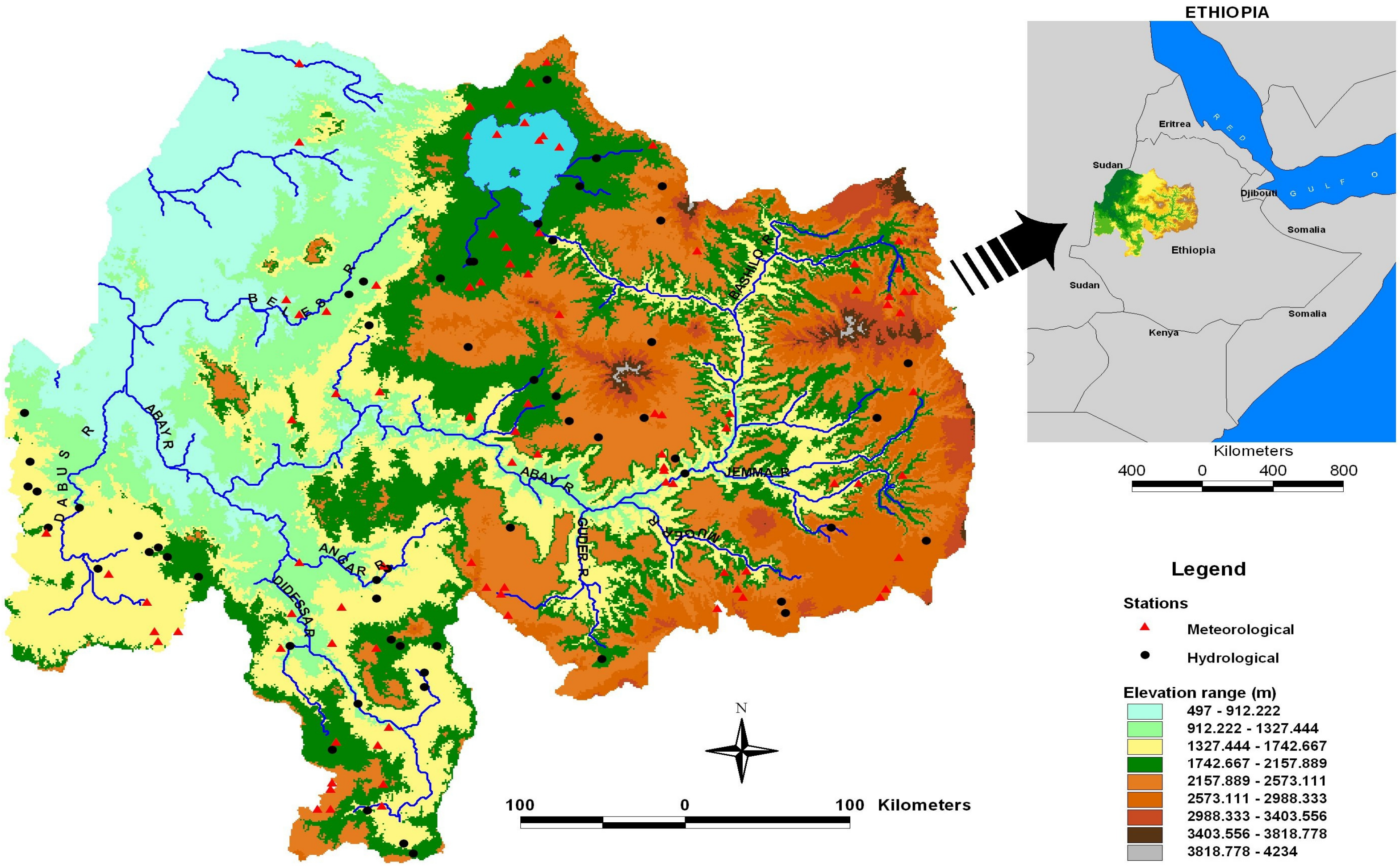

Figure 1.1 Abbay River Basin

1.2. Abbay and its Basin

The country is endowed with large amount of water resource potential having around seven major rivers such as: Tekezze, Abbay, Awash, Baro, Omo, Wabishebelle, and Genale. Abbay River is one of the longest and out of 12 drainage basins of Ethiopia Abbay ranks the second having an area of 199,407 km^2. Abbay River is the upper part of the Nile that runs North-South through eastern Africa and after joining with White Nile drains into the Mediterranean Sea.

The Abbay River is fed by seven main streams: Bashilo R., Jemma R., Muger R., Guder R., Didessa R. and Angar R., Dabus R and Beles R., (Figure 1.2), The Abbay River flows about 1,400 km to Khartoum where it joins the White Nile to form "Nile" and contributes nearly 80-90% of the Nile discharge, with the remainder being supplied by the White Nile and other tributaries. About 96% transported sediment carried by Abbay River originates in Ethiopia, but the runoff happens during the rainy season as a result of the monsoonal rains over Ethiopia. The flow of the Abbay River varies considerably over its yearly cycle and is the main contribution to the large natural variation of the Nile flow. The river is also an important resource for Sudan where dams produce 80% of the country's power as well as irrigation of the Gezira Plain.

The Blue Nile, - Geez-*Tikur Abbay* or Ghion*,* to Ethiopians and *Bahr al* Azrak to Sudanese is the major tributary of the Nile. The numerous names given to the river reflect the river's complex history involving the river, the people who make their livelihood from it and those who were determined to rule it.

Although James Bruce claimed to have been the first European to have visited the headwaters of the Nile and modern writers with better knowledge give the credit to the Jesuit Pedro Paez, a Portuguese priest in 1600's. It took almost 360 years before the gorge of the Nile was completely mapped by the west.

On April 28, 2004, geologist Pasquala Scaturro and his partner Kayaker and documentary filmmaker became the first people to navigate the Abbay River, from Lake Tana in Ethiopia to the beaches of Alexandria on the Mediterranean. They documented their adventure with an IMAX camera and two handheld video cameras sharing their story in the IMAX film **"*Mystery of the Nile*".**

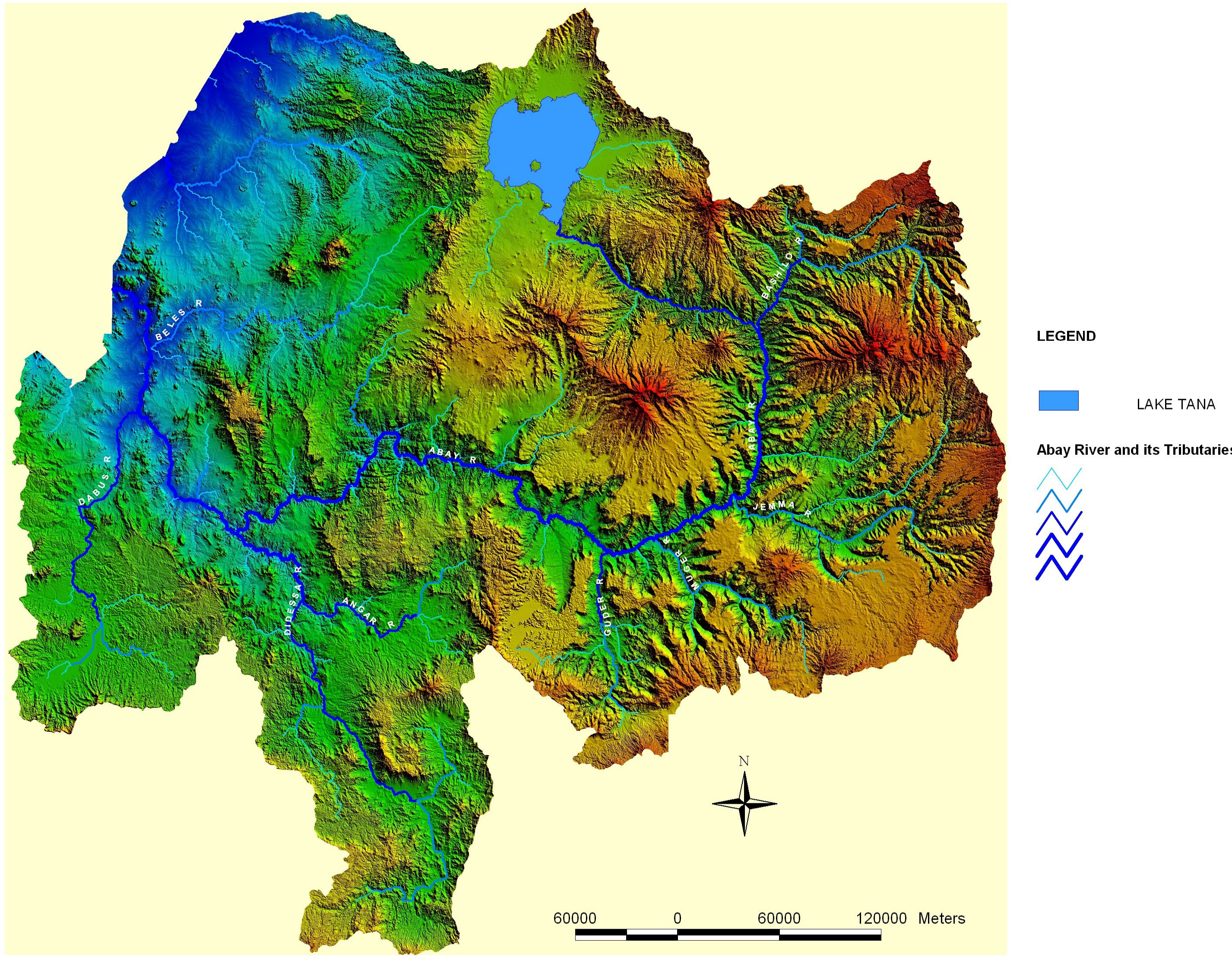

Figure 1.2 Abbay Basin and its main tributaries

Relief

The northern part of the East African Rift System known as the Ethiopian Rift Valley that runs North-North-East to South-South-West cut through the central highlands of Ethiopia and dividing them into Eastern and Western Plateaus. Peak mountains with an altitude of more than 4000 m, plateaus of more than 2000 m, plains of 100's m and even deserts below sea level, valleys and gorges as well as active volcanoes are the main morphological features of Ethiopia.

Abbay Basin as part of the western plateau system of Ethiopia, it travels through several plateaus which are above 2600 m, with several peaks up to 4000 or more in places the River flows 1300 below the level of the plateau on each side. Abbay continues at the foot of the plateau and then to the plain that slopes gradually westwards down into Sudan from a height of about 700m and flows down to an altitude of 490 in Sudan. With a difference of more than 2000 m in altitude the river passes through deep gorge within the plateau and when it reaches the White Nile in Sudan it flows to the north through Egypt entering the Mediterranean Sea.

Climate

Abbay Basin is approximately located between 7.7^0N to 12.75^0N and 34.0^0E to 39.8^0E (Figure 1.1). Its location being near the equator and the wide range of altitude between 5000m and 4,200 m experience a rich variety of local climate ranging from hot and nearly desert along the Sudan border to temperate on the high plateaus or even cold on the mountain peaks.

The Abbay Basin, which is one of the largest and wettest basin of Ethiopia around 16% of the total area of the country covers an area of 199,407 km^2 (*Admasu, Gebeyehu, 1988*).

The average annual rainfall over the Abbay River Basin is about 1600 mm, which increases from about 1000 mm near the Sudan border to about 1400-1800 mm over the parts of upper basin near lake Tana (*A. Mishra et al, 2004*). Based on the rainfall regimes, the National Meteorological Services Agency (NMSA) defined a general three – season division in Ethiopia – Bega (dry season), Belg, (small rainy season), and Kiremt (big rainy season), which the Basin also shares.

Land cover

The eastern part of the Abbay River basin is cultivated for crops and some are covered with natural vegetation and others are left as grassland. Whereas the western part of the basin, near the border of Sudan are lowlands and mostly savanna.

Population

The cultivated section of the Blue Nile, which is the eastern part, population is between 100-500 person per km^2 and between 40100 person per km^2 near the Sudan border.

1.3. Problems

The scarcity of hydrological and metrological data is drawback for the development of:

1.3.1. Hydropower

More than 85 % of the population of Ethiopia lives in rural areas with less than 2,000 inhabitants scattered over the whole country. This type of rural settlement is difficult and expensive for the provision of power. The Ethiopian Electric and Power Cooperation (EEPCO) provides electricity to about 500,000 domestic customers out of which 230,000 of them are in Addis Ababa. Only 1% of the rural population has access to electricity. The source of energy for the population is on fuel-wood, crop residues etc. (Table 1.1).

Table 1.1 Relative importance of different energy sources in Ethiopia (Hedi Feibel)

Energy source	Percentage of total Ethiopian energy consumption [%]*
Fuel-wood	77
Dry dung	9
Agro-residues	8
Petroleum products and electricity	5
Charcoal	1

*Human and animal tractive force not included

The use of alternate sources of energy for domestic and productive purposes consumes a disproportionately high share of people income and seriously damages the environment. Insufficient energy supplies also impede the development of businesses as well as social infrastructure and services.

Today the largest use of hydropower is for electric power generation, which allows low cost energy to be used at long distances from the watercourse.

Ethiopian power sector has installed capacity of 658.75 MW and additional 750 MW is under construction in hydro power. As compared to the number of population in Ethiopia (8*0Million*) the installed power capacity does not fulfill the demand of the country. It is one of the lowest power supply per capita in the world.

1.3.2. Irrigation

More than 85 % of the population of Ethiopia, living in rural areas, depends directly on agriculture and the remaining depends indirectly on agriculture. In most areas of the country agriculture is dependant on the amount of rain and its distribution. Heavy rain creates flooding and damages the crops. No rain or scarcity of rain creates famine.

To balance the distribution of water resources man discovered a method of water storing during excess rainfall for the during less or no rainfall period, and is called irrigation. Though agriculture products are the bases for the country's economy system, irrigation is not well developed.

1.4. Objective

The main objective of this study is to develop the regional flow duration curve for Abbay Basin by collecting the discharge data of gauged catchments for the use of the un-gauged catchments in the same region. Information about flow-duration curve at one catchment can be inferred from other catchments with similar characteristics by regionalization.

1.5. Previous studies

- Unpublished report, on regional analysis of some aspects of stream flow characteristics in Ethiopia by Admasu Gebeyehu (1988) was the major reference for this study. However, most of the hydrological and metrological data used are different and updated. The regional classification is found to be similar.

- Optimization of small hydropower sites for rural electrification by Zelalem Hailu (1991). Regionalization of flow duration curve was made.

- According to BCEOM (1999), Abbay Basin Master Plan project, there were a number of institutions which conducted a project feasibility study in the basin or nation wide master plan studies. These included LAHMEYER (1962), USBR (1964), JICA (1977), EVDSA (1980), HALCROW-UGL (1982), WAPCOS (1990). A good review of the available hydrologic data has been covered in respective studies and a better insight to particular project areas were available in these studies.

2. Hydrological analyses and Regionalization

2.1. Availability of data

2.1.1. Hydrological data

The hydrology department of the ministry of water resources (MoWR) is the responsible department for the collection of hydrological data in Ethiopia. Upon an official request to the water resource ministry, hydrological data relevant to the study have been collected for the basin. The provision of daily flow record is very restricted and was not available for the user; hence this thesis is based on monthly maximum, minimum and total discharge.

From the 56 stations collected from the Ministry, the longest data record has started from late 1950 (Gregorian calendar) but very few in number, most of the stations are relatively new around 1980. The selection of these stations is based on relatively long data record, more or less distributed over the basin and limited record gap. The location of these stations was obtained from the MoWR as a shape file. It was observed that these stations are unevenly distributed over the basin and are along the access roads. Due to inadequate maintenance, management and insufficient resources, some stations have large record gap and some are not operational. As a result few catchments are gauged. The name of the stations and their location is as shown in Appendix A.1

2.1.2. Metrological data

The National Meteorological Service Agency (NMSA) is the responsible organization for the collection and issuing of meteorological data. Even though, the number of stations is larger than the hydrological stations, the same problems hold true for the uneven distribution and record gap.

A choice for provision of rainfall data record was given by NMSA between daily rainfall data and limited number of stations and monthly rainfall data and large number of stations. It was decided that the number of rainfall stations has more relevancy than the daily rainfall record and 91 rainfall stations with monthly rainfall record was collected from the agency.

The name of stations and their location is as shown on Appendix B.1

In addition to rainfall data, parameters like, minimum temperature, maximum temperature, wind speed, relative humidity, sunshine hours and number of rainy days were obtained for Abbay basin.

2.2. Identification of regions

2.2.1. Monthly rainfall patterns and classification of regions.

In the hydrologic cycle, moisture comes from the atmosphere to the surface as precipitation. It is the source of surface and ground water. Since, the rainfall pattern and intensity greatly influences the runoff, it can be used to identify the homogeneous regions for Abbay basin.

The monthly rainfalls of each station were averaged. These values were expressed as percentages of the mean annual rainfall (Admassu Gebeyehu, 1988, 1989) as follows:

$$P_j = 100 \cdot \left(\frac{PR_j}{R} \right) \qquad \text{(2.1)}$$

Where:

$$R = \sum_{j=1}^{12} PR_j \qquad \text{(2.2)}$$

R	=	mean annual rainfall in mm
PR_J	=	mean monthly rainfall of the month $_J$ in mm
P_J	=	mean monthly rainfall of the month $_J$ in percent of the annual rainfall.

The monthly standardized (or dimensionless) profiles obtained from equation (2.1) vary substantially between stations in the basin in well defined patterns. (Appendix B.2). Three basically distinct rainfall patterns are observed as:

Type 1: Strongly peaked unimodal profile with peak between June and September and dry from October to May.

Type 2: Strongly flattened unimodal profile with maximum from May to September.

Type3: Skewed bimodal profile with absolute peak in August and relative peak in April.

Further re-division was made to narrow the differences in the magnitude of P_J and final eight homogeneous rainfall regions were identified.

Then, profiles for each region are calculated as:

$$\overline{P}_j = \frac{\sum (P_j)_k}{m} \qquad \text{.......(2.3)}$$

Where:

$\overline{P}_j$ = mean monthly regional rainfall profile for month $_J$.

$(P_J)_k$ = mean monthly rainfall profile of the k^{th} station.

m = number of sites included in the region.

The values of $\overline{P}_j$ are shown on table 2.1 and also on figure 2.1. Figure 2.1 also includes mean monthly regional stream flow profile for comparison. The region will be designated by the number shown on the figure 2.2.

Table 2.1 Regional mean monthly rainfall in percent of the mean annual rainfall.

Month	Regions							
	1	2	3	4	5	6	7	8
January	0.2	0.6	0.3	0.9	0.4	1.2	2.2	1.5
February	0.3	1.0	0.4	1.0	0.4	1.6	3.9	2.7
March	1.3	3.1	1.7	3.2	1.7	4.3	6.5	5.5
April	2.4	4.3	3.9	4.1	3.9	6.0	8.4	6.0
May	7.4	8.1	9.5	8.9	11.4	11.2	6.8	4.9
June	13.7	12.7	16.3	15.7	17.8	15.7	3.9	6.7
July	28.1	24.3	19.7	23.6	18.8	17.5	24.1	28.1
August	26.0	23.5	20.3	20.7	18.8	17.7	26.6	29.2
September	12.9	13.1	17.0	13.8	17.8	13.8	10.1	10.3
October	6.1	6.4	8.4	5.8	7.2	7.8	4.2	3.4
November	1.3	1.7	1.9	1.4	1.3	1.9	1.6	0.9
December	0.3	0.9	0.7	1.1	0.3	1.3	1.7	0.9

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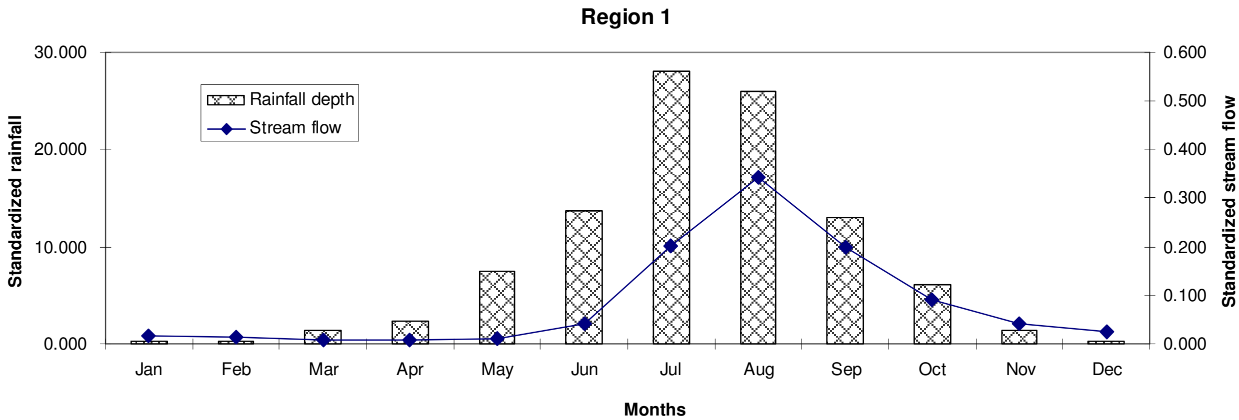

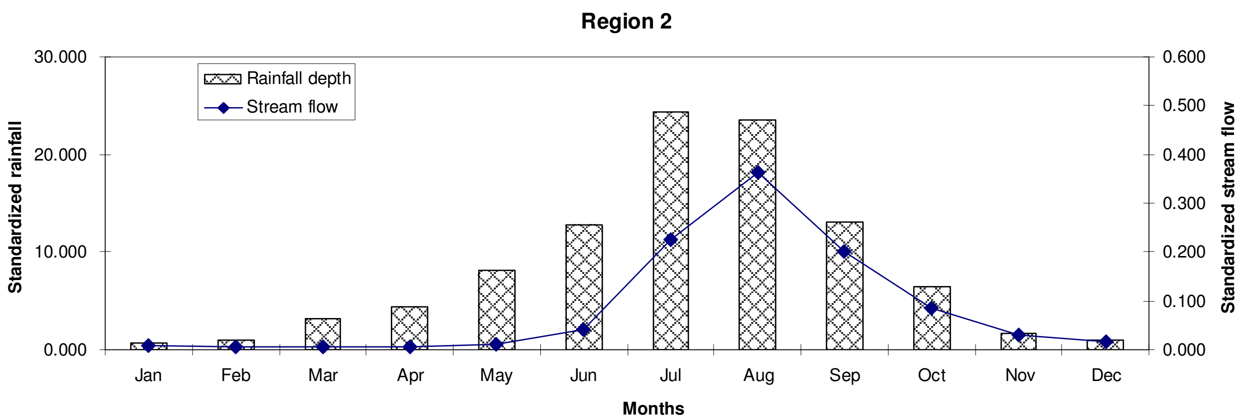

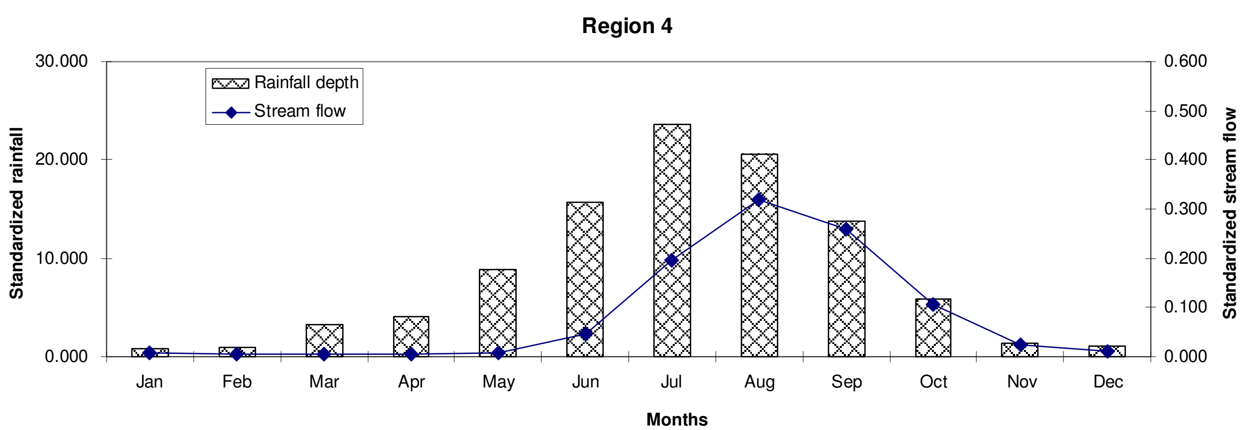

Figure 2.1 Monthly rainfall and stream flow in percent of the annual.

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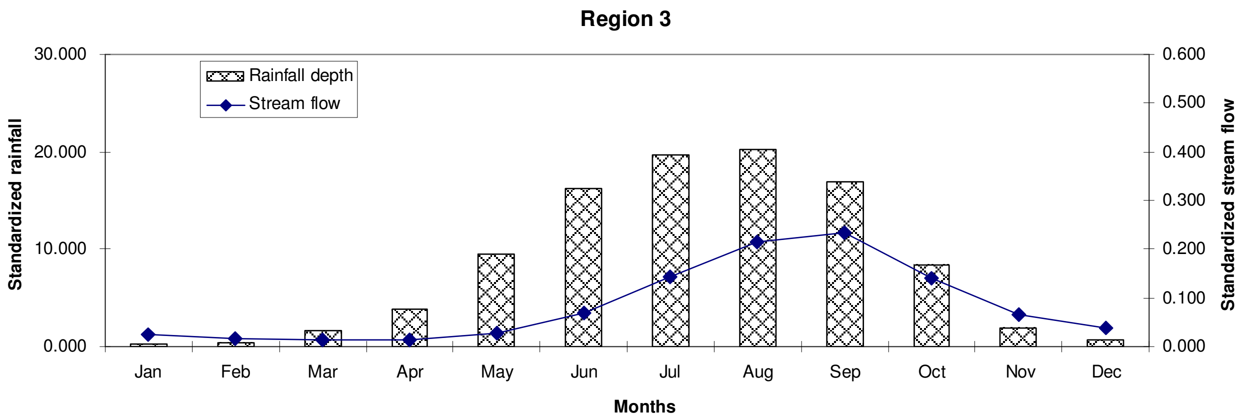

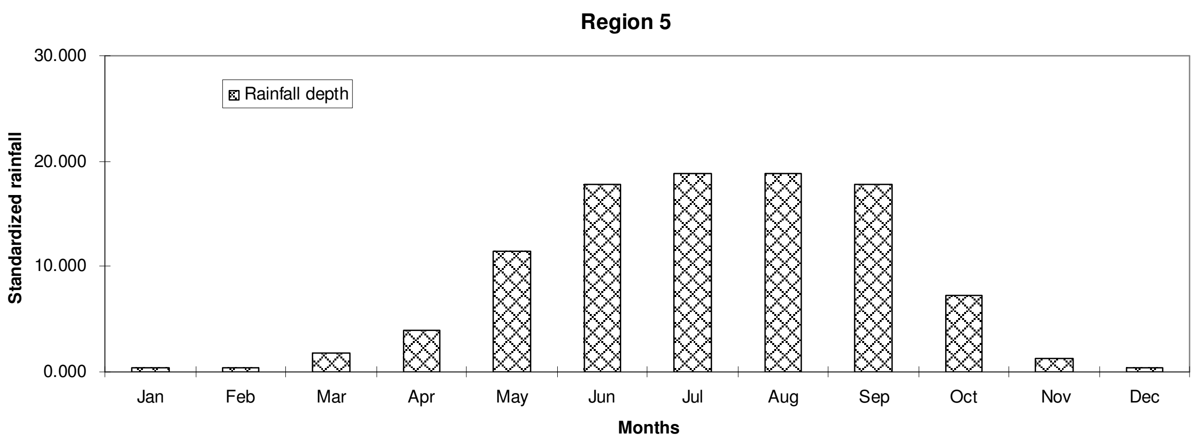

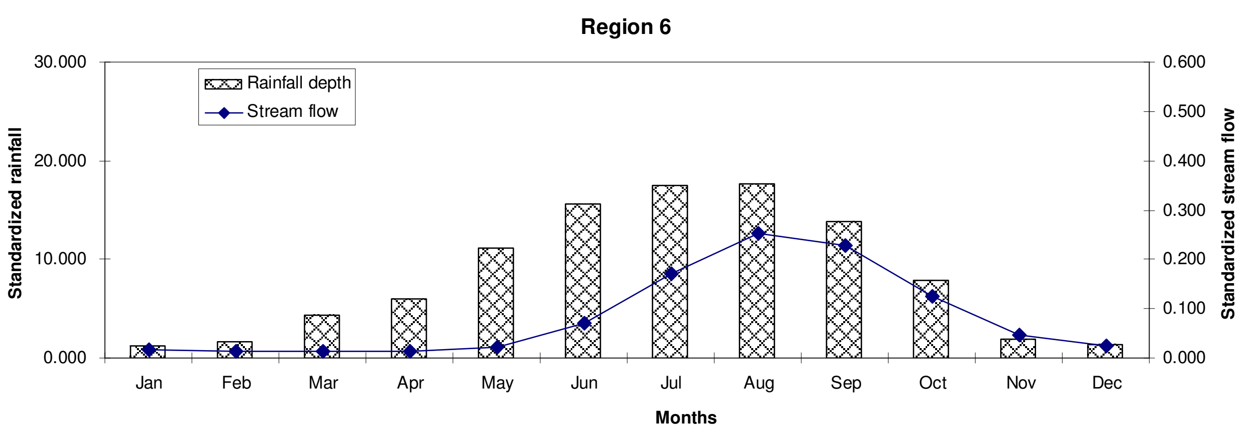

Figure 2.1 Monthly rainfall and stream flow in percent of the annual (Continued)

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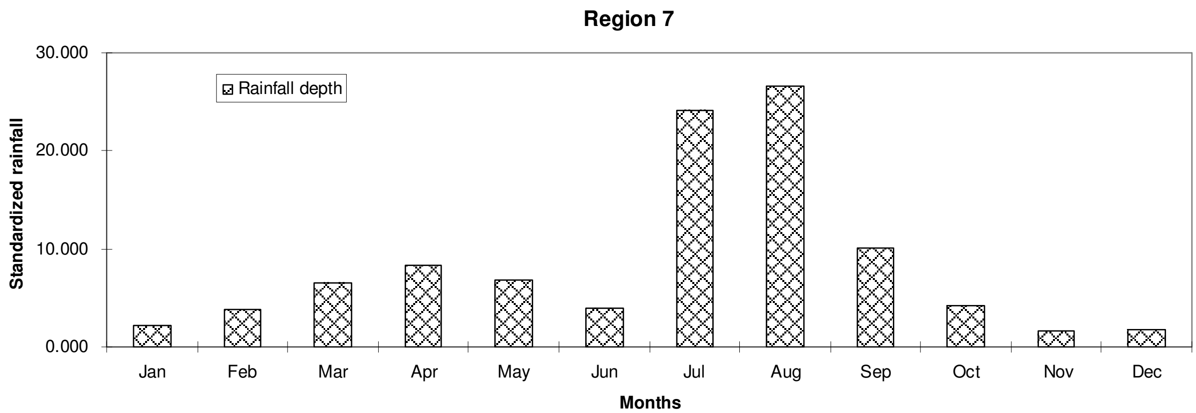


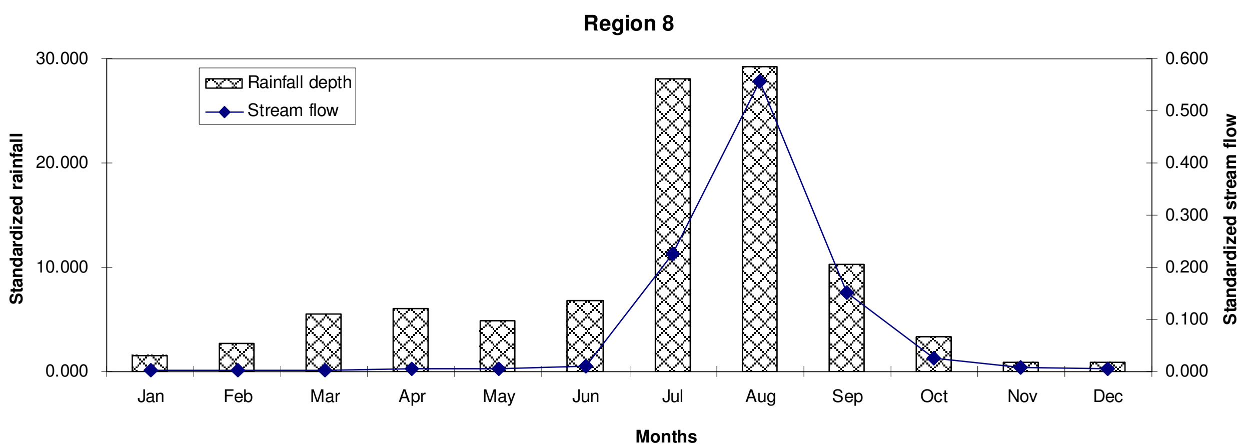


Figure 2.1 Monthly rainfall and stream flow in percent of the annual (Continued).

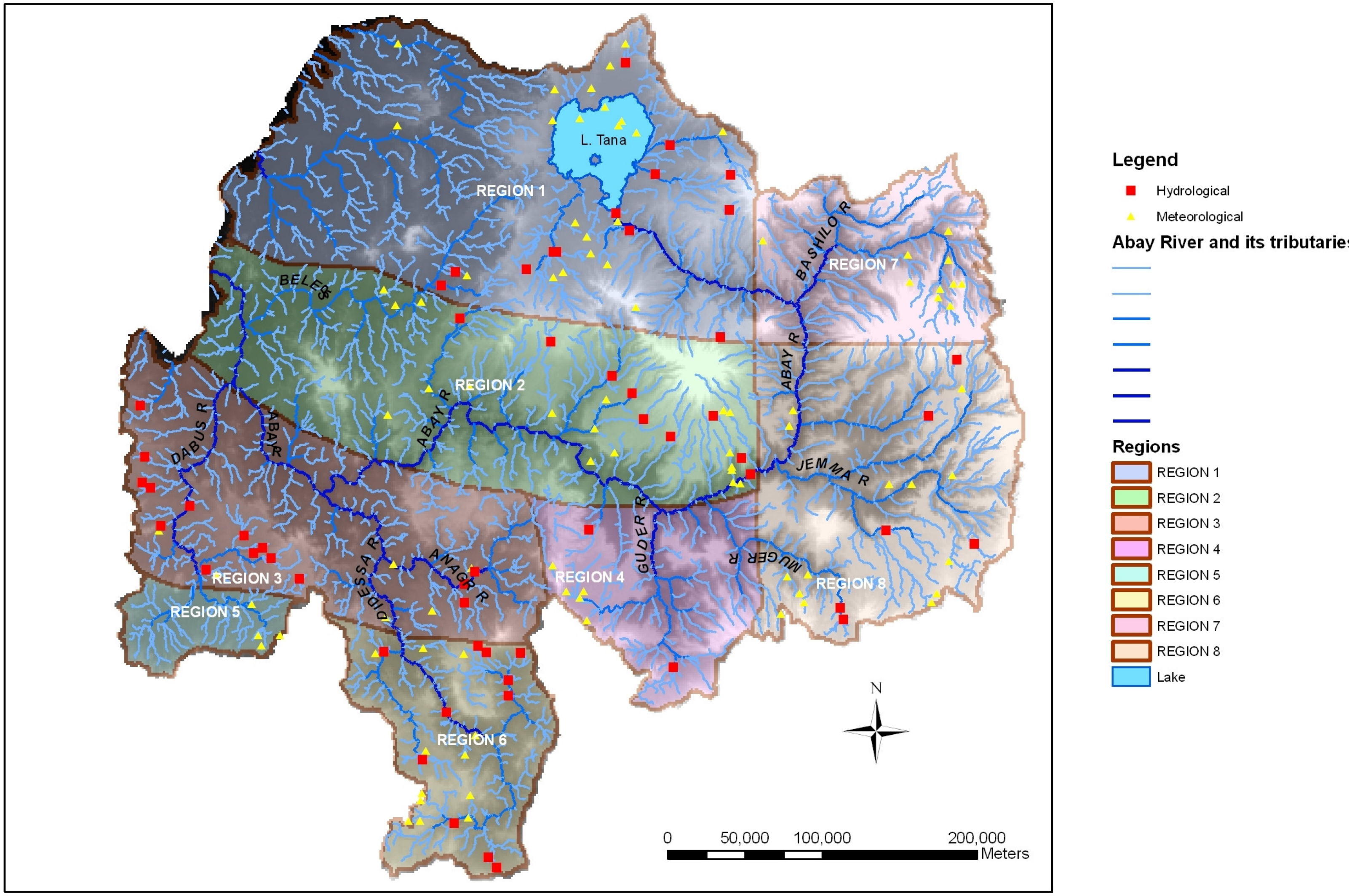


Figure 2.2 Map showing identified regions.

Similar homogeneous regions are obtained by comparing the map of identified regions, figure 2.2, with the map showing homogeneous humid hydrological regions, (Admassu Gebeyhu, 1988).

However, comparing, figure 2.2 with the climatic zones of Ethiopia (Lemma Gonfa, May 1996) quite large difference is observed.

Figure 2.2 is based on standardized rainfall and the pattern and intensity of rainfall is used for identification. In contrast, the climatic zones of Ethiopia identification is based on temperature, annual rainfall and rainfall range.

Focusing on the Abbay Basin from the climatic zones of Ethiopia; the western part about 40% of Abbay basin is classified as tropical climate, the eastern part about 60% of Abbay basin is mostly warm temperate rainy climate.

2.2.2. Evaporation patterns

To have a better understanding of hydrological cycle the impact of evaporation on water availability has to be analyzed. Minimum temperature, maximum temperature, wind speed, relative humidity and sunshine hours data are the basic parameters for estimating evaporation. Stations that collect the above parameters are classified by NMSA as class I stations.

Compared to the other empirical methods, the Penman method of estimating evaporation or evapo-transpiration is likely to provide the satisfactory results (FAO, 1977).

Out of the 91 stations, 13 stations only fulfill all the five parameters to be used in the Penman method. Classification of regions based on thirteen stations was found to be unrealistic.

Other methods like Blaney-Criddle, Thornthwaite and Christiansen can be applied but they all require at least one of the above parameters. (K.N. Mutreja, 1986)

Yilma Seleshi (Journal of EEA, 2002) developed a relationship between the potential evapo-transpiration and altitude for each month. This relationship is constant from year to year. Since the relationship is developed using regional regression analysis, the evapo-transpiration calculated is already regionalized in a different way. Regionalizing for the second time will duplicate the error and the result will be far out from the actual phenomena.

Because of the above reasons evaporation pattern for Abbay basin is not classified in this thesis.

3. Flow duration curve and low flow analysis

3.1. Analysis of Flow Duration Curve from monthly stream flow

A Flow Duration Curve (FDC) is one of the most informative methods of displaying the complete range of river discharges from low flows to flood events. It is a relationship between any given discharge value and the percentage of time that this discharge is equaled or exceeded, or in other words, the relationship between magnitude and frequency of stream flow discharge (V.U. Smakhtin, 2001).
The duration graphs were constructed based on monthly flow records, except that one month is divided into two parts by interpolation with the neighboring month's record. Thus a month followed by a wet month is assumed to have more flow in its

second half than the first half and it is a reasonable assumption that can be verified by the conditions of the available information.

Accordingly the annual records were divided into 24 parts and that helps to produce smooth hydrograph than is possible by 12 points. Thus for N years observation there are 24 x N flow averaged over half month time interval. These 24 x N values are then arranged in ranking order and again rearranged into 24 groups by taking the averages of the consecutive N points. (Admassu Gebeyehu, 1988).

The flows may be expressed in actual flow units, as percentages/ratio of mean annual runoff, mean daily flow or some other “index flow”, or divided by the catchments area. Such normalization facilitates the comparison between different catchments, since it reduces the differences in FDCs caused by differences in catchments area or mean annual runoff. (V.U.Smakhtin, 2001).

Therefore the 24 half month average flows were divided by the mean annual flow to a standardized form. FDCs are grouped according to rainfall regionalization pattern. The result obtained is shown in table 3.1 and figure 3.1.

Figure 3.1 shows for the discharge ratio to the mean annual flow below 0.1 for better visualization of the low flow. Full graph is shown on Appendix A.2

Since there is no hydrological station in region 5 and 7, six regional FDC are shown.

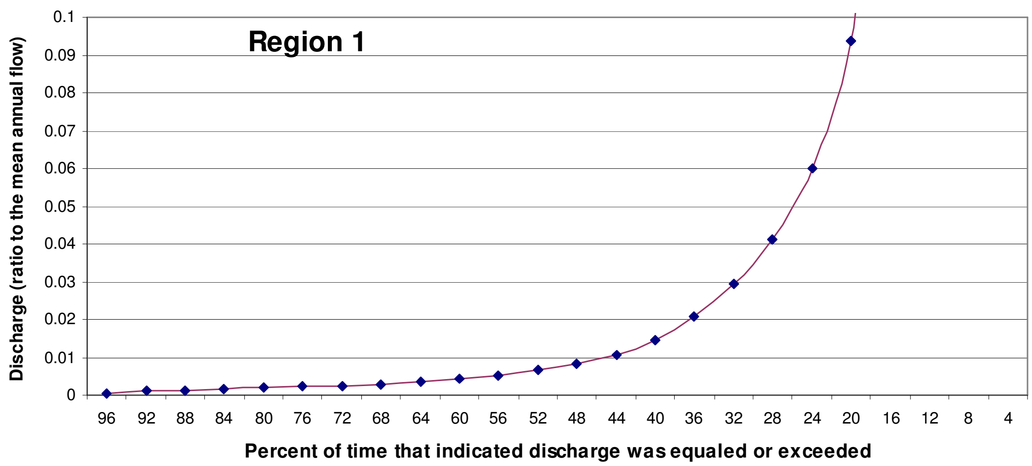
One can observe certain relationship between strongly peaked uni-modal type of rainfall profile (like region 1, 2, 4) or bimodal type rainfall profile (like region 8) (with relatively very small peak in April) have long low flow periods. And strongly flattened bimodal type rainfall profiles (like region 3 and 6) have relatively higher magnitude of flow during the low flow period. The rainfall distribution over the year has an impact on the magnitude of low flow.

Low-flow studies in the “low flow section” of a FDC, which may be arbitrarily determined as part of the curve with flows below MF (median flow, which corresponds to the discharge equaled or exceeded 50% of the time, Q50). The entire section of the curve may be interpreted as an index of groundwater (and/or subsurface flow) contribution to stream flow from subsurface catchments storage. If slope of the low-flows part of the FDC is small, groundwater/subsurface flow contribution is normally significant and low flows are sustainable. A steep curve indicates small and/or variable base flow contribution. In this sense, the shape of FDC is an indication of hydrological conditions in the catchments. (V.U. Smakhtin, 2000).

Smakhtin statement agrees with the observation made earlier.

Table 3.1 "Half month" average flows in percent of the mean annual flow.

	Ranked half month	Region 1	Region 2	Region 3	Region 4	Region 6	Region 8
Regional ranked "Half month" average flows in percent of the mean annual	1st half month	0.378	0.381	0.256	0.340	0.245	0.579
	2nd half month	0.280	0.288	0.203	0.288	0.201	0.349
	3rd half month	0.206	0.200	0.160	0.236	0.162	0.190
	4th half month	0.164	0.164	0.138	0.205	0.141	0.138
	5th half month	0.095	0.094	0.108	0.134	0.113	0.036
	6th half month	0.063	0.063	0.088	0.092	0.090	0.023
	7th half month	0.044	0.044	0.069	0.054	0.068	0.014
	8th half month	0.033	0.031	0.055	0.037	0.053	0.009
	9th half month	0.024	0.022	0.043	0.022	0.041	0.006
	10th half month	0.017	0.016	0.033	0.016	0.032	0.004
	11th half month	0.013	0.012	0.028	0.011	0.026	0.004
	12th half month	0.010	0.009	0.023	0.009	0.020	0.003
	13th half month	0.009	0.008	0.019	0.007	0.018	0.003
	14th half month	0.007	0.006	0.016	0.006	0.015	0.002
	15th half month	0.006	0.005	0.014	0.005	0.013	0.002
	16th half month	0.005	0.004	0.012	0.004	0.011	0.002
	17th half month	0.004	0.004	0.011	0.004	0.010	0.002
	18th half month	0.004	0.003	0.010	0.003	0.009	0.001
	19th half month	0.004	0.003	0.009	0.003	0.008	0.001
	20th half month	0.003	0.003	0.008	0.003	0.007	0.001
	21st half month	0.003	0.002	0.007	0.002	0.006	0.001
	22nd half month	0.002	0.002	0.006	0.002	0.005	0.001
	23rd half month	0.002	0.001	0.005	0.002	0.005	0.001
	24th half month	0.001	0.001	0.004	0.001	0.004	0.000



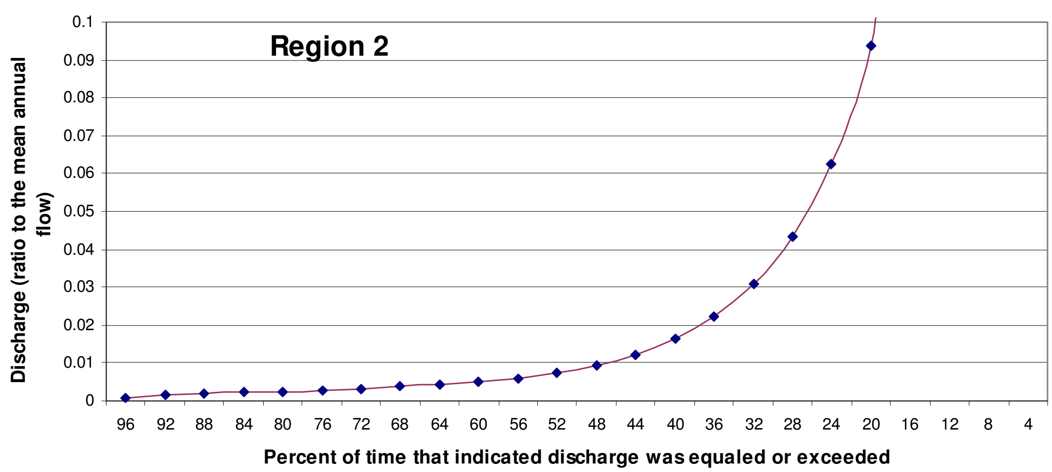
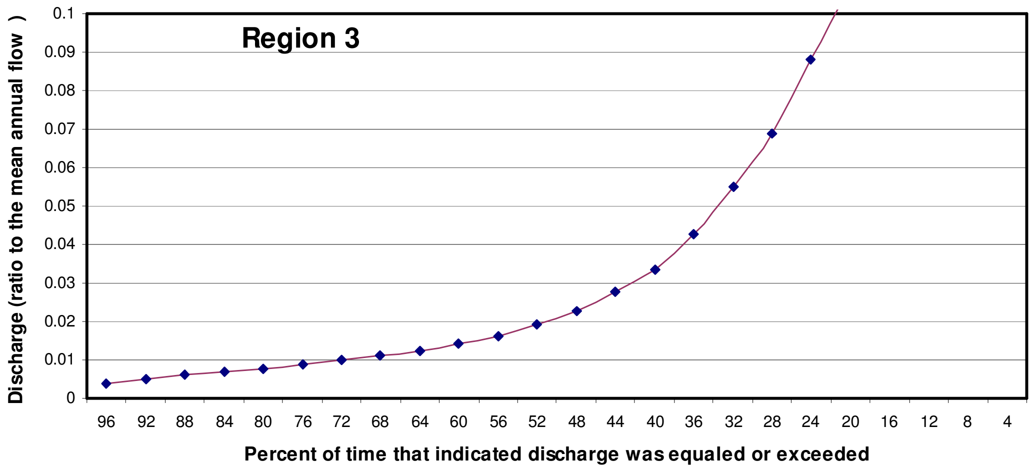


Figure 3.1 Flow duration graph at half-month interval.



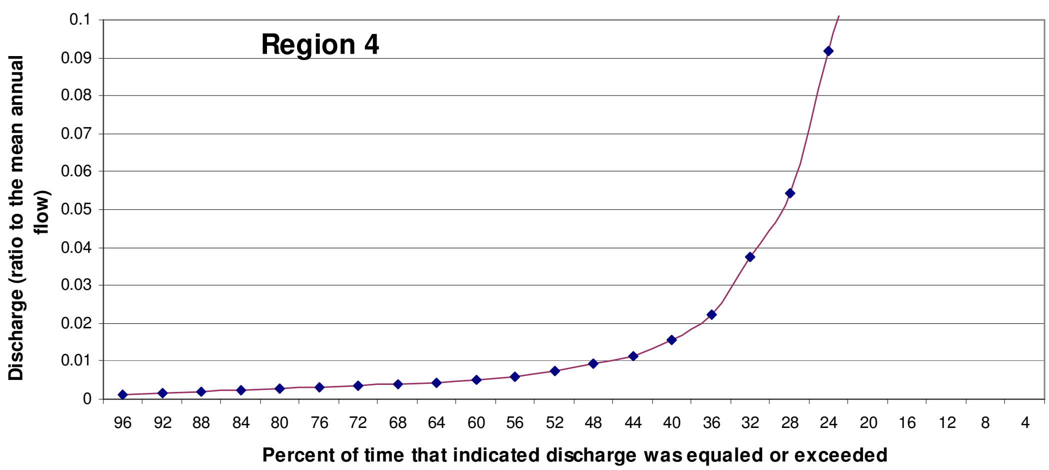
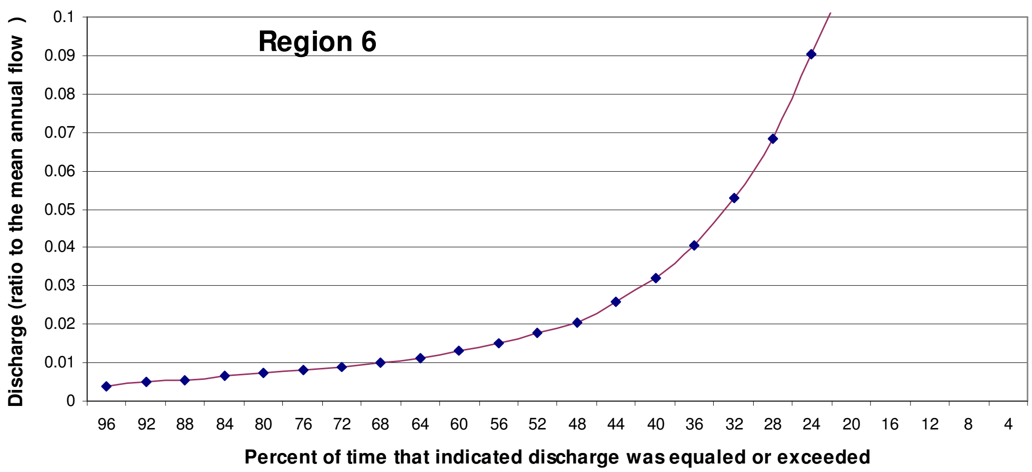


Figure 3.1 Flow duration graph at half-month interval. (Continued)



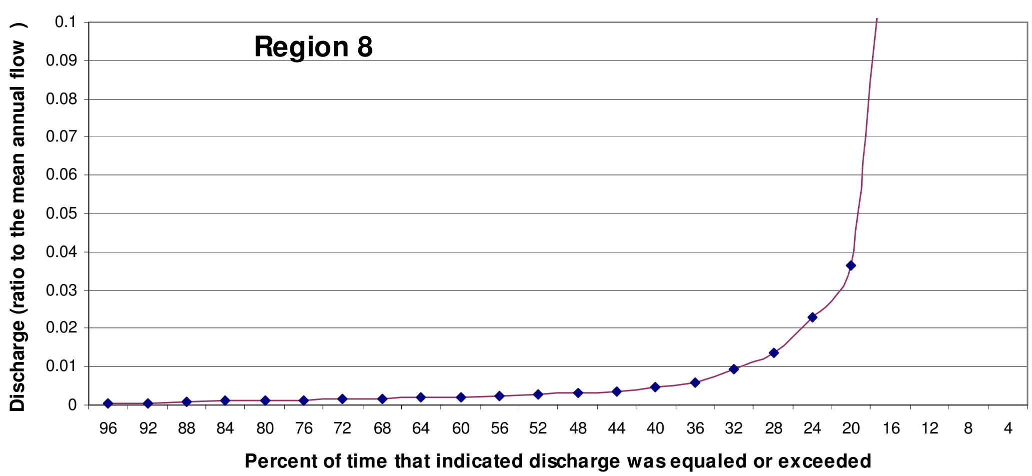


Figure 3.1 Flow duration graph at half-month interval. (Continued)

3.2. Estimation of daily flow from monthly flow

When flow duration curve developed using other than average daily flows, it must be remembered that any flow variation within the averaging period is camouflaged by using just the average value. (Jack J. Fritz, 1984). This camouflaged average value is definitely higher than the average minimum daily flow. And that will lead to overestimating the available flow and as a result the design flow will be overestimated as well.

The hydrological department of the MoWR categorizes the daily stream flow for the stations in Abbay Basin as closed or classified data, that is, it is not available for users. Therefore derivation of daily stream flow from the given maximum, minimum and average monthly flow was found to be essential.

The adequacy of stream flow, without regulating reservoir, for the use of hydropower, irrigation, water supply, waste disposal, etc., is the main aim in water resources study. The critical situation during the whole year of a given stream flow is during the low flow period. Therefore, further study of low flow characteristic variables is useful for the basis of determining regional analysis.

As stated on previous section, the “low flow section” of a FDC is determined as part of the curve with flows below MF (median flow). From the given three flows the main attention has to be given for the average and minimum flow. The requirements are:

- Average daily flow estimated for a given month should be equal to the given average monthly flow.
- Minimum daily flow estimated has to be close enough to the minimum monthly flow.

The shaded area of Figure 3.2 shows the average flow considered to be constant for all the days in the month.

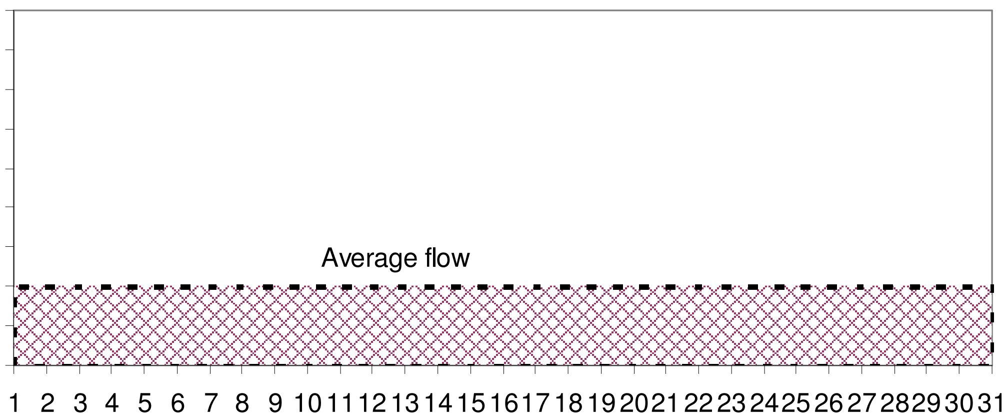


Figure 3.2 Average monthly flow for given station and month.

In addition, if one has to rank the two given flows, maximum and minimum monthly flows, over the days of the month. It is assumed to have similar distribution as shown in Figure 3.3.

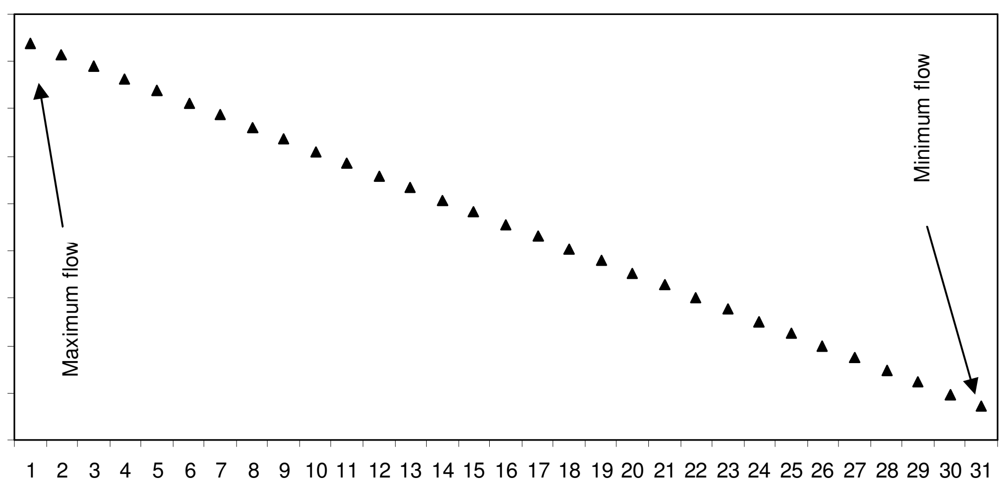


Figure 3.3 Maximum and minimum flows for a given station and month.

The combination of the above three flows given, maximum, average and minimum flows are shown in figure 3.4.

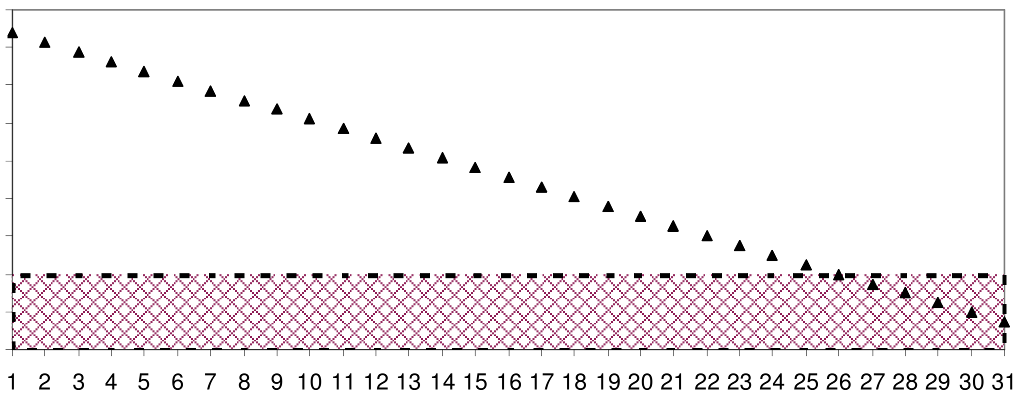


Figure 3.4 **Maximum, minimum and average flows for a given station and month**.

The shaded area (average flow) compared to the area under the linear distribution (between maximum and minimum flow) is relatively smaller, or can be larger depending on the relative magnitude of the maximum and minimum flow to the average flow. Therefore, this distribution is unacceptable and an alternative method has to be searched that satisfy the above two requirements.

A recession curve can be one of the alternatives. The proposed flow distribution behavior is as shown on the Figure 3.5.

Figure 3.5 **Proposed recession curve against the average flow for a given station and month**.

The shaded areas below and above the average flow, has to be equal to satisfy one of the requirements.

The mathematical expression used for the above Figure 3.5 is:

$$\frac{Q_{avg.(data)}}{Q_{avg.(estimated)}} = 1 \qquad \text{……………………..…………………………..……(3.1)}$$

Where:

$Q_{avg.(data)}$ = average monthly flow given

$Q_{avg.(estimated)}$ = average monthly flow estimated

The second requirement is that the minimum flow has to be close enough to the last ranked flow of the month.

The mathematical expression has to satisfy the condition that the ratio of the average monthly flow to the minimum monthly flow of the given data against the average monthly flow to the minimum monthly flow of the estimated data has to be close to one.

$$\frac{\left(\dfrac{Q_{avg.(data)}}{Q_{\min.(data)}}\right)}{\left(\dfrac{Q_{avg.(estimated)}}{Q_{\min.(estimated)}}\right)} = 1 \qquad \text{………………………………..…………(3.2)}$$

Where:

$Q_{min.(data)}$ = minimum monthly flow given

$Q_{min.(estimated)}$ = minimum monthly flow estimated

The combination of the two requirements is as shown in figure 3.6.

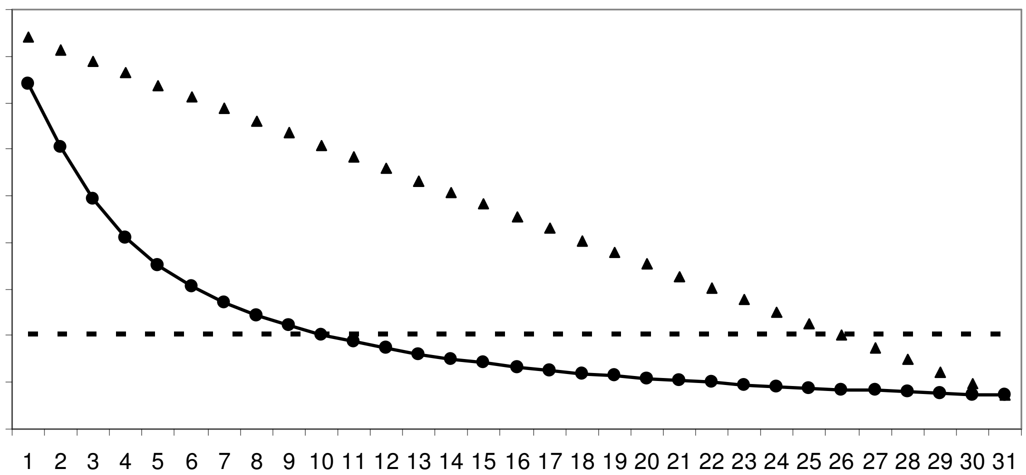


Figure 3.6 Proposed recession curve against the three given data.

The recession curve equation developed by Admassu Gebeyehu (obtained from personal communication):

$$Q_i = L \cdot \left(1 - \exp\left(\frac{-K}{i} \right) \right) \qquad \text{(3.3)}$$

Where:

Q_i = estimated daily flow of rank i in (m^3/s).

L = multiplier constant for each month

K = recession constant for each month

i = rank

By substituting different values for K and L, the estimated daily flow Q_i is calculated, subsequently the minimum flow and average flow of the month is calculated to check the requirements. This step is repeated till the requirements are satisfied to proceed for the next month.

A test of equation 3.3 was carried from a given daily data of Gumero station and the efficiency found to be 96.71%. A graph if this comparison is shown on Appendix A.5.

Using the above technique, average daily flow (ADF) was estimated for each month of the record length for all stations.

3.3. Flow duration curve in relation to low flow analysis

The flow duration curve (FDC) is usually used for the assessment of the available quantity of water that can maintain the stream flow or reservoir storage and variability of the water quantity with time. The theory and application of FDC is referred by several studies. Some of the applications are for:

- Run-of-river operations to hydropower feasibility studies by Warnick (1984)
- Capacity of waste water treatment plants including flow, flow duration, water quality requirements and costs, by Male and Ogawa (1984).
- Estimation of optimal release schedule from reservoirs by Alaouze (1989, 1991)
- Design of flow diversion by Pitman (1993) and Mallory and McKenzie (1993).
- A tool for rainfall-runoff model calibration and/or for the comparison of flow-series simulated for different scenarios of development by Gustard and Wesselink (1993), Lanen et al. (1997) and Smakhtin et al. (1998) and others.

FDC may be interpreted as an index of groundwater (and/or subsurface flow) contribution to stream flow from subsurface catchment storage. If the slope of the low-flow part of the FDC is small, groundwater/subsurface flow contribution is normally significant and low-flows are sustainable. A steep curve indicates small and/or variable base flow contribution. In this sense, the shape of FDC is an indication of hydro-geological conditions in the catchment. (V.U. Smakhtin, 2001).

In addition, D.R. Montgomery and S.M. Bolton (2003) express the steep curve is an indicator for a basin with highly variable flow, a quick response to precipitation, and little baseflow. Flatter slopes indicate more sustained and even flow, typically with a large groundwater component.

3.3.1. Prediction of low flows from catchments characteristics

A relationship between low flow characteristics and climatic variables and independent catchments characteristic has to be established using regional regression approach. The climatic variables like rainfall, number of rainy days were taken from NMSA. Some of the catchment characteristics are catchment area, channel slope, catchment slope, length of the main stream and mean catchment elevation. These characteristics were derived from Digital Elevation Model (DEM) for Abbay Basin.

3.3.2. Low flow analysis

Low flows are normally derived from groundwater discharge or surface discharge from lakes and marshes. The lowest annual flow usually occurs in the same season each year. The magnitude of annual low flows, variability of flows and the rate of stream-flow depletion in the absence of rain, duration of continuous low-flow events, relative contribution of low flows to the total stream flow hydrograph are a few of the widely used characteristics which are dealt with in low-flow hydrology in a variety of ways. Those effectively constitute the “temporal” component of low-flow hydrology and require continuous stream-flow time series for the analysis. “Spatial” component deals with the regional distribution of low-flow characteristics and attempts to estimate these characteristics in the catchments where no observed records are available. Both components of low-flow hydrology are closely related and require understanding and consideration of physiographic factors, which affect low flows (climate, topography, geology, soils etc) as well as various man-induced effects. (V.U. Smakhtin, 2001)

Some of the impacts of human activities on the low flow generating processes are:

- Direct river abstraction for industrial, agricultural or municipal purposes.
- Industrial and municipal waste disposed directly to the river.
- Irrigation return flows from agricultural fields
- Construction of dams and regulation of a river flow regime.

Hydropower capacity design is highly dependant on the low flow of the river. Since, the water used is directly returned back to the river, the impact on the quality and quantity of the flow is minimal, even though, the release might be regulated.

The ADF obtained from previous section was divided by the respective mean annual flow for standardization and was ranked for the calculation of the percent of exceedance. Selected standardized discharges, Q_{50}, Q_{70}, Q_{75}, Q_{80}, Q_{85}, Q_{90}, Q_{92}, Q_{95}, Q_{98}, Q_{99} were averaged for stations belonging to same region, as shown on table 3.2.

Table 3.2 Average standardized discharge.

Percent exceedance	Regions					
	1	2	3	4	6	8
0.990	1.54E-03	7.44E-04	2.49E-03	1.43E-03	2.86E-03	3.33E-04
0.980	1.86E-03	1.05E-03	3.35E-03	1.83E-03	3.66E-03	4.52E-04
0.950	2.54E-03	1.65E-03	5.18E-03	2.56E-03	5.15E-03	6.99E-04
0.918	3.15E-03	2.20E-03	6.76E-03	3.17E-03	6.44E-03	9.08E-04
0.900	3.46E-03	2.47E-03	7.56E-03	3.44E-03	7.09E-03	1.03E-03
0.850	4.31E-03	3.19E-03	9.63E-03	4.13E-03	8.71E-03	1.31E-03
0.800	5.23E-03	3.95E-03	1.18E-02	4.85E-03	1.06E-02	1.65E-03
0.750	6.25E-03	4.81E-03	1.41E-02	5.65E-03	1.27E-02	2.03E-03
0.700	7.45E-03	5.85E-03	1.69E-02	6.54E-03	1.50E-02	2.43E-03
0.500	1.79E-02	1.47E-02	3.51E-02	1.29E-02	3.00E-02	4.81E-03

For percent exceedance not stated in the above table an equation is developed for each region based on the standardized discharges against inverse of percent of exceedance level. The regional quadratic equation is:

$$Q_{(standardized)} = a + b\cdot\left(\frac{1}{E}\right) + c\cdot\left(\frac{1}{E}\right)^2 \quad \text{...(3.4)}$$

Where:

$Q_{(standardized)}$ = Standardized discharge dimensionless.

E = Percent of exceedance in (%)

a,b,c = Constants for each regions as shown in table 3.3

The above equation is applicable for standardized flows between Q_{50} and $Q_{99.7}$ only.

Table 3.3 **Constants for the low flow equations.**

	a	b	c
Region 1	-2.46E-03	5.50E-04	3.94E-03
Region 2	1.46E-02	-2.25E-02	1.11E-02
Region 3	-2.01E-02	2.00E-02	3.79E-03
Region 4	-5.72E-03	6.93E-03	1.52E-03
Region 6	-3.69E-03	2.28E-03	7.86E-03
Region 8	-3.12E-03	4.09E-03	-1.04E-04

4. Estimation of low flow characteristics for un-gauged catchments

4.1. Multiple linear regression approach

The regression model is a relationship between dependent low-flow characteristics and independent catchments and climatic variables. To establish a usable regression relationship, certain amount of observed stream flow data should be available to adequately represent the variability of flow regimes in a region and to allow required low-flow characteristics (dependent variables) to be estimated for further use in regression analysis. The stream flow data used should represent natural flow conditions in the catchments: the approach will most probably not work or will be misleading if flow regimes analyzed are continually changing under man-induced impacts.

Technically, regression model is constructed by means of a multiple regression analysis. This step includes selection of type or regression model, estimation of regression model parameters, and assessment of estimation errors. The “best” regression model is commonly estimated using stepwise regression approach when a model is derived one step-one independent variable at a time. (V.U. Smakhtin, 2001).

This thesis will evaluate by means of multiple linear regression analysis and the result will be compared with single linear regression (one independent variable at a time). The best result will be selected among the methods for final correlation.

At present, the use of statistical software package is well developed; and this thesis will use statistical analysis tools provided by Microsoft Excel, called the Analysis ToolPak.

Excel has two functions to analyze multiple linear regression model, called LINEST and LOGEST.

LINEST

It calculates the statistic for a line by using the "least squares" method to calculate a straight line that best fits your data, and return an array that describes the line. Because this function returns an array of values, it must be entered as an array formula.

The multiple linear regression equation used as 4.1:

$$y = m_1 \cdot x_1 + m_2 \cdot x_2 + m_3 \cdot x_3 + ... + m_n \cdot x_n + b \qquad \text{..........................(4.1)}$$

where:

y	=	stream flow characteristics (low flow)
$x_1, x_2, x_3 .... x_n$	=	catchment's characteristics (rainfall, area, slope, altitude…etc).
$m_1, m_2\ m_3 ... m_n$	=	coefficients of independent variables for $x_1, x_2, x_3 .... x_n$ respectively.
b	=	the value of y at the point where the line crosses the y-axis.

LINEST calculate the value of $m_1, m_{2,}\ m_{3,} ... m_n$ and b, in addition regression statistics as Table 4.1:

Table 4.1 Additional regression statistics by LINEST

Statistic	Description
$Se_1, se_2, ..., se_n$	The standard error values for the coefficients $m_1, m_2, \ldots, m_n$.
Se_b	The standard error value for the constant b.
r^2	The coefficient of determination. Compares estimated and actual y-values, and ranges in value from 0 to 1. If it is 1, there is a perfect correlation in the sample — there is no difference between the estimated y-value and the actual y-value. At the other extreme, if the coefficient of determination is 0, the regression equation is not helpful in predicting a y-value.
se_y	The standard error for the y estimate.
F	The F statistic or the F-observed value. Use the F statistic to determine whether the observed relationship between the dependent and independent variables occurs by chance.
d_f	The degrees of freedom. Use the degrees of freedom to help you find F-critical values in a statistical table. Compare the values you find in the table to the F statistic returned by LINEST to determine a confidence level for the model.
ss_{reg}	The regression sum of squares.
ss_{resid}	The residual sum of squares.

Remark: Known x's is an optional set of x-values that you may already know in equation 4.1.

The array known x's can include one or more sets of variables. If only one variable is used, known y's and known x's can be ranges of any shape, as long as they have equal dimensions. If more than one variable is used, known y's must be a vector (that is, a range with a height of one row or a width of one column).

If known x's is omitted, it is assumed to be the array {1,2,3,...} that is the same size as known y's.

The most determining statistical output from this model is coefficient of determination r^2, it is the square of the Pearson product moment correlation coefficient through data points. The r-square value can be interpreted as the proportion of the variance in Y attributable to the variance in y and is calculated as follows:

$$r = \frac{n\left(\sum yY\right) - (y)\left(\sum Y\right)}{\sqrt{\left[n\sum y^2 - \left(\sum y\right)^2\right]\left[n\sum Y^2 - \left(\sum Y\right)^2\right]}} \qquad \text{(4.2)}$$

Where:

Y	=	actual y-value
y	=	estimated y-value

LOGEST

In regression analysis, calculates an exponential curve that fits your data and returns an array of values that describes the curve. Because this function returns an array of values, it must be entered as an array formula.

The multiple regression equation used as (4.3)

$$y = m_1^{\;x_1} \cdot m_2^{\;x_2} \cdot m_3^{\;x_3} \cdot ... \cdot m_n^{\;x_n} \cdot b \qquad \text{(4.3)}$$

Where:

y	=	stream flow characteristics (low flow)
$x_1, x_2, x_3, \ldots, x_n$	=	catchment's characteristics (rainfall, area, slope altitude…etc).
$m_1, m_2, m_3, \ldots, m_n$	=	coefficients of independent variables for $x_1, x_2, x_3, \ldots, x_n$ respectively.
b	=	the value of y at the point where the line crosses the y-axis.

LOGEST calculate the value of m_1, m_2, m_3 …, m_n and b, in addition to regression statistics as described in LINEST function.

The methods used to test an equation using LOGEST are similar to the methods for LINEST. Since equation 4.3 is not linear, one can transform it to a multiple linear regression as:

$$\ln y = x_1 \cdot \ln m_1 + x_2 \cdot \ln m_2 + x_3 \cdot \ln m_3 + ... + x_n \cdot \ln m_n + \ln b \quad ....(4.4)$$

When evaluating the additional statistics, especially the se_i and se_b values, it should be compared to $\ln m_n$ and lnb, and not to m_n and b.

4.2. Single linear regression approach

Since the "best" regression model is commonly estimated using stepwise regression approach when a model is derived one step-one independent variable at a time. The same procedure is applied as in the multiple linear regression analysis. Instead of analyzing all the independent variables at one time, each independent variable will be correlated with the low-flow one by one.

Or after developing a chart for the two variables in Excel, one can use the trend line option to have the equation and the r-squared value very easily.

4.3. Selection of catchment characteristics

Basins and climate characteristics (independent variables) which are most commonly related to low-flow are numerous. Among those independent variables indices this thesis analyzes: catchment area, mean elevation of the catchment, mean catchment slope, station elevation, stream length, stream slope, mean annual precipitation and number of no rainy days.

Stream slope is measured for the channel slope similar to that proposed by Nash, 1960. It was obtained according to the following procedure. The main channel is divided into equal distances of 90m starting from the location of the gauging station to the head of the stream (or up to the divide line) were obtained from Shuttle Radar Topographic Mission, Digital Elevation Model (SRTM DEM), that will be described later. S_n are slopes calculated between each cell size.

$$SLOPE = \frac{S_1 \cdot D + S_2 \cdot D + S_3 \cdot D + ...S_n \cdot D}{L} \quad ....(4.5)$$

Where:

D = distances between cell sizes which is equal to 90m.

$S_1,S_2,S_3 \ldots S_n$ = Slope between adjacent cells in %.

L = length of the main stream form the gauging site to the head of the stream (or up to the divide line) in m.

The mean annual precipitation and number of rainy days are obtained from NMSA.

The first step in the regression analysis was to obtain the coefficients of correlation between every pair of catchments characteristics. The result is shown on the table 4.2a and Table 4.2b.

For higher correlation coefficient, one of the two characteristics has to be used in the regression analysis to see the individual effect. The significant correlation coefficients are between:

- Station elevation and catchment elevation. Obviously, the station elevation is part of the catchment elevation.
- Catchment area and stream length. As the stream length increases, the catchment area will also increase.
- Mean annual rainfall and station elevation and catchment elevation. As rainfall is highly dependent on elevation.
- Mean catchment slope and river slope. As the river slope is part of the catchment slope.

Table 4.2.a Correlation matrix of catchment characteristics with Q_{70} and Q_{80}

	Station elevation (m)	Average catchment elevation (m)	Catchment area (km^2)	Stream length (m)	River slope (%)	Mean catchment slope (%)	Mean annual rainfall (mm)	Number of no rainy days (n^o.)	Discharge at 70% exceedance (m3/s)	Discharge at 80% exceedance (m^3/s)
Station elevation (m)	1.0000									
Average catchment elevation (m)	0.9056	1.0000								
Catchment area (km^2)	0.1152	-0.0228								
Stream length (m)	-0.0653	-0.0758	0.9027	1.0000						
River slope (%)	0.0371	0.1253	-0.0173	-0.1577	1.0000					
Mean catchment slope (%)	0.0293	0.2204	0.2152	0.2150	0.6950	1.0000				
Mean annual rainfall (mm)	-0.7355	-0.7528	-0.0663	-0.0051	0.0314	-0.1547	1.0000			
Number of no rainy days (no.)	0.2955	0.1514	0.1076	-0.0174	-0.1053	-0.1079	-0.4518	1.0000		
Discharge at 70% exceedance (m^3/s)	-0.1346	-0.1957	0.8106	0.9041	-0.1606	0.1385	0.1329	0.0003	1.0000	
Discharge at 80% exceedance (m^3/s)	-0.1427	-0.2001	0.8001	0.9007	-0.1653	0.1350	0.1397	-0.0046		1.0000

Table 4.2.b Correlation matrix of catchment characteristics with Q_{70} and Q_{80} (log value)

Log value										
	Station elevation (m)	***Average catchment elevation (m)***	***Catchment area (km²)***	***Stream length (m)***	***River slope (%)***	***Mean catchment slope (%)***	***Mean annual rainfall (mm)***	***Number of no rainy days (n°.)***	***Discharge at 70% exceedance (m3/s)***	***Discharge at 80% exceedance (m3/s)***
Station elevation (m)		0.8908	-0.0857	-0.0477	-0.0898	-0.1165	-0.7472	0.2781	-0.4718	
Average catchment elevation (m)	0.8949		0.0894	0.1525	0.0216	0.0802	-0.7682	0.1428	-0.3525	
Catchment area (km²)	0.0965	-0.0070		0.3957	-0.0131	0.1786	-0.0595	0.1076	0.4887	
Stream length (m)	-0.0940	-0.0527	0.6826		-0.1270	0.1996	-0.0026	-0.0117	0.7322	
River slope (%)	0.0693	0.1291	-0.3671	-0.3381		0.7001	0.0264	-0.0968	-0.2145	
Mean catchment slope (%)	0.0489	0.2356	0.1643	0.1819	0.7044		-0.1534	-0.0892	0.1724	
Mean annual rainfall (mm)	-0.7113	-0.7265	-0.0693	-0.1007	0.1034	0.0148		-0.4294	0.3288	
Number of no rainy days (no.)	0.2599	0.0879	-0.1840	-0.2046	-0.1637	-0.2156	-0.4621		-0.3136	
Discharge at 70% exceedance (m^3/s)	-0.1576	-0.1824	0.5463	0.5016	-0.1538	0.1463	0.1354	0.0064		
Discharge at 80% exceedance (m^3/s)	-0.1479	-0.1701	0.5528	0.5102	-0.1686	0.1456	0.1235	0.0291		

5. Prediction of low flows from catchment characteristics

Some of the catchments characteristics like catchments area, mean elevation of the catchments, station elevation, stream length and slope were calculated from GIS software.

5.1. Geographic Information Systems

The more realistical analysis of the earth's terrain effect is the use of three dimensional model within GIS (Geographic Information System). A GIS can display the Earth in realistic, three dimensional perspective views and animations that convey information more effectively and to wider audiences than traditional, two-dimensional, static maps.

GIS can be used for scientific investigations, resource management and development planning.

GIS is a computer-based system that enters, stores, manages, analyzes, and displays spatial, and associated non-spatial data. These systems are composed of software, data, hardware and organization and people. The combination of these components allows for visualization of spatial data, and the creation of spatial models. This study used the Arc GIS 9.1 software for data collection and spatial analysis.

Spatial analysis, among the most important applications of GIS, requires logical connection between attribute data and map features. Two types of operations can be performed within spatial analysis: (1) spatial queries and (2) the generation of new data sets from the original data. To accomplish this, ArcGIS 9.1 utilizes spatial data of one of two types: vector or raster. Vector data are points, lines, or polygons, all composed of a location and a direction. Raster data is composed of regularly spaced cells arranged in rows and columns, called "grids". Each cell has a uniform size and is assigned a value according to the data that is being analyzed. To perform calculations on raster data, the Spatial Analyst extension must be used, a tool kit for understanding and analyzing spatial data. It allows the user to perform analysis on and between multiple data layers. (Annie J. Morris, 2002)
The Spatial Analyst functions used in this study were: map query, find distance, summarize zones, map algebra, cell statistics, derive slope, fill sinks, flow direction, and watershed.

The hydrologic modeling functions in the Spatial Analyst provide methods for describing the physical components of a surface. The hydrologic tools allow identifying sinks, determining the flow direction, calculating the flow accumulation, delineating watersheds, and create stream networks.

Shape files regarding the Abbay Basin was obtained from the hydrology department of Ministry of Water Resources. It includes the location of the metrological and hydrological stations, main towns, rivers, main access roads, lakes, and bore holes, and layouts for Abbay Basin, soil type, land use, land cover, and geology.

The Digital Elevation Model (DEM), which consist of surface elevation record was downloaded from the following website:
http://glcf.umiacs.umd.edu/data/srtm/desc.shtml

Global Land Cover Facility (GLCF) provides SRTM (Shuttle Radar Topography Mission (SRTM) obtained elevation data on a near-global scale to generate the most complete high-resolution digital topographic database of Earth. SRTM consisted of a specially modified radar system that flew onboard the Space Shuttle Endeavor during an 11-day mission in February of 2000. SRTM is an international project spearheaded by the National Geospatial-Intelligence Agency (NGA) and the National Aeronautics and Space Administration (NASA)) data at three resolutions:

- 1 arc-second/30-meter DEM of the United States,
- 3 arc-second/90-meter DEM of the world,
- 30 arc-second/1km SRTM-GTOPO30 product corrected by GTOPO30 30 arc-second DEM

These comprise the initial edition of the SRTM data set, per the USGS standard. USGS plans to process the data to a higher level to account for missing land values and negative values in water bodies. This “finished” SRTM product is anticipated in fall 2004, whereupon GLCF will update its holdings accordingly. (GLCF).

This thesis used the 3 arc-second /90-meter DEM of the world. 90-meter DEM describes 90m*90m ground area represented as one cell in the DEM. All details within the 90m*90m will not be reflected in the DEM.

First, raw DEMs are converted to ARC GRID format. Then, all sinks in the grid are filled. This is done in order to remove imperfections in the data and enable flow direction to run properly. Then a flow direction grid is created using the flow direction function to show the direction of flow from each cell in the elevation grid to its steepest down slope neighbor. Finally, the Arc Hydro is performed using a user defined point. It returns the upstream drainage area based on the flow direction grid from the user-defined point. Catchment characteristics are attached in Appendix C.1.

5.1.1. Water shade delineation

Watersheds were measured and employed as drainage areas upstream from each gauging station. This area was found using a 90-meter Digital Elevation Model (DEM) and the Arc Hydro. The later was used to delineate the upstream drainage basins for each of the gauging stations used in this study. In ArcGIS 9.1, the resulting temporary shape files were converted to permanent shape files for vector calculations and to grids with 90m cells for raster calculations. Drainage basin area was calculated using Arc Hydro.

5.1.2. Catchments elevation

Elevation of each watershed was determined using ArcGIS from the DEM. The analysis was masked to the extent of each watershed. The map calculator was used to multiply a grid of each watershed by the DEM, creating an output DEM the same size as the input watershed with a 90 m cell size. Statistics were then calculated on the value field of this grid's attribute table, yielding the maximum elevation, minimum elevation, mean elevation, change in elevation, and the standard deviation of the elevation.

5.1.3. Station Elevation

Each metrological and hydrological station elevation was determined from the DEM directly.

5.1.4. Stream length

Stream length was calculated as the length of all contributing streams in each watershed. Arc Hydro distinguishes the main stem from tributaries. For length calculation, the select by theme tool was applied to all stream lines within each watershed containing hydrological stations. The vector stream line shape file was clipped using the geo-processing wizard to include only stream centerlines within each watershed boundary. Field statistics were then performed on the length field in the attribute table.

5.1.5. Stream slope

The stream slope for each watershed, was found by analysis of a stream slope grid found in Arc Hydro. The stream slope grid was developed from a raster version of the stream line shape file, with each cell containing an interpolated elevation value from the DEM. Slope is calculated using equation 3.5 as per the detail explained in the section above.

5.2. Prediction of low flows

After analyzing the effects of high correlation coefficient, one by one with low flow, river length together with mean annual rainfall give the most significant relationship.

Two types of low flows (Q_{70} and Q_{80}) were considered for the analysis of correlation. The result is as shown on the table below.

Table 5.1 Regression of Q_{70} with river length and mean annual rainfall.

Statistics	Value
$Se_{2(\text{mean annual rainfall})}$	0.0016785
$Se_{1(\text{river length})}$	5.14E-06
Se_b	2.3995
r^2	0.8363
Se_y	3.0583
F	127.7183
d_f	50.0000
SS_{reg}	2389.1228
SS_{resid}	467.6549

Table 5.2 Regression of Q_{80} with river length and mean annual rainfall.

Statistics	Value
$Se_{2(\text{mean annual rainfall})}$	0.001171416
$Se_{1(\text{river length})}$	3.58747E-06
Se_{bl}	1.6746
r^2	0.8321
Se_y	2.1344
F	123.9059
d_f	50.0000
SS_{reg}	1128.9313
SS_{resid}	227.7800

The equations for the relationships between river length and mean annual rainfall with Q_{70} and Q_{80} are expressed as:

$$Q_{70} = (0.00403 \cdot RAINFALL) + (8.121 \times 10^{-5} \cdot LENGTH) - 7.79436 \quad \text{.....................(5.1)}$$

$$Q_{80} = (0.00292 \cdot RAINFALL) + (5.581 \times 10^{-5} \cdot LENGTH) - 5.52802 \quad \text{....................(5.2)}$$

Where:

Q_{70}	=	Average low flow with 70% exeedance in m^3/s
Q_{80}	=	Average low flow with 80% exeedance in m^3/s.
LENGTH	=	River length in m.
RAINFALL	=	Mean annual rainfall in mm.

While the coefficient of correlation between low flows with catchment area and mean annual rainfall are 0.69 and 0.68 for Q_{70} and Q_{80} respectively.

Then the two low flows are correlated with the mean annual flow respectively and the result is as below:

Table 5.3 Regression of $Q_{mean\ annual}$ with Q_{70}.

Statistics	Value
Se_1	8.131541858
Se_b	65.2388
r^2	0.7892
Se_y	434.6214
F	190.9045
d_f	51.0000
SS_{reg}	36061060.0120
SS_{resid}	9633684.8021

t-Test: Two-Sample Assuming Unequal Variances		
	$Q_{mean\ annual}$	Q_{70}
Mean	329.4739	3.20454
Variance	894029.7	55.96472
Observations	52	52
Hypothesized Mean Difference	0	
df	51	
t Stat	2.48822	
P(T<=t) one-tail	0.00807	
t Critical one-tail	1.67529	
P(T<=t) two-tail	0.01615	
t Critical two-tail	2.00758	

Table 5.4 **Regression of $Q_{mean\ annual}$ with Q_{80}.**

Statistics	Value
Se_1	12.20440527
Se_b	67.5734
r^2	0.7745
Se_y	449.5317
F	175.1234
d_f	51.0000
SS_{reg}	35388728.3615
SS_{resid}	10306016.4526

t-Test: Two-Sample Assuming Unequal Variances		
	$Q_{mean\ annual}$	Q_{80}
Mean	329.4739	2.22715
Variance	894029.75	26.57645
Observations	52	52
Hypothesized Mean Difference	0	
df	51	
t Stat	2.49571	
P(T<=t) one-tail	0.00792	
t Critical one-tail	1.67528	
P(T<=t) two-tail	0.01585	
t Critical two-tail	2.00758	

The equations for the relationships between mean annual stream flow with Q_{70} and Q_{80} are expressed as:

$$Q_{mean} = (112.35205 \cdot Q_{70}) - 27.99741 \qquad (5.3)$$

$$Q_{mean} = (161.50604 \cdot Q_{80}) - 27.7472 \qquad (5.4)$$

Where:

Q_{70} = Average low flow with 70% exeedance in m^3/s

Q_{80} = Average low flow with 80% exeedance in m^3/s

Q_{mean} = Mean annual stream flow in m^3/s.

It has been observed, by removing two stations covering a large drainage area, namely 2001 and 2003, the higher coefficient of correlation is obtained between the low flows and catchment area with mean annual rainfall as follows:

Table 5.5 Regression of Q_{70} with catchment area and mean annual rainfall.

Statistics	Value
$Se_{2(mean\ annual\ rainfall)}$	0.0009847
$Se_{1(catchment\ area)}$	0.0001207
Se_b	1.3725
r^2	0.9086
Se_y	1.7324
F	238.6277
d_f	48.0000
SS_{reg}	1432.3043
SS_{resid}	144.0541

Table 5.6 Regression of Q_{80} with catchment area and mean annual rainfall.

Statistics	Value
$Se_{2(mean\ annual\ rainfall)}$	0.00067844
$Se_{1(catchment\ area)}$	8.3148E-05
Se_{bl}	0.9456
r^2	0.9115
Se_y	1.1936
F	247.2189
d_f	48.0000
SS_{reg}	704.3610
SS_{resid}	68.3793

The equations for the relationships between catchment area and mean annual rainfall with Q_{70} and Q_{80} are expressed as:

$$Q_{70} = (0.00171 \cdot RAINFALL) + (0.00251 \cdot AREA) - 2.58325 \quad \text{.......................(5.5)}$$

$$Q_{80} = (0.00122 \cdot RAINFALL) + (0.00176 \cdot AREA) - 1.84521 \quad \text{.......................(5.6)}$$

Where:

Q_{70} = Average low flow with 70% exeedance in m^3/s

Q_{80} = Average low flow with 80% exeedance in m^3/s.

AREA = Catchment area in Km^2.

RAINFALL = Mean annual rainfall in mm.

Again, the two low flows are correlated with the mean annual flow respectively and the result is as below:

Table 5.7 Regression of $Q_{mean\ annual}$ with Q_{70}.

Statistics	Value
Se_1	1.945784456
Se_b	11.7898
r^2	0.9524
Se_y	77.2542
F	981.4554
d_f	49.0000
SS_{reg}	5857536.4575
SS_{resid}	292442.5159

t-Test: Two-Sample Assuming Unequal Variances		
	$Q_{mean\ annual}$	Q_{70}
Mean	193.68221	2.40917
Variance	122999.5795	31.52717
Observations	51	51
Hypothesized Mean Difference	0	
df	50	
t Stat	3.89432	
P(T<=t) one-tail	0.00015	
t Critical one-tail	1.67591	
P(T<=t) two-tail	0.00029	
t Critical two-tail	2.00856	

Table 5.8 Regression of $Q_{mean\ annual}$ with Q_{80}.

Statistics	Value
Se_1	2.752600513
Se_b	11.6786
r^2	0.9534
Se_y	76.5174
F	1001.3974
d_f	49.0000
SS_{reg}	5863088.5450
SS_{resid}	286890.4284

t-Test: Two-Sample Assuming Unequal Variances		
	$Q_{mean\ annual}$	Q_{80}
Mean	193.68221	1.68795
Variance	122999.5795	15.45481
Observations	51	51
Hypothesized Mean Difference	0	
df	50	
t Stat	3.90926	
P(T<=t) one-tail	0.00014	
t Critical one-tail	1.67591	
P(T<=t) two-tail	0.00028	
t Critical two-tail	2.00856	

The equations for the relationships between mean annual stream flow with Q_{70} and Q_{80} are expressed as:

$$Q_{mean} = (60.9579 \cdot Q_{70}) + 46.82427 \quad \text{......(5.7)}$$

$$Q_{mean} = (87.10567 \cdot Q_{80}) + 46.6525 \quad \text{......(5.8)}$$

Where:

Q_{70} = Average low flow with 70% exeedance in m^3/s

Q_{80} = Average low flow with 80% exeedance in m^3/s

Q_{mean} = Mean annual stream flow in m^3/s.

Further, by removing stations covering drainage area greater than 3,000 km^2, the following coefficient of correlation is obtained between the low flows and catchment area with mean annual rainfall as follows:

Table 5.9 Regression of Q_{70} with catchment area and mean annual rainfall.

Statistics	Value
$Se_{2(mean\ annual\ rainfall)}$	0.000507
$Se_{1(catchment\ area)}$	0.000237
Se_b	0.7130
r^2	0.7298
Se_y	0.8888
F	58.0805
d_f	43.0000
SS_{reg}	91.7705
SS_{resid}	33.9712

Table 5.10 Regression of Q_{80} with catchment area and mean annual rainfall.

Statistics	Value
$Se_{2(mean\ annual\ rainfall)}$	0.000359
$Se_{1(catchment\ area)}$	0.000168
Se_{bl}	0.5048
r^2	0.7304
Se_y	0.6294
F	58.2543
d_f	43.0000
SS_{reg}	46.1471
SS_{resid}	17.0316

The equations for the relationships between catchment area and mean annual rainfall with Q_{70} and Q_{80} are expressed as:

$$Q_{70} = (0.00168 \cdot RAINFALL) + (0.00238 \cdot AREA) - 2.36144 \quad (5.9)$$

$$Q_{80} = (0.00120 \cdot RAINFALL) + (0.00169 \cdot AREA) - 1.69041 \quad (5.10)$$

Where:

Q_{70} = Average low flow with 70% exeedance in m^3/s

Q_{80} = Average low flow with 80% exeedance in m^3/s.

AREA = Catchment area in Km^2.

RAINFALL = Mean annual rainfall in mm.

Again, the two low flows are correlated with the mean annual flow respectively and the result is as below:

Table 5.11 Regression of $Q_{mean\ annual}$ with Q_{70}.

Statistics	Value
Se_1	5.623089654
Se_b	10.9922
r^2	0.8082
Se_y	63.0543
F	185.3964
d_f	44.0000
SS_{reg}	737107.2889
SS_{resid}	174937.1435

t-Test: Two-Sample Assuming Unequal Variances		
	$Q_{mean\ annual}$	Q_{70}
Mean	108.28023	1.04299
Variance	20267.65406	2.79426
Observations	46	46
Hypothesized Mean Difference	0	
df	45	
t Stat	5.10849	
P(T<=t) one-tail	3.20228E-06	
t Critical one-tail	1.67943	
P(T<=t) two-tail	6.40456E-06	
t Critical two-tail	2.01410	

Table 5.12 Regression of $Q_{mean\ annual}$ with Q_{80}.

Statistics	Value
Se_1	8.037441676
Se_b	11.1046
r^2	0.8031
Se_y	63.8856
F	179.4650
d_f	44.0000
SS_{reg}	732463.9473
SS_{resid}	179580.4852

t-Test: Two-Sample Assuming Unequal Variances		
	$Q_{mean\ annual}$	Q_{80}
Mean	108.2802	0.73171
Variance	20267.65	1.40397
Observations	46	46
Hypothesized Mean Difference	0	
df	45	
t Stat	5.1235	
P(T<=t) one-tail	3.05E-06	
t Critical one-tail	1.67943	
P(T<=t) two-tail	6.09E-06	
t Critical two-tail	2.01410	

The equations for the relationships between mean annual stream flow with Q_{70} and Q_{80} are expressed as:

$$Q_{mean} = (76.56419 \cdot Q_{70}) + 28.42441 \quad (5.11)$$

$$Q_{mean} = (107.67323 \cdot Q_{80}) + 29.4947 \quad (5.12)$$

Where:

Q_{70} = Average low flow with 70% exeedance in m^3/s

Q_{80} = Average low flow with 80% exeedance in m^3/s

Q_{mean} = Mean annual stream flow in m^3/s.

All equations above are summarized in table 5.13.

Table 5.13 Summary of equations.

Type	Results	Q_{70}		
		Stream length in m	Catchment area in km^2	Q_{mean}
All stations	Equations	Q_{70}=0.00403*RAINFALL+8.122-05*LENGTH-7.79436		Q_{mean}=112.35205*Q_{70}-27.99741
	R^2	0.84		0.79
Removing Station 2001 and 2003	Equations		Q_{70}=0.00171*RAINFALL+0.00251*AREA-2.58325	Q_{mean}=60.9579*Q_{70}+46.82427
	R^2		0.91	0.95
Removing catchments above 3,000 km^2	Equations		Q_{70}=0.00168* RAINFALL+0.00238*AREA-2.36144	Q_{mean}=76.56419*Q_{70}+28.42441
	R^2		0.73	0.81

Type	Results	Q_{80}		
		Stream length in m	Catchment area in km^2	Q_{mean}
All stations	Equations	Q_{80}=0.00292* RAINFALL+5.581-05*LENGTH-5.52802		Q_{mean}=161.50604*Q_{80}-27.7472
	R^2	0.83		0.77
Removing Station 2001 and 2003	Equations		Q_{80}=0.00122*RAINFALL+0.00176*AREA-1.84521	Q_{mean}=87.10567*Q_{80}+46.6525
	R^2		0.91	0.95
Removing catchments above 3,000 km^2	Equations		Q_{80}=0.00120* RAINFALL+0.00169*AREA-1.69041	Q_{mean}=107.67323*Q_{80}+29.4947
	R^2		0.73	0.80

For catchment area ranging between 0.07km^2 and 3,000km^2 equations 5.9, 5.10, 5.11 and 5.12 shall be used. For catchment area ranging between 3,000Km^2 and 10,000km^2 equations 5.5, 5.6, 5.7 and 5.8 shall be used. And for catchment area ranging between 10,000km^2 and 64,444.25km^2 equations 5.1, 5.2, 5.3 and 5.4 shall be used.

The above relations can be explained as follows. It is well understood that as the river length increases the catchment area increases proportionally. But as the river length is larger than certain limit, the flow path will be meandering through the catchment area instead of being more or less straight. And that makes the low flow more correlated to the river length rather than the catchment area.

Equations developed by Admassu Gebeyehu for low flows with catchment area are as follows:

$$Min\,30 = 2.08\left(AREA\right)^{0.83} \qquad \text{(5.13)}$$

$$Min\,01 = 1.48\left(AREA\right)^{0.82} \qquad \text{(5.14)}$$

Where:

Min30	=	30 days average low flow in lits/sec.
Min01	=	1 day average low flow in lits/sec
AREA	=	area of catchment in Km^2.

Equation 5.13 and 5.14 can be used for the humid hydrological regions in Ethiopia as shown in his map.

The percent of exeedance for Min30 and Min01 is about 91.8% and about 99.7% respectively.

6. Discussions and recommendations

6.1. Discussions

Understanding low flow prediction is highly important for hydropower capacity design, water-supply planning and design, waste load allocation, irrigation design, recreation and wild life conservation.

Elementary identification of homogeneous regions was made on the basis of monthly rainfall data. However, additional and evenly distributed stations are used in the analysis; the homogeneous regions can be delineated on sub-basin level or even in watershed level.

In addition, the above classification would have been supported if evapotranspiration for the region was available. And water balance method can be applied to determine certain parameters for each catchment to relate with catchment characteristics.

To establish the low flow variation within the monthly flow, observed daily flow data is more accurate than the estimated daily flow for the analysis of FDC for each region.

The user is advised to use the estimated daily flow for the percent exceedance as a primary alternate. The second alternate, was to use the equation developed based on the standardized discharge against the percent exeedance level. The estimated daily flow is applicable for low flow analysis only.

A comparison between the mean monthly flow and daily flow for each station was made using the efficiency of fitted curve as shown on Appendix A.3. This comparison is based on the Q_{50}, Q_{70}, Q_{80} and Q_{90}, since our interest lies on the low flow of the stream. All stations, except station 6005, have an efficiency of more than 89% which is acceptable. Referring to K.N. Mutreja (1986), the efficiency of the fitted curve should be at least 80%. Generally, the computed daily flow is less in magnitude than the monthly flow for the above selected percent of exceedance as it was expected.

Another comparison was made between FDCs, based on monthly stream flow, for the gauged sites with FDC obtained from the regionalized FDC as shown on Appendix A.4. One can observe the regionalized FDC is a fair representative of gauged sites within the region.

In this research, attempt has been made to determine FDC for each region of Abbay Basin. Engaged sites or for short stream flow record length, Q_{70} and Q_{80} can be calculated from the regression analysis developed from the catchment characteristics, then mean annual runoff can be estimated.

6.2. Recommendations

The hydrometrological input and watershed characteristics used in the analysis have high significance in the determination of FDC in the basin. Therefore, each data used has to be accurate for better result. To improve the situation, it is recommended that:

- The hydrometrological stations need to be operational through out the year, periodic maintenance of the facilities and proper training for the data collector to understand the value of the data for the whole nation.

- Evenly distributed additional hydrometrological stations need to be established.

- Additional hydrological stations can be included in the regional FDC and same analysis, used in this thesis, need to be worked out, especially for regions at the periphery of Abbay basin.

- Applying the equations for the relationship of catchment characteristics and low flow may result in reliable result, as long as the physical characteristics of the watersheds under consideration are with in the range of those characteristics for the watersheds in this study.

- Proper identification of the stations location. In this thesis, it was observed that some hydrological stations do not lie on the river. And GIS tool needs accurate location of stations to delineate its catchments and subsequently determine its river length, catchment's area, catchment's slope and average elevation, etc.

- MoWR and NMSA provide as much as possible available information to enable student's research more certain and it is for the benefit of the same country we are all living in.

Finally, it is recommended that similar work can be done for all rivers in Ethiopia to facilitate the development in hydropower, irrigation, water supply and others that the country is in need at this stage.

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