



**ADDIS ABABA UNIVERSITY
SCHOOL OF GRADUATE STUDIES**

**FACULTY OF TECHNOLOGY
DEPARTMENT OF CIVIL ENGINEERING**

**RESERVOIR OPERATION AND ESTABLISHMENT OF
OPERATION RULES FOR LAKE TANA**

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By
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ABSTRACT

Lake Tana, naturally existed reservoir, located in the northern portion of the Abbay river basin is the largest lake in Ethiopia with an average water surface area of 3110 km² and estimated drainage area of 15340 km². It is fed by four major tributaries all of them rising in the highlands surrounding the Lake. One regulation weir, Chara-Chara, is constructed at its out let to regulate the lake water for hydropower productions from two existing plants (Tis Abbay I and II) and for the realization of the envisaged development works both in the Tana and Beles Basins. With an estimated mean annual inflow of 12051.5MCM, water resources of the Lake is currently utilized only for hydropower generation at Tis Abbay I & II, local transport from Gondar to Bahir Dar, largely traditional level fishing and for tourist attractions at Tis Esat fall.

Recently conducted Abbay river irrigated master plan project studies (BCEOM and associates, 1999) has indicated that the Tana and Beles basins all together have irrigation potential of more than 268,000ha out of which more than 145,000 ha is identified in the upstream reaches of the Lake Tana reservoir. At times of realization of the envisaged development works, irrigation and hydropower development works are, thus, becoming competing demands in the basin. Envisaged development works in the Beles basin are also competing with those in the Tana basin. This situation reveals that planning and reservoir operation in the basin is a serious issue that needs great attention, one of the principal reasons for this research work to be thought.

Establishing the water balance of the lake on a monthly time scale is a prerequisite to effect reservoir operation. This activity is performed applying the continuity equation. Final result of the water balance simulation for the lake has shown that 69.2% of the inflow is lost through reservoir losses and 31% lost as an outflow. Currently the reservoir is operated at some operation rule that satisfies the demand from the existing hydropower plants and minimum requirements of the Tis Esat fall. Reservoir operation in this research work is simulated based on deferent envisaged and existing development scenarios that bear different magnitude of demands to the reservoir. Including the existing condition the research work has come up with four development scenarios designated as the scenario-5, 6 and 7. Alternative operation rules for the existing condition and new operation rules for the three scenarios are developed accordingly.

1. INTRODUCTION

1.1 Background

The Lake Tana basin is situated in the northwestern portion of Ethiopia with an estimated drainage area of 15340km². The Lake is situated at an elevation of 1786masl (Studio Peterngeli, 1988) and fed by four major rivers, Gilgel Abbay, Megech, Gumara and Ribb, all of which rise in the highlands surrounding the Lake. Because of the restriction at its outlet, located in its southern tip, and its large storage capacity, the Lake rises slowly to reach the maximum stage near the end of the of heavy rains season, that is in August and September, and recedes slowly to its minimum stage during the beginning of the main rainy season that is in June and beginning of July. The basin is characterized by a large, flat to very gently slopping flood plain bordering the lake on the north and east and by an extensive area of gently rolling to hilly uplands in the north, east and south. Recent lava flows; hilly rocky land, low lying marshy areas and mountainous terrain comprise a sizable portion of the landscape of the basin.

One regulation weir, the Chara-Chara weir, is implemented at its outlet to regulate the lake water for hydropower generations from the two plants (Tis Abbay I and II) at the Tis Esat fall located some 30km d/s of the regulating weir. The weir has its minimum operating level at 1784masl and crest level of 1787, which gives a maximum water surface level of 1787.5masl with 0.5m afflux, resulted from the regulation effect of the weir. Furthermore, the regulating weir has resulted in regulatable depth of 3.5m that can regulate mean annual inflow of 12051.5MCM. Currently this huge amount of water resource is utilized only for generation of 84MW power at Tis Abbay fall, local transport from Gondar to Bahir Dar, largely traditional level fishing and for tourism attraction as a result of the naturally existed "Tis Esat" fall. Other envisaged areas of the basin's water resources, involve developments in the Beles basin.

The Beles basin is located west of the Tana reservoir. This basin is drained by the Beles River, which shares its watershed divide with the Tana basin in the west. The Beles River flows generally in the southwest directions to join the Abbay River close to the border of Ethiopia and Sudan.

The Tana Beles Project studies conducted in 1990 (Studio Pietrangeli, 1990) and recently conducted integrated master plan studies for Abbay river (BCEOM & associates, 1999) have revealed that huge amount of development potential has been thought at planning level. The Tana-Beles project study conducted by Studio Peterngeli in 1990 (Studio Pietrangeli, 1990) has the objective of diverting water from Lake Tana reservoir into the Beles river to develop two hydropower plants, upper and middle Beles hydropower plants, with an installed capacity of 220MW and 168MW respectively and a potential of more than 145000ha of land for the development of large scale irrigated agriculture. The first 63700ha of land is located d/s of the upper Beles hydropower plant and the remaining 80,000ha of land is located d/s of the middle Beles hydropower plant indicting that irrigation is the byproduct for hydropower development works planned in the Beles basin. In this basin the development of such a huge potential is thought by diverting water from the Tana reservoir using the Tana-Beles weir planned to be implanted in the western shore of Lake Tana near Kunzila town, a small town located on the west shore of Lake Tana. Diversion of water from Lake Tana is thought to be possible as a result of the regulation of the Lake water by the Chara-Chara weir.

The recently conducted Abbay river Integrated Master Plan Project studies (BCEOM & associates, 1999) has indicated that the Tana and the Beles basins all together have a potential of more than 268,000ha land for the development of large scale irrigated agriculture out of which more than 145000ha of irrigation potential is identified to be within the Tana Basin. This potential command area is located in the upstream reaches of the Lake reservoir. Thus development of irrigated agriculture in the basin would mean an abstraction from the inflows of the Lake Tana reservoir. Currently operated two hydropower plants, Tis Abbay I and II and the Tis Esat fall are located d/s of the envisaged irrigated agriculture development potential within the basin. This further indicates that the development of hydropower and irrigation competes for the same resource, the water in the Lake Tana reservoir. It can also be easily realized that the development plans thought in these two basins, Tana and Beles, are also competing needs, sharing the same water resource thus the reservoir of Lake Tana will be turned to a multipurpose reservoir built naturally in the system by the end of the realization of the planned development projects. The over all situation described so far is an indication how development planning and reservoir operation are serious issues in the Lake Tana hydro-system.

1.2 Problem Statement

In spite of the huge amount of untapped regulatable water resources available in the reservoir, the reservoir level has fallen close to its minimum operating level (1784.4masl) (Fig 1.1 and 1.2 below) in the year 2002/2003. This situation has been recorded as an unusual being the first event in its kind in the history of Lake Tana.

Figure 1-1 Time series plot for water surface elevation of Lake Tana reservoir

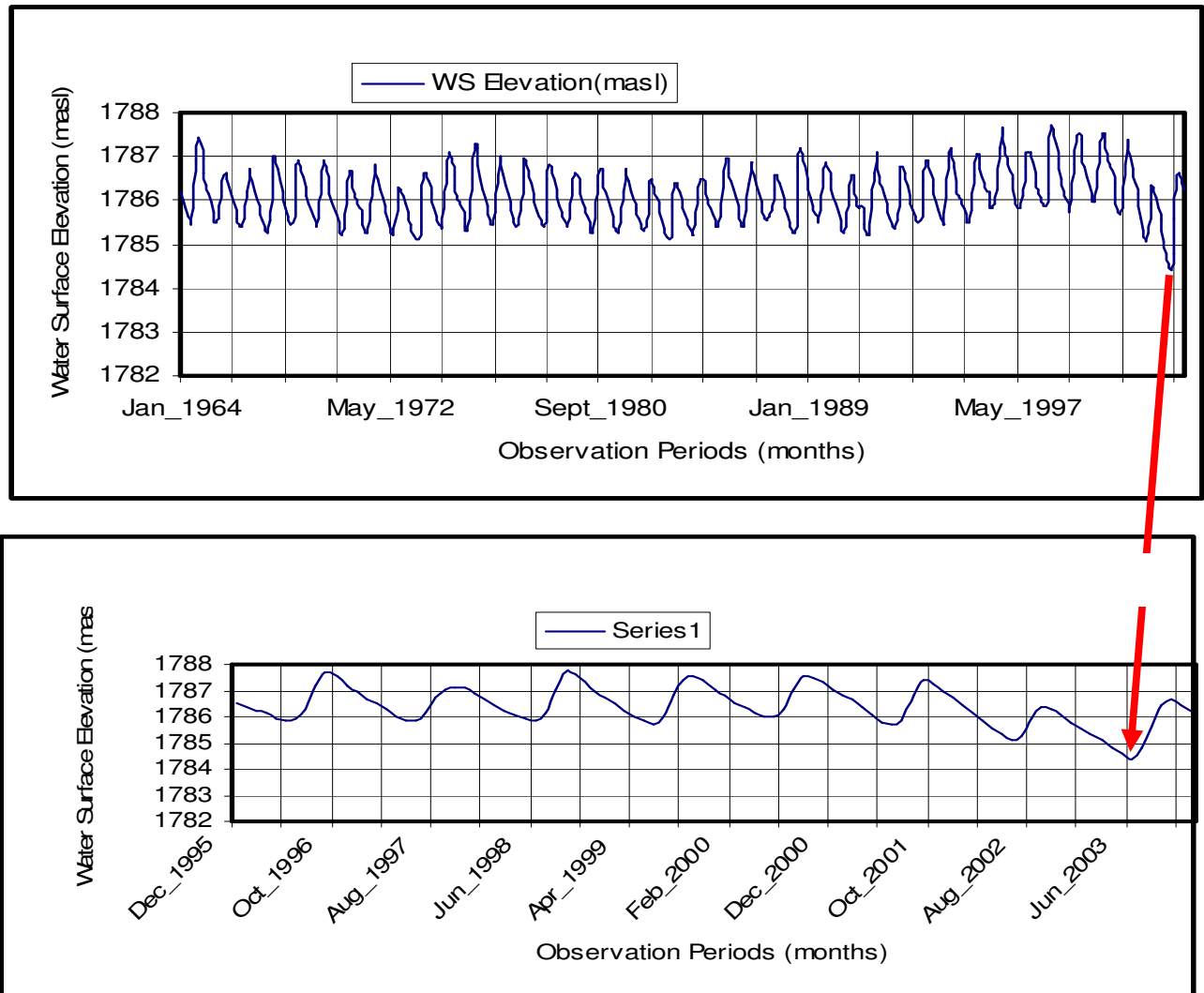


Figure 1-2 Time Series plot of Water surface Elevation after commissioning the Chara-Chara Weir

It was issued in the mass media that transport activities from Bahir-Dar to Gorgora (Gondar) was not possible starting April 2003 until mid July 2003. Similarly there was a fear that similar problems

will be encountered in the year 2004 at similar seasons as it was expected that the lake might not reach the natural reservoir level (1786 masl) in the rainy season of 2004. However, due to the regulation effect of the Chara-Chara weir the Lake level has been rehabilitated to its natural level in one-year time as a result similar problem was not faced in the year 2003/2004. Had it been in its natural context (with no regulation weir) the lake level might have taken six to nine years (Studio Peterngeli, 1990) to be back to its natural lake level. This is clearly observed from Fig 1.1 above, due to the 1983/84 drought the lake level has remained lower for more than 5 years until 1988.

With all these huge amount of regulatable water resources available in the lake, the reservoir is currently used only for transport purposes and to meet the demands of the Tis Esat fall and the two hydropower plants, Tis Abbay I & II. The regulation weir is operated by allotting more inflow ($60\text{m}^3/\text{s}$) for the fall during peak tourism period that mostly happens in December and January and a minimum discharge of $10\text{m}^3/\text{s}$ during the months of April to July. In some other period's large proportion of water as high as $64\text{m}^3/\text{s}$ is allotted for the two-hydropower plants. The Lake operated under such operation rule has been observed faced with unusual fall of lake level (as low as its minimum operating level) as issued in the mass media in the year 2002/ 2003.

This situation encountered by the Lake Tana hydro-system indicates that more problems would be manifested when all envisaged development works in the lake basin are fully implemented. These situations has initiated the idea of dealing with the operation of the lake reservoir to be made based on the water balance of the reservoir system and establish sound operation rules for the regulation weir so that regulation work would be made based on the water balance of the Lake hydro-system.

1.3 Objectives

General Objectives: - The general objectives of the thesis work include identifying the causes of current operational problems and developing alternative operation rules.

Specific Objectives: - The research work has a specific objective of studying the reservoir operation conditions of Lake Tana and establishing of operation rules using simulation techniques.

1.4 Methodology

The methodology used in this thesis work include, literature review, field level investigation of the study area and applying methods and techniques to estimate the runoff in to the reservoir, which has involved running four methods namely the regression model, the monthly water balance simulation techniques, the Area-Ratio methods and the SCS-CN methods. The reservoir operation is performed applying simulation techniques. Literature reviews are embodied in each and respective chapters and sections for convenience of referencing purposes. Finally the reservoir operation rules are established based on the simulation techniques.

2. THE STUDY AREA AND AVAILABLE DATA BASE

2.1 Location

2.1.1 Administrative Location

The research area usually known as the Lake Tana hydro-system is located in three administrative zones of the Amhara Region. North Gondar in the north and north-west, South Gondar in the east & south-east, and West Gojjam in the south and south-west. It covers five weredas (Wegera (20%), Gondar Zuria (fully), Dembia (fully), Chilga (10%) & Alefa (30%)) in north Gondar, five weredas (Kemkem & Dera 60% each, Estie-20%, and Farta and Fogera fully each) in South Gondar and six weredas (Achefer & Merawi fully each, Bahir Dar Zuria and Sekela 80% each, Fagta Laka -50% and Banja-10%) in west Gojjam. Large portion of the Tana water surface (the reservoir) is located in north Gondar, and some portion in south Gondar and west Gojjam administrative zones.

2.1.2 Geographical Location

The geographical location of the Tana basin extends from 10.95°N to 12.78°N latitude and from 36.89°E to 38.25°E longitude. The reservoir area is located from 11.62°N to 12.31°N latitude and from 37.01°E to 37.64°E longitude. **Error! Reference source not found.** below presents the Tana basin location in relation to the Abbay Basin.

2.2 Physical Features

2.2.1 Topography and Drainage

With a surface area of 3,110m² (as estimated in this research work) Lake Tana is the largest lake in the country. The study of the Tana-Beles project (Studio Peterngeli, 1990) has estimated the water surface area of Lake Tana, at its natural mean sea level of 1786, to be 3060km². The estimate made during this research work has been made using the image obtained from Digital Elevation Model (DEM) files so it is difficult to anticipate at what lake level the indicated area could be.

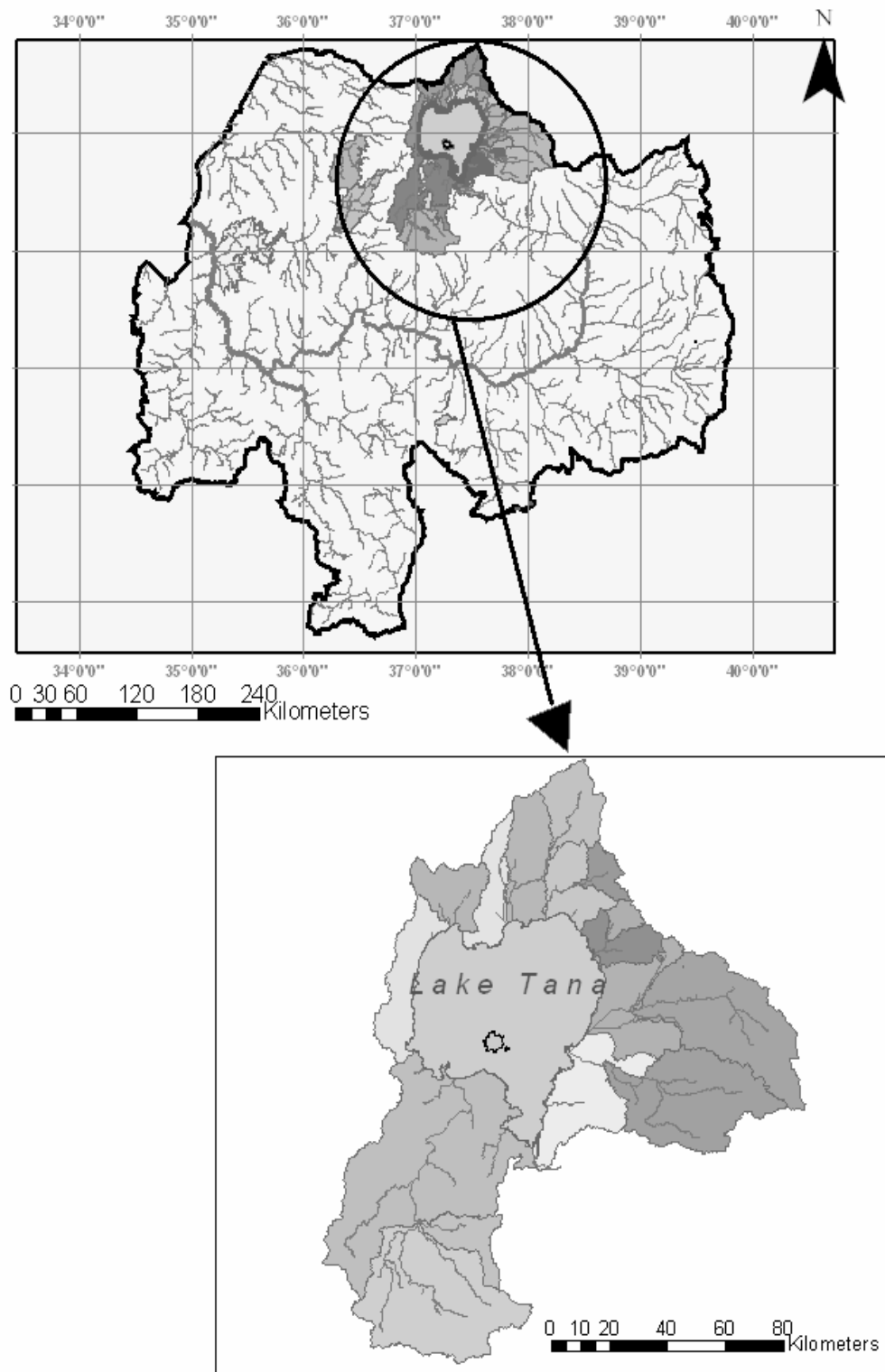


Figure 2-1 Location Map of Tana Basin

The drainage area of the Lake Tana sub basin is approximated to be 15,340km² (as estimated during this research work using DEM files). This Figure has been estimated to be 15320km² during the study of the Tana Beles Project (Studio Pietrangeli, 1990). The drainage area is drained with numerous rivers and streams flowing from the near by surrounding mountains crossing the flat valleys of Dembia in the north, Alefa-Bechigne in the west and north west, Achefer in the south and Fogera flood plains in the east. An average land slop of these flood plains is observed to be less than 5%.

The northern and northwest part of the basin is drained largely by five rivers namely, Ambagenene, Dirma, Megech, Gumaro and Arno-Garno, which account 18% of the basin. The Megech River is the major tributary contributing large proportion of Lake Inflows coming from north and northwest directions of the lake. These tributaries are considered as the Megech sub basins in the reports of the Tana Beles study (Studio Pietrangeli, 1990). The eastern portion is drained by Ribb and Gumara that accounts for 28% of the basin. Koga and Gilgel Abbay are the two major rivers draining the southern portion of the basin constituted to be 30% of the basin. The water surface of the Tana basin accounts 20% and the remaining 4% of the basin is drained by small intermittent streams in the west.

The northern portion starts from the Wegera highland plateau descending from the Ras Dashen peak (4620masl) and extending to the west in to the Sekelt and Chilga high land plateaus and to the south east in to the Degoma plateau. The Wegera and Sekelt plateaus are the recharging areas for the watersheds of Ambagenene, Dirma and Megech rivers attributed for reasons of observing base flow in these rivers. The Degoma plateau is also a recharging area for the watersheds of the Gumaro and Arno-Garno rivers. These plateaus are characterized with relatively flat land topography with an altitude ranging from 2000 to above 2500masl. Towards the south of all these plateaus, before they join the Dembia and the Alefa-Bechigne flood plains considerable portion of the basin is characterized with rolling type of topography, intensively cultivated, dissected with numerous streams that join the above mentioned major rivers. The land slope in some of this portion of the basin exceeds 10 to 20% with an average slope of more than 5%.

The eastern portion is subtended by the Farta highland plateau on the top descending from the Guna Mountain having an altitude of above 4000masl. The altitude of the Farta plateau is in the range of 2200 to 2600 with a relatively gentle slope and relatively uniform topography in nature. The

transition between the Farta plateau and the Fogera flood plain is characterized with rolling and non-uniform topography. This portion of the basin has short reach compared to the northern portion.

In the south the plateau part descends from the Choke Mountain (above 3900masl) , sharing some portion of the well known degraded land the “*Feres Bet*” in Sekela wereda, where it shares a water divide with the Birr valley, and finally joining the Achefer flood plain. Land topography in this portion of the basin is relatively uniform and gentle compare to the eastern and northern portions. This portion of the basin has very vast recharging area the reason that relatively sustained base flow is observed at Gilgel Abbay River.

The western portion of the basin is small bounded by chain of small hills (largely less than 2000masl) that serves as water divide between the Tana and the Beles basin. Land topography is highly rolling and non-uniform with little or no recharging plateau on the top; the reason being the landmass in this portion of the basin is drained by dry and/or intermittent streams.

Table 2-1 Drainage Area of sub Basins in the Tana basin

Sub Basin Name	Drainage Area (km ²)	Coverage (%)
Megech-Dirma	1000	7
Gumaro-Sizele	575	4
Arno-Garno	410	3
Ambagenen	360	2
Northwest Tana	405	3
West Tana	540	4
Ribb-shine	2110	14
Gumara-Gelda	2130	14
Koga-Gilgel Abbay	4700	31
Tana Water Surface	3110	20
Sum	15340	100

2.2.2 Climate and Rainfall

According to the study of NMSA (NMSA, Jan 1996) the Tana basin is identified to have two distinct dry and wet seasons. As per to the rainfall regime classification of Ethiopia by NMSA, the Lake Tana basin is included in the rainfall regime designated as region-B, dominated by single maxima rainfall pattern. The wet period, in this rainfall regime, decreases northwards. As a result region-B is subdivided in to three parts indicated as b1, b2 and b3, where the wet period runs from February/March to October/November, April/May to October/November and from June/July to

August/September respectively (Tesfaye and Yarotskaya, 1988). The Lake Tana basin falls in the last two sub rainfall regimes, b2 and b3, where the north portion is classified as b3 type of rainfall regime and the south portion as b2 type of rainfall regime. The eastern portion is also classified as b2 type with slight changes in the length of the wet periods, which extends from May/June to September/October. The Lake Tana basin in general is characterized by mono-modal rainfall pattern (NMSA, Jan 1996).

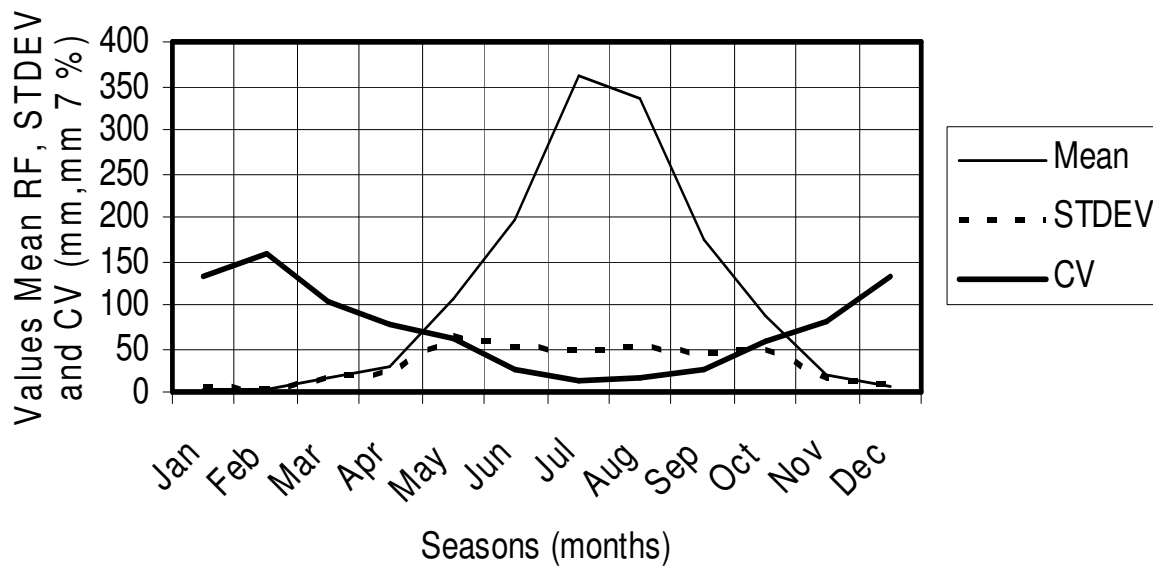
The mean annual rainfall at Bahir Dar (south portion of the basin) is 1450mm, 1200mm at Addis Zemen (eastern portion) and 1050 at Gondar Air Port meteorological station (northern portion), indicating the spatial variation of rainfall in the basin. Rainfall distribution, both in time and space, decreases northwards in the basin. The weighted mean annual rainfall over the basin as computed applying the inverse distance square method using the FEWS model (section 6.3.3) is estimated to be 1341.6mm.

The wet season lasts for relatively longer periods in its southern portion, which is extended from April/May to October/November. This wet period is relatively short in the north portion extending from June/July to August/September. The wet period is identified to have an intermediate length, May/June to September/October, in the eastern portion of the basin. The eastern portion mainly experiences intermediary conditions.

In the basin, seasonal rainfall distribution further indicates that more than 90% of the annual rainfall happens in the wet season of the year, which usually is called as the main rainy season or "*Kermet*". The average monthly rainfall coefficient of variation over the main rainy season is in the range of 13.2% to nearly 80% in which the highest coefficient of variation happens in April/May and in October/November, which are considered to be the beginning and end of the wet periods respectively. The coefficient of variation is lower in June, July and August, which are considered to be the wettest months in the basin where rainfall distribution acquires less variability due to the existence of uniform moisture in the atmosphere. The coefficient of variation increases northwards. The coefficient of variation of the mean annual rainfall is less than 20% (less variable) in the south portion, 20% to 30% (moderately variable) in the eastern portions and more than 30% (highly variable) in the northern portion. Fig 2.2 below depicts the situation described in the preceding paragraphs.

The mean annual temperature in the basin reaches up to 23°C in the low-lying areas (below 2000masl) like Bahir Dar and in the range of 15 to 20°C in the middle and high altitudes (above 2000masl). According to the study of NMSA (NMSA, Jan 1996) the mean annual evapotraspiration in the basin is indicated to be in the range of 1400 at Bahir Dar to more than 1600mm at Gondar AP. This indicates that evapotraspiration, in general, exceeds the annual rainfall amount in the basin. This coupled with high rainfall coefficient of variation especially at the beginning (April) and end (Oct/Nov.) of the main rainy season causes crop failure and yield reduction in the rain-fed agricultural system of the basin.

Figure 2-2 Seasonal Distribution of Mean weighted Rainfall at Tana Basin



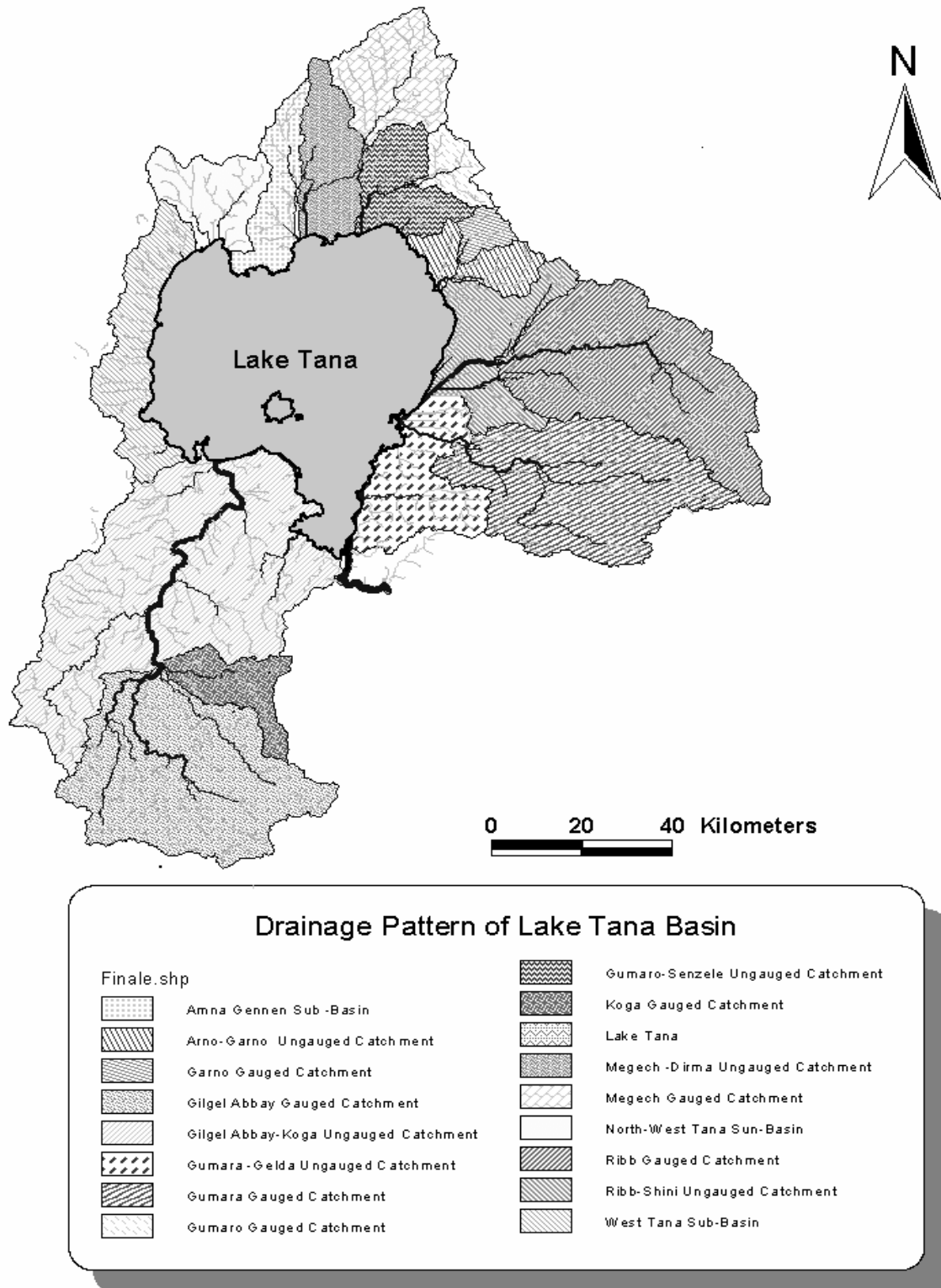


Figure 2-3 Sub Basin Drainage Pattern

2.2.3 Water Resources

At natural reservoir level of 1786masl (Studio Pietrangeli, 1990), the lake has a maximum depth of 15.2m and an average depth of 9m with a width of 65km (east-west directions) and length of 70km (south-north directions).

The inflow into the reservoir has been estimated applying the monthly water balance simulation techniques for the south and eastern sub basins and area ratio methods for north and northwest sub basins (section 6.2.4). Accordingly, the mean annual inflow to the reservoir has been estimated to be 12051.5MCM. This Figure has been estimated as 9380MCM during the study of the Tana-Beles Project (Studio Pietrangeli, 1990). The Tan-Beles study has estimated the inflow from the water balance of the Lake assuming the pitche evaporation recorded at Bair Dar could represent the direct evaporation of the Lake. The mean annual inflow, after the compilation of the data for gauged rivers only, is presented in table 2.2 below:

Table 2-2 Water Resources Potential of Lake Tana Basin (Gauged Catchments Only)

Sub Basin/River Name	Mean Annual Inflows	
	m ³ /s	MCM
North Sub Basins		
Megech	5.2	215.30
Gumaro	0.7	37.07
Garno	0.7	18.44
East Sub Basins		
Ribb	14.0	454.60
Gumara	31.6	960.00
South sub Basins		
Koga	5.0	155.65
Gilgel Abbay	54.2	1715.04
Total for the basin (gauged)	111.5	3556.10

From the data compiled for gauged rivers only the mean annual inflow for the gauged catchment is 111.5m³/s which is equivalent to 3556.10Mm³. The mean annual outflow, as gauged at the inlet of the Blue Nile at Bahir Dar, is recorded as 120.92m³/s which is equivalent to 3820MCM.

The Tana-Beles project study has further reported that the mean annual evaporation loss from the lake is 6000MCM, which represents 63% of the total inflow (9380MCM).

2.3 Geological Settings

2.3.1 Formations Occurring at Lake Tana

Basalt lavas of the tertiary volcanic, fresh and massive in structure and of the Miocene age are observed in the highlands surrounding the Lake. In the west and south west of Gondar the Chilga beds dominated with shale's and sand stones are observed. These beds are possibly of Pliocene age, contemporary with the last occurrence of Tertiary volcanicity (Studio Pietrangeli, 1990).

Quaternary Volcanics mostly represented by olivin alkali basalts, often inter-bedded with clayey palaeosoils are observed. Near Bahir Dar rhyolite lava is observed too. The attitude of the Quaternary volcanics is not always perfectly horizontal. Besides congenital dips of some lava flows, also gentle tectonic deformations can be noted, like the anticline fold found between Chara-Chara and Kamforo along the Blue Nile. Other edifices, mostly lavic, rise over the plain covered by basalt flows, extending from Bahir Dar to beyond the Gilgel Abbay. Also the small Dek Island, rising close to the larger and flat Narga Daga lavic island, is one of such edifices (Studio Pietrangeli, 1990).

Alluvium deposits cover the banks of the lower reaches of the main Lake Tana tributaries. They are composed of fine sediments, partly of marsh environment, which usually are represented by clays (Studio Pietrangeli, 1990).

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The Lake bottom is often lined by very fine sediments, the thickness of which is of the order of 1m. In the deepest part of the lake they cover consolidated sediments, which hinder the reflections coming from the bedrock to the echo sounder (Studio Pietrangeli, 1990).

2.3.2 Geological Impact as a Result of Regulation

The hydro-geological study made during the study of the Tana Beles Project (Studio Peterngeli, 1988) has indicated that nothing-negative impact emerges from the immediate consequences of the

high water level regime modifications resulted from reservoir regulation. The positive impact is indicated as the opportunity of having the greater productivity of water wells in the alluvial plains as a result of high water tables and does represent no danger. In long-term conditions, however, the situation could aggravate siltation in the d/s end of the tributaries and may result most gently sloping profiles. It is further reported that land slide at the banks do not occur, even at a potential stage neither by erosion of steep slopes nor by bank collapse consequent to natural draw down of the lake level (Studio Pietrangeli, 1990).

2.3.3 Sedimentation

By correlation of the solid loads with the recorded discharges, a total amount of 8.7 million m³ per year of suspended sediments has been obtained for the sum of the contributions of the rivers Gilgel Abbay, Koga, Megech, Rib and Gumara. This Figure could be increased to about 10MCM if the minor tributaries are considered (Studio Pietrangeli, 1990).

2.3.4 Seepage

The hydro-geological study made during the Tana-Beles Project (Studio Pietrangeli, 1990) has considered the possibility of water losses from the weir section, within a stretch of about 2km in the southern coast of the lake, located between the Tana hotel at the west and the Blue Nile at the east. The possibility of its unfavorable configuration has been taken in to consideration during their investigation. During this investigation possible seepage around the indicated area with a maximum flow of 0.14 m³/sec was observed and this has been estimated to be an annual seepage loss of 4 MCM (Studio Pietrangeli, 1990).

2.3.5 Land Resources

Agriculture, predominantly rain-fed, is the main stay of the basin economy. The surrounding flood plains known as Fogera, Dembia, Alefa-Bechigne & Achefer and the highland plateaus in the uplands of these flood plains are intensively cultivated areas for more than a century.

Rain-fed agriculture is predominant both in the uplands of the four major sub basins and in the flood plains. Recession cropping, mainly for maize, is also being carried out along the shores of the lake in

the Fogera, Dembia and Alefa-Bechigne flood plains. Small scale irrigated agriculture is practiced in the Fogera flood plain following the Bebeks, Shini, Gumara and Ribb river courses. Some are gravity command schemes (in the order of 200ha to 250ha) and some are pump schemes especially along the courses of Gumara and Ribb Rivers.

As per to the Abbay river integrated master plan studies (BCEOM & Associates, 1999) the Tana basin is indicated to have a potential of more than 145000ha and the Beles basin has an estimated potential of more than 123000ha of land for the development of large scale irrigated agriculture, which constitutes a total potential of 268000ha both in the Tana & Beles basins. The development in the Beles basin has been thought to be realized by transferring the water from Tana in to the Beles basin.

Recession Cropping: - Recession cropping around the Lake Tana reservoir is commonly practiced by the farmers living in the periphery of the reservoir. Maize is the major growing crop and cultivation is made using the residue moisture following the recession of the reservoir water level.

2.4 Socio Economic Features

2.4.1 Population

The total population in the basin is estimated to be in the order of 3,046,095 out of which the female constituted 47%. Majority of the population is from the Amhara ethnic group. Average family size, is reported to be 5.1 in the basin (CSA, 2001/02).

2.4.2 Economic Activities

Agriculture, dated back more than a century, is the main stay of the basins economy. Mixed farming is widely practiced, in which animals are largely used for draught purposes. Cultivated land in the basin is estimated to be 517500ha with total households of 588640 (CSA, 2001/02).

Nearly all types of crops are grown in the basin with cereals 77%, pulses 17% and oilseeds 6% and vegetables & root crops together with fruits account less than 1% (CSA, 2001/02).

Cultivation in the basin is largely mono crop harvest system with little practices of the Belg (spring) season in the high lands of south Gondar. Crop husbandry is predominantly rain fed, dependent on the natural rainfall system.

Despite the huge potential it is endowed with, irrigated agriculture development practice is very little known in the basin. Large scale irrigation practice is not practiced so far. Small scale irrigated agriculture development is practiced very little following the Gilgel Abbay basin, the Gumara and Ribb basins and the Garno streams. So far less than 500ha is developed.

The total livestock number in the basin is estimated as 7,525,741 in which cattle accounts 28%, poultry 50%, sheep and goats 15% and horses, asses, mules, camels & beehives account the remaining proportion (CSA, 2001/02).

2.5 The Available Data Base

2.5.1 Hydrologic Data

River Hydrograph Records: - The Ministry of Water Resources (MWR) collects hydrometric data at eight gauging stations, including the outflow data of the Lake at Bahir Dar. The gauging stations in the basin include, the Megech river near Azezo (642Km²), the Gumaro river at Maksegnit (174Km²), the Garno River at Enfiranze (94km²) in the north sub basin: Ribb (1592km²) and Gumara (1394km²) rivers near Addis Zemen & Bahir Dar respectively in the eastern sub basins and the Koga (244km²) & Gilgel Abbay (1664km²) in the south sub basin. All together the gauged portion of the Tana basin is estimated to be 5624km², which accounts 36.7% of the total catchment area of the basin and 45% of the total basin excluding the water surface. Table 2.3 below indicates the profile of the basin in this regard.

Table 2-3 Gauged and Un-Gauged Area Coverage of the Tana Basin

Sub Basin Name	Drainage Area (km ²)			Coverage (%)		Total Area Coverage (%)
	Gauged	Un-Gauged	Total	Gauged	Un-Gauged	
Megech-Dirma	462	538	1000	3.0	3.5	6.5
Gumaro-Sizele	174	401	575	1.1	2.6	3.7
Arno-Garno	94	316	410	0.6	2.1	2.7
Ambagenen	-	360	360	0.0	2.3	2.3
Northwest Tana	-	405	405	0.0	2.6	2.6
West Tana	-	540	540	0.0	3.5	3.5
Ribb-shine	1592	518	2110	10.4	3.4	13.8
Gumara-Gelda	1394	736	2130	9.1	4.8	13.9
Koga	244	-	244	1.6	0.0	1.6
G Abbay	1664	2792	4456	10.8	18.2	29.0
Tana Water Surface	0	3110	3110	0.0	20.3	20.3
Sum for Basin total	5624	9716	15340	36.7	63.3	100.0

Lake Level Fluctuation Records: - Lake Levels are recorded at Bahir Dar, Gorgora and Kunzila stations. The data recorded at Bahir Dar is observed to have both long recording life (since 1964) and quality so that the record at Bahir Dar has been used for the analysis. The records at other two stations are observed to have appreciable discontinuity and advised by the hydrology department of the MWR not to use it.

Reservoir Outflow Record: - Out flows from the basin are recorded in the Abbay River at Bahir Dar since 1964.

Bathymetry Survey: - Bathymetry survey of the Lake reservoir has been conducted in 1990 during the Tana-Beles (Tana-Beles project study, Studio Peterngeli 1990). Accordingly, the elevation-area and volume curves are prepared for the reservoir. These curves are used in this research work.

2.5.2 Climatic Data

In the Lake Tana basin 34 meteorological stations are available. 32 stations are selected and have been used in the data analysis and mean area rainfall computation process of the sub basins. It is only at Gondar Airport and Bahir Dar meteorological stations that all meteorological data are recorded and in the remaining 30 stations only temperature and rainfall data are recorded.

Evaporation data using pitch reading is recorded both at Bahir Dar and Gondar Air Port stations. Daily level data has been collected for all the 32 stations from the NMSA. In these 32 meteorological stations, rainfall and other meteorological data are recorded for reasonably sufficient (15 to 40 years) record periods. In some of these stations such as Bahir Dar, Gondar AP, Koladiba, etc to mention some, recording has been started since 1964 following the master plan study of the Blue Nile by the USBR.

2.5.3 Hydropower Related Data

Hydropower related data has been collected from master plan studies of the Abbay River basin (BCEOM and associates, 1999), the Tana Beles Project study (Studio Pentangle, 1988) and the Tis Abbay II feasibility and detail design reports (Humphrey and associates, 1996). Current operation rule for the Chara-Chara weir has been studied by Humphrey and associates and the data obtained has been used in this research work (Humphrey and associates, 1996). Moreover, pertinent data has been collected in the master plan document of the hydropower development of the country as collected from EEPCO (Acres International, 2003). Energy production at Tis Abbay I & II hydropower plants and releases for Tis Abbay I & II at Tis Esat off-take on monthly basis, since July 2001, has been collected from EEPCO.

2.5.4 Socioeconomic Data

The federal Central Statistics Authority (CSA) has conducted sample enumerations on the Ethiopian agricultural sector in the year 2001/02 (CSA, 2001/02). This enumeration has also been conducted in the Amhara region where the research area is located in. Quite a number of bulletins with various detailed information's are prepared and made available for use (CSA, 2001/02). The agricultural population, land holdings, economic activities at zonal and wereda levels, livestock population by type, production and productivity by crop type at weredas level are some of the basic information's compiled during the sample enumeration by the federal CSA. The research work has used this advantage to collect pertinent socioeconomic data of the basin.

2.5.5 Crop Husbandry Data

Major crop types grown in the basin were collected from the CSA agricultural enumeration bulletin. Irrigated cropping pattern in the available potential sites of the basin were collected from the current Koga project offices and the recently conducted Abbay River Integrated Development Master Plan Study reports.

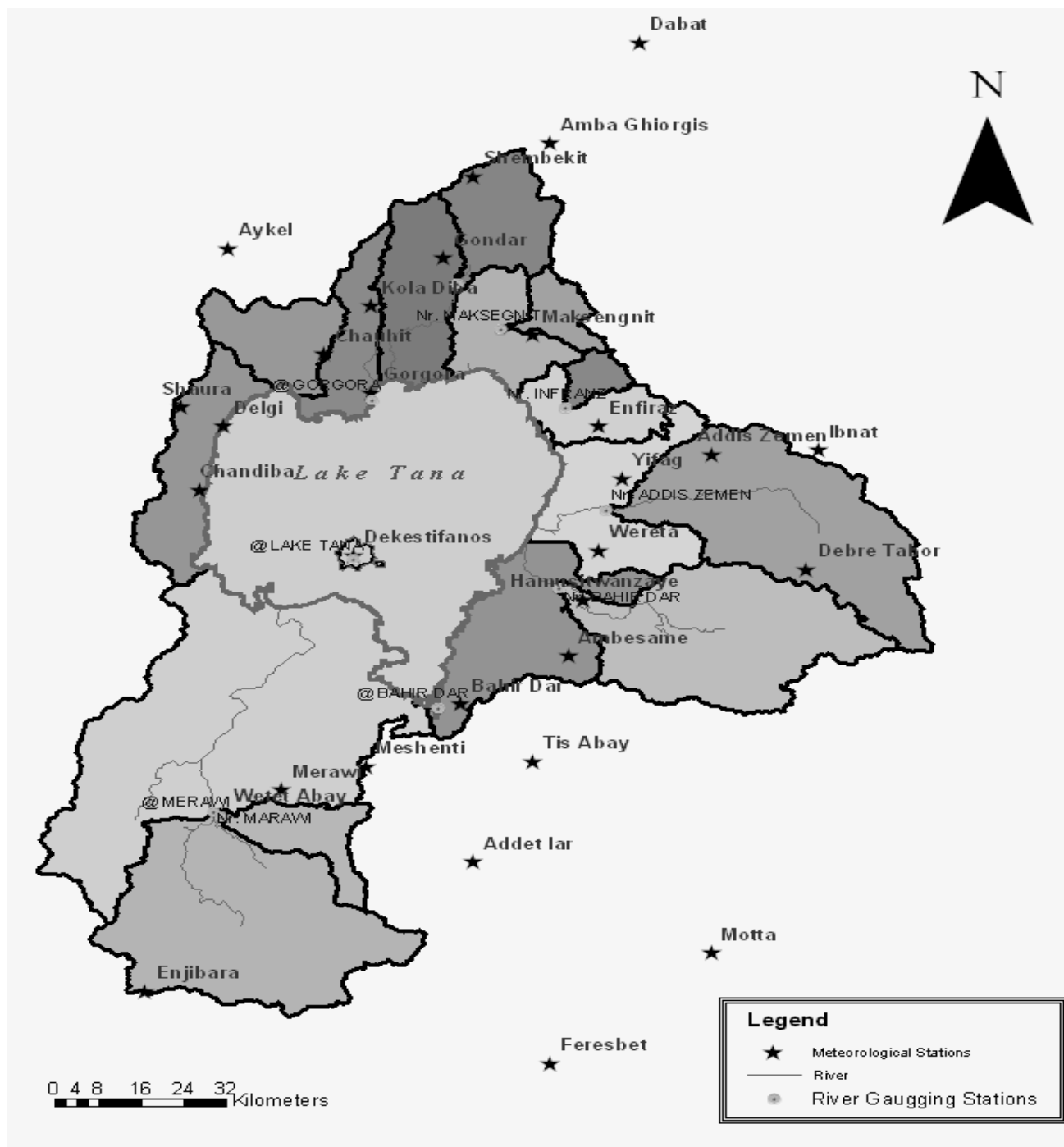


Figure 2-4 Hydrometric and Meteorological Gauging Stations in the Tana Basin

2.6 Water Resources Potential and Current Level of Utilization

2.6.1 Potential for Irrigated Agriculture Development

So far no large scale irrigated agriculture has been implemented in the basin. Only few hectares of recession cropping along the shore of the lake and some small scale irrigation activities are being practiced in the eastern portion of the basin. These small-scale development works are estimated to be in the order of not more than 500ha

The recent Abbay River master plan study (BCEOM and associates, 1999) has sub-divided the Tana basin in to nine sub basins (excluding the Beles sub basin) while studying the irrigated agriculture development potential of the basin. As per to the Abbay river integrated master plan studies (BCEOM & associates, 1999) irrigated agriculture potential for the basin is identified based on different development scenarios. Three development scenarios are developed based on the implementation capacity of the country taking the involvement of the public and the private sector in to consideration. Theses scenarios are indicated as the do nothing scenario, the conservative scenario which emphasis an active involvement of the public sector; the accelerated scenario that considers an active involvement of the private sector in the development of water resources and the fourth scenario which is based on the implementation of all identified projects in the basin (BCEOM & associates, 1999).

The basin is indicated to have a potential of about 100,000ha, for conservative development scenario (excluding the Beles basin potential area) for the development of irrigated agriculture and about 135,000ha for the accelerated development scenario/model. The latter includes the development in the Beles basin by transferring water from Tana in to the Beles basin (BCEOM & associates, 1999). There is also a proposal to develop a recession cropping along the shore of Lake Tana. The study in its phase-2 report has indicated that there exists a potential for recession cropping development following the shore of Lake Tana. A typical cost estimate for 200ha land has been made and it is estimated to be Birr 56000/net ha. Total potential is not known and/or indicated in the report (BCEOM & associates, 1999).

2.6.2 Potential for Hydropower Development

In the Tana basin the existing Tis Abbay I & II hydropower plants with installed capacity of 84MW, are considered as the only medium scale hydropower scheme available so far. Small scale hydropower development potentials are observed to be considerable. A number of preliminary level studies have been conducted so far in this regard and it is reported that the Abbay river basin as a whole has considerable potential in the development of small-scale hydropower plants. The basin accounts more than 50% of the country's, potential for the development of small scale hydropower plants. The potential in the Fetam and Andasa rivers, the possibility of incorporating small scale hydropower development plants within the u/s reservoirs of Ribb, Gumara, Gilgel Abbay and Megech, which are basically planned for the development of irrigation are to mention some of the possible potentials of small scale hydropower development works in the Tana basin in particular and in the Abbay river basin in general.

In the Beles basin two sites have been identified as a potential for the development of large scale hydropower plants. The first with installed capacity of 220MW is located in the upper reach of the Beles basin (upper Beles-1) and the second with estimated installed capacity of 168 MW is located in the middle reach of (middle Beles-2) the Beles river (BCEOM & associates, 1999).

2.6.3 Other Development Potentials

Tourism and recreations are also of considerable potential in the basin. The “*Tis Esat*” fall (water that smokes) is known to be one of the tourist attractions in the country. Proper environmental management of the fall would create an immense tourism potential in the future. More over, the lake shore at Bahir Dar and Gorgora (Gondar Side) are observed to be more suitable for recreation and would attract more tourists and could be coupled with tourism to generate more income in the future.

3. PREVIOUS STUDIES

3.1 General

Water resources development in the Tana basin has been studied at different level of details by different consultants of various times since 1900's. The most relevant recent studies are enumerated as:

- **The USBR Studies:** - In 1964, Land and Water Resources of the Blue Nile Basin, has been studied by the United States Department of the Interior, Bureau of Reclamation (USBR) (USBR, 1964), the study was made for the Ministry of Public Works and Communications of the King's regime. The Tana basin as one major sub basin of the Blue Nile basin has been included as part of this study.
- **The 1990, Tana-Beles Project Study,** - This study was conducted by Studio Peterngeli (Studio Pietrangeli, 1990) for the Ministry of Construction during the Dergue regime. This was by far the most detailed study that has been made for the basin so far, though it is made to concentrate on the Tana-Beles project only.
- **Abbay River Basin Integrated Development Master Plan Project:** - In 1998-99, the country has conducted an updating study for the study made by the USBR in 1964. Abbay River Basin Integrated Development Master Plan Project, (BCEOM & Associates, 1999), owned by the Ministry of Water Resources of the current regime is the latest study the basin has. Like wise the Lake Tana basin has been considered as part of the Blue Nile basin and the study has also been conducted for it.
- **The Lahmayer International (LI) Study (Lahmayer International, 2003):**- Lahmayer International (LI) has conducted a feasibility level study for the Beles basin hydropower works. This is the first document dealt at feasibility level for Beles basin. This document has been reviewed and pertinent data is collected.

The above studies have been reviewed and that most relevant information and conclusions are presented in the following sections.

3.2 USBR Studies (1964)

The study conducted by the USBR in 1964 is named as study of land and water resources of the Blue Nile basin, as the name implies includes the entire Blue Nile basin. This study has also included the entire basin of Lake Tana and the Beles basin (USBR, 1964).

The study conducted was made at reconnaissance level and have identified considerable sites both for irrigation and hydropower in both the Tana and Beles basins. This reconnaissance study has identified six major irrigation sites in the Tana basin and summarized in table 3.1 below.

Table 3-1 Identified Projects in the Tana Basin by the USBR Studies

Project Name	Purpose	Source (River)	Res Capacity (MCM)	Command Area (ha)
Megech Gravity	Irrigation	Megech	225.3	6940
Ribb River	Irrigation	Ribb	312.6	15270
Gummara River	Irrigation	Gummara	236.7	12920
West Megech Pump*	Irrigation	Lake Tana	12,987	7080
East Megech Pump*	Irrigation	Lake Tana	12987	5890
Northeast Tana Pump*	Irrigation	Lake Tana	12987	5000
Sum				53100

* Reservoir Capacity of Lake above elevation of 1783masl

Source: Land & water Resources of the Blue Nile Basin, Ethiopia, Volume-I USBR Studies in 1964 (USBR, 1964)

The USBR studies ((USBR, 1964) has also proposed a regulation dam for Lake Tana at Chara-Chara with the objective of diverting the lake water to the upper Beles hydropower plant. The reservoir is planned to be operated between the water surface levels of 1783 and 1787.57m in which the spillway crest level is fixed at 1787.25masl. The study also anticipated that minimum releases of $3\text{m}^3/\text{s}$ for the Tis Esat fall (USBR, 1964).

The report further indicates that the Beles River Basin covers an area of $20,000\text{Km}^2$ (USBR, 1964). The elevation difference between Lake Tana (maximum water surface level 1,787masl) and the Upper Beles Valley would be exploited to generate 200MW of electrical power and 1,200GWh of energy at a surface powerhouse (tailrace elevation at 1500masl) adjacent to the Beles River. The design capacity of the diversion scheme was $110\text{m}^3/\text{s}$ (USBR, 1964).

Land classification studies, based on aerial photo interpretation, estimated that some 63,200ha of land in the Upper Beles Valley is suitable for irrigation (USBR, 1964). The soils in this basin, especially in its northwest portion are predominantly black clay soils. The reddish-brown lateritic soils that cover some 40% of the project area are found mostly in the southern parts. However, the

studies concluded that despite the suitability of the land for irrigation, there is insufficient water in the Upper Beles Valley to support any but the smallest of irrigation schemes(USBR, 1964)..

The diverted water in excess of the irrigation demand in the upper Beles valley is planned to develop another hydropower plant with installed capacity of 168MW and annual energy of 741GWH.

3.3 Tana-Beles Study (Studio Peterngeli, 1990)

These studies were carried out between late 1986 and mid 1990 (Studio Peterngeli, 1990). The core objective of the studies was to develop a plan to resettle up to 1.47 million people from drought affected areas of Ethiopia. As such, the study did not attempt to maximize the utilization of available resources (land and water), rather it was focused on drawing up a workable staged development plan which would provide a sustainable livelihood for the resettled population. The result of the studies was a seven-stage resettlement plan over some 40 years (Studio Peterngeli, 1990):

The study has envisaged the construction of an underground hydropower scheme exploiting the head difference between Lake Tana and the Upper Beles Valley. This hydropower station would have an installed capacity of 270MW and a firm annual energy of some 1,860GWh/year (Studio Peterngeli, 1990).

The study also envisaged the development of irrigation schemes. In total, irrigation schemes serving some 225,000ha were planned. None of the irrigation schemes were studied beyond reconnaissance level. The proposed irrigation schemes, relevant to the multipurpose use of diverted Lake Tana water, were indicated as follows (Studio Peterngeli, 1990):

Upper Beles Irrigation Project: - A gravity scheme covering 15,000ha between elevations 1250 and 1,000 was proposed to support the planned resettled population. This scheme does not rely on water resources of Lake Tana reservoir (Studio Peterngeli, 1990).

Upper Dindir Irrigation Project: - It is reported that a total of 100,000ha of land is available in this valley and only about 40,000ha of land is reported as suitable for agriculture. It is observed that only 10,000ha of land is suitable for irrigation as the soil is predominantly vertisol type. The demand of

irrigation for this scheme is not envisaged to be met from the Lake Tana reservoir. It was planned to settle 100,000 people in this area.

Lower Beles Irrigation Project: The total area is reported to be 200,000ha out of which some 150,000ha of land were reported to be suitable for agriculture. Considering a gravity command the command area estimated in this valley is reported to be 90,000ha. The Lower Beles Valley is located between elevations 800 and 600masl. This scheme would rely on water diverted from Lake Tana (Studio Peterngeli, 1990).

The report indicates that the Beles 1515 dam is the preferred option for hydropower development in the upper Beles valley that utilizes the regulated water from Lake Tana. The scheme utilizes the 270m head difference b/n Lake Tana and the tailrace level of the Beles 1515 dam to implement a hydropower plant with installed capacity of 270MW and firm power of 215MW with energy production of 1860GWH/year (Studio Peterngeli, 1990).

Further more the report has considered the development of six irrigation sites in the periphery of Lake Tana to be realized in stage two. These schemes constitutes: North Megech (15,000ha), North West Tana (Delgi) (7000ha), west Tana (Kunzila) (5000ha), Gilgel Abbay (4000ha), Southwest Tana (Zege) (8000ha) and East Tana (5000ha). The study disregards irrigation development works in Ribb and Gummara rivers for reasons of drainage problems and if development is required it can be developed by means of intake works on the Ribb and Gummara water courses (Studio Peterngeli, 1990).

A water resource of Lake Tana is estimated applying water balance simulation techniques for the reservoir. The study has applied a backward computation procedure on the water balance equation of the Lake. Availability of insufficient rainfall data in the entire Tana basin has been taken as an excuse for not to employ conventional methods in the computation of reservoir inflows. The report further indicated that the inflow computed applying backward steps of the water balance simulation of the Lake reservoir is more reliable. While estimating the inflow they have started from the outflow, taking monthly level variations of the Lake water surface and evaporation at Bahir Dar in to account in the monthly water balance simulation. The report has indicated that evaporation recorded

(Pitch reading) at Bahir Dar is assumed to be equivalent with the direct evaporation from the lake water body (Studio Peterngeli, 1990).

3.4 Abbay River Basin Integrated Master Plan Studies (BCEOM & Associates, 1998-99)

This study was carried out over three years period between 1996 and 1999 and comprised three phases – Inception, Inventory and Analysis and, finally, Master Planning. The Master Plan has been conducted for 50-years planning horizon concentrating on the following resources of the basin: Water, Minerals, Land, in particular irrigation, Vegetation, Soil, Energy, and Fisheries (BCEOM & associates, 1999).

The consultant has established different scenarios while effecting master planning of the water resources development in the Abbay River basin. These scenarios are established based on the idea that planning is primarily the function of finance and implementation capacity of the country. In assessing the implementation capacity of the country the consultant has given due emphasis the involvement of the public and private sectors in the development of water resources in the basin within the planning horizon. Accordingly the master planning of the basin has developed four scenarios for the development of water resources largely irrigation in the Abbay River basin, which are enumerated as (BCEOM & associates, 1999):

- A: Reference scenario, or the existing situation;
- B: Possible development within the Master Plan period, with both conservative and accelerated variants, exclusively limited to identified project sites;
- C: A full set of scenario with all identified projects;
- D and E: The maximum potential which has been evaluated on the basis of comparing water resources with potential irrigable area in sub basin units and administrative zones with both restricted and unrestricted alternatives.

The above scenarios, except D & E, were studied using the Water Balance software (WATBAL) developed by the consultant. The Bs and Cs are developed from various combinations of previously identified potential irrigation schemes. According to the study of the consultant, total net area of identified potential irrigation schemes in the Abbay River basin is estimated to be 525,929 hectares

including 114,550ha in the Northwestern basins of Dindir, Rahad and Galegu. Out of this potential the Tana-Beles basin is estimated to have a total potential of 268000ha, which accounts 50% of the total basin potential. The development plan for the envisaged projects is summarized and presented in table 3.2 below. The consultant has further formulated the Bs scenario in to two parts (BCEOM & associates, 1999):

- The Conservative Model, with a total of about 235000ha in the Abbay River basin, out of which the Tana-Beles sub basin constitutes 114056ha in which 79056ha is in the Tana Basin and the remaining 35000ha in the Beles basin. The planning in this scenario gives more emphasis to the involvement of the public sector.
- An accelerated development, with a total of about 350,000ha in the Abbay River basin and the Tana-Beles sub basin constitutes 176163ha of which 87163ha is located in the Tana basin and the remaining 89000ha is located within the Beles basin. The planning in this scenario has assumed considerable involvement of the private sector in the development of water resources.

3.5 The Lahmayer International (LI) Study (August 2003)

The Lahmayer International (LI, 2003) study conducted in 2003 is specific to the Beles basin and the first attempt made at high level of the project development both in the Tana and Beles basins. The study concentrates on the hydropower development aspects in the Beles basin working a feasibility level study on the Beles 1515 hydropower plant. The study reports that the project would divert flow from Lake Tana to the upper reaches of the Beles River. The diverted flow would serve for irrigation purposes as well as for hydropower generations. The power plant has an installed capacity of 220MW, a rated flow of 80m³/sand a head of 308m. The feasibility study further acknowledges that the Beles scheme would reduce flow to the existing Tis Abbay I & II projects (LI, 2003).

3.6 Important Conclusions and Remarks

The USBR Studies: - Land and water resources study of the Blue Nile by the USBR was constrained limited by data scarcity. River gauging was attempted for few years earlier in the Abbay River at Kase. Also during the investigation some measurements were collected at the outlet of Lake Tana.

Long period records at the Roseires gauging station in the Sudan located short distances below the Ethio-Sudan border was made and this data has been made available for the study. The study, during its investigation, has given due emphasis for the installation of gauging stations in various rivers in the Abbay basin and collected data for one year and little longer periods. The short-time stream flow records obtained within the Abbay River basin were correlated with longer records downstream in the Sudan on the Blue Nile, Dindir, and Rahad Rivers to estimate flows at the various reservoir sites.

The Tana-Beles Studies (1990): - According to this study the Chara-Chara regulation weir is planned to be realized initially and to be followed by the diversion Tunnel and the Beles 1515 power plant. The study plans to utilize the regulated water of Lake Tana by realizing six irrigation projects (mentioned in section 3.3) in the periphery of Lake Tana for the time gap available until the implementation the Beles 1515 hydropower. This implies that the study disregards development works in the Tana basin identified during the USBR studies.

The reason cited by the consultant to compute reservoir inflows applying a backward simulation of the monthly water balance equation for the Lake seems not inconsistency with the conditions prevailed during the study. During this research work, it is learnt that rainfall data has been recorded at Koladiba, Addis Zemen, Chilga, Wettet Abbay, Wereta, Debere Tabor, and Engibara; for some of them since 1959 and for others since 1973. Thus this should not be taken as an excuse. Furthermore, effecting backward simulation of the monthly water balance of the Lake would provide the inflow what it should be not what it is. The reliability is questionable for various reasons. For instance in water balance simulation of such huge water surface system; evaporation is the most uncertain component that shall be given due attention. The Tana Beles study has only made an assumption that the evaporation recorded at Bair Dar is equivalent to water surface evaporation at Lake Tana, with out giving any justification and/or reason. The pitche reading is collected from a very small water body, which may aggravate evaporation. The study should have developed a coefficient that will relate these two parameters. Using the pitch reading with out developing a coefficient may not guarantee quality and reliability. Moreover the evaporation recorded at Bahir Dar shows a significant trend (refer to the next section) which is largely associated with the trends and shifts in the recorded data of wind speed. This could be attributed by systematic errors or due to the location of the gauging stations, which may not be compatible with the relative position of the Lake water body. This issue needs to be resolved before directly using the pitche reading at Bahir

Dar as equivalent value for water evaporation from the Lake water body. Further more the study assumes that the seepage component of the water balance of the Lake is negligible by conducting an investigation on the outlet area of Lake Tana, which would not be the representative for the entire water surface area of the lake. This is also another area for inducing errors in simulating the monthly water balance of the Lake. This assumption might have been made to simplify the computation problem as the problem will be indeterminate with one equation and two (inflow and seepage) unknowns.

Abbey River Basin Integrated Master Plan Studies: - This is the recently accomplished study conducted on the Abbey River basin in the year 1999. The study has the objective of updating the findings of the USBR studies which has been conducted in 1964, 35-years back. During this study the basin has been provided with better data recording situations as compared to the time of the USBR studies. The consultant in charge of the study has used such advantages and applies a water balance model to optimize resources development opportunities in the basin.

Tana and Beles basins were considered as sub basins of the Abbey river basin and development opportunities were investigated. The report has indicated that the consultant has formulated three scenarios in which the first two scenarios (designated as the Bs scenario) have dealt with possible potential development sites in the Abbey River basin in general and in the Tana-Beles sub basins in particular. The first scenario referred as the conservative scenario gives much emphasis for the development of the Tana basin with little development opportunities (the Beles-2 project) given to the Beles basin. This has been emanated from the understanding of that water resources available in the Tana reservoir will not be sufficient to develop both basins equally. This was the first attempt so far. None of the previously conducted studies has considered the effect of the development of these basins to one another. The third scenario termed as the accelerated scenario gives more emphasis to the development of the Beles basin with considerable development opportunities in the Tana basin too. As a result of the fore going discussions the researcher is kin to adhere more to this recently developed master plan studies and the various alternatives evaluated and established in this research work are developed largely based on the findings of this study. In conclusion the identified projects in both Tana and Beles basins are presented in table 3.2 below.

The Lahmayer International (LI) Study: Though the study is conducted at feasibility level, the water resources available for the development of the envisaged hydropower plant is made based on the outflow of Lake Tana. The inflow in the system is not computed using some other conventional methods.

All of these projects, alike to the other previous studies, are studied at reconnaissance level. Furthermore, neither detailed topographic surveys of pilot areas nor subsequent preliminary designs of potential irrigation schemes have been carried out. Therefore the above irrigable areas are only preliminary estimates which have not been confirmed by ground surveys and subsequent mapping (land suitability, soil and topography).

Table 3-2 Projects Identified in the Tana-Beles Basin during Master Planning of the Recently Developed Studies

a) Conservative Scenario

Region	Zone	Selected Schemes for Master Planning Phase				Master Plan implementation periods			Total (ha)
		Codes	Project Name	Sub Basin	Total Area (ha)	Years 1-15	Years 16 - 30	Years 31-50	
Amhara	North Gondar	MEG1-4	Megech pumping	Lake Tana	24510	4000	8510	12000	24510
		NWT1-4	Northwest Tana	Lake Tana	6720			2200	2200
		DIN2	Lower Dindir	Dindir	25000			2000	2000
	South Gondar	NET	Northeast Tana	Lake Tana	5475	3000	2475		5475
		RIB1-2	Ribb 1800	Lake Tana	19925		8000	6459	14459
		GUM1-6	Gumara	Lake Tana	13776			10000	10000
	West Gojjam	KOG1	Koga	Lake Tana	5100	5100			5100
		GIL1-8	Gilgel Abbay	Lake Tana	16499	4000	5999	6500	16499
		SWT1-4	Southwest Tana	Lake Tana	5132			5132	5132
TIS1-2		Tis Abbay	Tis Abbay	4132			4132	4132	
TIS3-5		Tis3-5	Tis Abbay	7167			7167	7167	
Benishangul	Metekel	Bel2	Lower Beles	Lower Beles	85000		12000	8000	20000
Gumuze Sum Conservative Scenario					218436	16100	36984	63590	116674

b) Accelerated Scenario

Region	Zone	Selected Schemes for Master Planning Phase				Master Plan implementation periods			Total (ha)
		Codes	Project Name	Sub Basin	Total Area (ha)	Years 1-15	Years 16 - 30	Years 31-50	
Amhara	North Gondar	MEG5-6	Megech Gravity	Lake Tana	7311			7311	7311
		NWT1-4	Northwest Tana	Lake Tana	6720		6720		6720
		DIN2	Lower Dindir	Dindir	33555		15000	18000	33000
		BEL1	Upper Beles	Beles	8000			8000	8000
South Gondar	NET	Northeast Tana	Lake Tana	5475	5475			5475	
	RIB1-2	Ribb 1800	Lake Tana	9104	5000	4104		9104	
	RIB3-4	Rib 1820		10821		5000	5821	10821	
	GUM1-6	Gummara	Lake Tana	13776		7000	6776	13776	
West Gojjam	KOG1	Koga	Lake Tana	5100	5100			5100	
	GIL1-8	Gilgel Abbay	Lake Tana	15938	4000	11938		15938	

Table 3.2 Cont'd

		SWT1-4	Southwest Tana	Lake Tana	5132			5132	5132
		TIS3-5	Tis3-5	Tis Abbay	7167			7167	7167
		BEL1	Upper Beles	Beles	8000			8000	8000
Benishangul	Metekel	Bel2	Lower Beles	Lower Beles	85000		21000	30000	51000
Gumuze Sum Conservative Scenario					221099	19575	70762	96207	186544
c) All Identified Projects for the Master Plan									
Region	Zone	Selected Schemes for Master Planning Phase				Master Plan implementation periods			Total (ha)
		Codes	Project Name	Sub Basin	Total Area (ha)	Years 1-15	Years 16 - 30	Years 31-50	
Amhara	North Gondar	MEG1-4	Megech pumping	Lake Tana	24510	4000	8510	12000	24510
		MEG5-6	Megech Gravity	Lake Tana	7311			7311	7311
		NWT1-4	Northwest Tana	Lake Tana	6720		6720		6720
		DIN2	Lower Dindir	Dindir	33555		15000	18000	33000
		BEL1	Upper Beles	Beles	8000			8000	8000
	South Gondar	NET	Northeast Tana	Lake Tana	5475	5475			5475
		RIB1-2	Ribb 1800	Lake Tana	19925	1362	12104	6459	19925
		RIB3-4	Rib 1820		10821		5000	5821	10821
		GUM1-6	Gummara	Lake Tana	13776		7000	6776	13776
	West Gojjam	KOG1	Koga	Lake Tana	5100	5100			5100
		GIL1-8	Gilgel Abbay	Lake Tana	15938	4000	11938		15938
		SWT1-4	Southwest Tana	Lake Tana	5132			5132	5132
		TIS1-2	Tis Abbay	Tis Abbay	4132			4132	4132
		TIS3-5	Tis3-5	Tis Abbay	7167			7167	7167
		BEL1	Upper Beles	Beles	8000			8000	8000
Benishangul	Metekel	Bel2	Lower Beles	Lower Beles	85000	20000	21000	30000	71000
Gumuze Sum Conservative Scenario					236052	35937	78762	106798	246007

4. PRELIMINARY DATA ANALYSIS

4.1 Aspects of Data Quality

4.1.1 Hydrologic Data

In general terms, hydrologic data collected from eight gaging stations in the basin are observed to have good quality. As these data were used continuously by the consultants during the various studies conducted for the basin, the MWR, has continuously keep updating the rating curves as a result most of the data, especially from 1973 are reasonably well recorded. The data in wet periods are well recorded as compare to the dry periods. In the year 1990/91 almost all gaging stations, except the Tana outflow recording station, has data missing for dry months the reason being the war at the fall of the Dergue regime. Though data recording for most of the rivers in the basin has started in 1964, the records before 1973 were not of good quality. Unavailability of computer for data processing purposes is considered as an excuse by the MWR's. Nevertheless the data from 1964 up to 1988 was properly treated and well documented by the Tana-Beles project study (Studio Pietrangeli, 1990).

4.1.2 Climatic Data

The data in those meteorological stations available in the basin is observed to have considerable missing data. For most of the stations the missing data for rainfall especially, accounts more than 10%. From all climatic data, rainfall data is the most extensively used data in this thesis work. Missing data has been observed for more than 75% of the gaging stations during the year 1990/91 for similar reasons expressed above. Nevertheless, in some of the recording stations, especially Gondar Air Port and Bahir Dar it is observed that good quality records are available, since 1964.

4.2 Data Treatment

4.2.1 Hydrometric Data

Dry Period Data Infilling: -Data infilling for dry periods is made following the recession curve of the hydrograph. The hydrograph of the daily inflow has been plotted at a daily level and the

depletion master curve has been established. The data required to utilize the recession curve formula is abstracted from the master depletion curve and the missing data is estimated accordingly. The hydrograph recession curve used in the data infilling process is presented as:

$$Q_t = Q_o K_r^t \dots\dots\dots (4.1)$$

Where:

- Q_o is a specified initial daily mean discharge (m^3/s);
- Q_t is mean daily discharge at time t ;
- K_r is the recession constant which is less than unity; and
- t is time in days at which surface runoff ceases contributing to the hydrograph.

An EXCL out put indicating the plotting process of the master depletion curve and the correlation of the in-filled data with that of the observed data made for Gilgel Abbay River is presented below in Fig 4.1 and 4.2 respectively.

Figure 4-1 Gilgel Abbay Near Merawi Daily Hydrograph for the Year 1986

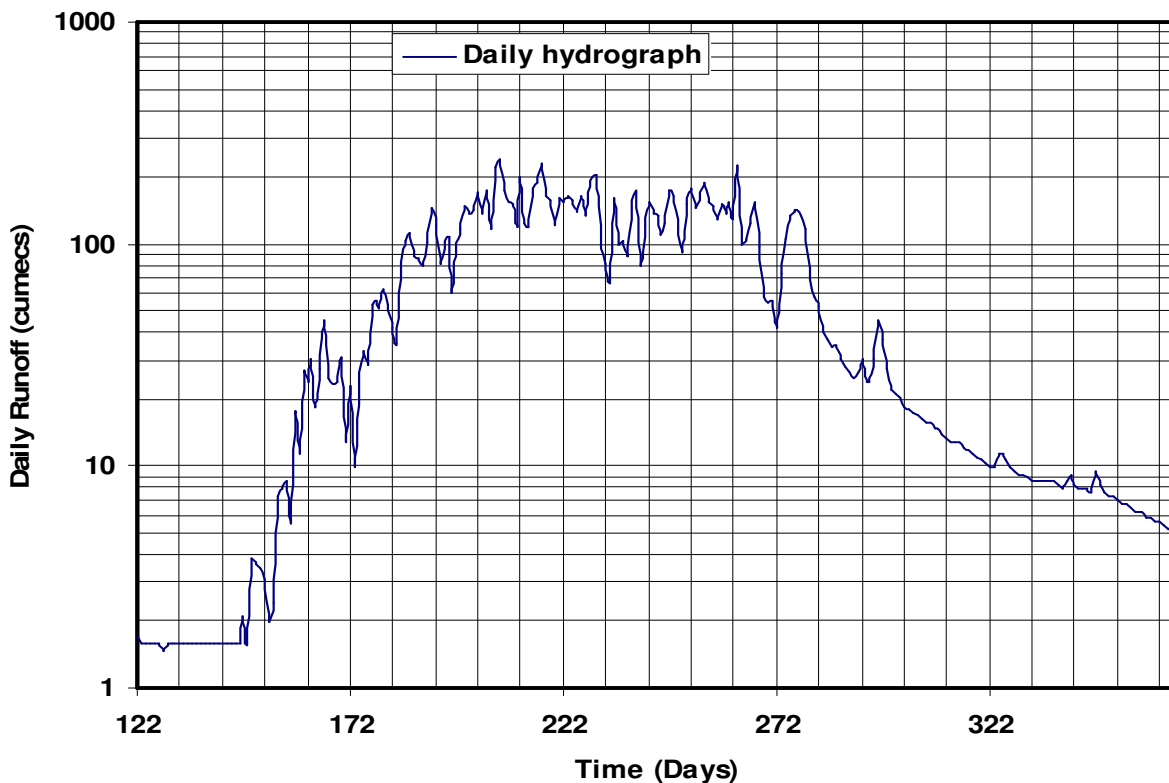
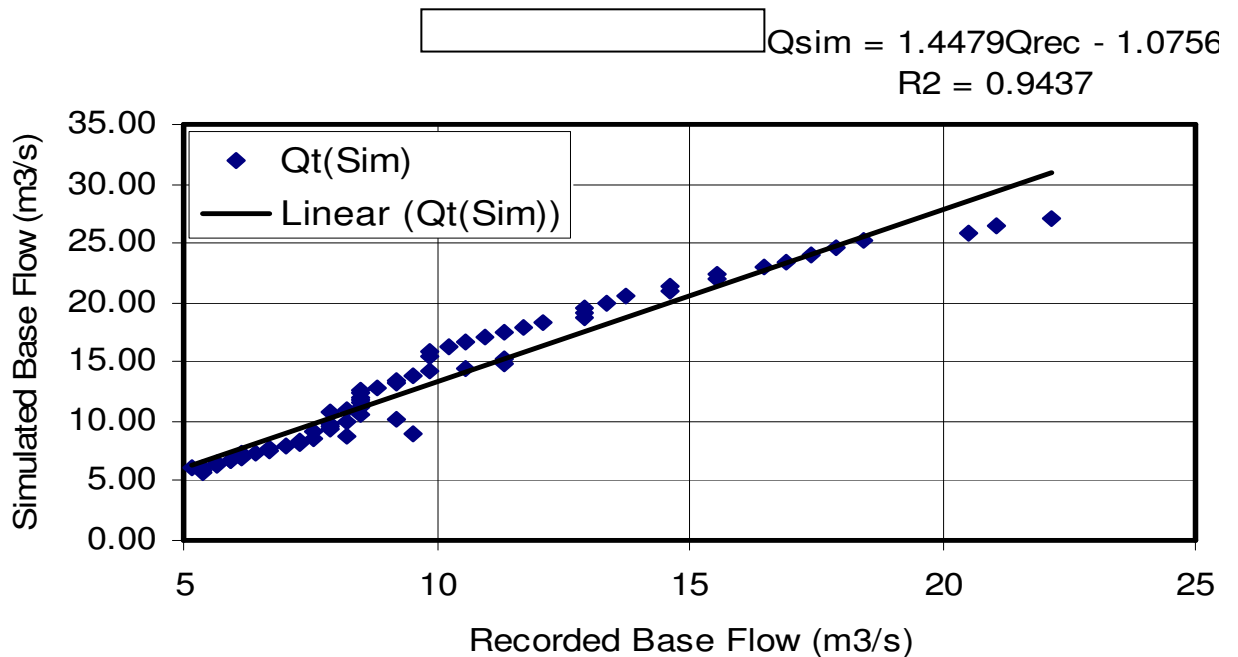


Figure 4-2 Checking of Recorded Vs Simulated Base Flows a Gilgel Abbay River



Data Infilling for Wet Periods; - The wet period data infilling is made by directly taking the data from the Tana-Beles project document as this is properly compiled during the study of the Tana Beles Project (Studio Pietrangeli, 1990). For very few cases data infilling process for wet periods have been made by employing area proportions and the ratio of the mean monthly inflows to transfer data from adjacent gagging stations.

4.2.2 Meteorological Data

Data In-Filling: - To reduce possible errors in the data infilling process, the meteorological stations in the basin are categorized in three rainfall regimes.

Meteorological stations located south of Lake Tana reservoir (B/Dar, Merawi, Wettet Abbay, Dangela, Enjibara, Feresbet, Tis Abbay, Adet and Motta) are considered to be in one rainfall regime. The wet period in this regime is relatively longer extending from April/May to October/Nov. The mean annual rainfall in this regime for most of the stations is observed to be more than 1200mm reaching to more than 2000mm in some stations like Enjibara.

Meteorological stations located north and northwest of Lake Tana reservoir (Gondar Airport, Koladiba, Maksegnit, Enfiranze, Gorgora, Chauhit, Aykel, Ambagiorgis, Dabat Chandiba, Delgi,

Shembekit and Shaura) are observed to have a relatively shorter wet period extending from June/July to August/September. The mean annual rainfall in this part of the basin ranges from slightly above 900mm to 1100mm. The mean annual rainfall at Gondar Airport, for instance is 1050mm.

Climatic stations located east of the Lake Tana reservoir (Hamusit, Wereta, Wanzaye, Anbesame, Yifag, Addis Zemen, Ebinat and Debre-Tabor) are observed to have an intermediate rainfall distribution pattern where the wet period is extended from May/Jun to Sept/October. Mean annual rainfall in this rainfall regime is in the range of 1000mm to 1200mm. For instance the mean annual rainfall at Addis Zemen is observed to be 1200mm. The data infilling process is made using these three rainfall regimes as a basis and simple arithmetic mean and normal ratio methods are utilized.

Missing data are observed mainly due to the absence of the observer or because of instrumental error. "In the procedure used by the U.S Environmental Data Service (US-EDS), precipitation amounts are estimated from observations at three stations as close to and as evenly spaced around the station with the missing record as possible. If the normal annual precipitation at each of the index stations is within 10% of that for the station with the missing record, *a simple arithmetic average* of the precipitation at the index stations provide the estimated amount" (.Linsely R.K etal, 1982).

In some stations where their relative location is very close (estimated to be less than 30km), simple arithmetic mean method is employed. Gondar Airport, Maksegnit, Koladiba; Gorgora, Chauhit and Aykel & Chandiba in the north and northwest rainfall regime; Yifag, Addis Zemen, Wereta, Hamusit & Wanzaye; in the east rainfall regime; and Wettet Abbay, Merawi, Bahir Dar & Tis Abbay in the south rainfall regime are observed to be located very close to each other and the data infilling process for these stations is made using the simple arithmetic mean method in which the station weights are all $1/n$. This method is appropriate for dense networks with uniform gage locations (Maidment, 1993).

If the normal annual precipitation at any of the index stations differs from that at the station in question by more than 10%, the *normal-ratio method* is used (.Linsely R.K etal, 1982). This situation prevails for most of the stations in the basin. The normal ratio method as presented below is widely used in the infilling process of the missing rainfall data in the basin.

$$P_x = \frac{1}{3} \left[\frac{N_x}{N_A} P_A + \frac{N_x}{N_B} P_B + \frac{N_x}{N_C} P_C \right] \dots\dots\dots (4.2)$$

in which N_x is the mean monthly precipitation for the station with missing data, and N_A , N_B , and N_C represents the mean monthly rainfall data for index stations and P_A , P_B and P_C represents the normal monthly rainfall values of the index stations.

More over for most of the stations located in the periphery of the Tekeze and Abbay River water divide (such as Chilga, Ambagiorgis, Dabat, Gondar, Maksegnit, Enfiranze, Ebinat, Debere Tabor) much of the data infilling process has been conducted during the master plan study of the Tekeze river. This data were also utilized in this research work.

4.3 Preliminary Level Data Analysis

The consistency and trends of some of the major components in the water balance of the Lake are treated here.

4.3.1 Rainfall

There are 32 gauging stations in the basin where rainfall data is recorded. Observation of the trends and consistencies for major gauging stations like Bahir Dar, Gondar and Addis Zemen are observed taking these stations as a representative for the three rainfall regimes in the basin. Trend analysis for the above representative stations made using MINITAB is presented in annex-I.

In all the representative sites except Addis Zemen rainfall is observed to have a negative trend although the trend observed is not significant. The rainfall at Addis Zemen indicates a significant positive trend. To observe more about the behavior of rainfall in the area of Addis Zemen, trend analysis for two more stations located adjacent to it has been conducted. The rainfall both at Yifag (located some 10km south of Addis Zemen) and Debere Tabor (located some 40km east south of Addis Zemen station) shows a negative trend of not significant.

The Negative trend, though not significant, observed in most of the representative stations has an agreement with the existing situation of global warming. In most of the cases it is observed that rainfall is getting less through time which is observed as a general trend.

At Bahir Dar it is observed that the mean of the lower half (1984 to 2003) is lesser by 6.97% to the mean of the upper half (1964 to 1983) which is less than 10% indicating that there exists a relative stationarity in the data and/or rainfall system. Similar analysis at Addis Zemen station indicates that the mean of the lower half exceeds the mean of the upper half by nearly 20% indicating that relative stationarity does not exist in the rainfall system of that station. The Gondar Airport and the Debere Tabor stations indicate that the upper mean exceeds the lower mean by 7.5% and 16.4% respectively. This also indicates that the reduction in rainfall at Debere Tabor Station is relatively stronger than the Gondar Airport.

4.3.2 Evaporation

Evaporation data is recorded at two stations in the basin, Gondar Air port and Bahir Dar stations. The Pitche reading at Bahir Dar has been observed for its inconsistency and trend conditions. TS plot is presented in annex-I. Evaporation recorded at Bahir Dar station shows a significant negative trend indicating that evaporation from open water surfaces in the area is getting reduced.

Though it is not as strong as that of the evaporation, RH at Bahir Dar also shows a negative trend. Another important component in evaporation, wind, is also observed and it shows both trend and shift. This is indicated in annex – I.

4.3.3 Wind Speed at Bahir Dar

TS plot of wind speed (annex-I) recorded at Bahir Dar meteorological station has indicated that wind speed has both negative trend and downward shifts. Trend in the wind speed is observed since in the early seventies having irregular pattern until in the mid eighties and afterwards the trend becomes steady and regular in pattern. Shifts are observed at early seventies and latter at mid eighties.

4.3.4 Lake Water Surface Level and Area

Time series plot for water surface level for all recorded period shows significant positive trend (annex-I) which is attributed due to the effect of the regulation at Chara-Chara weir. The time series plot before the commencement of the Chara-Chara weir shows no significant trend. Alike the water surface levels; water surface elevation for the whole observation period (annex-I) shows a positive trend largely attributed due to the regulation effect of the Chara-Chara weir. On the other hand water surface elevation before commissioning the Chara-Chara weir shows no significant trend (Annex - I). This is one possible indication that the inflow and outflow in the lake system is balanced out, which is contrary to the situation that is observed in the case of Lake Evaporation.

4.3.5 Lake Storage

The Time series plot of the monthly reservoir storage for all the recorded period, (Annex - I) has significant trend, which is largely attributed due the regulation effect of the Chara-Chara weir. In this plot it is observed that by the end of the observation period the reservoir volume seems to show a shift. This was due to the fall of the reservoir level in the year 2002/2003 as it is operated with the newly established operation rule (section 5.3.1.2). The time series plot observed before the commencement of the regulation shows no trend (Annex-I). This strengthens the assumption that the inflow and outflow of the reservoir in long-term periods is balanced.

4.3.6 Hydrometric Data

A trend analysis for some of the hydrometric stations, Megech, Ribb, Gilgel Abbay and the outflow at Bahir Dar has been observed and in all of them no significant trend has been observed. In the case of runoffs, except for Ribb, inflows from other sampled watersheds indicate a general positive trend, contrary to the rainfall in these watersheds. Land degradation is one possible reason attributing to such conditions. Due to increased land degradation runoff coefficient in the watershed is likely to increase which in turn may increase runoff though rainfall shows a decreasing trend. The case of Ribb is specific in this case too.

4.3.7 Lake Outflow

Outflow from Lake Tana, for all recording period, indicates a positive trend which might be attributed by the regulation effect of the Chara-Chara weir. It can also be associated with increased inflow trend observed from the inflows of the major tributaries (section 4.3.6). Outflow before commissioning Chara-Chara weir, however, show negative trend of no significant. This is also contrary to the situation observed for Lake Evaporation.

5. FEATURES OF THE LAKE TANA RESERVOIR

5.1 Lake Tana Bathymetry

The Bathymetry survey conducted during the Tana-Beles project study was performed in 22 bathymetry profiles for a total of about 900km of measurements. The survey of the Lake profile was made based on 22 bathymetric profiles, 15 in the east-west directions at 5km interval and numbered from south to north for an estimated total distance of 550km. The remaining 7 bathymetric profiles were conducted in the north-south directions at 10km intervals and numbered from east to west for a total distance of about 330km. So far it is only this bathymetry survey that has been conducted for the lake. This research work has also used the data from this bathymetric survey for the purpose of reservoir operations and water balance simulations.

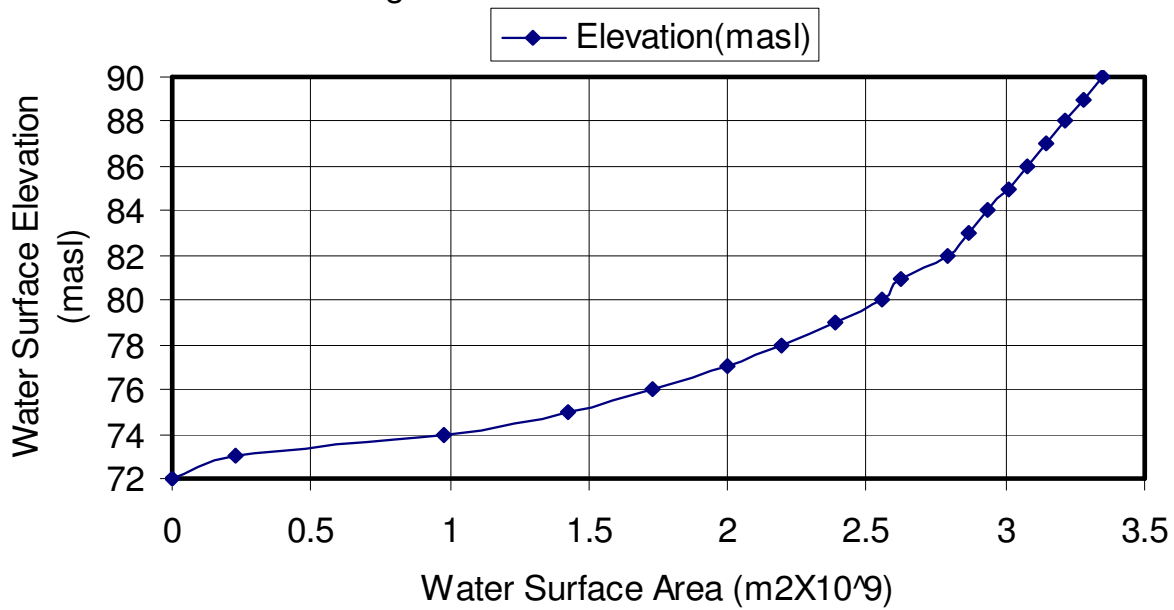
The bathymetric survey result has indicated that the lake has very regular lake bottom with low bed slop (ranging from 0.01% to 0.09%), with the maximum depth of 15.3m (located about 5km NNW direction of Narga Daga Island) and an average maximum depth of 13.2m. The water surface of the lake has an area of 3060Km² at a reservoir level of 1786masl. The water surface at similar reservoir level spans 76km north-southwards and 65km east-westwards and has a perimeter of 300km.

5.2 Reservoir Capacity

5.2.1 Reservoir Volume-Area-Elevation Curves

On the basis of the bathymetric profiles some bathymetric maps at a scale of 1:50,000 and 1:100,000 were prepared (Studio Pietrangeli, 1990). Using these maps the Volume-Area-Elevation relationships of the lake reservoir were estimated and associated curves were established. The reservoir volume versus area and area versus elevation curves are directly taken from the reports of the Tana-Beles Project (Studio Pietrangeli, 1990) and presented in Fig 5.1 and 5.2 below for reference purposes.

Figure 5-1 Elevation Vs Area Curve

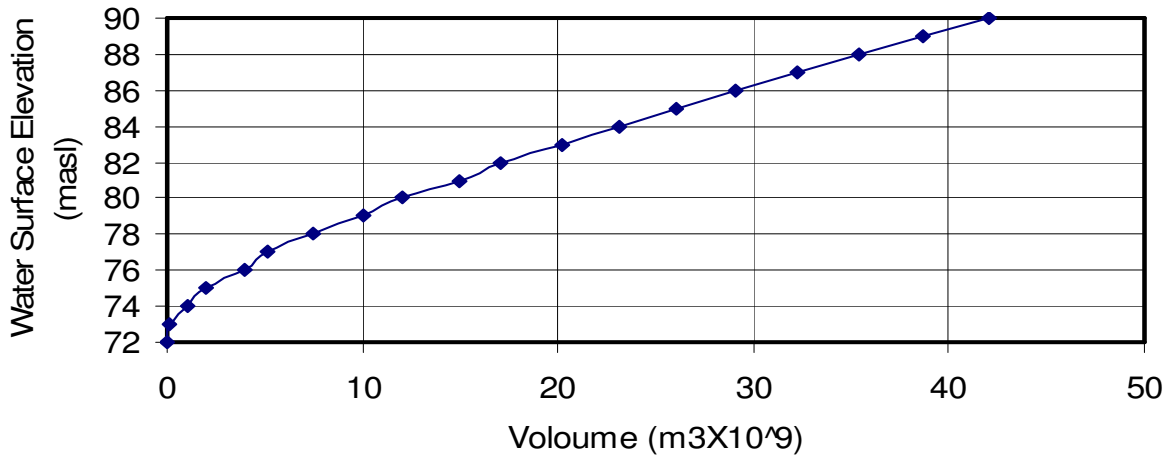


5.2.2 Reservoir Capacity

The capacity of the reservoir at 1786masl is estimated to be 29175Mm³. The dead storage level is fixed to be at 1784, the minimum regulating level of the Chara-Chara weir, and the dead storage capacity at this minimum operating level is reported as 23147Mm³. Fig 5.2 below represents Elevation-Volume relationships of the Lake Tana Reservoir.

The Volume-Area-Elevation relationships are established by curve fitting techniques (Studio Pietrangeli, 1990). These relationships as presented below are also used in this thesis work to run the water balance simulation of the reservoir.

Figure 5-2 Elevation Vs Volume Curve



These relationships are expressed in a general form of equation presented as (Studio Pietrangeli, 1990):

$$Y = a + bX + cX^2 + dX^3 \dots\dots\dots(5.1)$$

Equation Parameters:

$Area = f(Volume)$	$a = 1581.3705$	$b = 0.11045$	$c = -2.9435$	$d = 3.14436$
$Area = f(Level)$	$a = -1271815.49017$	$b = 1231.913$	$c = -0.219$	$d = -0.0000398$
$Level = f(Volume)$	$a = 1775.36551$	$b = 4.098622$	$c = -1.7557$	$d = 6.9938$
$Volume = f(Level)$	$a = 91957052.1156$	$b = -82630.3363446$	$c = 4.35125$	$d = 0.007332$

5.3 Chara-Chara Weir

5.3.1 Physical Features

5.3.1.1 Basic Components of the Weir

The Chara-Chara weir is located 1km upstream of the Gondar-Bahir Dar Bridge locally known as Kamforo Bridge. The shape of the lake narrows towards the south from the center reaching its minimum width at the inlet of the Blue Nile where the Chara-Chara weir is located. At this location the topography of the lake is complex, and during the dry period the lake outlet has four water courses, one major and three minors. During the wet period the lake level raises covering all the high spots available between these minor courses and widening the water course.

The purpose of the Chara-Chara weir is to improve the existing natural shape of the water course by raising the water level so that effective regulation of the water resources is possible. The weir has, in plan a shape of an inverted L shape, with a minor leg of 170m and major leg of 600m which forms a total weir length of 770m. The effective weir length is taken as 600m. The weir has seven regulating gates, all radial gates, out of which only five are operational and the other two are operational during emergency cases. The minimum operating level of Tana reaches 1784masl. The Maximum operating level is fixed to be at 1787.5masl while the crest level is fixed at 1787masl, the 0.5m being the afflux created as a result of the regulating weir. The weir is implemented to regulate the reservoir water available between the minimum and maximum operating levels. During minimum lake levels due to insufficient head problems, the required amount of water may not be released to “Tis Abbay” hydropower station. To accommodate this problem the intake level the regulating gates is fixed at 1782.5masl. The assumption is to operate the lake below its minimum operating level (1784masl) during low flow periods so that enough hydraulic head that enables to drive the required amount of discharge for “Tis Abbay” hydropower plants can be secured, for the Lake level remains above or equal to the minimum operating level.

5.3.1.2 Current Operation Rules

In the year 1996 a feasibility level study and detail design works for Tis Abbay II hydropower plant located d/s of the existing Tis Abbay I hydropower plant has been conducted (Humphrey & associates, 1996). During this study the consultant has established two alternative operation rules applying a water balance model for the reservoir (Humphrey & associates, 1996). The feasibility report indicates that after running the model it allows a guaranteed flow for Tis Esat falls averaging 35m³/s, ranging from 60m³/s in December and January to 10m³/s between April and July as shown in table 5.1 below (Humphrey & associates, 1996).

Table 5-1 Existing Reservoir Operation Rule

Months	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Q(m ³ /s)	60	50	35	10	10	10	10	40	40	4	50	60

According to the report (Humphrey & associates, 1996) this inflow to Tis Esat represents the preferred pattern of minimum flow requirements recommended by the environment study of the

project component. Operating the Lake at this minimum release to the fall constantly for 24-hours per day, it will give $77.2\text{m}^3/\text{s}$ inflow for Tis Abbay I & II hydropower plants at a reliability of 95% (Humphrey & associates, 1996). If this allocation is maintained for 10-hours a day and a minimum inflow of $3\text{m}^3/\text{s}$ to the fall is provided for the remaining 14 hours a day an average supply of $94\text{m}^3/\text{s}$ to Tis Abbay I & II hydropower plants can be granted at 95% of reliability (Humphrey & associates, 1996).

The water balance simulation during this study (Humphrey & associates, 1996) does not consider future possible upstream abstractions. In the master plan (BCEOM & associates, 1999) considerable numbers of large reservoirs are planned for the development of large scale irrigated agriculture in the basin. Some of them, such as Koga with a command area of 5100ha, are already started being realized. Some of them like Ribb and Megech for instance are to be realized in the near future. The implementation of these reservoirs will have considerable impact on the water availability in the reservoir of Lake Tana. The water balance made both by the Humphreys & associates and the Studio Pietrangeli does neglect the impact of these reservoirs on the future outflow series of the Lake.

5.4 “Tis Abbay” Hydropower

The “Tis Abbay” hydropower has two components; the Tis Abbay I and II Hydropower Plants. These plants are located some 30km downstream of the Blue Nile inlet at Bahir Dar. The Tis Abbay I is designed for 12MW installed capacity (82.2GW-h/yr energy) with a rated head and discharge of 46m and $29\text{m}^3/\text{s}$ respectively; and the Tis Abbay - II is designed for 73MW installed capacity at a rated head and discharge of 55m and $150\text{m}^3/\text{s}$ respectively. The dependable power at the two plants is 12MW and 68MW respectively. Tis Abbay I is commissioned in the early 60s right after the commissioning of the Awash-Koka hydropower plant while the Tis Abbay-II is commissioned in the year 2001.

The “Tis Abbay” hydropower (that is Tis Abbay I) utilizes only 16% of the mean annual regulated capacity of the reservoir (that is the reservoir capacity b/n the 1784 and 1787.5masl water surface elevation of the lake (Studio Pietrangeli, 1990).

6. WATER BALANCE SIMULATION OF THE LAKE SYSTEM

6.1 The Water Balance Equation

The water balance equation for the basin is established as indicated in equation 6.1 below. To get the first impression for the water balance of the lake system, the simulation process is initially effected exclusively for dry periods only and the inputs during the wet period usually known to be from June to October are excluded from the simulation process.

$$\text{ChangeInStorage}(\Delta S) \equiv \text{AllInflow}(\sum Qi) - [\text{Evaporation}(Ep) + \text{Seepage}(Sp) + \text{Outflow}(Qo)] \dots\dots (6.1)$$

In which $\text{AllInflow}(\sum Qi)$ is the sum of surface runoff, direct runoff on the lake surface and groundwater contribution in the system.

6.2 Water Balance Recursive Formula

The above is the general water balance equation formulated for the lake. Using equation 6.1 and knowing the initial storage (at some reference time), the recursive continuity equation is formulated as:

$$S_t = S_{t-1} + SR_t + RL_t + GW_t - EP_{L_t} - SP_{L_t} - Q_o \dots\dots\dots (6.2)$$

Where:

- S_t → Storage at the current month (MCM)
- S_{t-1} → Storage at the end of the preceding month (MCM)
- SR_t → Surface run off at the current month (MCM)
- RL_t → Direct rainfall on the water surface at the current month (MCM)
- GW_t → Any ground water contribution at the current month (MCM)
- EP_{L_t} → Evaporation loss at the current month (MCM)
- SP_{L_t} → Seepage loss from the reservoir at the current month (MCM)
- Q_o → Out flow from the reservoir at the current Month (MCM)

From the foregoing discussions and data collected it can be understood that there are two unknowns, the groundwater contribution and the loss from the reservoir due to seepage, and only one recursive equation. The case is therefore indeterminate and has no solution. To solve such problem in the computation process the following assumption is made. SP_{Lte} is considered as the effective seepage loss and/or gain from or to the reservoir, which can be considered as net groundwater inflow, and this converts the above recursive formula in to:

$$S_t = S_{t-1} + SR_t + RL_t - EP_{Lt} - SP_{Lte} - Q_o \dots\dots\dots (6.3)$$

Where:

$$SP_{Lte} = GW_t - SP_{Lt} \dots\dots\dots (6.4)$$

The three basic conditions in the operation of the above recursive formula could be if:

$SP_{Lte} \approx 0$ indicates that the inflow and outflow in the ground water flow system of the reservoir is balanced;

$SP_{Lte} > 0$ the groundwater inflow is substantial which could be the possible contribution to the reservoir system;

$SP_{Lte} < 0$ the seepage loss from the reservoir is in excess of the ground water inflow to the reservoir, which has a negative impact to the storage of the reservoir system.

6.3 Components of the Water Balance Equation

As it can be seen from the recursive formula the components of the water balance for Lake Tana reservoir can be enumerated as:

- The reservoir storage;
- Surface Runoff;
- Direct Runoff over the Lake Water Body;
- Lake Evaporation;
- Seepage/Ground water inflow; and
- Outflow

6.3.1 Reservoir Storage

Reservoir Storage, denoted as S_t , is obtained from the records of the lake level at Bihar Dar. Lake level record at Bihar Dar is available for 40 years (1964 to 2003). Area Vs Elevation and Reservoir Storage Vs Elevation curves as presented in Fig 5.1 and 5.2, section 5.2 are used for the water balance simulation of the Lake. During the simulation process S_t is read from these curves applying the data obtained from Lake level records.

6.3.2 Gauged Surface Runoff

Gauged Surface Runoff: - After infilling the missing data (section 4.2) surface runoff for eight gauging stations, including the outflow record of Lake Tana at Abbay near Bihar Dar, is considered for dry periods Water balance simulation of the reservoir.

6.3.3 Area Rainfall over the Lake Tana Basin

Direct Surface Runoff on the Lake Water surface: - Direct surface runoff on the water surface of Lake Tana (which accounts 20% of the total basin area) is noted to be considerable. This input has been estimated taking it as a separate sub basin in the system. There are eight meteorological stations (Gorgora, Delgi, Bahir Dar, Hamusit, Wereta, Yifag, Enfiranze and Maksegnit) around the periphery of the lake and one meteorological station (Dekestifanos) inside the water body of the Lake. These meteorological stations are nearly evenly spaced and properly distributed around the periphery of the lake.

Estimating Weighted Mean Area Rainfall over the Basin: - To estimate the weighted mean area rainfall over the basin, the entire basin of Lake Tana has been sub divided in to seventeen sub basins as presented in Fig 6.1 below, taking the similarity of the rainfall regime and the variation in drainage pattern of the basin as a basis. The Lake Tana water surface as part of the basin has been categorized as one sub basin in the system.

Delineation of Sub Basins: - The Digital Elevation Model (DEM) grid file is used to delineate the basin of Lake Tana in to 10 major sub basins, which are again sub divided in to 17 minor sub basins. The Ten major sub basins are further sub divided in to 17 minor sub basins to account the spatial variation of rainfall in the gauged and un-gauged watersheds. The HYDRO DEM grid file is a geographic, database providing comprehensive and consistent global coverage of topographically derived data sets. Developed from the US Geological Survey's (USGS) EROS Data Center, recently released 30 arc-second digital elevation model (DEM) of the world (GTOPO30), HYDRO1k provides geo-referenced data sets (at a resolution of approximately 90m) that will be of value for all users who need to organize, evaluate, or process hydrologic information on a continental scale.

To delineate each grid system the spatial analysis utility extension of the Arc-view3.2 is used. It uses the data in the DEM grid files and produces the sub watershed and stream net work grids which are then converted to shape file format for convenience of further analysis. These sub watersheds, after delineation are grouped to form the 17 sub basins of the Lake Tana basin. The out put is presented as indicated in Fig 6.1 below. The area of each sub basin is computed after delineation and the output is presented in table 2.3 section 2.0. Accordingly, the total basin area is found to be 15340km²

The basin area computed during the Tana-Beles study (Studio Pietrangeli, 1990) is indicated to be 15320Km² indicating that the estimate made in both cases (Tana-Beles study and from DEM grid files) has no appreciable differences.

Estimation of Area Rainfall from Rain Gauges: - For hydrologic applications it is often necessary to compute estimates of mean aerial precipitation for a catchment from rain gauge observations. Most of the procedures that are used for computing mean areal precipitation can be expressed as linear combinations of the observations. If n gauges, with values P₁, , P_n, are available for estimating precipitation in a catchment, then the estimate of mean areal precipitation is (Maidment, 1993):

$$\bar{P} = \sum_{i=1}^n a_i P_i \dots\dots\dots (6.5)$$

Where the station weights a₁,.....,a_n are nonnegative constants that sum to 1.

The simplest method for computing mean aerial precipitation is the *arithmetic mean* method in which the station weights are all $\frac{1}{n}$ (Maidment, 1993). This method is appropriate for dense networks with uniform gauging stations.

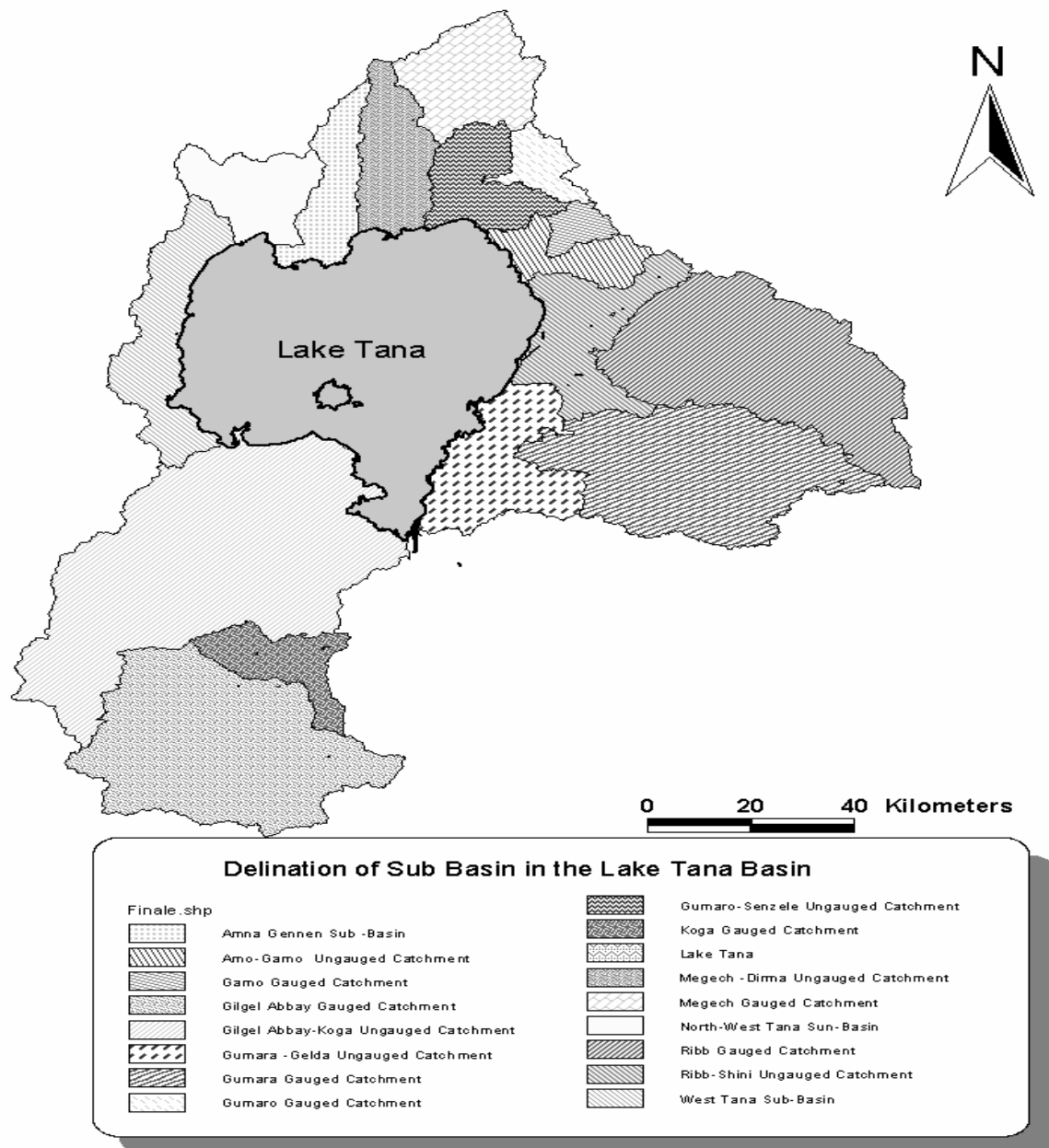


Figure 6-1 Sub Basin Delineation of the Lake Tana Basin

According to WMO (World Meteorology Organization) for mountainous physiographic units the minimum non recording gauging stations is one in 250Km² (NEDECO, 1998). In the case of Tana

basin, on the average, one non recording gauging station is available for 450km² area of the basin. The *Thiessen* polygon and *Isohyetal* methods which can provide better results can also be used in estimating spatial rainfall from rain gauge observations. For computer implementation, it is often convenient to compute mean aerial rainfall by first interpolating rainfall at gauge sites onto a rectangular grid and then estimating aerial rainfall by summing estimates from grid boxes within the catchment. The *inverse distance-squared* method is commonly used for this purpose (Maidment, 1993). The estimate for the jth grid box is expressed as:

$$\bar{P}_j = a \sum_{i=1}^n d_{ij}^{-2} P_i \dots\dots\dots (6.6)$$

Where d_{ij} is the distance from gauge i to the center of grid box j and a is the inverse of the sum of the *inverse distance-square* d values for all gauges (Maidment, 1993):

$$a = \left(\sum_{i=1}^n d_{ij}^{-2} \right)^{-1} \dots\dots\dots (6.7)$$

If m grid boxes cover the catchment the mean areal precipitation is the arithmetic mean of the m estimates obtained from equation 6.6. The station weights in equation 6.5 for *inverse distance-square* method are given by (Maidment, 1993):

$$a_j = \frac{1}{m} \sum_{j=1}^m \frac{a}{d_{ij}^2} \dots\dots\dots (6.8)$$

Estimating Sub Basin Rainfall: - The weighted mean area rainfall for each sub basin is estimated using the graphic user interface extension of the FEWS Flood model. It initially estimates the surface rainfall at each grid using the data from the nearby meteorological stations by employing the *inverse distance-square* method. The DEM grid files data are used to interpolate and compute the rainfall at each sub watershed. Finally the rainfall at each grid of the same sub basin is aggregated to compute the weighted mean area rainfall of each sub basin. The mean annual areal rainfall over the water body of Lake Tana is computed to be 1252.3mm. The weighted mean area rainfall for Lake Tana water surface area is presented graphically in Fig 6.2 below to indicate the output of the area rainfall

estimation process. The long-term mean annual rainfall for the ten sub basins is summarized in table 6.1below.

Figure 6-2 Annual Rainfall at Lake Tana Water Body

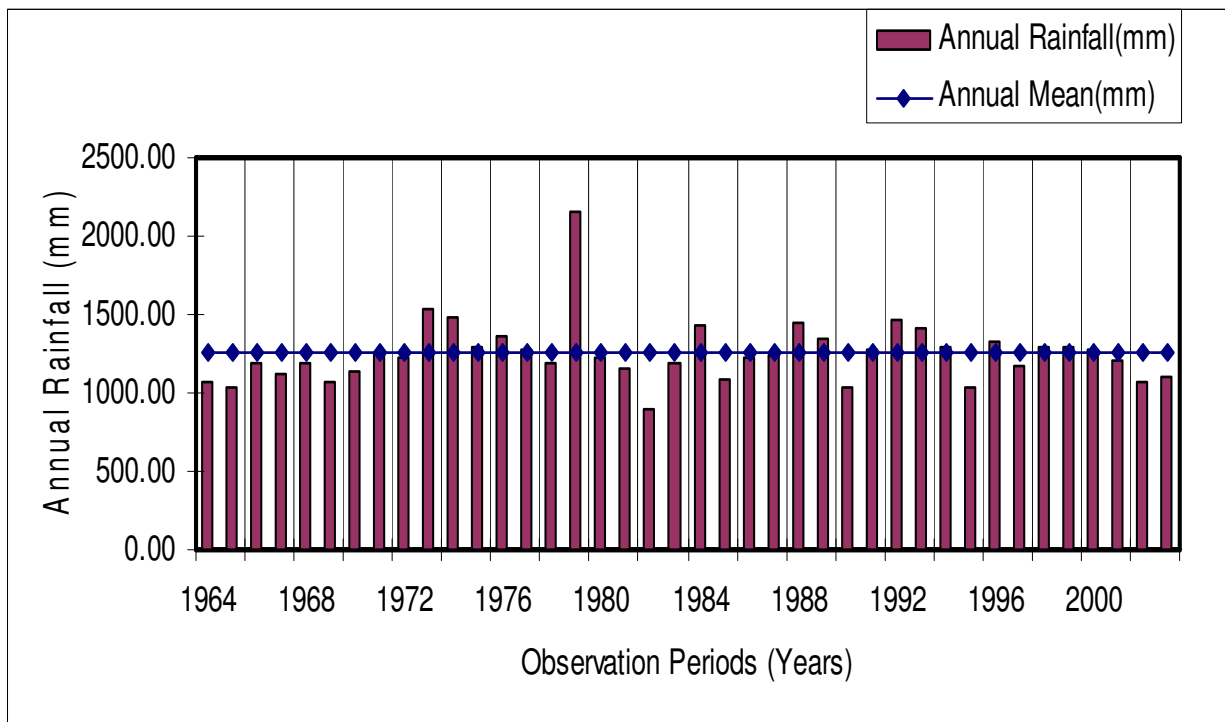


Table 6-1 Weighted Mean Annual Area Rainfalls of Sub Basins in the Lake Tana Basin

Sub Basin Name	Mean Annual Area Rainfall (mm)	
	At the Gauged watershed	At the Un-Gauged watershed
Megech-Dirma	1031.12	999.01
Gumaro-Sizele	1016.26	1009.71
Arno-Garno	1043.16	1046.24
Ambagenen		988.04
Northwest Tana		1015.49
West Tana		1118.04
Ribb-shine	1290.84	1176.34
Gumara-Gelda	1353.12	1333.08
Koga	1570.42	
G Abbay	1815.71	1560.43
Tana Water Surface		1252.3
Weighted Mean Annual Rainfall over the Basin		1341.57

6.3.4 Estimating Direct Surface Runoff over the Lake Water Body

The rainfall over the water surface of the Lake is considered as a direct runoff with a runoff coefficient of nearly one. The Area Vs Elevation curves and equations presented in section 5.0 are used to convert the linear runoff in to the runoff volume. Accordingly, mean annual runoff over the water body of the Lake is estimated to be $121.5\text{m}^3/\text{s}$ which is equivalent to 3863.05MCM. The dry period runoff over the water surface of the Lake as computed applying the above procedures has been used in the dry period water balance simulation of the Lake.

6.3.5 Lake Evaporation

Of the several phases in the hydrological cycle, that of evaporation is one of the most difficult to quantify. Certainly, it is difficult to define the unseen amounts of water stored or moving underground, but above the ground surface, the great complexities of evaporation make it an even more elusive quantity to define: yet evaporation can account for the large differences that occur between incoming precipitation and water available in the rivers (Shaw E. M, 1983).

Evaporation from open water surfaces can be measured applying different methodologies. There are two major approaches that may be adopted in calculating evaporation from open water: the *Mass Transfer* method and the *Energy Budget* method. The third method uses a combination of the two physical approaches (Shaw E. M, 1983).

Tanks and pans are also used. Although there may be difficulties in relating the measurements of evaporation from small bodies of water to the real losses from large reservoirs, like Tana for instance, the advantages of using pans and tanks are numerous, portability being one of these advantages (Shaw E. M, 1983).

The American class-A pan, whose pan coefficient is approximated to be 0.7, is the most widely used instrument ((Elizabeth M. Shaw, 1983). The Pitch evaporimeter is also used in measuring evaporations from open water bodies. When the pitch evaporimeter is exposed in a standard temperature screen, the annual values have been found to be approximately equal to the open water evaporation from a US Class A pan (Shaw E. M, 1983).

In the research area, two readings, both pan evaporation and pitch readings, are collected at Bahir Dar meteorological station since 1964. Unfortunately, the experts in the NMSA have advised the researcher that the pan readings are not good for some unknown reasons. Instead Pitch readings have been collected from NMSA. The researcher has asked NMSA if they have any coefficient that would relate the pitch reading with open water surface evaporation rates. Unfortunately this data was not available. To develop an appropriate relationship, the researcher has computed lake evaporation using the combined method, the method that combines the energy budget and the mass transfer (aero dynamic) methods.

A detailed computation procedure for computation of evaporation from open water surfaces using the combined method is presented in the Handbook of Hydrology (Maidment, 1993). According to Maidment, the preferred method for estimating the rate of evaporation from open water is presented as (Maidment, 1993):

$$E_p = F^1_p A + F^2_p \bar{D} \text{ mm/day} \dots\dots\dots (6.9)$$

where:

A is the energy available for evaporation in mm/day,

\bar{D} is the average vapor pressure deficit (in KPa),

The coefficient F^1_p is a function of temperature and the elevation of the site:

$$F^1_p = \frac{\Delta}{\Delta + \gamma} \dots\dots\dots (6.10)$$

Where Δ represents the slope of the curve of saturated vapor pressure plotted against temperature.

The coefficient F^2_p is a function of temperature, wind speed, and elevation of the site:

$$F^2_p = \left(\frac{\gamma}{\Delta + \gamma} \right) \frac{6.43(1 + 0.536U_2)}{\lambda} \dots\dots\dots (6.11)$$

In which U_2 is wind speed at 2m height and λ is the latent heat of vaporization.

The open water evaporation computed using the combined method has been correlated with the pitche reading applying regression analysis techniques. This has helped to establish a coefficient that is used to convert the pitche reading in to Lake Evaporation. The final out put of the regression analysis indicated that the pitch reading is correlated with Lake Evaporation with a mean weighted pan coefficient of 0.80. Accordingly the mean annual lake evaporation of Lake Tana water surface is computed to be $161.8\text{m}^3/\text{s}$ which is equivalent to 5102.3MCM per annum. This value corresponds to the evaporation of 1654.64mm of water from Lake Tana per annum. According to the study of Tana-Beles project (studio Pietrangeli, 1990) the mean annual Lake evaporation is estimated to be $190.3\text{m}^3/\text{s}$, which is equivalent to 6000MCM per annum. The Studio Pietrangeli has assumed that the pitch reading is directly proportional to Lake Evaporation.

The trend of the computed data and some other statistical parameters has been computed to see the statistical parameters relationships between the computed and the observed evaporation values.

As it can be observed from TS plots in annex-I the pitche reading and the computed Lake evaporation indicates similar decreasing trend indicating that Lake Evaporation has decreased through time. The computed evaporation rate indicates there is an average annual reduction of 8.2mm and the pitche value indicates mean annual reduction of 40.3mm, which is unlikely to happen. For Pitche reading, the upper half mean exceeds the lower half mean by 50%, which again is unlikely to happen.

In general the negative trend of evaporation is not in agreement with the prevailing global warming phenomena. The wind speed recorded at Bahir Dar meteo station shows both shift and negative trend (annex-I) and this situation might have affected both the computed and recorded evaporation values. Reasons attributed to such conditions could be various, of which systematic error in recording (for instance the wind speed might have been recorded at different heights in the recording period) and the location of the measuring instruments could be among these factors. For instance the meteo station of Bahir Dar is located at the middle of the town where wind movement is limited by the trees having considerable height which acts as a wind break. The height of these trees might be less in the earlier periods (in the 60, and 70), so that wind speed by that period was strong and as the forest cover increases and height of trees increases (as the town gets growing) the wind speed might have been limited. This situation might have local effect only and the pitch reading might have been

influenced and the negative trend of the pitch reading might have been resulted from this situation. However this situation might not be on the lake surface as the wind movement will not be restricted on such an extensively vast water body.

Both computed and recorded evaporation data are questionable, which needs further investigation. This is one of the serious limitations for all the water balance computation of the Lake conducted in the previous studies like Studio Pietrangeli (1990), Humphrey and associates (in 1996) and also the recently developed Abbay River Master Plan studies (BCEOM and associates, 1999). They have assumed that the pitch reading is correctly recorded and utilized the backward computation of the water balance simulation techniques to estimate the inflow of the Lake reservoir. None of the studies so far have checked the water balance system of the Lake. They simply assume all the inputs are correct and try to compute the inflow by effecting backward computation of the water balance simulation for the Lake.

In this research work Lake Evaporation as computed applying the pitch coefficient has been used for dry period water balance simulation.

6.3.6 Seepage/Ground Water Inflow

Seepage in the lake system is assumed to be negligible during the Tana Beles project study (Studio Pietrangeli, 1990). In this research work this assumption is taken for dry period simulation. .

6.4 Dry Periods Water Balance Simulation

6.4.1 Objective

The principal objective of simulating the water balance for Lake Tana reservoir /basin/ is to investigate the significance of seepage loss in the reservoir system and correlate the out put with the conclusions that has been derived during the Tana-Beles study conducted in 1990. This is also used to investigate the water balance situation of the lake with easily identified inputs in the dry period. For instance inflow from un-gauged watersheds in dry periods can be considered negligible since most of the un-gauged watersheds are drained by intermittent streams with no base flow.

6.4.2 The Simulation Process

While simulating dry period water balance of the Lake, only inflow data from gauged watersheds are used. In this simulation, possible gaps are identified and the out put is used as a pre-requisite for further water balance simulation works.

The water balance recursive formula as presented in section 6.2 equation 6.3 is used to run the simulation. Simulation is made using EXCEL. The above mentioned recursive formula has been adjusted to simulate reservoir volumes on monthly basis and compare the result with the recorded values. The simulation has been executed on a monthly time scale continuously starting from Jan 1973 to Dec 2003. The output has indicated that the deviation between the simulated and the recorded values is so an immense and errors are progressive. The possible reason attributed to such high variation is due to the fact that the recorded values in some of the water balance components like storage and outflow accounts the inflow to the reservoir for all seasons, while the inflow used in the simulation process accounts dry period runoffs only. Seepage, if significant in the system was not accounted in the simulation process. Moreover, the evaporation data with all the discrepancies indicated in section 6.3.5 was also used. This has indicated that water balance of the Lake has to be performed for all season inflows using gauged data.

6.5 All Season Water Balance Simulations Using Gauged Data

The out put achieved from dry period water balance simulation has indicated that all season water balance of the Lake using gauged data has to be simulated. The recursive formula as indicated in equation 6.3 has been used for this simulation purpose. The simulation has also indicated that there is an enormous gap between the simulated and recorded reservoir volumes, the gap reaching more than 100% (Fig 6.3 below). This seems not realistic. Possible reasons could be inflows from ungauged watersheds, which are accounted by the recorded reservoir volumes and not accounted by the simulated reservoir volumes. One possible way of investigating this condition was to run the water balance simulation on a yearly basis (Fig 6.4 below). This has been investigated by substituting the storage at the end month of each year as an initial storage (S_{t-1}) value for the simulation of the next year. While doing this a maximum deviation of not more than 30% has been observed which can be

attributed to seepage losses and the unaccounted surface runoff inflow from the un-gauged watersheds. This also indicates that an inflow from un-gauged watersheds is significant. In conclusion this has lead the research work that the inflow shall be estimated for the whole basin and the water balance simulation has to be effected for all seasons.

Figure 6-3 Checking Simulated Vs Observed Storage at Lake Tana Reservoir (Monthly Basis)

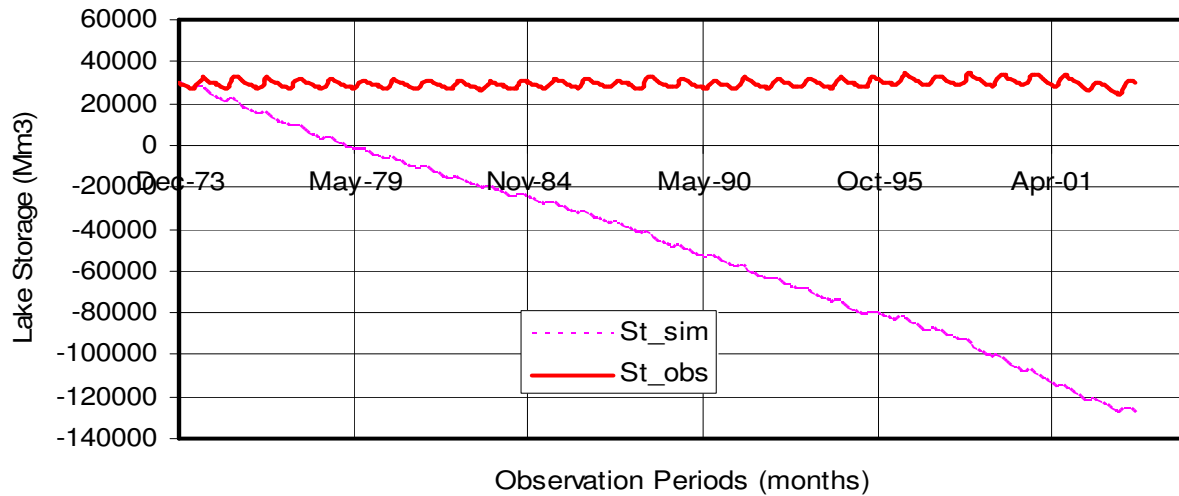
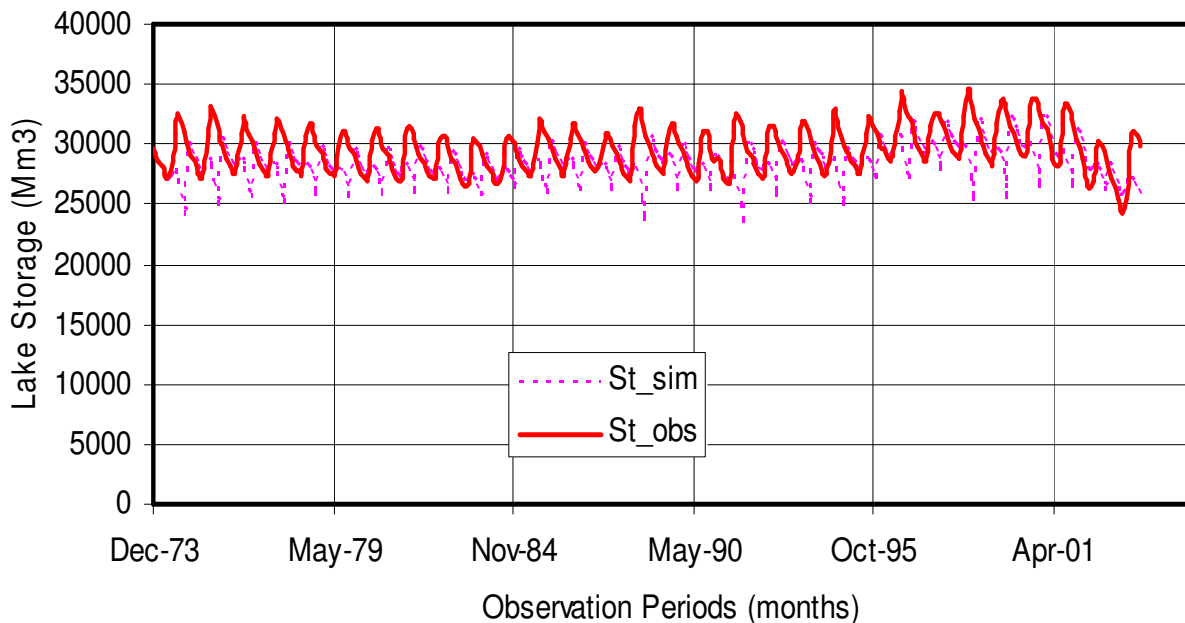


Figure 6-4 Simulated Vs Observed Storage at Lake Tana Reservoir (Annual Basis)



6.6 Simulations of Water Balance for all Seasons & for All Inflows

6.6.1 Equations for All Seasons

The recursive formula (equation 6.3) presented in section 6.2 is used here too with the surface runoff considered to account all possible runoff in the basin. Initially seepage loss is assumed negligible and modeling of the recorded versus the simulated reservoir volumes is made. The objective is still to investigate the gap that could be available between the simulated and recorded reservoir volumes and correlate the result with that of the Tana-Beles study.

6.6.2 Water Balance Components

Except the surface inflow, the other components (Lake Evaporation, seepage/ground water inflow, reservoir storage, outflow and direct surface runoff from the lake water body) remain the same. Moreover, areal rainfall in each sub basin, as computed in section 6.3.3, is used in the computation of reservoir inflows. Rainfall-runoff relationships for each sub basin have been established to compute reservoir inflows from computed areal rainfall of each sub basin.

6.6.3 Computation of Reservoir Inflows

6.6.3.1 Concepts of Rainfall-Runoff Process

The water which constitutes stream flow may reach the stream channel by any of several paths from the point where it first reaches the earth as precipitation. Some water flows over the soil surface as *overland flow*, other water infiltrates through the soil surface and flow beneath the surface to the stream called as *interflow* and other component percolates downwards until it reaches the water table to join the stream channel during dry period, usually termed as *base flow*.

Runoff processes operating at any location vary from time to time. Large variations in hydrologic characteristics, and therefore in runoff processes, also occur over small, apparently homogeneous areas to the extent that all the three runoff process, (Hortonian overland flow, saturated overland flow and through flow), may occur during a single storm event. Associated with the recognition of several processes producing storm runoff has been the concept that storm runoff may be generated

from only a small part of many drainage basins. In addition, this source area may vary in extent in different seasons and during the progress of a storm (Maidment, 1993)

The derivation of relationships between the rainfall over a catchment area and the resulting flow in a river is fundamental problem for hydrologists and water resources planners. Estimating runoff from rainfall measurements is very much dependent on the time scale being considered. For short durations (hours) the complex interrelationship between rainfall and runoff is not easily defined., but as the time period lengthens, the connections becomes simpler until, on annual basis, a straight line correlation may be obtained. The time interval used in the measurement of the two variables affects the derivation of any relationship, although with continuously recorded rainfall and stream discharge this constraints is removed and only the purpose of the study influences choice of time interval. For instance, relating a flood peak to a heavy storm requires continuous records, however, determining water yield from a catchment can be accomplished satisfactorily using relationships between totals of monthly or annual rainfall and runoff (Shaw E. M, 1989).

Reservoir inflow is one basic component to run the water balance simulation of the Lake, which is a prerequisite for reservoir operation. From the out puts of the preceding two water balance simulations it is concluded that inflows from un-gauged watersheds has to be estimated to simulate the water balance of the Lake on the basis of all inflows at all seasons. This in turn has enquired establishing rainfall-runoff relations in the basin.

6.6.3.2 Previously Used Methodologies

A Reservoir inflow from sub basins was estimated during the study of the Tana-Beles Project (Studio Pietrangeli, 1990) and the feasibility study of Tis Abbay II (Humphrey & associates, 1996). Both studies utilize the same procedure, effecting backward computation of the water balance of the Lake system. The Tana Beles project study (Studio Pietrangeli, 1990) have used 27-years (1964 to 1989 both ends inclusive) of recorded data. The feasibility study of Tis Abbay II (Humphrey & associates, 1996) has also used relatively longer period (1964 to 1995 both ends inclusive) of historic series. The water balance equation as first used by Studio Pietrangeli is presented as:

$$Q_{in(gross)} = Q_{out} + E_o + \delta V \text{ ----- (6.12)}$$

Where:

$Q_{in(gross)}$ = River Inflow Plus Direct Rainfall on the Lake Surface

Q_{out} = Outflow

δV = Change in Lake Storage

In the feasibility study of Tis Abbay II (Humphrey & associates, 1996) it is noticed that the evaporation record used by Studio Pietrangeli might have some errors (it has been noticed that there might be some confusions with PET and Pitche readings). They have further noticed that the PET computed for Bahir Dar using FAO cropwat program shows mean annual values of 1400mm while the pitche reading used by Studio Pietrangeli is estimated to have mean annual value of 1940mm, which is equivalent to 6000MCM at 3080km² surface area of the lake. This Figure is 50% higher than the mean annual rainfall (estimated inflow) volume of the basin (Humphrey & associates, 1996).

Humphrey and associates has decided to compute the net inflows by avoiding initially the evaporation and reformulate equation 6.12 in a form represented as (Humphrey & associates, 1996):

$$Q_{in(net)} = Q_{out} + \delta V \text{ ----- (6.13)}$$

Where: $Q_{in(net)}$ = River Inflow + Direct Rainfall – Evaporation ----- (6.14)

This was a good attempt to avoid the use of the evaporation record which has discrepancies as indicated in section 4.0. However, Humphrey and associates has used assumed lake evaporation to compute gross inflows to the reservoir of the Lake. According to Humphrey and associates the mean annual net inflow is computed to be 112.2m³/s which is equivalent to 3537MCM. Recorded mean annual inflow from gauged watersheds is estimated to be 111.5m³/s, which is equivalent to 3556.1MCM. The estimate made by Humphrey & associates include direct runoff over the lake water body while the recorded inflow from gauged watersheds does not include direct runoff at the lake water body. This indicates that inflow computation applying backward computation of the water balance equation under estimates reservoir inflow.

6.6.3.3 Currently Used Reservoir Inflow Computations Methods/Models

For practical estimation of rainfall excess or storm runoff volume, numerical representations or models or establishing of the relation of runoff to rainfall is required. The data availability, the runoff process and the type of problem governs the choice and validity of the methods used to represent the rainfall-runoff relationships. In this research work four approaches/methods have been used to simulate the surface runoff of the Lake Tana basin, namely:

- The SCS-CN Method;
- A Simplified Water Balance Method;
- Linear Regression Techniques; and
- The Area-Ratio Method

The SCS-CN Method: - The SCS-CN method, usually known as the curve number method, is developed by the U.S. Soil Conservation Service and consists of two parts; the first step being an estimation of the volume of runoff resulting from rainfall (which this research work is interested in) and the second step defines the time distribution of the runoff including the peak flow determination (ILACO B.V, 1985).

The SCS-CN method is widely used for estimating rainfall excess on small to medium-sized ungauged drainage basins. The method is widely used for reasons of using wider data base and the physical characteristics of a watershed are represented in its application (Maidment, 1993). The same is true in this research work. For most of the cases, the available rainfall data are the amounts measured at non-recording rain gauges. For the use of such data the rainfall-runoff relationship has been developed. The data collected in the stations under consideration are totals for one or more storms occurring on a calendar day, and nothing is known about the time distributions. The relationship, therefore, excludes time as an explicit variable (ILACO B.V, 1985).

To estimate the rainfall excess from actual storm, allowance must be made for the condition and wetness of the drainage basin immediately prior to the event. The SCS-CN method, provided that

local data has been used in their calibration, could be employed in such conditions (Maidment, 1993).

The basic principles underlying are: for a rainfall amounts (P) smaller than I_a , the *initial abstraction*, no runoff (Q) occurs. I_a , largely consists of interception losses, depression storage and infiltration before runoff occurs. Furthermore, for increasing runoff the curve Q versus P approaches asymptotically a straight line parallel to the line $Q \equiv P$. The vertical distance between these two lines (S) is called *potential maximum retention*. This is the maximum amount of rainfall that the basin can absorb. This is only possible because time as an explicit variable is excluded (ILACO B.V, 1985).

However, there are many curves which fulfill the requirements of continuing ($I_a, 0$) and approaching asymptotically to $Q \equiv P - S$. In order to define the shape of the curve another requirement has to be introduced. This is the statement that the ratio of actual retention ($P - I_a - Q$) to potential maximum retention (S) equals the ratio of actual runoff (Q) to potential maximum runoff ($P - I_a$). According to this definition the runoff equation can be written as (ILACO B.V, 1985):

$$Q = \frac{(P - I_a)^2}{(P - I_a) + S} \dots\dots\dots(6.15)$$

Experience has shown that the initial abstraction I_a is about 20% of the potential maximum retention (ILACO B.V, 1985)., thus:

$$I_a = 0.2S \dots\dots\dots(6.16)$$

The runoff equation can then be written as:

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S} \dots\dots\dots(6.17)$$

Functionally the value of S is related to the so called runoff curve number (CN) by the definition (ILACO B.V, 1985):.

$$CN = \frac{25000}{250 + S} \quad (S \text{ in mm}) \dots\dots\dots (6.18)$$

Estimating CN Values for Each Sub Basin: - The land use land cover data of the basin, as obtained from the DEM grid files (Fig 6.5) has been used while fixing the runoff curve number for each sub basin. Initially, the CN value for each hydrologic soil group and land use land cover is fixed using the data from the attribute table of the DEM grid files. Using the spatial analysis extension of the Arcview3.2 the delineated sub basin has been superimposed onto the DEM grid files and computed the mean weighted CN values for each sub basin. The final output is presented in table 6.2 and 6.3 below.

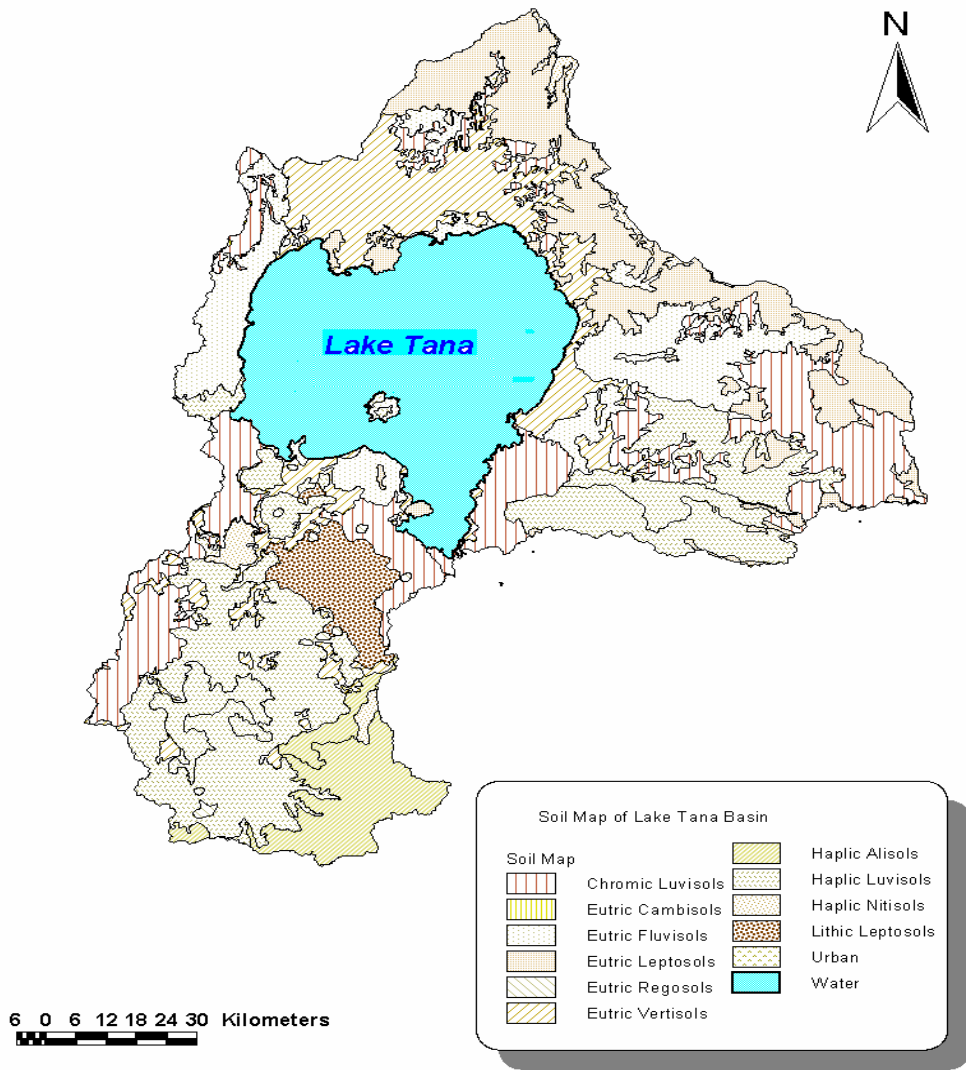


Figure 6-5 Soil and Land Use coverage of Tana Basin

Table 6-2 Weighted SCS Curve Number Values for each Sub Basin in the Tana Basin

Sub Basin Name	CN at Cond-II	Antecedent Moisture (AM) Conditions		CN Value for Other Conditions		S Value for AM Conditions (mm)		Dormant Season		Growing Season	
		Dormant Season	Growing Season	Dormant Season	Growing Season	Dormant Season	Growing Season	0.8S	0.2S	0.8S	0.2S
Tana Water Surface	100.0	I	III	100.0	100.0	0.0	0.0	0.0	0.0	0.0	0.0
North-West Tana SB	76.2	I	III	45.0	50.0	305.6	250.0	244.4	61.1	200.0	50.0
Arno-Garno SB	78.5	I	III	55.0	60.0	204.5	166.7	163.6	40.9	133.3	33.3
Ambagenene SB	78.0	I	III	45.0	50.0	305.6	250.0	244.4	61.1	200.0	50.0
Megech-Dirma SB	77.4	I	III	60.0	65.0	166.7	134.6	133.3	33.3	107.7	26.9
Gumaro-Senzele SB	76.6	I	III	55.0	60.0	204.5	166.7	163.6	40.9	133.3	33.3
Ribb-Shine SB	74.2	I	III	50.0	65.0	250.0	134.6	200.0	50.0	107.7	26.9
Gumara-Gelda SB	71.0	I	III	50.0	65.0	250.0	134.6	200.0	50.0	107.7	26.9
Koga-G/Abbay	75.0	I	III	48.0	58.0	270.8	181.0	216.7	54.2	144.8	36.2
West Tana SB	75.0	I	III	40.0	48.0	375.0	270.8	300.0	75.0	216.7	54.2

Table 6-3 Sub Basin Season Classification

North Basins	Dormant Periods	October - May	Inclusive	West Tana SB, NWT SB, Ambagenen SB M-D SB, Gumaro-Senzele SB & Arno-Garno SB
	Growing Periods	June - September	Inclusive	
East Basins	Dormant Periods	Nov - April	Inclusive	Ribb-Shine and Gumara Gelda SBs
	Growing Periods	May - Oct	Inclusive	
South Basins	Dormant Periods	Nov - March	Inclusive	Koga-Gilgel Abbay Sub Basin
	Growing Periods	April - Oct	Inclusive	

A Simplified Water Balance Method: - This technique is developed by writing the water balance equation for a watershed under consideration. On un-gauged streams where stream flow measurements are not available, precipitation and potential evapotranspiration records can be used to calculate continuous flows (Fritz, 1984).

The basic principle in simulating the water balance of a given watershed follows the basic principles of rainfall-runoff process. Water that flows over land surface during and immediately following precipitation produces runoff. Part of the precipitation absorbed by the soil in the watershed during rain storms moves as subsurface flow in to stream channels and provides low flows in periods when rain does not occur. That part of the precipitation after the initial infiltration capacity of a soil is exceeded, forms an over land flow to form direct runoff in the river channel system. In this process, precipitation, actual evapotranspiration, and runoff are the volumes of water entering and leaving the watershed in the time interval, and storage is the change in soil moisture and ground water storage in the time interval, the initial storages less the final storages (Fritz, 1984). This process virtually establishes the water balance of a given watershed under consideration. This rainfall-runoff process is schematically presented in Fig 6.6 below (Fritz, 1984).

The simplified water balance simulation technique uses monthly precipitation, P and potential evapotranspiration, PET data to calculate monthly stream flow. The time of flow in stream channels of small watersheds is usually less than 1 day and this time of flow can be neglected when monthly time scale is used (Fritz, 1984).

As stated in the preceding paragraph, calculations of monthly runoffs from meteorological data are based on the water balance in the watershed, which can be expressed as (Fritz, 1984):

$$P - AET + S = Q \dots\dots\dots (6.19)$$

Where:

P is basin precipitation in mm;

AET is Actual Evapotranspiration over the basin in mm;

S is Basin Storage in mm; and

Q is Basin Runoff in mm.

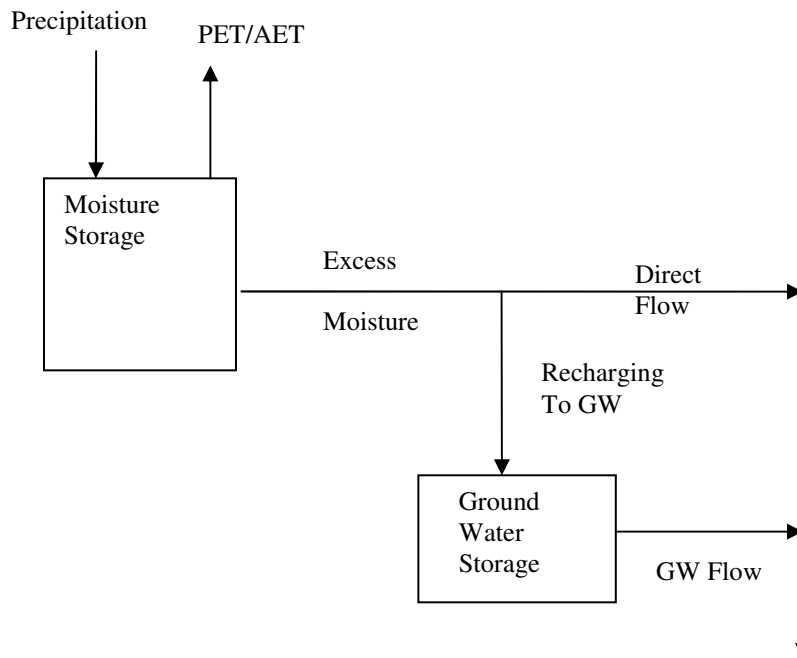


Figure 6-6 Schematic Representation of a Simplified Water Balance of a Watershed

The water balance equation applies to the watershed over any time interval. Initially, runoff is estimated for gauged catchments applying equation 6.11 for each sub basin under consideration, then modeling of the simulated versus recorded runoff is effected to see the best fit of the simplified monthly water balance simulation techniques with the respective watersheds.

Linear Regression Techniques: - Using estimated area rainfall data and runoff at the river gauging stations, direct correlation of the rainfall versus the runoff were effected applying regression analysis techniques so as to develop a rainfall-runoff relationship for the watershed under consideration.

Area Ratio Method: - This is establishing a relationship between the gauged and un-gauged watersheds based on the area ratios. This is made based on the assumption that major sub basin categories (North, East and South sub basins) have relative homogeneity. Land use and drainage patterns of these sub basins are observed from 1:50,000scale topography map of the area. Small watersheds available within the major sub basins are observed to have similar features. This situation has been given due consideration while applying area-ratio method in estimating runoff.

Small watersheds in the north sub basin are largely characterized with flat topography flood plains in the periphery of the lake followed by fragile topography of short length with an average land slope of exceeding 10% and finally intercepted with high land plateaus of relatively gentle slope. The geologic formation in this sub basin is reported to be similar with basaltic origin (Studio Pietrangeli, 1990).

Spatial variability of rainfall is taken in to account by computing area rainfall for the gauged and un-gauged watersheds within the watershed of gauged rivers. The area for gauged and un-gauged watersheds is computed separately (table 2.3). The rainfall in the un-gauged watershed is converted in to runoff applying the area ratio developed between the two watersheds located in similar rainfall regimes.

Selection of Best Fit for Rainfall-Runoff Relationships: - As discussed in section 6.0 hydrometric gauging stations in the basin are divided in to three categories. These are Megech, Gumaro and Garo in the north & northwest, Ribb & Gumara in the east & south east and Koga & Gilgel Abbay in the south. Rainfall-Runoff relationships have been established applying the four methodologies described in the preceding paragraph. The computation of surface runoff at each sub basins applying these four runoff estimation methodologies is made using EXCEL. The curves that demonstrate the simulated versus the recorded runoff and the rainfall-runoff relationships are presented in annex II to IV. The purpose of simulating the rainfall-runoff relationships applying the four methods is to find an appropriate methodology that establishes proper rainfall-runoff relationships for each sub basin category in the system.

The simulated runoff was compared with the recorded runoff and accordingly a runoff estimation methodology that best describes the runoff process of the respective sub basin is selected. In the rainfall-runoff modeling process, two criteria are used to select the best fit. The coefficient of determination (R^2) is used as one criterion. Another popular criterion for the evaluation of the goodness-of-fit between observed runoff, Q_r , and simulated runoff, Q_s , is the sum of squares of deviations between Q_r and Q_s (Andreini M etal, 2000). The smaller the sum the better the fit is. This can be expressed as:

$$\min(f) = \sum(Q_r - Q_s)^2 \dots\dots\dots (6.20)$$

The best fit between the simulated and the recorded runoff is evaluated using these two criteria's. The output of the rainfall-runoff simulation process is presented in tables 6.4 and 6.5 below.

Out Put Description: -The efficiency of each runoff estimating method, in general, increases from north to south. For all methods it is observed that the coefficient of determination (R^2) increases from south sub basins to north sub basins. Moreover, the methodologies are less efficient in small watershed areas. The Gumaro and Garo from north sub basins, having a watershed area of 174Km² and 94Km² respectively; and the Koga watershed (244Km²) are observed to have lesser coefficient of determination in all cases indicating that the then mentioned models are less effective in smaller watersheds.

SCS-CN Method: - While modeling the simulated runoff versus the recorded runoff for all the gauged sub basins applying the SCS-CN method, the determination coefficient, in a general term, increase from north to south; in which the value of the determination coefficient, R^2 ranges from 0.383 (for Megech in the north) to 0.601 (for Gilgel Abbay in the south) (table 6.5). The size of the drainage area of sub basins increases from north (Megech, 462km²) to the south (G Abbay, 1664km²) indicating that the size of drainage area is one important factor in rainfall-runoff processes. The case of the Koga sub basin ($R^2=0.204$) located in the south but with small watershed size is observed to have very weak rainfall-runoff correlation, which strengthens the above argument. It is evident that there are quite a number of factors which governs rainfall-runoff relationships, drainage pattern and topography especially slope could be some of them. These parameters may have their own influence in the rainfall-runoff relationship and it is difficult to draw firm conclusions in this regard as it needs ground level verification. Spatial rainfall variation is also another factor which shall be considered here. Initially the area rainfall for each basin was estimated by lumping the gauged and un-gauged parts of the watershed in one delineation. The rainfall-runoff relationship observed in this case was the weakest. For instance applying the SCS-CN method the value of R^2 for north basins were as low as 0.199. This indicates that spatial rainfall variability influences the rainfall-runoff relationships.

In general the determination coefficient (R^2) observed in the SCS-CN methods for all basins are observed to be below 0.65, an average minimum value that justifies best fit of two regressed parameters. Similar observations are made for the second method selection criteria. The sum of the square of the difference of the observed and simulated runoffs is observed to be higher in the case of the SCS-CN methods in almost all sub basins (table 6.4).

Simplified Water Balance Method: - Alike the SCS-CN method, the determination coefficient for water balance simulation also increases from north to south wards, the value of R^2 ranging from 0.328 (Megech) to 0.8667 (Gilgel Abbay). Longer wet period and relatively gentle land slop together with the size of the watershed (watershed area increases from north to south) could be among the various possible reasons attributing for the monthly water balance method is more effective as we move from north to south. As it can be observed from table 6.5 below, the determination coefficient for east and south sub basins satisfies the average minimum requirements for the determination coefficient ($R^2 \geq 0.65$) for best fit of the given model. More over these two sub basin categories are known to have relatively longer wet periods (April/May to October/November) with uniform topography of relatively gentle slope. As a result while calibrating the water balance simulation process for these catchments, the conditions of sustained base flow would help to effect better approximations of the runoff by the method.

Linear Regression: - The direct correlation of the rainfall versus the runoff has resulted in weakest fit in general where the determination coefficient varies from 0.219 to 0.615. Similar trend, increment of R^2 south wards, is also observed here though it is not in a definite manner like the SCS-CN and water Balance methods. The second criteria, minimum of the summation of the square of the differences, seem to be attractive in the case of linear regression techniques. However, this out put is not supported by reasonably high values of determination coefficient. It could be misleading to select the method by considering one criterion alone.

Conclusion: As a result of the foregoing discussions of the rainfall-runoff relationship simulations, it is concluded that the water balance simulation technique is adopted for the south and east sub basins. For north sub basins a fourth method, Area Ratio method has been introduced and used for simulating the runoff from the north sub basins.

Table 6-4 Values of the Sum of the Square of the Deviations for the Respective Methods.

Sub Basin Name	Rainfall-Runoff Simulation Methods/		
	SCS-CN	WATBAL	Linear Regression
N & NW SBs			
Megech	524038.67	6534687.93	93164
Gumaro	415250.05	465295.38	6988
Garno	967670.23	203844.39	11482
E & SE SBs			
Ribb	604486.42	446687.00	558632
Gumara	1816009.92	1567939.17	2407194
South SBs			
Koga	4106984.59	-	129233
G Abbay	2505773.65	811266.51	6346810

Inflow Computation: - In this research work, runoff (in mm) from each sub basin is computed using the selected methodologies. This runoff is converted in to volume (MCM) by multiplying the mm runoff with the area of the respective sub basin. The simulation result has indicated that the mean annual inflow is $378.8\text{m}^3/\text{s}$ which is equivalent to 12051.5MCM. The mean annual inflow is computed to be $297.4\text{m}^3/\text{s}$, which is equivalent to 9380MCM as per the Tana-Beles project studies (Studio Pietrangeli, 1990). The gap is more than 20% indicating that the backward simulation of the lake water balance to estimate inflows might have under estimated the inflow of the basin. The summary of the long term mean annual runoff for each sub basin is indicated in table 6.6 below.

The inflow to the Lake Tana reservoir is largely contributed from the south sub basins (33%), in which the eastern sub basins account 25% and the northern sub basins account some 10%. Direct runoff from the water surface is also considerable accounting 32% of the total inflow. This is because the area of the Lake is big and the rainfall falling on the water body is directly converted in to runoff with almost no loss.

Table 6-5 Summary of Rainfall-Runoff Relations Simulation Output

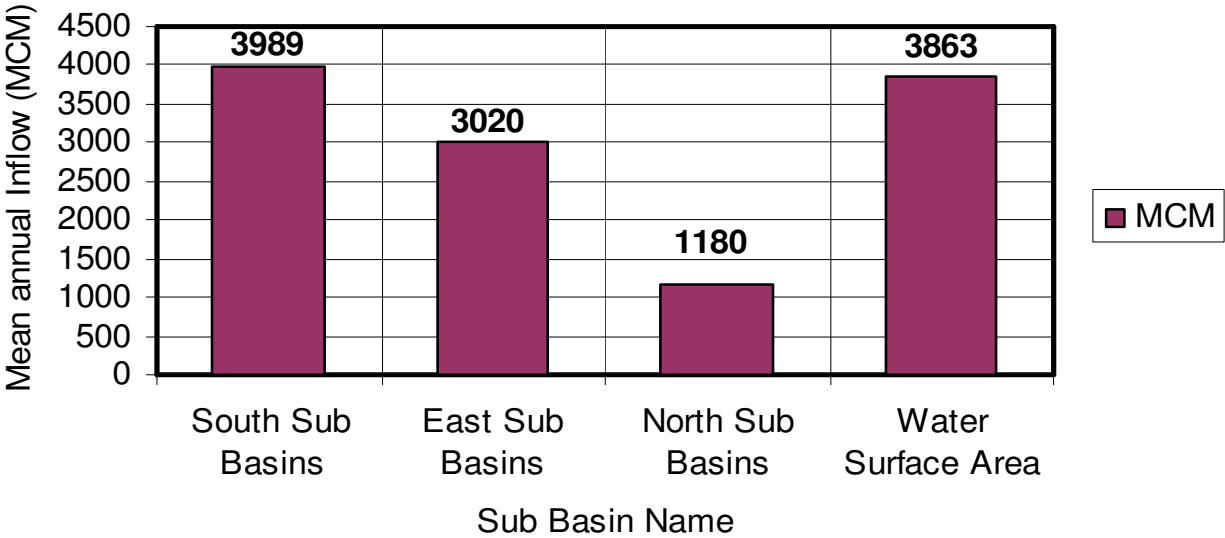
Sub Basin Name	Rainfall-Runoff Relation Equations and R^2		
	SCS-CN Method	Water Balance Simulation Techniques	Linear Regression Techniques
Megech Catchment	$Q_s = 22.53 + 0.473Q_r$ $R^2 = 0.383$	$Q_s = 0.1066Q_r - 2.139$ $R^2 = 0.328$	$Q_s = 0.472Q_r + 7.50$ $R^2 = 0.47$
Gumaro Catchment	$Q_s = 12.291 + 0.981Q_r$ $R^2 = 0.524$	$Q_s = 1.2133 + 0.9019Q_r$ $R^2 = 0.5214$	$Q_s = 0.36Q_r + 2.014$ $R^2 = 0.36$
Garno Catchment	$Q_s = 12.738 + 1.377Q_r$ $R^2 = 0.541$	$Q_s = 7.526 + 0.74Q_r$ $R^2 = 0.597$	$Q = 2.05 + 0.18P$ $R^2 = 0.32$
Ribb Catchment	$Q_s = 13.933 + 1.857Q_r$ $R^2 = 0.649$	$Q_s = 6.07 + 0.984Q_r$ $R^2 = 0.639$	$Q = -0.58 + 0.24P$ $R^2 = 0.615$
Gumara Catchment	$Q_s = 14.793 + 0.8355Q_r$ $R^2 = 0.5865$	$Q_s = 0.5583Q_r - 1.5012$ $R^2 = 0.7202$	$Q = 4.77 + 0.53P$ $R^2 = 0.587$
Koga Catchment	$Q_s = 40.122 + 0.4488Q_r$ $R^2 = 0.204$	-	$Q_s = 10.35 + 0.22Q_r$ $R^2 = 0.219$
G/Abbay Catchment	$Q_s = 17.15 + 0.7145Q_r$ $R^2 = 0.601$	$Q_s = 4.106 + 0.924Q_r$ $R^2 = 0.867$	$Q_s = 55.55 + 0.611Q_r$ $R^2 = 0.61$

The water balance simulation for east and south sub basins estimates that out of the total precipitations over these sub basins, 57% is back to the atmosphere through actual evapotranspiration, 35% is transformed in to runoff and only 8% joins the ground water system including soil moisture storages. Similar conclusions can be considered at an average level for north sub basins with some exaggeration on the evaporation component that reduces the groundwater component. Most of the rivers in the north sub basins are observed to be with little or no base flow.

Table 6-6 Mean Annual Inflow (MCM) from each Sub Basin

Sub Basins Name	m3/s	MCM
Ribb Shine	43.4	1379.06
Gumara-Gelda	51.5	1640.51
G Abbay	125.4	3989.12
Megech - Dirma	12.6	402.62
Gumaro-Senzele	3.8	121.24
Arno-Garno	2.5	80.31
Ambagenen	4.4	140.45
NWT	5.3	167.774
WT	8.4	267.34
WS Area of Tana	121.5	3863.05
Total Inflow	378.8	12051.47

Figure 6-7 Sub Basin Inflow Contribution



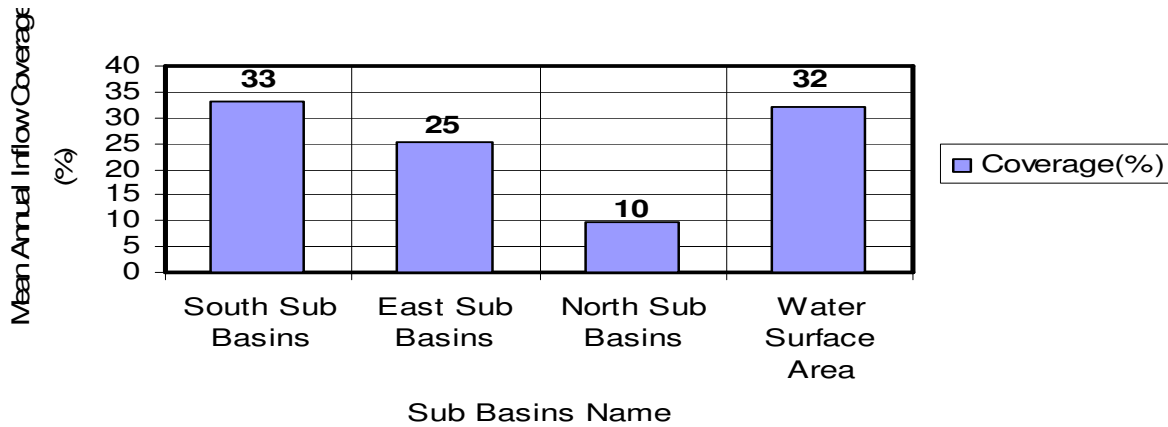


Figure 6-8 Sub Basin Inflow Contribution Coverage

6.6.4 All Season, All Inflow Water Balance Simulation Process

Initially reservoir simulation is effected assuming seepage loss is negligible. The simulation result has shown that there is still a considerable gap between the simulated and observed reservoir storages, when it is executed continuously. As compare to the dry period and all season simulations (section 6.5 & 6.5) the gap is narrowed and the simulated exceeds the observed (Fig 6.9 below) reservoir volumes. As it can be clearly noticed from Fig 6.9 below, until 1971 the simulated storage shows good agreement with the observed storage of the Lake. The mean departure during this period is estimated to be below 20%. It is from 1972 onwards that the deviation between the observed and simulated reservoir storages is getting larger in such a way that the error seems to have a cumulative effect in which finally the error becomes more than 100%. The TS plot of the Lake water evaporation is presented in Fig 6.10 below for comparison purposes. From Fig 6.10 it is observed that the pitch reading starts exhibiting a significant reduction from 1973 onwards, with high fluctuations observed until 1986 and again exhibits substantial reduction from 1986 onwards. This has induced cumulative error in the simulated reservoir storage resulting wide range of gaps between the observed and the simulated storage volumes. This is one possible reason why the water balance of the Lake is not established reasonably. This has lead the research work to bring out the recorded evaporation component in the lake water balance simulation process and compute evaporation and un-accounted part as a loss in the system, which requires the reformulation of the water balance equation as:

$$ChangeInStorage = Inflow - Losses - Outflow \text{ ----- (6.21)}$$

Where: $Losses = Evaporation + unaccounted \text{ ----- (6.22)}$

Figure 6-9 Checking of the Observed with Simulated Lake Storages; All Season Computed Inflow Considered

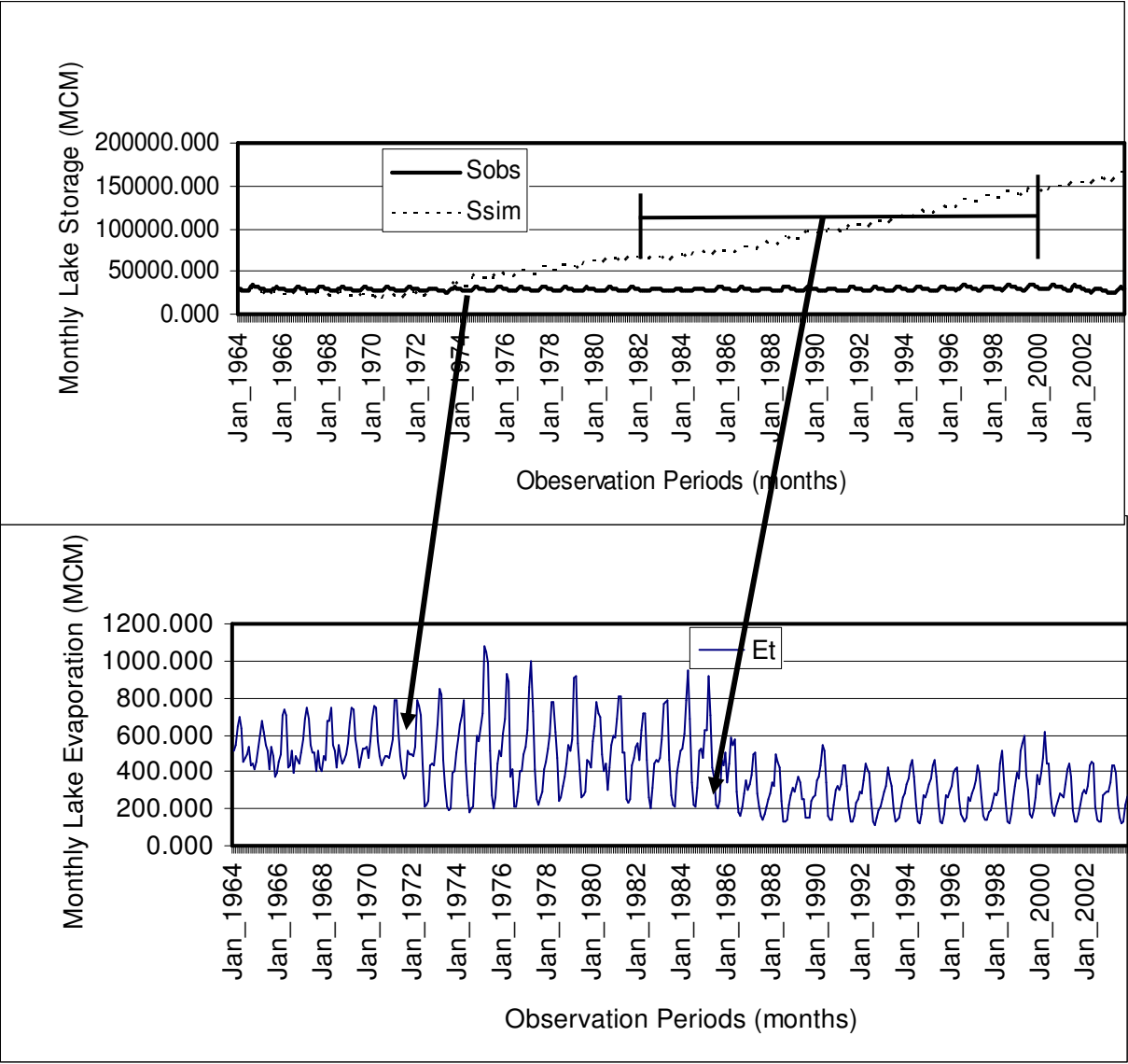


Figure 6-10 TS Plot of Lake Evaporation at Bahir Dar (Pitche Reading)

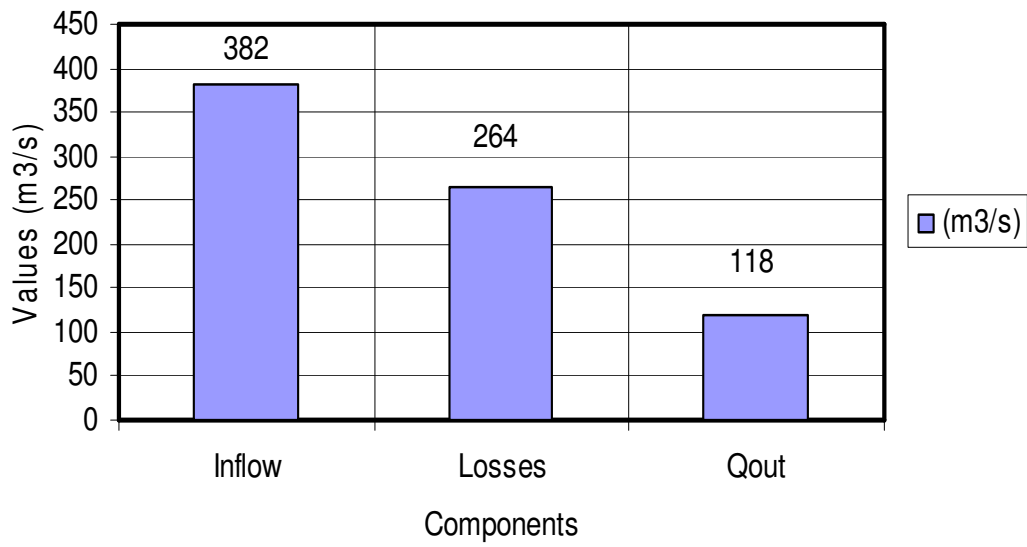


Figure 6-11 Water Balance Components of Lake Tana Reservoir

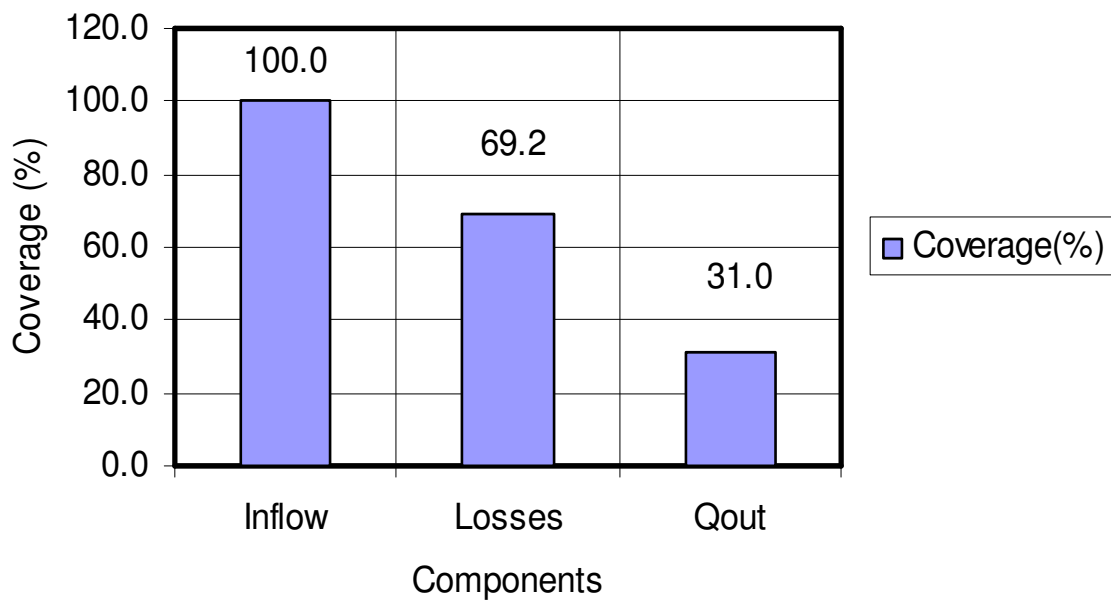


Figure 6-12 Coverage of Water Balance Components

7. RESERVOIR OPERATION

7.1 Introduction

The adequacy of the storage reservoir is established by a reservoir operation study. A *Reservoir Operation* study is defined as a simulated operation of the reservoir being managed according to a set of rules. If the reservoir can supply all of the water requirements plus seepage and evaporation losses, it is presumed that the reservoir storage is adequate (Schulz E.F., 1974).

The operation study is based on a month – by – month solution of the hydrologic storage equation designated as (Schulz E.F., 1974):

$$\frac{dS}{dt} = I - D \text{ ----- (7.1)}$$

OR

$$\frac{\Delta S}{\Delta t} = \bar{I} - \bar{D} \text{ ----- (7.2)}$$

For most of operation studies; Δt is one month; then \bar{I} is an average inflow for the month and \bar{D} is the average outflow for the month. There are several elements in the inflow and outflow terms, which are illustrated in a reservoir continuity equation expressed as (Schulz E.F., 1974):

$$\Delta S = \bar{I} - \bar{D} \text{ ----- (7.3)}$$

OR

$$\bar{I} + \Delta S - \bar{D} = 0 \text{ ----- (7.4)}$$

This is systematically presented in Fig 7.1 below that expresses the various components in equation 7.2.

The reservoir operation study is completed by sequentially solving equation 7.2 when the inflow and outflow have been expanded to include all of the terms illustrated in Fig 7.1 below (Schulz E.F., 1974).

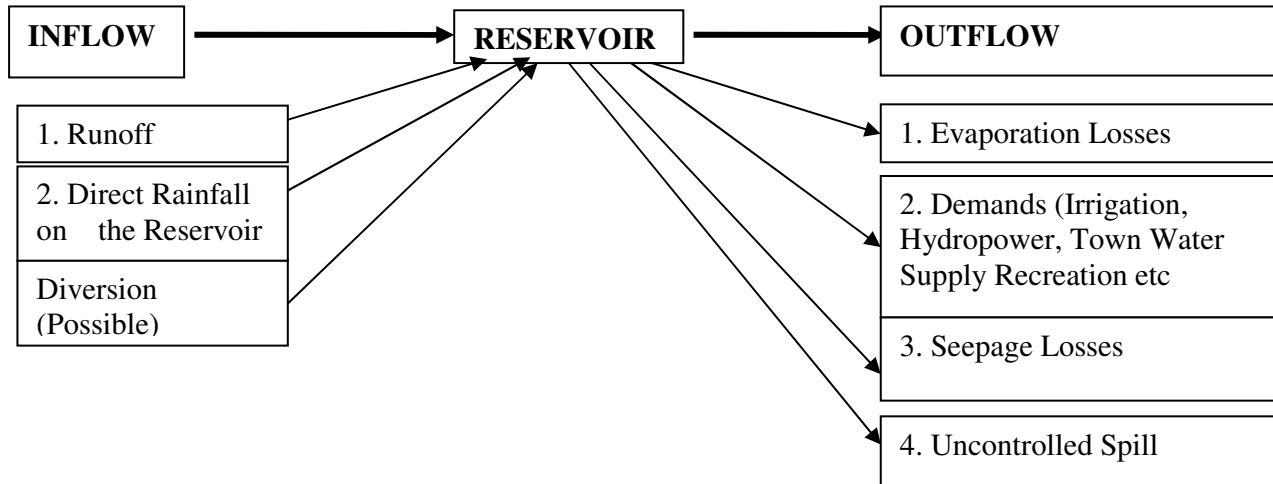


Figure 7-1 Schematic Representation of Hydrologic Reservoir Storage Equation

Reservoir operation, which is necessarily a simulation process, is a method by the use of which probability distribution of system response (out put) is estimated for a given system input in probabilistic terms (AAU, 2003).

Reservoir operation is used for various purposes in planning water resources systems. In design it is used to determine active storage capacity of reservoirs; in evaluation of the existing water resources system it is used to evaluate the adequacy of reservoir capacities and operating rules; in reservoir and/or system operations when size of reservoirs and target demands are given, it is used in determining optimal operation rules; and also it is used in determining minimum yields (AAU, 2003).

Reservoir operation in this research work is used both for evaluating the existing system and develop optimum operation rules accordingly. Lake Tana, naturally existed reservoir, is planned to meet the demands of multi objective needs. Currently two conflicting demands are required to be met by the reservoir, hydropower development at Tis Abbay and minimum environmental requirement at Tis Esat fall. Very soon demands regarding irrigation (Koga irrigation project with development size of more than 5100ha is currently under implementation) development works will

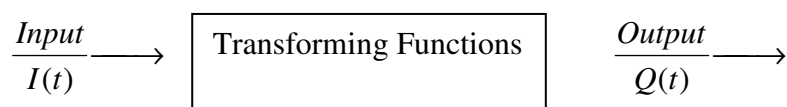
be realized. Through time, population size increases, which enhance more development needs, and then the realization of envisaged development works in the basin, will be a necessity. Recently conducted master plan studies (BCEOM & associates, 1999) justify this situation. On the other hand water resources in the basin are limited resources that can only support limited development works. This situation, the balance between demand and supply in the system, necessitates proper planning and establishing of optimum operation policies/rules for Lake Tana reservoir, so as to get possible optimal benefits from the system. It is behind this situation that reservoir operation and establishing of optimum operation policies for Lake Tana has become in to picture.

The output from such research work would have been more complete if reservoir operation is supported with analytical optimization tools. Initially the research work was intended to establish optimum operation rules both by reservoir simulation and analytical optimization tools. However, in the course of the research work it is experienced that time is becoming the limiting factor. To run reservoir operation properly the various components of the water balance of the reservoir have to be evaluated necessarily. Reservoir inflow is one of the most important components that shall be estimated properly. The research work has required much time to accomplish the estimation of reservoir inflow. Moreover, establishing the water balance of the reservoir, which is a prerequisite for reservoir operation, has consumed much time. Due to these reasons there was no much time left to apply analytical optimization tools for the research work. As a result, the researcher, together with the research advisor has opted to run reservoir operation applying simulation techniques.

7.2 Basic Concepts of Monte Carlo Simulation

A hydrologic system consists of an input represented as I and an out put represented as O . Such a hydrologic system can be simple or complex consisting of inputs and out puts which can be either a single variable or a vector of several variables or any combination of these. If a simple watershed can be considered as a hydrologic system, the input could be an average precipitation over the watershed and the out put is defined as the stream runoff generated at the out let of the watershed.

This can be schematically represented as:



In general Monte Carlo Simulation is a method for obtaining the probability distribution of the output O given for the probability distribution of the input (Maidment, 1993).

The inputs to be used in Monte Carlo simulation studies may be a historical hydrological series or artificially/synthetically generated series. The transformation of the input I to the output is made by means of a mathematical model which represents the behavior of the physical system under consideration. In the case of the reservoir system that constituted a series of inflows as an input and outflow series as an output, the inflows are transformed into outflows by operating the reservoir as per to its operation rule, satisfying a set of constraints available in the system and the mass balance equations of the reservoir system. The transformation process in the reservoir system, hence, involves routing the input through the reservoir system to achieve the system output. Finally the system output is analyzed statistically so that it can be used for decision making purposes.

The analysis of the output may consist of determining basic output statistics, such as the mean and the variance, graphical presentation and overall frequency distribution of the output variables under consideration (Maidment, 1993).

7.3 Need for Time Series Analysis in Reservoir Operation

7.3.1 Introduction

Stochastic approach to planning water resources systems is viewed as a consequence of not neglecting the stochastic nature in time series of both water supply and water demands. Present trend in applying stochastic approach to planning is to treat risks, uncertainties and acceptable/ non-acceptable regions of random decision variables properly (Yoganarasimhan G.N., Dec 20-22, 1980).

Many decisions in planning, design, construction and operation of water resources systems are governed by the economic process and the techniques in matching the supply and the demand in the system itself. Water supply and demand have characteristics that affect development, conservation, operation, control and protection of water resources. General characteristics of water resources related environments and time series that define water supply and water demand provide information needed for making decision. Therefore, defining and understanding the stochastic process of both the water supply and demands while effecting proper planning and operation of

water resources system requires sufficient knowledge in water supply and demand time series and information on properties of water resource related environments, which are the necessary prerequisite for correct planning and decision making (Yoganarasimhan G.N., Dec 20-22, 1980).

Many water resources specialists do agree in conceptualizing that planning and operation of water resources systems are different so different sets of techniques are needed. Others however, do believe that basic techniques and approaches to planning and operation of water resources systems are nearly identical except in two aspects (Yoganarasimhan G.N., Dec 20-22, 1980):

- a) In planning an alternative of the future of water resources system are operated (or simulated using computers) considering as if that alternative physically existed. This is needed for obtaining information on system performances basically assessing benefits, costs and risks, for purposes of further planning analysis, comparison and final selection of an alternative out of a set of alternatives. The physical existing system must, however, be operated continuously day-by-day, month- by-month and/or year-by-year basis (Yoganarasimhan G.N., Dec 20-22, 1980).

- b) While an alternative in planning water resources systems may be operated by the simulation on a computer, for its entire economic life in a couple of hours of computer time (even by supplying the forecast information by another computer program) the operation of an existing system is a continuous repetitive process even when a computer is used (Yoganarasimhan G.N., Dec 20-22, 1980).

Hydrologic time series that define water supply and water demand or use and other time series that affect planning, design, construction and operation of water resources systems all may have these four most general properties: **trend, periodicity, intermittence** and **stochasticity**. They are well interrelated basically as the periodic-stochastic, trend or no trend, intermittent or continuous time process. The most general case is then trend-intermittent-periodic-stochastic process (Yoganarasimhan G.N., Dec 20-22, 1980).

Trends in water supply time series result either from inconsistency (system errors) in data or from man induced changes and various discrepancies in nature in the form of non homogeneity (non stationarity) in time series parameters(Yoganarasimhan G.N., Dec 20-22, 1980).

Intermittence in water supply is resulted either from time processes in supply that are intermittent by their nature such as precipitation, a runoff of relatively small time intervals of small watersheds or it is resulted in demand such as irrigation applied only during the moisture deficit season. However, the time intervals of no supply and no demand are also periodic stochastic variables with in this intermittence (Yoganarasimhan G.N., Dec 20-22, 1980).

Periodicity in both water supply and water demand time series results from well defined astronomical cycles, as the determinative components of time series (Yoganarasimhan G.N., Dec 20-22, 1980).

Stochasticity in water supply series results from various random (chance) processes in earth's environments, especially in atmosphere. It appears either as an independent or a dependent stochastic component of trend-intermittent-periodic stochastic time series. Stochasticity in demand series results from two sources (Yoganarasimhan G.N., Dec 20-22, 1980):

- Stochasticity effects of geophysical time series (stochasticity in precipitation and temperature time series); and
- Stochasticity effects in economic and social process that affect water demands.

Water resources environment often contain non negligible stochastic components especially when they are result of cumulative effects of stochastic time series apart from periodicity such as large lake storages (Yoganarasimhan G.N., Dec 20-22, 1980).

7.3.2 Need of Time Series

Time series analysis is a major tool in hydrologic simulations like reservoir operations. It is used for establishing mathematical models to generate synthetic hydrologic records, to forecast hydrologic events, to detect trends and shifts in hydrologic records and to fill in missing data and extend records (Maidment, 1993).

Analysis of supply and demand time series in water resources has the objectives of (Yoganarasimhan G.N., Dec 20-22, 1980):

- modeling processes by using adequate mathematical forms;
- understanding their structure and causal factors of their special properties; and
- appropriate simulation of the processes in terms of generated sample series of given sizes.

These objectives are accomplished by extracting information from historical observation. Three basic parameters in this analysis and simulations are:

- Size N of historical sample that is either directly used or the needed information is extracted from them;
- Sizes N_0 of generated samples that is related to the investigation problem (say N_0 is the economic life of a project); and
- The number m of generated samples determined by the desired accuracy in problem solution.

Water supply and water demand time series are used in planning water resources systems basically in two ways (Yoganarasimhan G.N., Dec 20-22, 1980).

i) Use of Historical Time Series: water supply time series and derived future water demand time series are used for planning basically either as the result of observations in case of supply or as a result of synthesis and extrapolation of experiences in past water demands. In this approach, the planner assumes:

- The operation of a water resources system started at the initiation of observations of water supply or collection of data for water demand;
- The trial operation of the system in planning phase ends with the latest available data;
- The system will operate under the same or even identical occurrence of historical time series; and

- Only one value is obtained for each key decision variable in the final use of data.

ii) *Use of Large Number of Generated Samples:* - the use of generated sample of supply and demand time series of prescribed sizes are the potential (likely equally probable) water supply and water demand time series of the future or to occur during the economic (or even physical) life of the water resource system. This approach then produces as many solution values in planning as there are samples.

The basic criterion whether the first or the second approach should be used depends on the horizon (time period) the planner looks ahead in various decisions. For instance, if a storage reservoir is intended to increase low flows during dry seasons, while wet seasons always (or nearly always) have sufficient water supplies to fill that reservoir the use of historical samples may be sufficient. There will be N independent fillings and corresponding employing of the reservoir, with the corresponding variations in yearly low flow increases. If N is sufficiently large (say 25-30 years), n values are obtained for each variable related to reservoir operation and low flow augmentation. These N values provide a reliable basis for computing frequency distributions (or fitting them by the estimated probability functions); or problems to be decided up on by the planners (Yoganarasimhan G.N., Dec 20-22, 1980).

If, however, the planning horizon, H_0 , is large, then the second approach of using sets of m generated samples, each with N_0 sample size, will produce more reliable results than the first approach. As an example, many storage reservoirs for the over-the-year flowing regulations have the average period of full turn over, ... nearly from a given storage volume to full or empty reservoir, and then to empty or full reservoir respectively, back to the initial storage volume, ... that may be much larger than a year (say $N_0 = 5$ to 25 years or longer). Similarly, if the planners interest is to assess benefits, costs and risks of planned facilities over the project economic life (say $N_0 = 25$ to 80 years), the historical samples usually will provide less reliable information than the generated samples. The unique value obtained from historical series may be way out either at one or the other extreme of probability distribution of values that would be provided using the generated samples. Therefore, the horizon for which the decisions are made or information supplied, or horizon at which the planners look in to the future, determine the critical H_0 value, that should intern affect the decision whether the historical sample approach or the generated samples approach (simulated by models inferred from

the historical samples) should be used in planning a particular water resources systems or solving the supply-demand problems of its particular project (Yoganarasimhan G.N., Dec 20-22, 1980).

As per to the revised integrated river master plan studies of the Abbay river, the planning horizon for the intended development programs in the Lake Tana basin is thought to be 50-years. Moreover, the size of the Lake Tana reservoir with water surface area of 3110km² at mean sea level of 1786 is considerable and can be categorized as a reservoir of having over-the-year storage. In the study of the Tana-Beles Project (Studio Pietrangeli, 1990) it is indicated that, in the absence of the regulation weir, for the lake once it reaches to its minimum operating level (1784masl) it needs some 6 to 9 years to stabilize, indicating that the reservoir is not a within a year type of storage.

In conclusion, application of historic time series in decision making in planning water resources systems and design of individual projects is warranted as accurate when one looks on short-horizon decisions (up to one year). Application of sets of generated series of given sizes, on the other hand, will give reliable results when one looks on long-horizon decisions (say several years or project economic life) (Yoganarasimhan G.N., Dec 20-22, 1980).

In selecting one of these two approaches the reliability of information is a crucial factor in solving problems. Historical samples contain various errors that should be assessed and taken in to account. Generation of samples from inferred models has additional uncertainties in form of model errors and errors in estimation of its parameters. From the forgoing discussions and from the planning horizon and the type of storage exhibited by the lake, it is evident the case of the Tana reservoir has to be treated using generated samples each having a length of 40 years and as many as possible.

7.3.3 Model Description

Hydrologic data given from gauging stations, which form basic information for the design of water resources systems, are viewed as samples from infinitely long time series. The sequence within the existing hydrological record has a probability very close to zero to repeat itself identically. What has a considerably high probability is that any future sequence of hydrologic events will be different from the existing record (Buras, 1972).

Since water resources systems are designed for the future, we are interested in estimating their performance (and behavior) with hydrological inputs statistically indistinguishable from the observed record but with different internal patterns. We are, therefore, interested in generating a sequence of numbers that are statistically indistinguishable with anticipated sampling errors from the existing hydrological records ((Buras, 1972).

Stochastic simulations of hydrologic time series is generally conducted using mathematical models. A mathematical model representing a stochastic process is called “stochastic model” or “time series model” (V.Yevjevich et al, 1985). Several of time series models are available to be used as a tool in the process of data generation. The autoregressive (AR) models, AR combined with Moving Average (ARMA) models and the AR integrated with the Moving Average (ARIMA) models are to mention some of the widely used time series models.

One of the most popular and simplest models widely used in stochastic hydrologic process such as stream flow generations is the autoregressive model denoted as $AR(p)$ and represented as (Sveinsson O.G.B etal, 2003):

$$X_t = \mu + \sum_{j=1}^p \phi_j (X_{t-j} - \mu) + \xi_t \dots\dots\dots (7.5)$$

$$\mu = \bar{X}$$

$$\phi_1 = r_1 \quad (\text{for } p = 1)$$

$$\sigma_{\xi}^2 = S^2(1 - r^2) \quad (\text{for } p=1)$$

Where:

\bar{X} = Sample Mean

S^2 = Sample Variance

r_1 = Sample Lag-1 Serial correlation Coefficient

σ_{ξ}^2 = Noise Variance

A schematic representation of a stochastic model as described in the preceding paragraphs is presented in the Figure 7.2 below.

These models commonly require analyzing the temporal and spatial variability of the series under consideration. For example first and second order statistics such as the mean, variance and covariance are useful in any type of statistical analysis. Higher order moments such as skewness and

some other statistics related to surplus, drought and storage are of interest from practical point of view.

If the then mentioned statistical parameters are constants with time the models are stationary representing stationary time series or stationary stochastic process. Non-stationary models would result if such parameters would vary with time. For instance a stochastic process is constant in the mean or first order stationary if the expected values do not vary with time that is $E(X_1) = E(X_2) = \dots = E(X_t) = E(X) = \mu$. Similarly, when $Var(X_t) = \sigma^2, t = 1, 2, \dots$, is a constant, the stochastic process is stationary in the variance. A stochastic process is stationary in the covariance when the covariance depends only on the time lag K but it does not depend on the position t . That is, $Cov(X_t, X_{t-k}) = Cov(k)$ regardless of t . A stochastic process is also considered second order stationary when it is stationary in the mean and in the covariance and note that stationarity in the covariance implies stationarity in the variance (Yevjevich et al, 1985).

7.4 Analysis of Hydrologic Time Series

7.4.1 Normality Test

Most time series models such as AR (p) assume that the variable under consideration is normally distributed (Maidment, 1993). However, most of hydrologic events, including the inflows of Lake Tana reservoir, are not normally distributed, rather they are positively skewed. It is, therefore, important that running normality test before running further analysis in modeling the historic series is a must. A historic data series has no normality if it exhibits trends/shifts, periodicity or cyclicity. Transformation is made to normalize the historic series that has no normality.

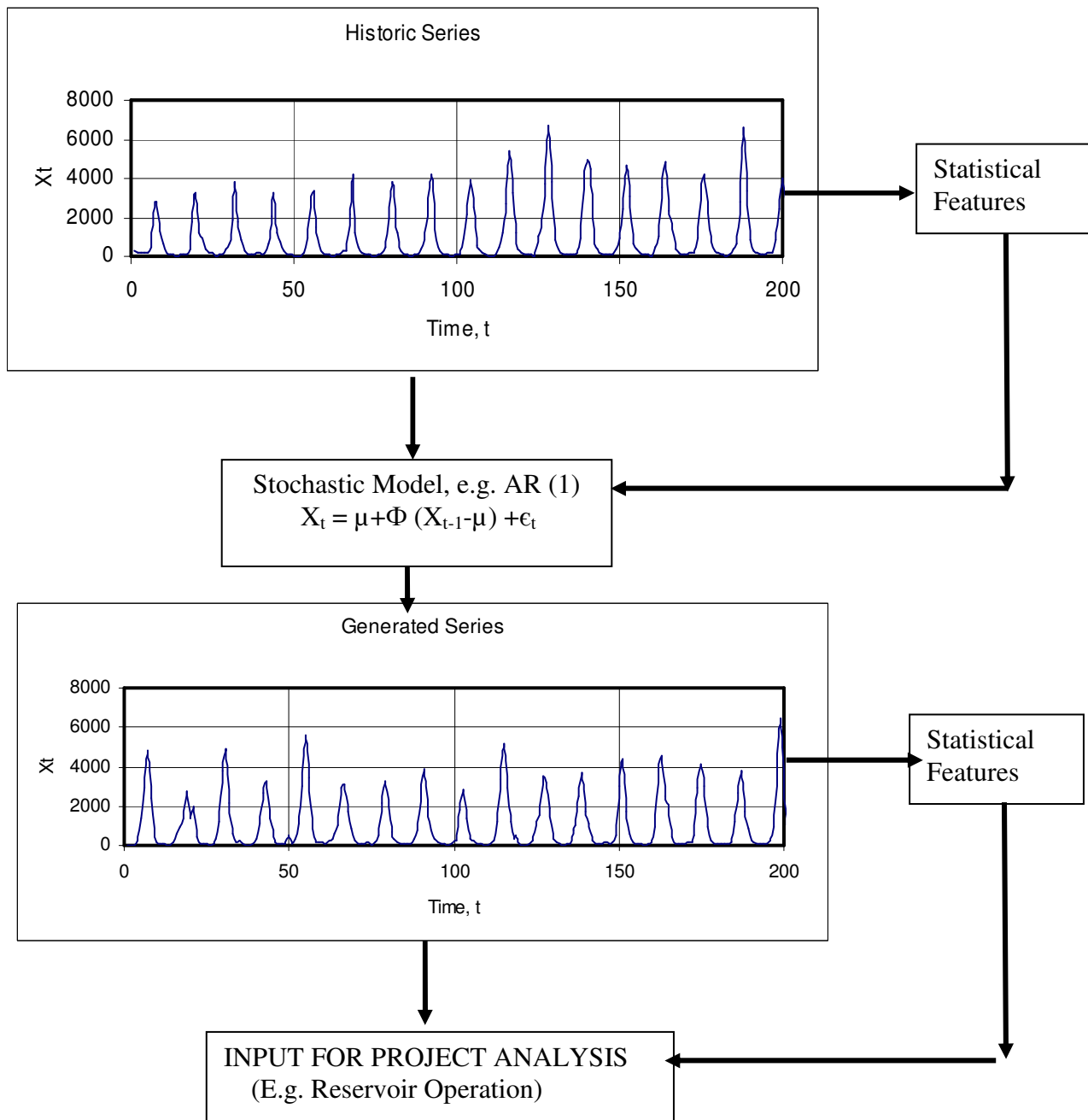


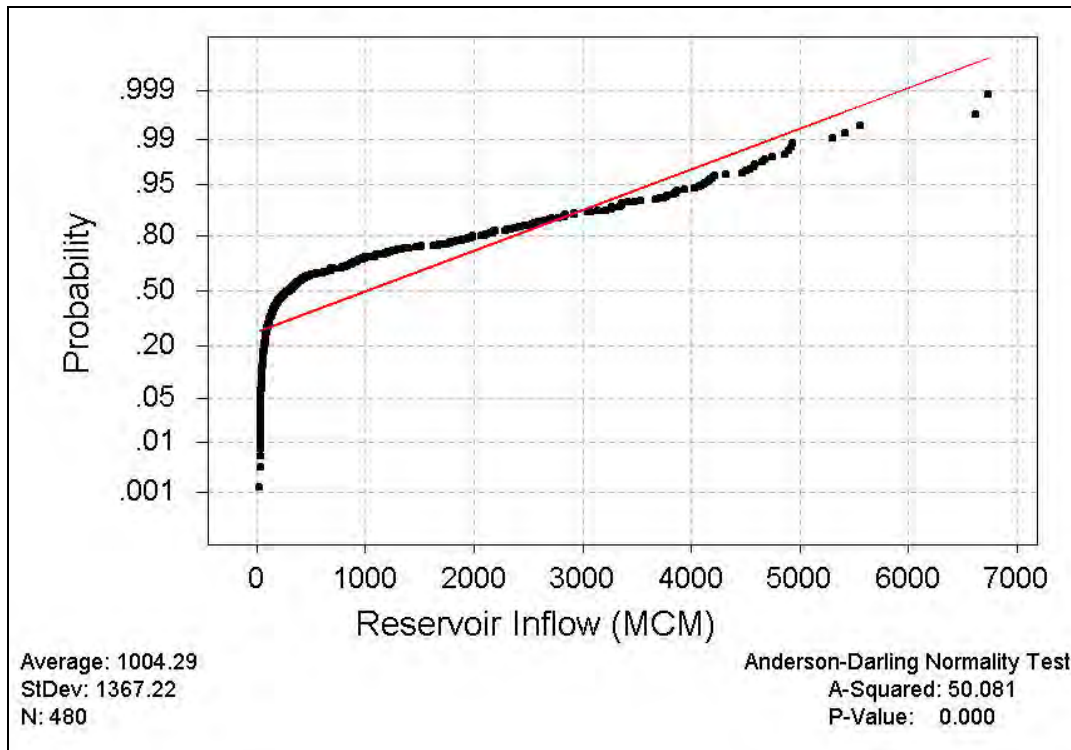
Figure 7-2 Schematic Presentation of Stochastic Model.

Accordingly the normality test for the reservoir inflow of Lake Tana is made before advancing in the time series modeling activities. MINITAB, statistical software, has been used to effect the normality test for the reservoir inflow of the Tana basin. The computer output is presented in Fig 7.3 below.

The common procedure used for judging whether a certain data set is normally distributed is to plot the empirical frequency distribution of the data on normal probability paper and a straight line probability plot indicates the data are normally distributed. Otherwise the data are not normally distributed and transformation is required to make the historic series normal so that the use of time series model as a tool for data generation purposes can be implemented.

The normality test has been made using the Kolmogorov-Smirnov test. Fig 7.3 below depicts that the reservoir inflow of Lake Tana is not normally distributed as it does not form a straight line curve when drawn on the normal probability paper. This indicates that the data exhibits trends/shifts, periodicity or cyclicity which needs transformation before hydrologic time series modeling is implemented.

Figure 7-3 Reservoir Inflow (Historic Series) Normality Test



7.4.2 Analysis of Seasonality for Reservoir Inflows

Periodicity/cyclicity means that statistical characteristics change periodically within a year. Astronomic cycles are the basic causes of periodicity/cyclicity of hydrologic series. Periodicity is nearly the characteristics of all hydrologic series (Yevjevich, etal, 1980).

As it is true for most hydrologic series, the reservoir inflow of Lake Tana reservoir exhibits periodicity/cyclicality. The mean monthly inflow series and annual inflow series are presented in Fig 7.4 to 7.5 below for illustrative purposes.

The three Figures below indicate that the reservoir inflow exhibits seasonality/periodicity, in the mean, standard deviation and the skewness. The periodicity exhibited by the historic data series has to be removed to apply the hydrologic models like AR(p) in the data generation process.

Figure 7-4 Seasonal Distribution of Basic Statistical Parameters for Reservoir Inflow

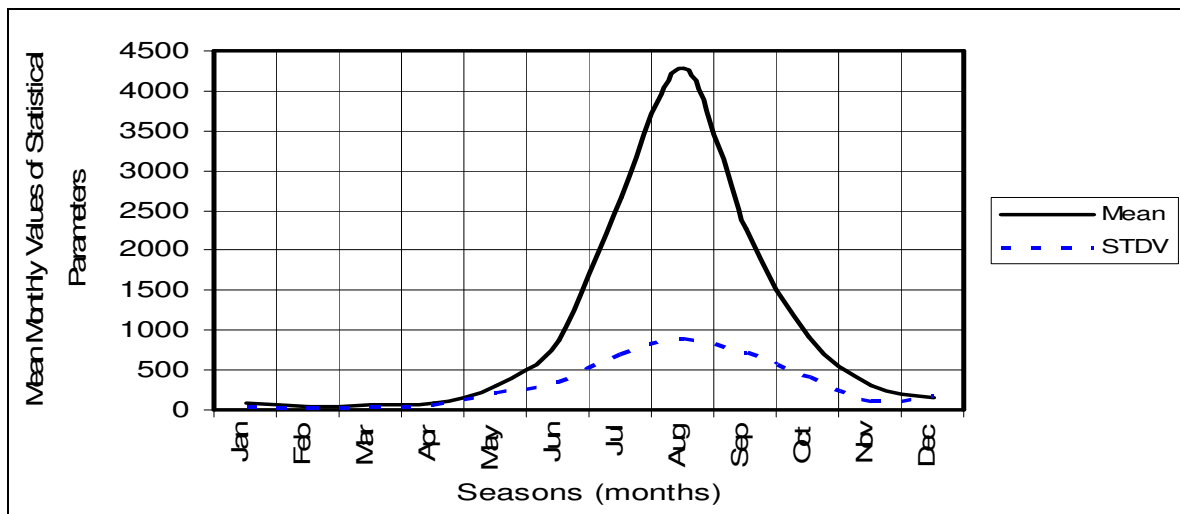
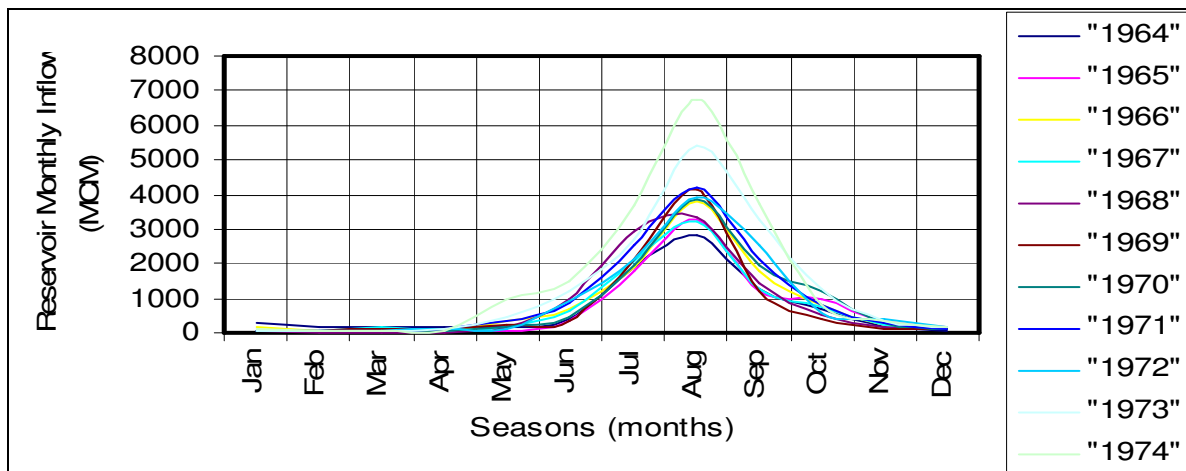
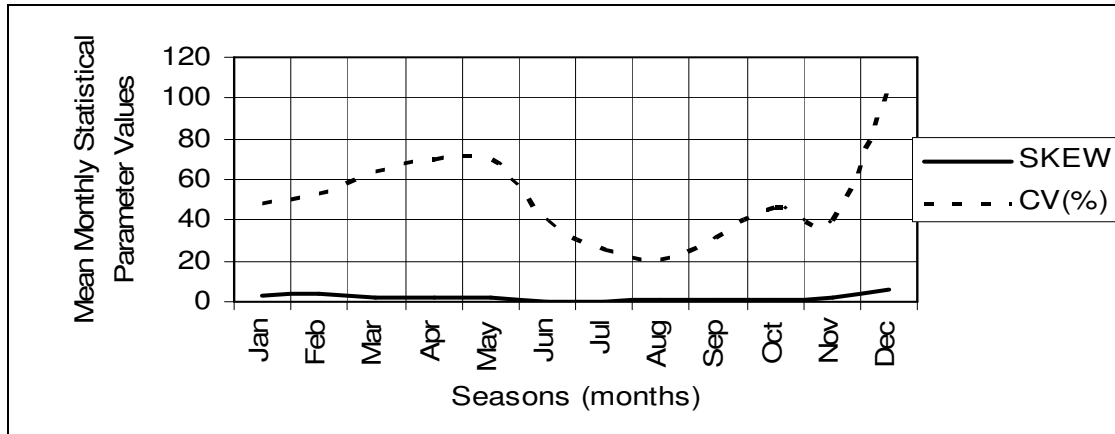


Figure 7-5 Seasonal Distribution of Reservoir Inflows



Removing periodicity from the historic series involves two steps, transformation and standardizations of the historic series.

Figure 7-6 Res Inflow Seasonal Distribution of Skewness & Coefficient of Variation



7.4.3 Transformation to Normal

For most of the hydrologic series, if x_t is the original series (historic series) logarithmic transformation having a form of:

$$y_t = \text{Log}(x_t - a) \dots\dots\dots (7.6)$$

is normally distributed provided that x_t is lognormal with lower-bound parameter a . Often the simple log transformation with $a = 0$ works approximately, even if the original series x_t is not lognormal (Maidment, 1993). In this thesis a log transformation, as described in preceding paragraph is used after optimizing the value of a so that the skewness of the historic series approaches a value of zero.

The normality test has been run using the facilities in MINITAB to observe that the log transformation has transformed the historic series to normal distribution. The optimization process for the lower bound value a indicates that the skewness of the log transformed series is zero indicating that skewness is removed from the historic series by log transformation. Using similar facility from MINITAB normality test for log transformed series has been conducted and the p-value is less than 0.15 for Kolmogorov-Smirnov test (annex-I), indicating the transformed series is not yet normally distributed. Thus the data needs standardization to change it into normal distribution.

7.4.4 Standardization of Transformed Series

This process is used to remove periodicity effectively from the historic series. The Log- transformed series is standardized using a relationship (Maidment, 1993):

$$Z_t = \left[\frac{Y_t - \bar{Y}_t}{S_t} \right] \dots\dots\dots (7.7)$$

Where:

Z_t = Standardized Series;

Y_t = Log transformed Series;

\bar{Y}_t = Mean of Log Transformed Series; and

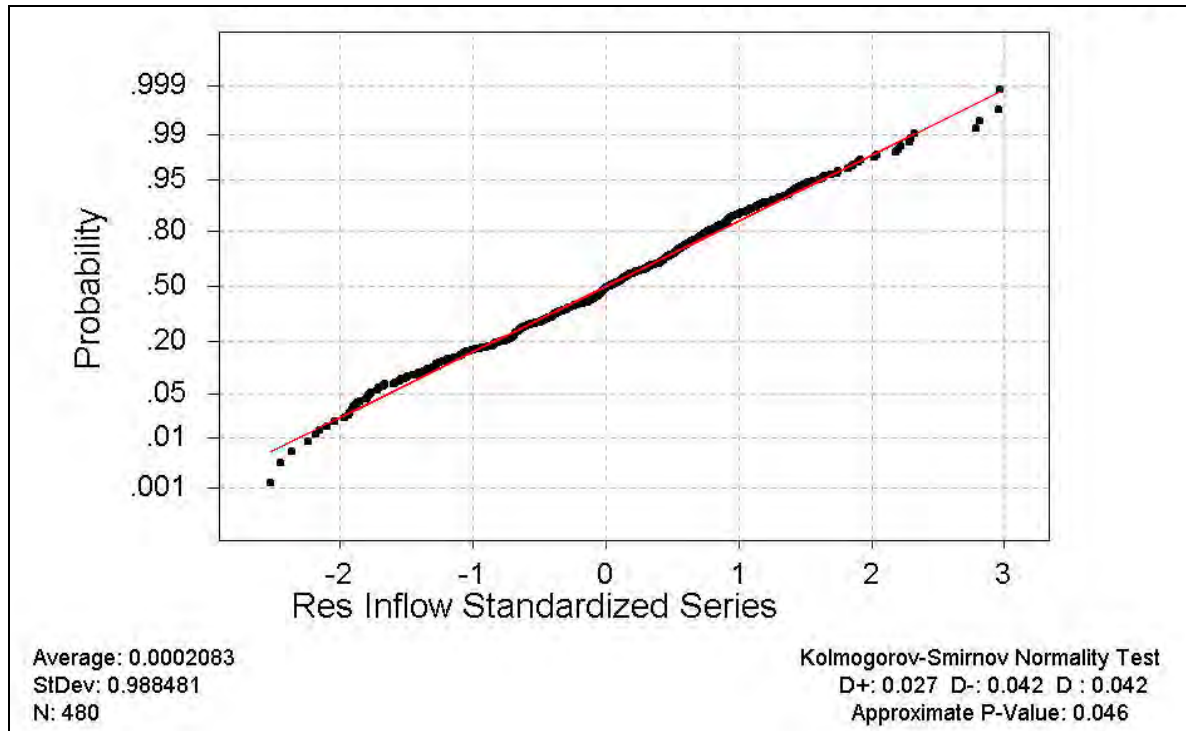
S_t = Standard Deviation of Log Transformed series.

Normality test has been run for standardized series (Fig 7.7 below) to check that periodicity is removed from the historic series effectively. The normality test made using Kolmogorov-Smirnov Normality Test indicates that P value is greater than 0.15. For significance level $\alpha = 0.025$ at 97.5% confidence interval, the value of P exceeds the given significance level justifying that the normality of the standardized series can not be rejected.

7.4.5 Analysis of Trend and Shifts for Reservoir Inflows

In general, natural and human induced factors may produce gradual and instantaneous trends and shifts (jumps) in hydrologic series. Large scale devastating in forest land of the watershed can produce a jump or shifts in hydrologic series as it significantly affects the rainfall-runoff process. Conversely, gradual changes in the watershed such as a gradual deforestation as a result of population growth would result the formation of trends in hydrologic series. In the last three to four decades the latter phenomenon has been happening in the watershed of the Lake Tana basin. The forest land has been put in to cultivated land resulted from high population growth and backward and/or primitive, almost no growth, agricultural production system.

Figure 7-7 Reservoir Inflow Normality Test for Standardized Series



The time series plot and trend analysis for the reservoir inflow is made using MINITAB software and presented in annex-I. An observation of the TS plot indicates that the historic hydrologic series exhibits a trend. A trend having a slope of 0.545 is observed and the significance of this slope has to be tested.

Testing the Significance of Trend: - In many situations, both parametric and nonparametric tests are available. Nonparametric tests depend on a specific distribution of the hydrologic data series. If the data distributions depart substantially from the assumed distribution, nonparametric tests can be much more powerful than the parametric test. On the other hand procedures for testing the fit of data to probability distributions are often insensitive to departures that are large enough to cause a serious loss of power for the parametric test. Thus, unless there is a great deal of prior knowledge of the distributional characteristics of the data, it is risky to use the test that depends on a specific distribution. For parametric tests that depend on the normal distribution, the significance levels are reasonably accurate regardless of the actual distribution of the data (Maidment, 1993). However, the power of the tests may be severely diminished if the data are truly non-normal.

Following the foregoing discussions, the significance of the trend slope for the historic series of the reservoir inflow is tested applying the parametric test after transforming the historic series to normal using log transformation mechanisms. The procedures of log-transformation and normality test for log transformed series are indicated in section 7.4.4. The time series plot and trend analysis for the transformed series is presented in annex –I.

Assume that y_t , $t = 1, \dots, N$ is an annual series and $N =$ sample size. A simple linear trend can be written as:

$$y_t = a + bt \dots\dots\dots (7.8)$$

where a and b are the parameters of the regression model. Rejection of the hypothesis $b = 0$ can be considered as a detection of a linear trend. The hypothesis that $b = 0$ is rejected if:

$$T_c = \left| \frac{\sqrt{N-2}}{r\sqrt{1-r^2}} \right| > T_{1-\frac{\alpha}{2}, \nu} \dots\dots\dots (7.9)$$

in which r is the cross-correlation coefficient between the sequences y_1, \dots, y_N and $1, \dots, N$, and $T_{1-\alpha/2, \nu}$ is the $1-\alpha/2$ quantize of the Student t distribution with $\nu = N - 2$ degree of freedom (Maidment, 1993).

For $T_c = 1214.82$, which is greater than the $T_{1-\alpha/2, \nu} = 1.96$, at 97.5% confidence of interval, the null hypothesis $b = 0$ is rejected indicating the monthly inflow hydrologic series exhibits a significant level of trend (Fig 7.8 above). The possible reason for a historic series of reservoir inflow exhibits a trend could be do to the fact that most of the inflows from gauged watersheds has indicate positive trend (Annex-I). Increment of runoff coefficients resulted from an immense, but gradual land degradation, would be one possible reason for the reservoir inflow to exhibit a positive trend. It has to be remembered that most of the rainfalls from meteo stations has shown negative trend (annex-I).

Removing the trend has been detected by running normality test for the standardized series. As indicated in Fig 7.7 the standardized series is observed to acquire normal distribution as it fits a straight line for the probability plot.

Test for the Shift in the Mean: - Applying similar techniques as that of the trend analysis the shift in the mean for both annual and monthly series of the reservoir inflow has been tested. Both the annual and monthly series are sub divided in to two equal sub series denoted as N_1 and N_2 .

The test statistics in the case of shift analysis is given as:

$$T_c = \frac{|\bar{y}_2 - \bar{y}_1|}{S \sqrt{\left(\frac{1}{N_1} + \frac{1}{N_2}\right)}} \dots\dots\dots (7.10)$$

$$S = \sqrt{\left[\frac{((N_1 - 1)S_1^2 + (N_2 - 1)S_2^2)}{N - 2}\right]} \dots\dots\dots (7.11)$$

Where \bar{y}_1 & \bar{y}_2 and S_1^2 & S_2^2 are the estimated means and variances of the first and the second sub series, respectively. The null hypothesis $\mu_1 = \mu_2$ is rejected if $T_c > T_{1-\alpha/2, \nu}$, where $T_c > T_{1-\alpha/2, \nu}$ is as defined in the preceding paragraph.

After running the test for the shift in the mean of the monthly series at 97.5% of confidence interval; $T_c = 0.56$, which is less than $T_{1-\alpha/2, \nu}$ that is equivalent to 1.96, indicating the null hypothesis $\mu_1 = \mu_2$ ca not be detected. This signifies no shift detection in the mean of the monthly series. The mean of the annual series for the upper and lower half of the historic series has been observed and the difference is well below 10% (actual value is 6.99%) conforming that no significant shift in the historic series.

7.5 Data Generations

7.5.1 Model Selection

To observe to which model the standardized series fits, the Autocorrelation (AC) and Partial Autocorrelation Functions (PACF) are plotted as presented in annex-I. From these two plots it is observed that the standardized series would fit to autoregressive models (AR-Models). The PACF further indicates that only the first lag is beyond the 95% confidence interval indicating that the standardized series fits to AR (1) model.

Based on the ACF and PACF indications, initially AR (1) model has been tested for the standardized series. Then model adequacy test is run applying AR (2). In this model adequacy test it is observed that the probability of the data fits in to AR (1) is observed to be more than 2.5% indicating that AR (1) model best describes the standardized series.

The normality test for the residuals made for the two models AR (1) and AR (2) (presented in annex-I) indicate that the residuals are normal (p-value >0.15 for Kolmogorov-Smirnov test for both cases) except at the lower and upper tails of the graph which can be resulted from in-exhaustive optimization of the parameter “a” during the process of normalization. This can be taken as an acceptable for all practical purposes. From the foregoing discussions it is observed that the standardized series of the Lake Tana reservoir inflow is best described by AR (1) model. Thus the coefficient from AR (1) model computed as 0.4501 is used in the data generation process.

7.5.2 Data Generation Process

To achieve an optimum operating rule, it is essential to have sufficiently long historic flow data and this is unlikely for most practical situations where data recording by itself is commenced not more than two or three decays before. In countries like Ethiopia, data recording has no periods longer than two to three decades; hence acquiring sufficiently long historic data is hardly possible. In the Lake Tana basin data recording in very few sites (Gondar air port and Bahir Dar, for instance) have been commenced since 1964 which amounts four decades only. Generating synthetic data applying time series models is one way of solving such problems.

The most frequent stochastic models in use are Markovian class models of stochastic stream flow simulations preserving the lower order moments (mean, standard deviations, and some times skewness coefficient) and the first higher order autocorrelation coefficients. As described in section 7.4.1, the standardized series is best described by AR (1) model which is classed as Markovian model and it is presented as:

$$X_t = \phi_1(X_{t-1} - \mu) + \sigma_x(1 - \phi_1^2)^{\frac{1}{2}} \xi_t \dots\dots\dots (7.12)$$

Where:

X_t is the generated series;

ϕ_1 is lag-1 autocorrelation coefficient of AR (1) model;

μ Is the mean of the standardized series;

σ_x is the standard deviation; and

ξ_t is the random component or the white noise.

The random variables (white noises) are generated using MINITAB. 200 sets of random variables are generated to generate 200 realizations. In actual practice it shall be generated as many as possible. Linsely has recommended generating 500 to 1000 realizations (Linsely, etal, 1964). The generated random variables were tested for normalization, (mean zero and Standard deviations 1). The mean and the standard variations are not exactly 0 and 1 as the theory says. The mean varies between -0, 0228 to 0.0704 and the standard deviation b/n 0.94 to 1.012. The white noises were, therefore, standardized before used for generation purposes. After standardization the mean and the standard deviation have been reduced to exactly 0 and 1 respectively for all sets.

While generating the synthetic flow series the process of de-standardization has been taken care-off. The antilog values were also processed to offset the effect of transformation.

7.5.3 Testing of the Generated Data

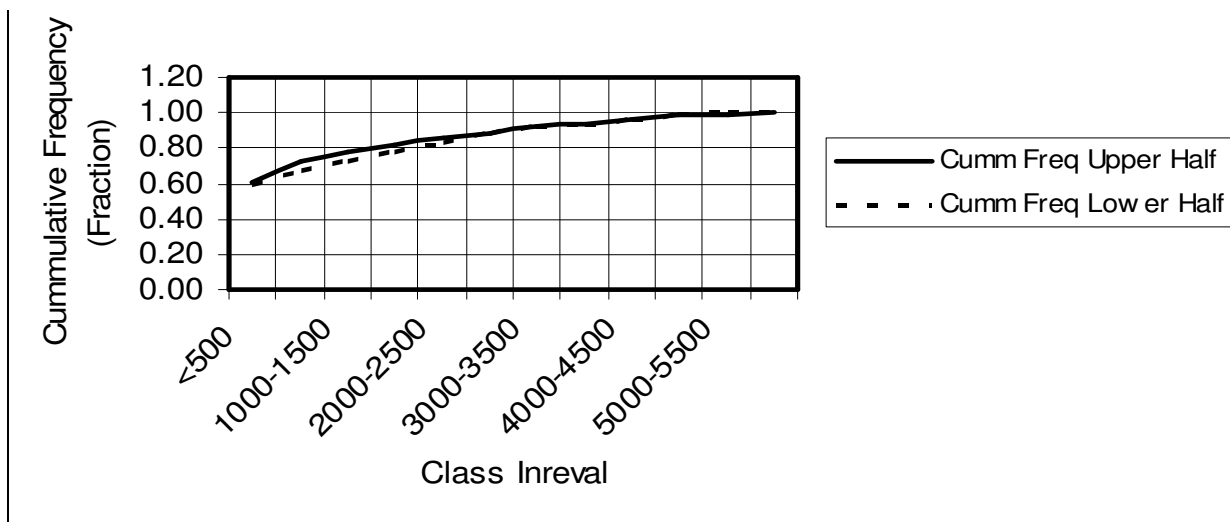
To test whether the generated data are represented by the historic data or not; a comparative study between the annual and monthly means, standard deviations, skewness coefficient, the monthly serial correlations and the high & low flows of historic and generated data and for a long record (recorded for longer than 25 years), between the first half of the historical record and the generated data from the second half of the historical record and the data generated from the first half of the historical record was suggested by HAMLIN (1971) and found to be a very power full test for data generated from a long period of historical data (Yoganarasimhan G.N., Dec 20-22, 1980).

Before testing the generated data the quality of historical record is checked for stationarity. Historical data is first divided into two equal parts (from 1964 to 1983 as first half and from 1984 to 2003 as the

second half) and the cumulative distribution function for each part is computed and compared. Fig 7.8 shows this graph using the output of an EXCEL operating system. The cumulative frequency curve is observed lying collinear to each other, indicating that the two components are from the same population and there is no significant change in the historical data thus providing there exists stationarity in the historic series.

Comparison between the Historic and Generated Series: Initially, ten realizations having equal length with the historic series is generated to test that the AR (p) model represents the process of the historical series. The mean, the standard deviations, skewness coefficients, first lag serial correlation coefficients, Maximum and Minimum inflows were computed for the historical and the generated (ten realizations) series and this result is presented in table 7.1 below. The results show good agreement except for the skewness coefficient which shows significant change, and in general it is observed that the process of the historical series is represented by the AR (1) model.

Figure 7-8 Cumulative Frequency Curve for Upper & Lower Half Series of Historic Series



The seasonal parameters for both historic and generated series has been compared as indicated in Fig 7.9 though Fig 7.11 below. From these Figures it is observed that seasonality in the mean and standard deviation for the generated and historical series shows similar pattern indicating that these statistical parameters are also preserved in the process of data generation. The skewness has indicated significant variations (Fig 7.11) owing to the reason that AR (p) models are weak in preserving third moment statistical parameters like skewness of the historic series. In general the comparison made has demonstrated that there exists good agreement of statistical parameters, both monthly and annually,

between the historic and generated series and from this it can be fairly concluded that the generated series reasonably represents the same population as that of the historical series. From this conclusion a total of 200 realizations having equal length of time as that of the historical series have been generated to be used as an input for reservoir operation through simulation.

Figure 7-9 Comparing Seasonal Distribution of Means of Historic & Generated Series

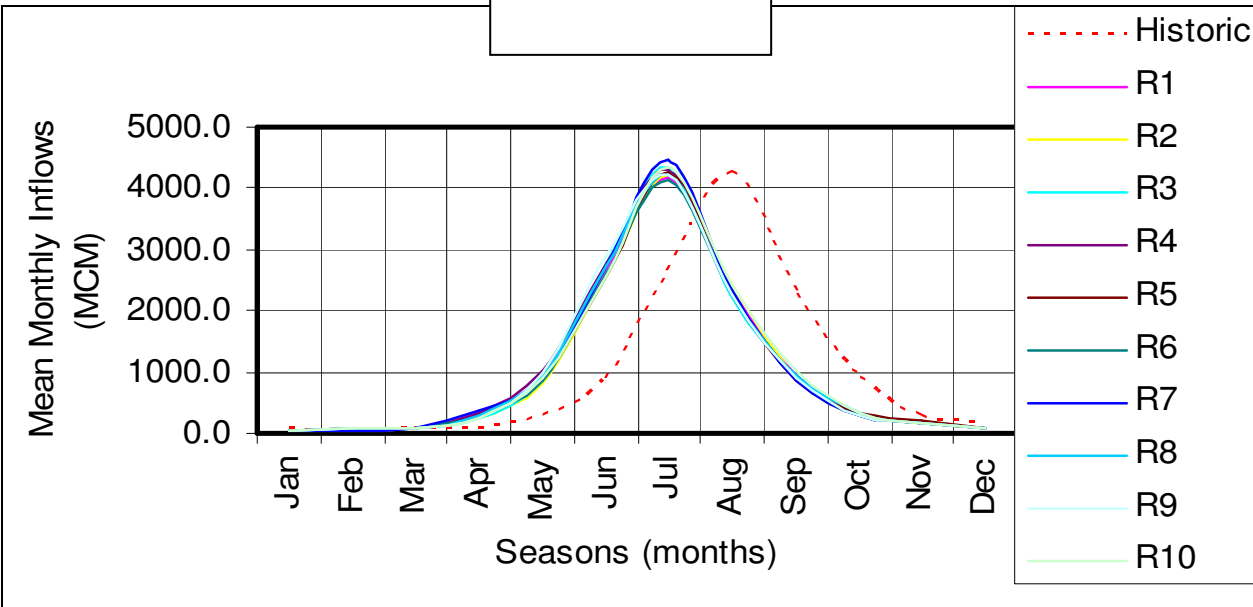


Figure 7-10 Comparing the Seasonal Distribution of the STDEV of Historic Vs Generated Series

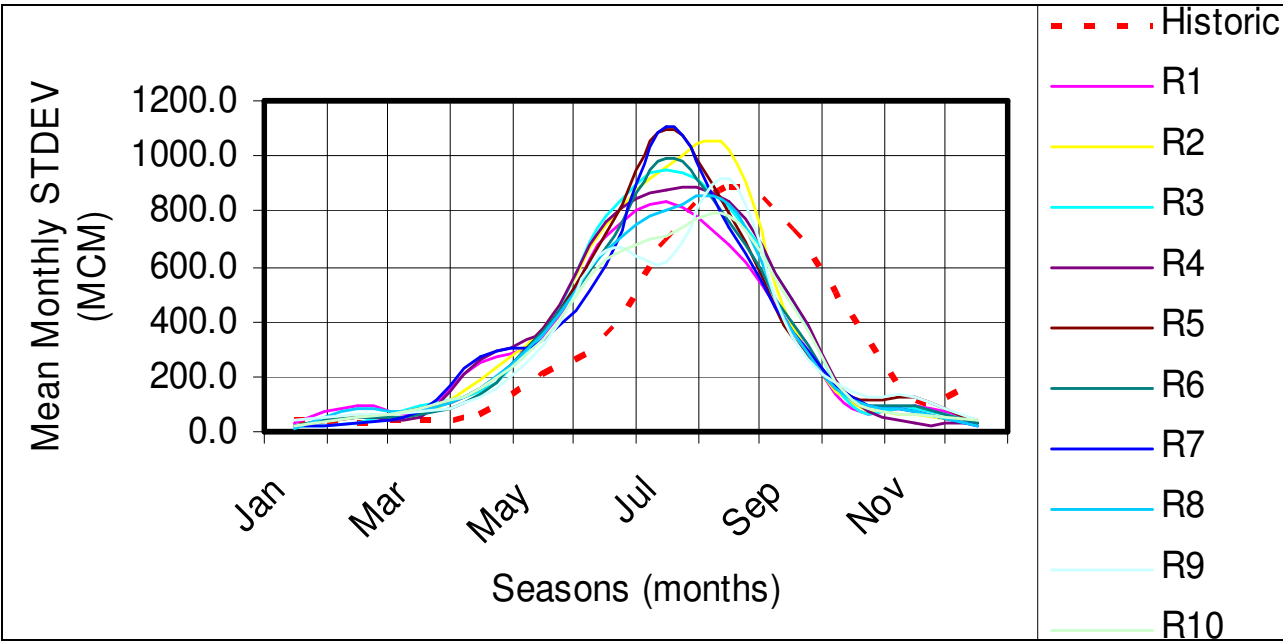
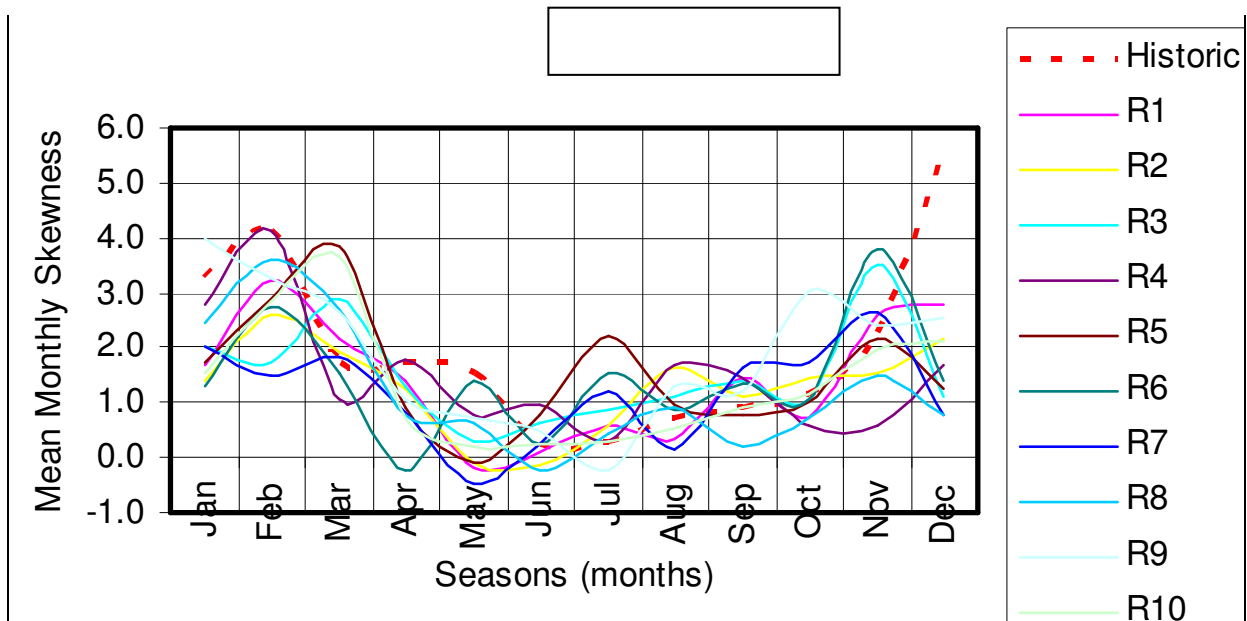


Table 7-1 Comparison between the Historical and the Ten Generated Series

Realization	r_1	Mean	STDV	Skewness Coefficient	Max Inflow (MCM)	Min Inflow (MCM)
Historical	0.67	12051.5	2387.9	0.36	18270.1	7813.2
1	0.68	1258.9	1987.4	0.18	16180.0	7487.0
2	0.67	11932.5	2515.5	0.70	17480.9	8036.2
3	0.65	12116.4	2149.1	0.40	16697.8	7276.7
4	0.67	12370.2	2128.4	0.88	18656.7	9129.9
5	0.65	11937.7	2070.6	0.46	16927.5	7486.4
6	0.66	11879.3	1832.8	0.40	16074.3	8759.9
7	0.66	12418.9	2334.3	0.39	17545.9	7289.7
8	0.67	12179.5	1799.9	0.68	17709.5	9157.6
9	0.68	12267.6	1713.6	0.12	15441.2	9176.2
10	0.66	12269.7	1572.2	0.44	16746.4	9498.0

Figure 7-11 Comparing Seasonal Distribution of Skewness: Historic Vs Generated Series



7.6 Mass Balance Equation and Components for Lake Tana Reservoir

7.6.1 Mass Balance Equation

The mass balance equation developed for the Lake Tana reservoir operation has the general form of:

$$\Delta S = Q_i - E - D - S_p - Q_o \dots\dots\dots (7.13)$$

Where:

ΔS = Change in storage in the reservoir system;

Q_i = Reservoir inflow including direct runoff on the water body of the reservoir;

E = Lake Evaporation;

D = Demand/Abstraction from the reservoir that includes abstractions for irrigated agriculture & hydropower development works and minimum downstream release requirements to maintain the Tis Esat fall;

S_p = Net Ground water flow from and/or to the reservoir system; and

Q_o = Spillage from the reservoir system through the spillway crest of the Chara-Chara weir.

The recursive equation for the above mass balance equation is presented as:

$$S_t = S_{t-1} + Q_{it} - L_t - D_t - Q_{ot} \dots\dots\dots (7.14)$$

Where:

S_{t-1} = Reservoir storage at the previous month (MCM);

S_t = Reservoir storage by the current month (MCM);

Q_{it} = Reservoir Inflow including direct runoff at the water body by the current month (MCM);

L_t = Loss from the reservoir system at the current month (MCM);

$$= E_t + S_{pt}$$

E_t = Evaporation from the reservoir water body by the current month (MCM);

S_{pt} = Unaccounted component in the water balance of the reservoir system, which can be resulted from Groundwater flow in the reservoir system and from model applications by the current month (MCM);

$$D_t = D_t(I) + D_t(Hp) + D_t(Tr);$$

$D_t(I)$ = Abstractions from the reservoir for the development of Irrigated agriculture by the current month (MCM);

$D_t(Hp)$ = Abstraction from the reservoir for the development of hydropower by the current month (MCM);

$D_i(Tr)$ = Minimum d/s release requirement to maintain the *Tis Esat* fall by the current month (MCM); and

Q_{ot} = Spillage over the crest of the Chara-Chara spillway by the current month (MCM)

7.6.2 Components of the Mass Balance Equation

Current development activities in the Tana basin are limited to be hydropower development and transport facilities including tourism activities. The *Tis Esat* hydropower development work located d/s of the Chara-Chara weir (regulating weir) is the only development work implemented in the basin so far. Further more, Tana is being utilized as a transport means b/n Gondar and Bahir Dar and the *Tis Esat* fall located adjacent to the hydropower is used as a truism attraction in the area. The water resources available in the Tana reservoir has been planed,(BCEOM & associates,1999) for considerable size of large scale water resources development works that constitutes both irrigation and hydropower development works.

The mass balance equation for the reservoir system is thus designed to constitute the water balance components as described in section 6.3 and the demand which constitutes the irrigation water requirements for planned irrigated agriculture development works, release for hydropower generation purposes both for currently operated plant and planned hydropower development works and safe down stream releases for the Tis Esat fall that will maintain truism attractions in the area. These components are described below while the water balance components are not described here to illuminate repetitions.

i) Irrigation Water Requirements: Concerning the development of large scale irrigated agriculture, the recently performed Integrated River Master Plan Studies for Abbay River (BCEOM and associates, 1999) has sub divided the Tana basin in nine sub basins and identified considerable number of projects to be implemented in the master plan planning horizon which is fixed to be 50-Years. The master plan has developed three scenarios (section 3.4) and allocated possible development potential in each scenario. The development potential in each scenario as presented in the master plan has been used as a demand for irrigated agriculture development works in the basin. These development potentials in their respective scenario are presented in section 3.0 table 3.2. The reader is advised to refer this section to illuminate repetitions.

In the recently performed master plan studies for Abbay River (BCEOM and associates, 1999) it is reported that in the Abbay basin as a whole, cropping patterns were developed by selecting 25 crops. Based on the preliminary investigation of the soil, land topography and local climate, seven different cropping patterns were proposed during the master plan studies. Out of these seven, four of them were designed to be representative for the Tana and Tana-Beles sub basins and these are enumerated here for reference purposes (BCEOM & associates, 1999):

CROPPAT1- this cropping pattern is assumed to be the representative for Lake Tana Basin, with maize, wheat, barley and sugarcane as major irrigated crops;

CROPPAT2- designed to represent future development cropping patterns in the lower Beles and Northwest Basins dominated with cotton and maize during the wet season and maize, sunflower, sugarcane and soybean during the dry season;

CROPPAT3- this is for projects in the upper Beles with sugarcane as a dominant crop; and

CROPPAT6-which assumed to be representative for rice projects in Lake Tana basin with rice as major crop covering 60% of the command area during the wet and dry seasons.

Kc values for each crop selected was fixed using Doorenbos and Pruitt methods as presented in FAO Drainage papers (FAO 24 and 33). In designing the cropping pattern a maximum of 100% cropping intensities during the rainy season and 80% during the dry season was considered and in the report it is further indicated that higher intensities are not realistic. The period from May to October (inclusive) is considered as wet period and November to April (inclusive) as dry period while designing the cropping pattern in the master plan studies of the Abbay river (Phase-3 Vol-1, Appendix to Main report part I, Irrigation)..

ET₀ is computed using the FAO cowpat program version 5.7, which employees the Penman-Montieth modified equation as recommended by the FAO expert consultation held in 1990. Effective rainfall has been computed using the USBR methodology at 80% dependable rainfall. The report further indicates that other methods for effective rainfall (USDA, Regionally developed proportion constants etc,) evaluation gives higher values, the reason why the USBR method is

selected for the computation of the effective rainfall in the basin (Phase-3 Vol-1, Appendix to Main report part I, Irrigation)..

Irrigation efficiencies were applied while estimating irrigation water requirements. Projects largely based on vertisol conveyed with unlined canals are assumed to have 60% over all project efficiency, those in permeable soils with lined canals 50% and those with permeable soils and unlined canals 40% (Phase-3 Vol-1, Appendix to Main report part I, Irrigation).

Irrigation water requirements and canal capacities were fixed based on the crop/irrigation water requirements developed assuming the above basic situations. Irrigation water requirements for each cropping pattern group were computed on a monthly basis and these Figures were used in this thesis for the purpose of reservoir operation.

ii) Hydropower Development Works: - Excluding micro level hydropower generation works; two major plants are located in the Tana-Beles hydro-system, the *Tis Abbay I & II* and the Tana-Beles hydropower development plants. The Tis Abbay hydropower plants are developed in two phases, the first phase known as *Tis Abbay-I* hydropower development plant is installed in Jan, 1964 following the Blue Nile master plan study by the USBR. The second phase, named as Tis Abbay –II is commissioned in Feb 2001 after 36 years of the first phase implementation. These two plants have a total installed capacity of 84MW (Tis Esat I 12MW and Tis Esat II 72MW) at a rated discharge of 29m³/s and 150m³/s respectively.

The Tana-Beles hydropower development plant as studied by LI (Aug 2003) at feasibility level is estimated to have an installed capacity of 220MW at a rated flow of 80m³/s. The discharge that will be utilized for hydropower generations at this plant is directly abstracted from the Lake Tana reservoir.

iii) The Tis Esat Fall: - The Tis Esat fall, literally known as “*water that smokes*” is one of the major tourism attraction in the country. Various environmental studies conducted so far in the basin and especially the environment studies conducted as a component for the detail design works of the *Tis Abbay-II* hydropower development work has recommended a minimum safe d/s release of 35m³/s to preserve the Tis Esat fall for tourism attraction.

The proposed and identified projects in the Tana Basin together with Beles basin are indicated in Fig 7.12 below.

7.7 Development Scenarios

The Abbay River Basin Integrated Development Master Plan Project (BCEOM and associates, 1999) has developed three scenarios for the development of irrigated agriculture in the whole basin of the Abbay River (BCEOM & associates, 1999). These three scenarios are developed giving due emphasis to the involvement of the public and private sectors in the development of irrigated agriculture in the basin. These development scenarios are summarized and presented in section 3.4 for reference purposes.

Scenario Selection: - After looking in to these alternative scenarios, the researcher has identified four similar scenarios with little modifications. Scenario-3, which considers all available land and water potentials in the basin, does not seem feasible as it would be limited with information and/or data. The Three scenarios designed as Bb, Bbac and Scenario-2 (or C) seems to be more realistic and considered as preferred scenarios for this thesis work. The rearranged scenarios are described as:

Scenario-1 This is designated as “*the do nothing scenario*”, which signifies the existing situation of the Tana basin. In this scenario the development of two existing hydropower plants (Tis Abbay I and I) and the minimum downstream release for Tourism requirement of the Tis Esat fall are considered. According to the environment component study of Tis Abbay-II, minimum d/s release of 35m³/s is required to maintain the tourism requirement of the Tis Esat fall. The two hydropower stations are designed at a rated flow of 29 and 150m³/s respectively. To develop a dependable power of 12MW and 68MW these two hydropower plant requires a rated flow of 29 and 140m³/s respectively.

Scenario-2 – The second scenario is designated as Bb scenario (the conservative scenario) in the master plan (BCEOM, & associates, 1999) which deals with projects studied at feasibility and pre-feasibility level exclusively. In this scenario, for the master plan planning period, a total of 114056ha of land will be developed under irrigation and the two hydropower plants, the Tis Abbay I & II and the Beles 1515 hydropower plant. A total of 79056ha is planned to be developed in the

Tana basin and 35000ha in the Beles basin. In this scenario emphasis is given for the Tana basin and the Tis Abbay I & II hydropower plants are thought to be operated at full scale while the development scale of the Beles 1515 hydropower plant is totally dependent on the size of the irrigation demand planned in the envisaged scenario. This scenario also includes the minimum release for the Tis Esat fall to maintain the tourism requirements.

Scenario-3 – This scenario, designated as an accelerated scenario-Bbac, (BCEOM & associates, 1999) is planned to develop 176163ha of land under irrigation of which 87163ha in the Tana Basin and 89000ha in the Beles basin. The Tis Abbay and the Beles hydropower plants are also included in this scenario. The size of the Beles hydropower plant is planned to get a release of $64\text{m}^3/\text{s}$ (based on the demand of irrigation d/s) and the Tis Abbay I & II planned to abstract $94\text{m}^3/\text{s}$. At these flow rates the Beles and Tis Abbay (I&II) hydropower plants are expected to have an installed capacity of 224MW and 45MW respectively. More over the minimum release for the Tis Esat fall that maintains the tourism requirement is also included in this scenario. The planning in this scenario is made based on the assumption that the private sector will play the dominant role in the development of the sector in the basin.

Scenario – 4 – This scenario includes the development of all identified projects in the Tana-Beles basin. The total development area is estimated to be 268081ha and two hydropower plants, the Tis Abbay and the Beles hydropower projects. The development area in the Tana Basin is thought to be 145081ha and in the Beles basin 123000ha. In this scenario the two hydropower plants are planned to operate at $97\text{m}^3/\text{s}$ for Beles and $94\text{m}^3/\text{s}$ for Tis Abbay I & II. At this flow rate the Beles hydropower plant will have an installed capacity of 340MW and the Tis Abbay I & II will have 45MW. The minimum release for Tis Esat fall is also considered in this scenario. This scenario assumes both the private and the public sector plays the dominant role in the development of the water sector in the Tana-Beles basin.

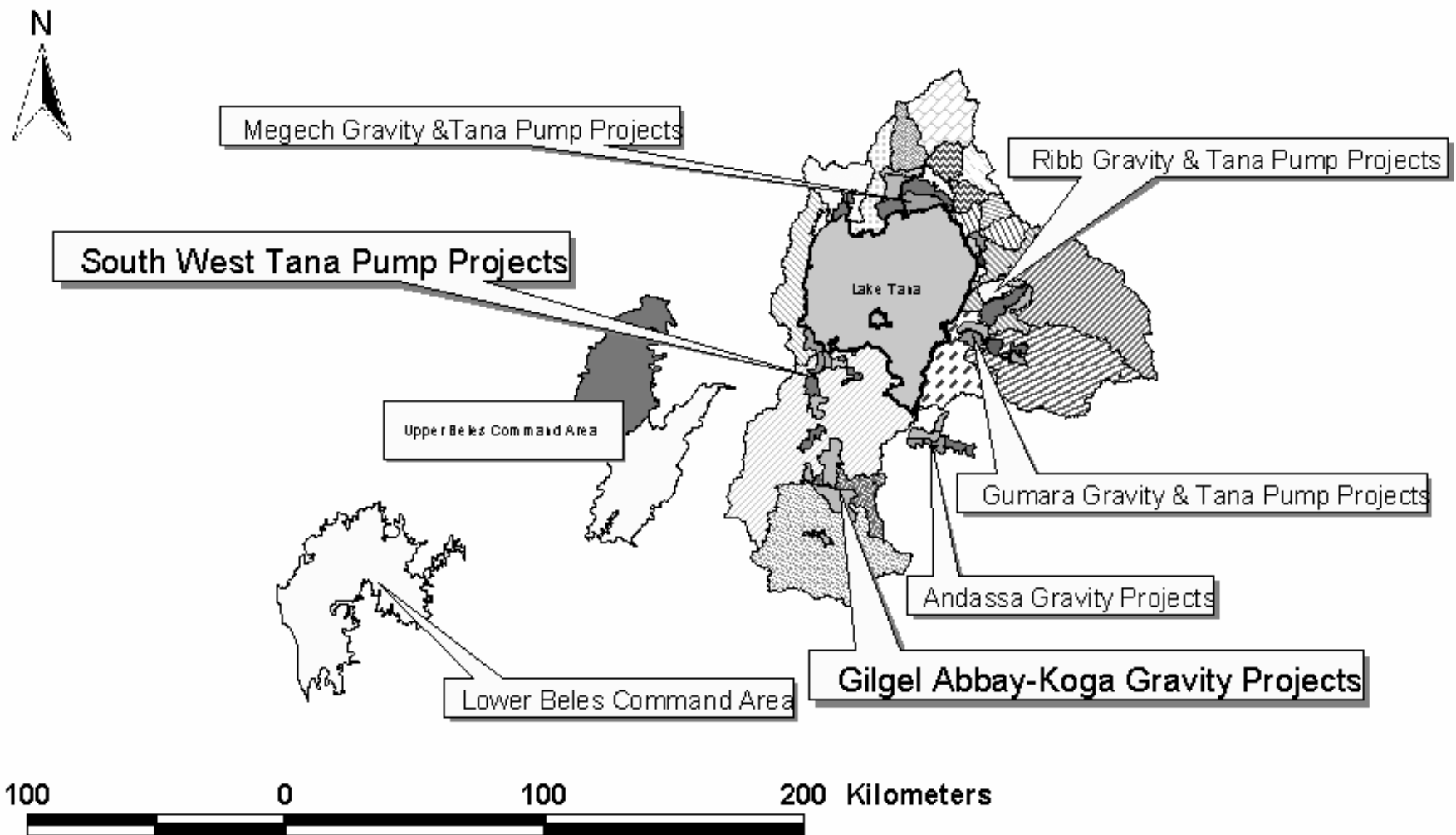


Figure 7-12 Identified Projects in the Tana and Beles Basins

Scenarios 1-4 are those scenarios thought in the recently developed master plan project (BCEOM & associates, 1999). These scenarios are brought here to test that the associated demands are possibly met by the existing reservoir capacity of Lake Tana.

The research work has defined three scenarios after running the reservoir operation for the above mentioned scenarios. These three scenarios are designated to be scenario-5, 6 and 7.

Scenario-5: - This scenario disregards development works in the Beles basin. It is planned to develop the whole potential development area, 145081ha of land, in the upstream reaches of the Tana reservoir and keep sustaining the development of the Tis Abbay I & II hydropower plants and the Tis Esat fall.

Scenario-6: - This Scenario disregards most of the irrigated agriculture development works in the upstream reaches of the Tana reservoir and provokes full development of the Beles 1515 hydropower plant. The plan is to develop 123000ha and the Beles 1515 hydropower plant in the Beles hydropower and any size development in the Tana basin maintaining the Tis Esat fall.

Scenario-7: - This scenario assumes what possible development work could be possible if the Chara-Chara weir was constructed for a spill way level of 1787.5masl, an additional 0.50m height from the present. The development first tests whether it could have been possible to develop all the development potentials both in the Beles and Tana basins by raising the Chara-Chara weir for 0.50m.

7.8 Results of Reservoir Operation at Lake Tana

The Lake Tana reservoir operation has been implemented applying simulation techniques based on equation 7.9 and its recursive formula, equation 7.10. Reservoir operation was simulated for both historic and generated series. Even though 200 realizations are generated reservoir operation is simulated for 50 realizations and one historic series. Time is the limiting factor not to simulate the operation with all generated series.

Scenario-1: - The result for reservoir operation made under “the do nothing scenario” has indicated that the current reservoir capacity of Lake Tana can release a flow rate of 95m³/s to Tis Abbay I & II hydropower plants and the minimum requirement for Tis Esat fall at 95% of reliability. The schedule of release for Tis Esat fall is presented in the next section where the operation rule is dealt.

Under this scenario the current operation rule has been tested and it is found that the second alternative is achieved at 95% reliability. As per to the given operation rule the reservoir has never failed. The operation rule indicates that the water resources in the reservoir is operated safe until the reservoir level reaches its minimum operating level, which is fixed to be 1784. However, the Tana transport has reported that ship navigation was not possible from April to mid of July in 2002/2003 due to the unusual fall of Lake Level. While investigating the lake level for that particular period the minimum lake level reached was recorded as 1784.50, which is 0.50m above its minimum operating level. The reason behind is not because of the failure of the reservoir, it is because the ships of the transport section are unable to float in some reaches of the reservoir perhaps due to outcropped rocks/hills available in the reservoir. Proper selection of deepest routes and/or changing the ships type into easily floating ships might be the possible solutions.

Scenario 2-4: - These scenarios are proposed by the recently developed master plan studies of Abbay River basin (BCEOM and associates, 1999). These were tested for their sustainability in terms of the adequacy of the water resources available in the Tana reservoir.

The operation result under the condition of these scenarios indicates that the demand for all of them can not be met by the current reservoir capacity of the Lake. The demands from these scenarios were observed in both the historic and generated series and failures are observed in both cases.

In the case of scenario-2 failure of 84% is observed. This failure is observed increasing to 92% and 95% for the cases of scen-3 and scen-4 respectively. This indicates that the development plan set in the master plan studies as scen2 to 4 will never be realized as far as the water resources in the Lake tan reservoir is concerned.

Scenario-5: - This scenario together with scen-6 & 7 are developed during this research work. Reservoir operation under the case of scenario-5 indicates that at 95% of reliability a development

of 72541ha in the upstream reaches of the Lake Tana reservoir are possible with a constant release of 86.5m³/s to Tis Abbay I and II hydropower plants and the minimum release requirement to Tis Esat fall as indicated in section 8.2 below. Operating the reservoir under this condition we will be benefited by generating a firm energy of 290GWH/year (equivalent to installed capacity of 42MW) from the Tis Abbay I & II hydropower plants, which is only 50% of the current installed capacity of the reservoir. The maximum possible rate of flow achievable at 95% reliability is observed to be 95m³/s which can produce a firm energy of 320GWH/year, equivalent to 55% of the currently installed capacity. Lake Tana operated under this condition would also benefit 145082 families (0.5ha/family), which is equivalent to 740,000 populations at 5.1persons/family. This account's 25% of the basins population (refer to section2.4.2 of this paper).

Scenario-6: - If the reservoir of Lake Tana is to be operated under the conditions of this scenario, at 95% reliability, the would be achievable benefits include: the development of 110700ha of irrigated land in the Beles basin and the development of the Beles 1515 hydropower plant at a rated flow of 87m³/s, which is equivalent to an installed capacity of 306MW and production of a firm annual energy of 2145GWH at a plant factor of 0.80. Operating under this scenario also allows developing 23213ha of irrigated land in the upstream reaches of the Tana reservoir and meeting the minimum requirements of the Tis Esat fall under the operation rule indicated in section 8.2. This would increase the total development area to 133913ha, which would benefit 267826 families (at similar rate as for scen-5) and a total population of 1,365910, that accounts 45% of the population in the Tana basin.

Scenario-7: - Under this scenario development plan is thought in both the Tana and Beles basins. If the reservoir is operated under the conditions of this scenario, at 95% reliability the would be benefits include:

- The development of 112278ha of land under irrigation (50778ha in the upstream reaches of the Tana reservoir and 61500ha in the Beles basin. This benefits 224556 families in both the Tana and Beles basins which is equivalent to a population of 1,145240 that accounts nearly 40% of the population in the Tana basin;

- The development of Beles 1515 hydropower plant at a rated release of 49m³/s which is equivalent to an installed capacity of 170MW and the production of a firm annual energy of 1190GWH at 0.8 plant capacity;
- The development of Tis Abbay I & II hydropower plants at a rated release of 41m³/s, equivalent to an installed capacity of 20MW and a firm annual energy production of 137GWH at 0.8 plant factor; and
- Meeting the minimum requirements of Tis Esat fall at an operation schedule as specified in section 8.2 below.

Remarks: - From the outset it seems that scen-6 is the preferred scenario as it could produce a firm energy of 2145GWH/annum at 0.8 plant capacity and 95% reliability and supports 50% of the population in the Tana basin if settled in the Beles basin, or can support a population equivalent to 50% of the Tana basin transferred from drought affected areas in the country. It also meets the minimum requirements of the Tis Esat fall at 95% reliability, the release schedule as specified in section 8.2 below.

Looking at scenario-7, it seems to be the second attractive scenario developed in this research work. It develops a firm energy of 1327GWH per annum at 0.8 plant factor production distributed in both the Tana and Beles basins. It also supports a population equivalent to 40% of the population in the Tana basin. More specifically it would support a population equivalent to 22% of the Tana basin as a settlement in the Beles basin by developing a total area of 61500ha in the Beles basin and for 18% of the population in the Tana basin by developing a total of 50778ha in the upstream reaches of the Tana reservoir. It also meets minimum requirements of the Tis Esat fall at an operation schedule specified in section 8.2 below. This scenario has one more advantage. It provides a minimum firm release of more than 45m³/s for any future d/s development considerations in the course of the Abbay River.

In conclusion it is hard to decide which scenario is most beneficial out of these three in general and out of scen-6 and 7 in particular. There are a number of issues which are not treated in this research work. For instance, each resource in each basin has to be initially optimized and optimum level of

combinations for each component within each target shall be investigated. Optimum combination for suggested cropping patterns under the various development constraints shall be investigated. The social factors and environmental requirements along with d/s benefits shall be investigated thoroughly before reaching the selection of optimum development scenario. Thus this reservoir operation attempt has to be supported with optimization techniques to select the optimum development scenario.

8. ESTABLISHING OPERATION RULE FOR CHARA- CHARA REGULATION WEIR

8.1 Introduction

Water is a basic prerequisite for life and development. Good administration, protection, and exploitation of water resources are needed especially due to population growth and increasing water demand (Lene Dyrbak, July 2000).

Optimal development of water resources is conditional on the establishment of appropriate operating policies. By *operating policy*, we understand a time schedule of releases from reservoirs, of pumpages from aquifers and/or reservoirs, and of aquifer recharge operations. At any rate, the establishment of such schedules, which indicate quantities of water to be affected through the action of the manager at defined points in time, is an important problem in water resources engineering (Nathan Buras, 1975).

The establishment of guideposts for the operation of storage facilities is one of the crucial problems to be solved in water resources engineering. It is, in fact an effort to overcome the discrepancy so often observed between the desirable amounts of water at a certain point in time and the naturally available quantities at the same point. The operating rules then become indicators for the decisions connected with keeping water in storage or releasing it (Nathan Buras, 1975).

In order to derive an optimal procedure for the operation of water resources system, usually three avenues are open: (a) application of analytical techniques; (b) use of simulation, as in the case of this research work; and (c) a combination of these two methods (Nathan Buras, 1975).

In the case of the Tana reservoir, simulation techniques are used to run reservoir operations and to fix operation rules. The reservoir storage of Lake Tana is designed to operate between the maximum flood level fixed at 1787.5masl and the minimum operating level fixed at 1784masl. The crest level of the regulating weir is fixed at 1787masl, in which any water in the reservoir above this level is subject for loss through spillage. The principal objective of reservoir operation in the Lake Tana is thus, to minimize the spillage and use this water to meet the demands coming from different

development objectives such as hydropower and irrigation and also to meet the minimum requirements of the Tis Esat fall located down stream of the regulating weir. It is, therefore, evident that the reservoir of the lake has to be operated in such a way that water surface level of the lake shall not be less than the minimum operating level, 1784masl. It shall also avoid high water surface levels such as above 1787.5masl in order to reduce flooding in the surrounding flood plains. The operation rule curves shall be established taking these constraints in to consideration meeting the demands coming from the development objectives and minimum requirements of the Tis Esat fall.

Moreover, operation rules for anticipated development scenarios are performed considering two conditions, the average and the worst inflow conditions represented by the historic inflow and the R2 generated series. R2 stands for realization-2 or the second generated series out of the 200 generated series. These two series are selected after the reservoir operation is run for the first 51 series including the historic series. The operation result has indicated that operating the reservoir at the historic series provides an average conditions while at R2, the maximum failure (as high as 78%) has been observed, in which demands were kept similar in both conditions while effecting the reservoir operation.

8.2 Construction of Operation Rule Curve

8.2.1 Average Conditions (Historic Inflow Series)

Operation rule curves are established for four scenarios, the existing situation denoted as the do nothing scenario, scenario-5, 6 and 7, in which their details are presented in the preceding sections.

8.2.1.1 Operation Rule Curve for Scenario-1: (The Do Nothing Scenario)

This operation rule is similar to the current operation rule except minor adjustment to the minimum requirements of the Tis Esat fall to increase the reliability of the reservoir operation meeting the stated demands. The existing operating policy is set to release minimum requirements of Tis Esat fall (section 5.3.1.2, table 2.7) for 10hrs a day (e.g. from 8:30am to 6:30pm) and the minimum $3\text{m}^3/\text{s}$ during the remaining 14hours. Operating the reservoir guarantees an average supply of $94\text{m}^3/\text{s}$ to Tis Abbay I & II hydropower plants at 95% reliability (Humphrey & associates, 1996).

In this research work the release schedule is revised in such a way that the minimum requirement is adjusted as indicated in table 8.1 below assuming that any release to Tis Esat above $35\text{m}^3/\text{s}$ (the minimum inflow set from environment studies during feasibility study and detail design works of Tis Abbay II hydropower plant (Humphrey & associates, 1996)) can satisfy the requirement of Tis Esat fall and increasing this release to $50\text{m}^3/\text{s}$ during the months of December and January in which truisms activity is at its peak stage. Further more an adjustment is made in such a way that the $3\text{m}^3/\text{s}$ release shall be operated for 10hours a day only; assuming environmental requirement d/s of the fall for the remaining 14hours could be satisfied by the water released from Andasa River and from the two hydropower plants after energy is generated. This can be achieved by doing regulations both at Chara-Chara weir and at Tis Esat off-take structure. Operating the reservoir using this regulation would guarantee an average firm release of $100\text{m}^3/\text{s}$ for Tis Abbay I & II hydropower plants at Chara-Chara weir and an annual average inflow of $119\text{m}^3/\text{s}$ at the Tis Esat off-take structure both at 95% reliability. Similarly the Tis Esat fall will have an inflow scheduled as indicated in table 8.1 below both at Chara-Chara weir and Tis Esat off-take structure at 95% reliability. This adjustment has improved the current firm inflow to the hydropower plants by $6\text{m}^3/\text{s}$ for the same reliability.

Under this scenario, a firm power of 59MW with the corresponding mean annual firm energy of 411GWH is achieved. Regulating the release at the Tis Esat off-take the power is raised to 74MW and the corresponding mean annual energy is raised to 518GWH. Current operation yields an average firm power of 40MW and mean annual energy of 455GWH. Graphical representation of this operation rule is indicated in Fig 8.1 below.

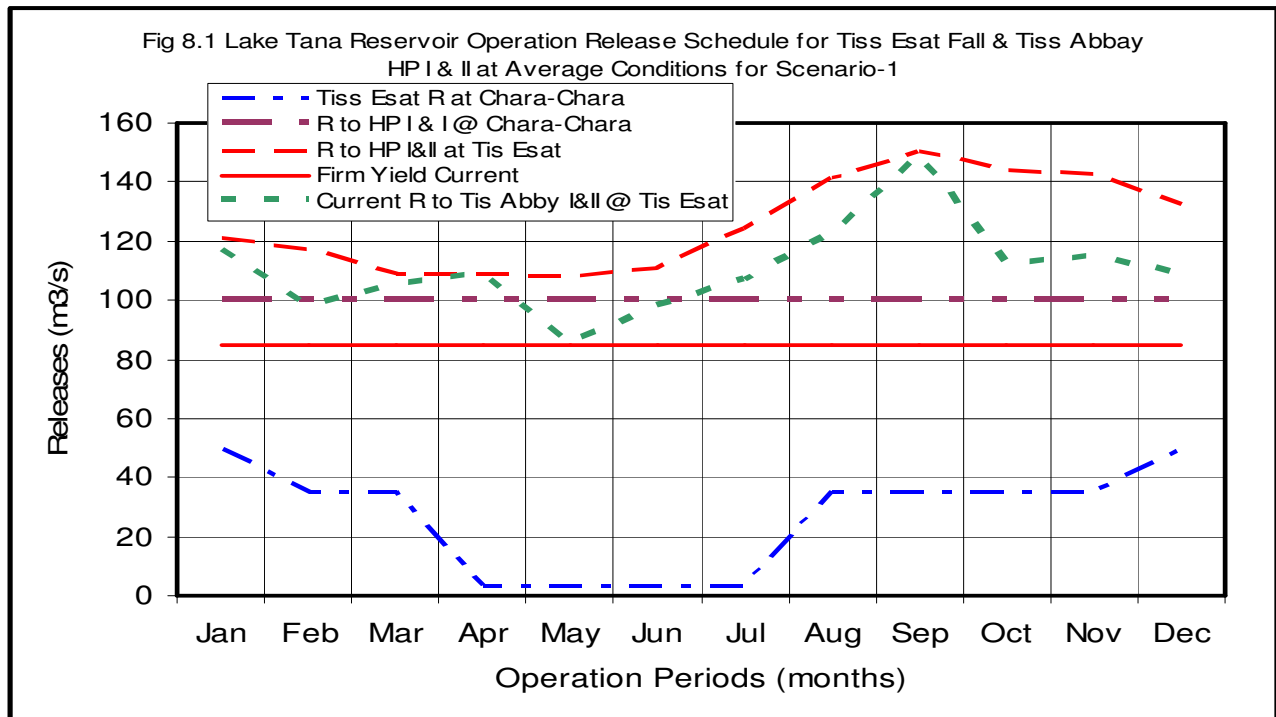
Under this scenario mean annual regulated outflow at Chara-Chara weir is summed up to be 4070MCM while mean annual natural outflow is recorded to be 3735MCM indicating that there is imbalance in the system. While operating in its natural state before commissioning the Chara-Chara weir, the minimum Lake level is observed to be largely above 1785masl. After commissioning the Chara-Chara weir the minimum Lake Level is set at 1784. The imbalance observed between the regulated and natural outflows (335MCM) is, therefore, expected to come from lake storage below 1785masl and also from the storage below 1784masl, which operates during failure periods because the reservoir is subjected to operate at 95% of reliability only. In case of the 5% failures the reservoir

is forced to operate below 1784masl. It shall be noted that the bed level of the regulating gates at Chara-Chara weir are set at 1782.5masl.

Table 8-1 Adjusted Operation Rule for Existing Situation (Average Conditions Considered)

Months	Min Tis Esat R at Chara-Chara (m ³ /s)	R to HP I & I at Chara-Chara (m ³ /s)	R to HP I & II at Tis Esat (m ³ /s)
Jan	50	100	121
Feb	35	100	117
Mar	35	100	109
Apr	3	100	109
May	3	100	109
Jun	3	100	111
Jul	3	100	124
Aug	35	100	141
Sep	35	100	151
Oct	35	100	144
Nov	35	100	143
Dec	50	100	132
Sum/Mean	27	100	126

Figure 8-1 Scen -1: Reservoir Operation Rule Curves for Tis Esat Fall and Tis Abbay HP I & II (Average Conditions)



8.2.1.2 Operation Rule at Scenario-5

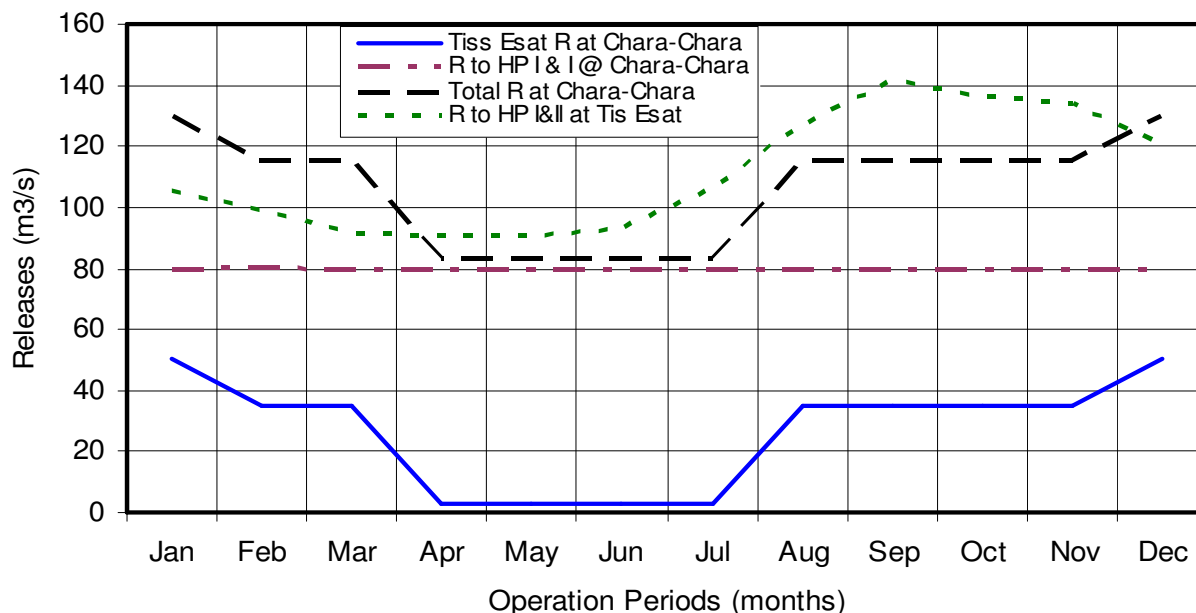
Under this scenario the minimum release to Tis Esat fall remains the same. Upstream abstractions are considered and as a result firm release to Tis Abbay I & II hydropower plants at Chara-Chara weir is reduced to 80m³/s. Regulating the outflow at Tis Esat off-taking structure, annual average firm yield of 111m³/s is achieved for Tis Abbay I&II hydropower plants at 95% reliability. The seasonality of this release is indicated in table 8.2 below. Graphical representation of this operation rule is presented in Fig 8.2 below.

Firm power of 47MW and an average annual firm energy of 329GWH is achieved at Tis Abbay I & II hydropower plants. Operating at Tis Esat off-take the firm power is raised to 65MW with the corresponding mean annual energy of 458GWH at 0.8 plant factor. Further more this scenario realized the development of a total command area of 73700ha in the Tana Basin. No development is considered in the Beles basin under this scenario. The release schedule is presented in table 8.2 and Fig 8.2 below.

Table 8-2 Release Schedule at Scenario-5 (Average Conditions Considered)

Months	Min Tis Esat R at Chara-Chara (m3/s)	R to HP I & I at Chara-Chara (m3/s)	R to HP I & II at Tis Esat(m3/s)	Total Release at Chara-Chara(m3/s)
Jan	50	80	105	130
Feb	35	80	100	115
Mar	35	80	91	115
Apr	3	80	91	83
May	3	80	91	83
Jun	3	80	93	83
Jul	3	80	106	83
Aug	35	80	127	115
Sep	35	80	142	115
Oct	35	80	136	115
Nov	35	80	134	115
Dec	50	80	120	130
Sum/Mean	27	80	111	107

Figure 8-2 Scen-5: Reservoir Operation Rule Curves for Tis Esat Fall & Tis Abbay HP I&II (Average



Total regulated outflow at Chara-Chara weir is computed to be 4358MCM. Compared to the natural outflow there is an imbalance of 625NMCM per year and this water is drafted from the reservoir storage of the Lake available below 1785masl.

8.2.1.3 Operation Rule at Scenario-6

This scenario gives emphasis to development works in the Beles Basin. The minimum release to Tis Esat fall remains the same. Upstream abstractions are highly limited and the development of Beles 1515 hydropower plant and associated irrigated farms are considered. Allocating the minimum requirement for Tis Esat fall at Chara-Chara weir, an average release of 94m³/s at 95% reliability is achieved for Beles Hydropower and Irrigation Development works.

A firm power of 329MW with mean annual energy of 2306GWH is achieved at Beles 1515 hydropower plant. Regulating the reservoir during peak water surface level, resulted that the power is raised to 418MW and associated mean annual energy to 2927GWH. During this scenario the forced spillage and inflow from Andasa River has been regulated to flow in to the Tis Abbay I & II hydropower plants so that these two hydropower plants can be served as stand by plants. Mean annual power of 22MW with the corresponding mean annual energy of 155GWH is achieved. This adds up

to raise the power produced to be 440MW and the associated mean annual energy of 3085GWH under this scenario.

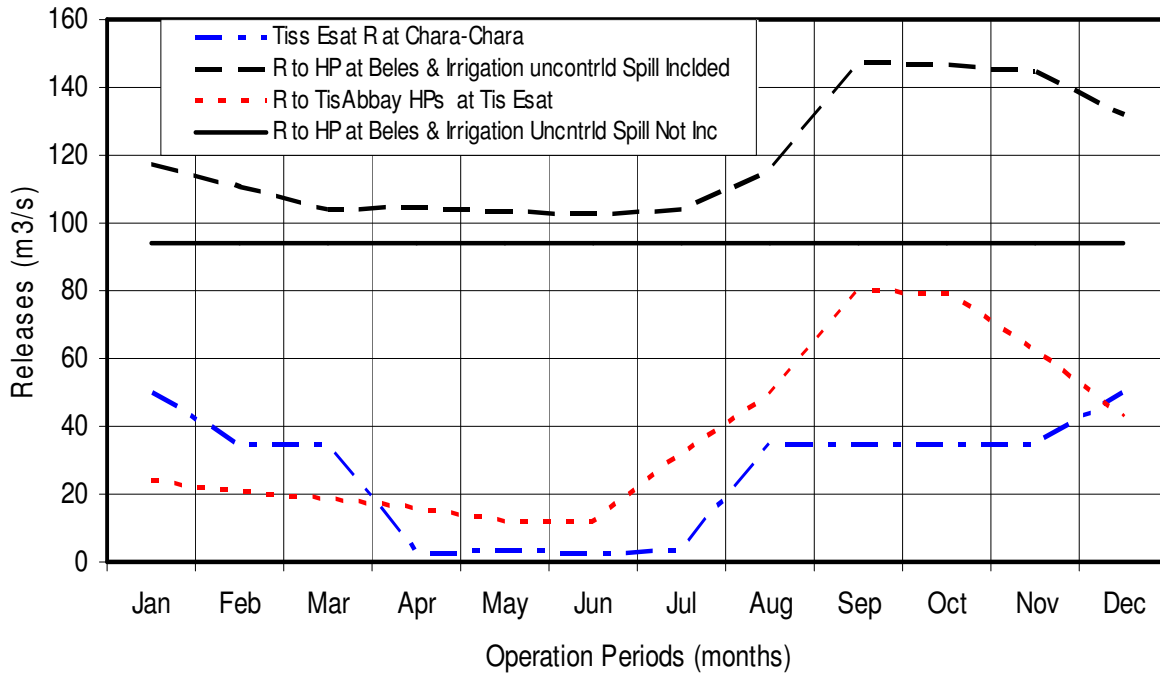
Further more a total of 133300ha would be developed of which 110700ha is in the Beles basin and 22600ha is in the Tana basin. The release schedule is indicated in table 8.3 below and its graphical representation is presented in Fig 8.3 below.

Under this scenario the imbalance that will be with drawn from the reservoir storage below 1785masl is computed to be 875MCM/ year. Total regulated outflow is estimated to be 4610MCM.

Table 8-3 Scen-6: Release Schedule (Average Conditions Considered)

Months	Min Tis Esat R at Chara-Chara(m3/s)	R to HP at Beles & Irrigation Uncontrolled Spill Included(m3/s)	R to Tis Abbay HPs at Tis Esat(m3/s)	R to HP at Beles & Irrigation Uncontrolled Spill Not Inc
Jan	50	117	24	94
Feb	35	111	21	94
Mar	35	104	19	94
Apr	3	105	16	94
May	3	103	12	94
Jun	3	102	12	94
Jul	3	104	32	94
Aug	35	115	49	94
Sep	35	147	80	94
Oct	35	146	79	94
Nov	35	145	63	94
Dec	50	132	43	94
Mean/Sum	27	119	37	94

Figure 8-3 Scen-6: Reservoir Operation Rule Curves for Tis Esat Fall & Beles HP & Irrigation Projects (Average Conditions)



8.2.1.4 Operation Rule for Scenario-7

This scenario assumes an increase of 0.50m at the crest level of the Chara-Chara weir. As a result both hydropower and irrigation development activities are planned in both basins. The minimum requirement for Tis Esat remains the same as before. Operating the reservoir under all the conditions stated in section 7.6 (scenario-7), firm yield of 50m³/s is released for Beles basin development and a firm yield of 36m³/s for Tis Abbay I & II hydropower developments at 95% reliability.

Operating the reservoir under this scenario, a firm power of 175MW and 21MW (all together 196MW) is produced at Beles and Tis Abbay hydropower plants respectively. The corresponding mean annual firm energy that will be produced at Beles & Tis Abbay hydropower plants would be 1226GWH and 148GWH respectively at a plant factor of 0.8. Regulating the reservoir during peak water surfaces for Tis Abbay hydropower plants the power produced would be raised to 37MW and the mean annual energy to 260GWH. This when added together raises the development of power in both basins to be 212MW and the energy production to be 1485GWH.

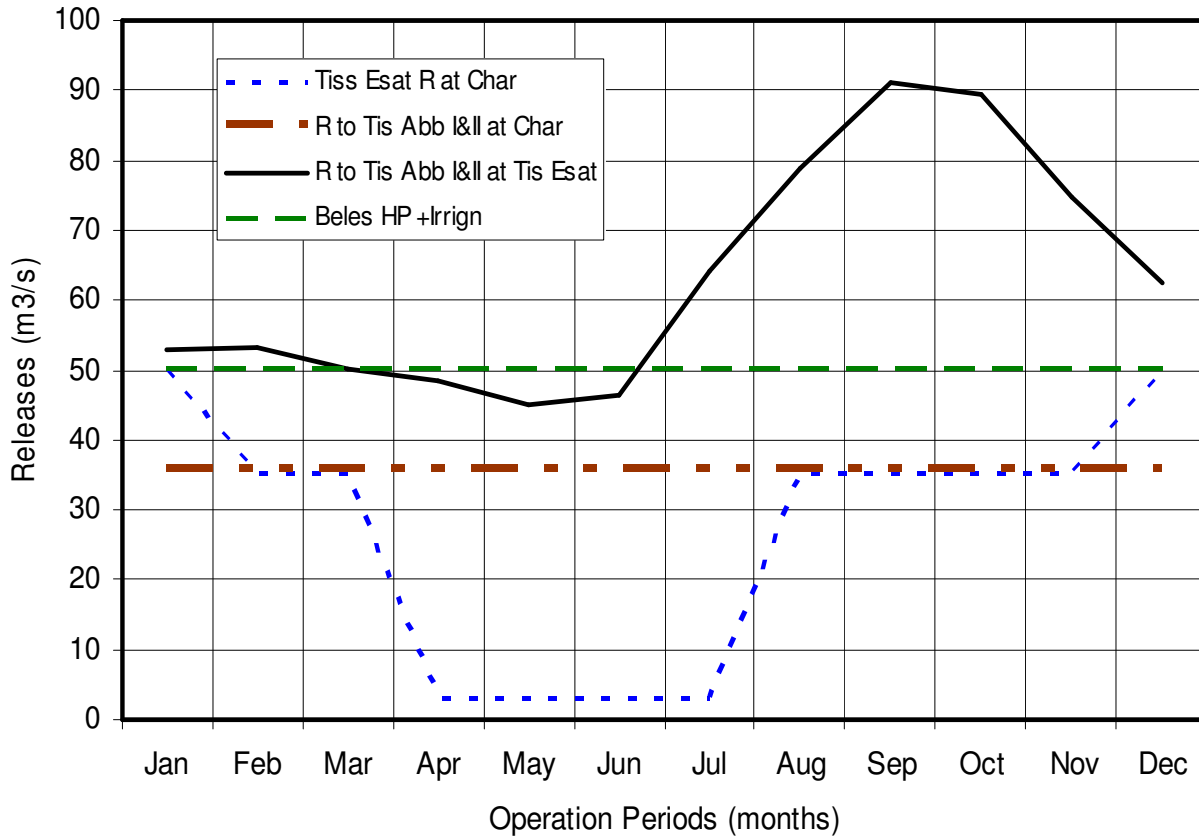
Moreover, under this scenario a total command area of 112800ha would be developed in which 61500ha in the Beles basin and the remaining 51300ha in the Tana basin. Release schedules are indicated in table 8.4 and Fig 8.4 below.

Total regulated outflow at Chara-Chara weir while operating the reservoir under this scenario is computed to be 3875MCM indicating that there exists mean annual imbalance of 140MCM which is expected to come from the lake storage available below 1785masl. This scenario is observed to have relatively lesser imbalance.

Table 8-4 Scen-7: Release Schedule (Average Conditions)

Months	Min R to Tis Esat at Char-Chara (m3/s)	R to Tis Abbay I&II at Char-Chara (m3/s)	R to Tis Esat fall & Hps at Chara-Chara (m3/s)	R to Tis Abbay I & II at Tis Esat (m3/s)	R Beles HP & Irrigation (m3/s)	U/S Abstraction for Irrigation (m3/s)
Jan	50	36	86	53	50	16
Feb	35	36	71	53	50	18
Mar	35	36	71	50	50	16
Apr	3	36	39	48	50	8
May	3	36	39	45	50	1
Jun	3	36	39	46	50	0
Jul	3	36	39	64	50	1
Aug	35	36	71	79	50	0
Sep	35	36	71	91	50	0
Oct	35	36	71	89	50	0
Nov	35	36	71	75	50	7
Dec	50	36	86	62	50	11
Sum/Mean	27	36	63	63	50	10

Figure 8-4 Scen-7: Reservoir Operation Rule Curves for Tis Esat Fall, Tis Abbay HP I & II and Beles HP & Irrigation Projects (Average Conditions)



8.2.2 Worst Conditions (Generated (R2) Inflow Series)

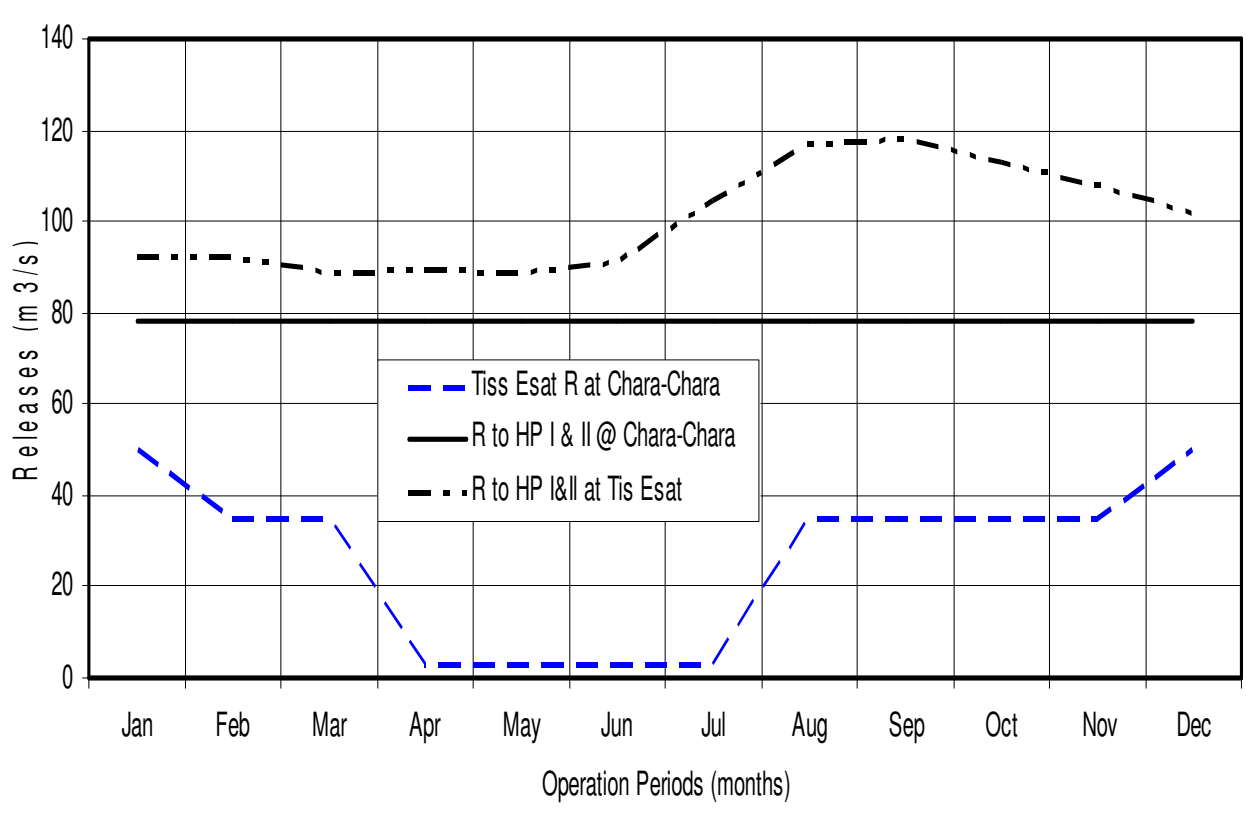
8.2.2.1 Operation Rule Curve for Scenario-1: (The Do Nothing Scenario)

Current situation of the reservoir has been observed by running simulations under the worst conditions. Operating the Tana reservoir under this condition yields a firm release of 78m³/s to Tis Abbay I & II hydropower plants. The minimum requirement for Tis Esat fall remains the same. A firm power of 46MW and mean annual firm energy of 320GWH is produced under this condition. Regulating the inflow at Tis Esat off-Take, including forced spillage during wet periods, the power and energy generated is increased to 59MW and 415GWH respectively. Release schedules are presented in Table 8.5 and Fig 8.5 below.

Table 8-5 Scen-1: Release Schedule to Tis Esat fall & Tis Abbay HPs (Worst Conditions)

Months	Min R to Tis Esat Fall at Chara-Chara (m ³ /s)	R to HP I & I at Chara-Chara (m ³ /s)	R to HP I & II at Tis Esat (m ³ /s)
Jan	50	78	92
Feb	35	78	92
Mar	35	78	89
Apr	3	78	89
May	3	78	89
Jun	3	78	91
Jul	3	78	104
Aug	35	78	117
Sep	35	78	118
Oct	35	78	113
Nov	35	78	108
Dec	50	78	102
Sum/Mean	27	78	100

Figure 8-5 Scen-1: Reservoir Operation Rule Curves for Tis Esat Fall & Tis Abbay HP I & II (Worst Condition)



8.2.2.2 Operation Rule at Scenario-5

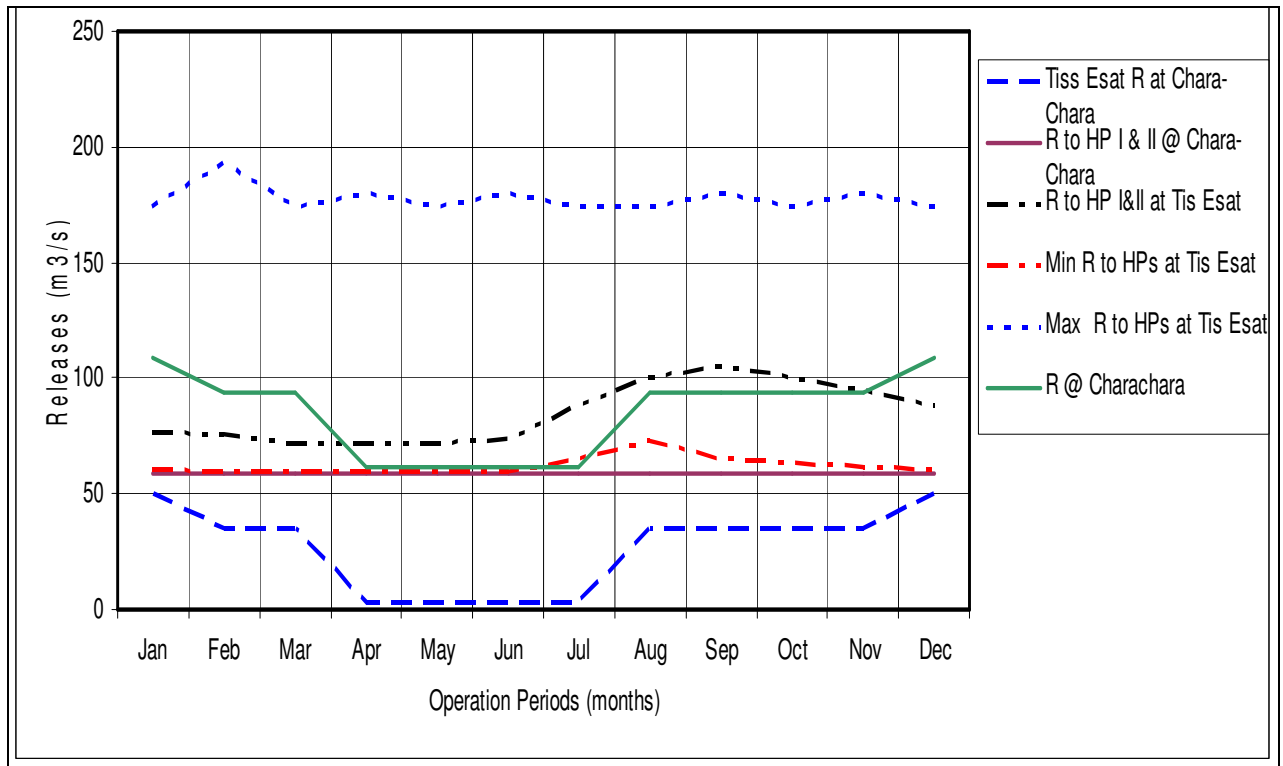
Operating the reservoir under this scenario for the worst condition yields a firm release of 59m³/s to Tis Abbay I & II hydropower plants to produce a firm power and energy of 28MW and 197GWH respectively. When the inflow is regulated at Tis Esat off-take structure, the firm power and energy produced would be raised to 40MW and 284GWH respectively. Forced spillage at Chara-Chara weir is also regulated at Tis Esat off-take structure during wet periods and this has raised mean annual energy production to 350GWH.

More over 68100ha of land is envisaged for the development of irrigated agriculture in the Tana basin. No development is considered in the Beles basin under this scenario. The release schedules are presented in table 8.6 and Fig 8.6 below.

Table 8-6 Scen-5: Release Schedule (Worst Condition)

Months	Releases (m ³ /s)			
	Tis Esat R at Chara-Chara	R to HP I & II @ Chara-Chara	R to HP I & II at Tis Esat	R Total at Chara-Chara
Jan	50	59	77	109
Feb	35	59	76	94
Mar	35	59	72	94
Apr	3	59	72	62
May	3	59	72	62
Jun	3	59	74	62
Jul	3	59	88	62
Aug	35	59	101	94
Sep	35	59	105	94
Oct	35	59	101	94
Nov	35	59	94	94
Dec	50	59	88	109
Sum/Mean	27	59	85	86

Figure 8-6 Scen-5: Reservoir Operation Rule Curves for Tis Esat Fall & Tis Abbay HPs (Worst Conditions)



8.2.2.3 Operation Rule at Scenario-6

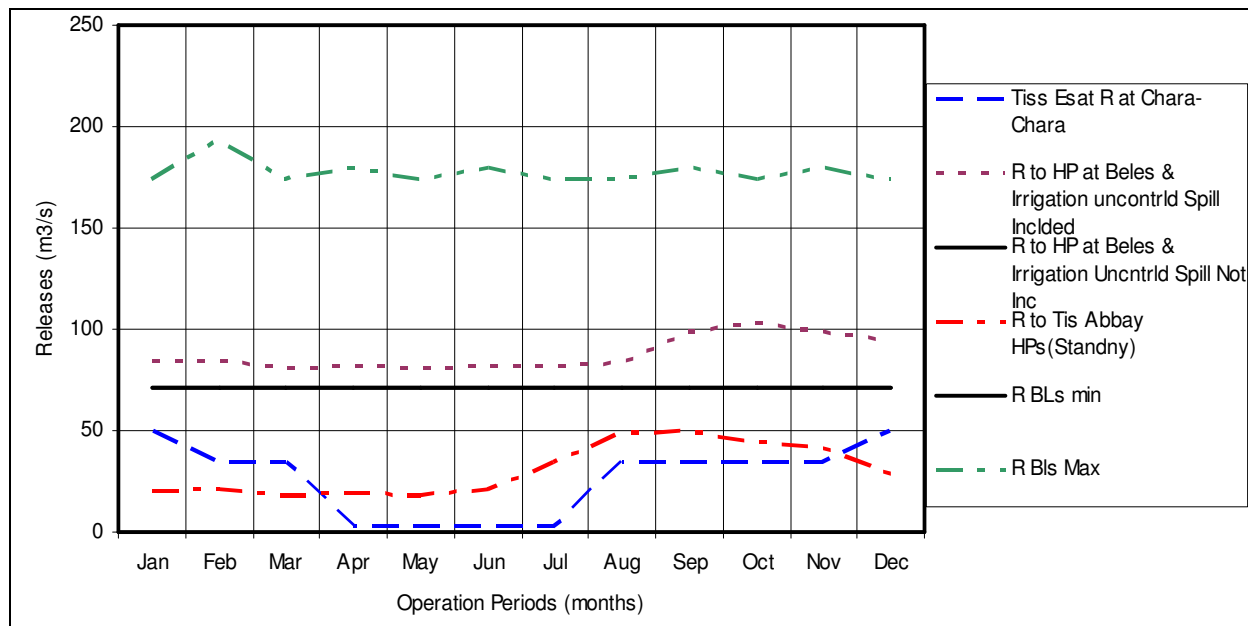
The result of reservoir operation under this scenario for the worst condition has indicated that a firm release of $71\text{m}^3/\text{s}$ to Beles 1515 hydropower plant is possible at 95% reliability, to produce a firm power and energy of 248MW and 1740GWH respectively. Regulating the reservoir volume at peak season (wet season) the power and energy produced at Beles 1515 hydropower plant would be raised to 308MW and 2160GWH respectively. Similarly regulating excess outflow at Chara-Chara during peak inflow periods resulted power and energy production of 15MW and 102GWH respectively. At this scenario more emphasis is given for development works in the Beles basin and hydropower plants at Tis Abbay station are considered as standby plants that will be operated during wet periods. Total energy production in both basins is estimated to be 2286GWH/year.

Moreover, a total of 114500ha of land is envisaged to be developed under irrigated agriculture of which 89800ha is in the Beles basin and 24700ha in the Tana basin. The release schedules are presented in table 8.7 and Fig 8.7 below.

Table 8-7 Scen-6: Release Schedule to Tis Esat Fall, Beles & Abbay HPs (Worst Conditions)

Months	Release (m3/s)			
	at Chara-Chara	at Beles & Irrigation Uncontrolled Spill Included	at Beles & Irrigation Firm Yield (Firm Yield)	to Tis Abbay HPs (Standby)
Jan	50	85	71	20
Feb	35	85	71	21
Mar	35	81	71	19
Apr	3	82	71	19
May	3	81	71	19
Jun	3	82	71	21
Jul	3	81	71	34
Aug	35	84	71	49
Sep	35	99	71	50
Oct	35	103	71	44
Nov	35	99	71	42
Dec	50	94	71	29
Mean/Sum	27	88	71	31

Figure 8-7 Scen-6: Res Operation Rule Curves for Tis Esat Fall & Beles & Abbay HPs (Worst Conditions)



8.2.2.4 Operation Rule for Scenario-7

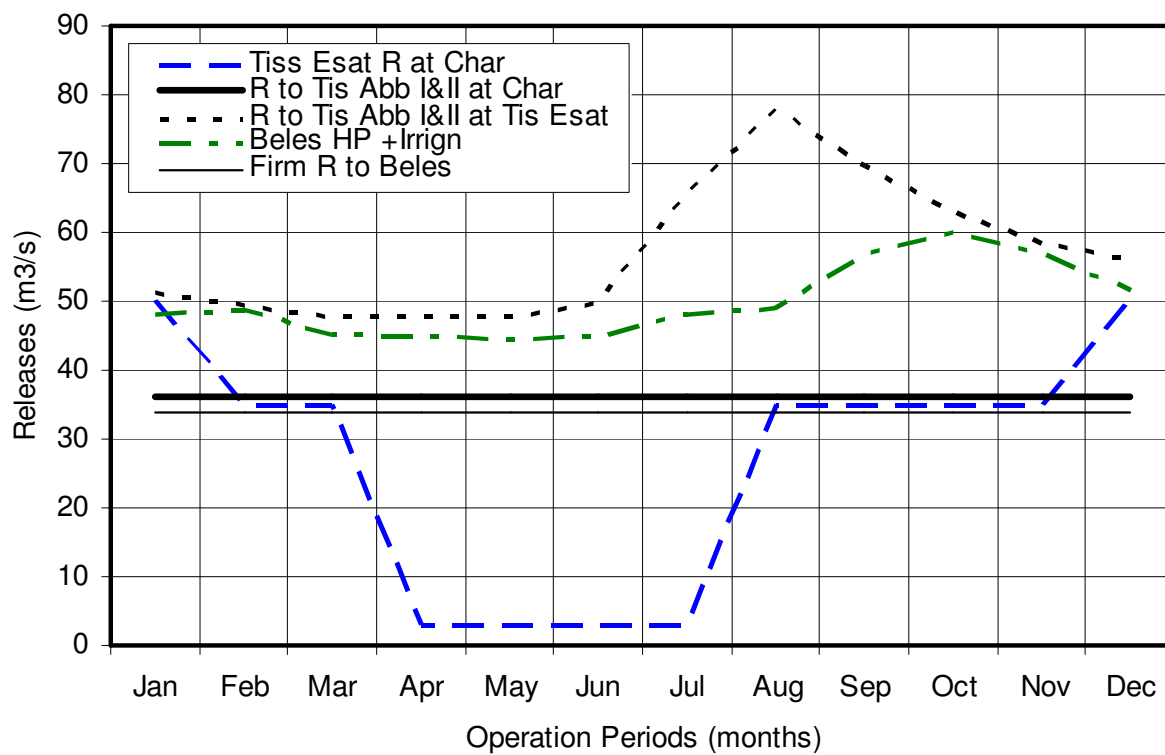
It is observed that, under this scenario for the worst condition, a firm release of 34m³/s to Beles 1515 hydropower plant and 36m³/s to Tis Abbay hydropower plant is possible at 95% reliability, to produce a firm power and energy of 120MW & 834GWH at Beles, and 17MW & 41GWH at Tis Abbay stations respectively. Regulating the reservoir volume at peak season (uncontrolled spill during wet season) the power and energy produced at Beles 1515 hydropower plant would be raised to 175MW & 1225GWH and this Figure is raised to 32MW & 224GWH at Tis Abbay station. Under this scenario total energy of 1450GWH/year is produced in both Tana and Beles basins. Moreover, a total of 76150ha of land is envisaged to be developed under irrigated agriculture of which 43050ha is in the Beles basin and 33100ha in the Tana basin. The release schedules are presented in table 8.8 and Fig 8.8 below.

While concluding the balance for the regulated and natural outflows under the worst condition for all four scenarios is observed to be on the safe side. Mean annual regulated outflow at Chara-Chara weir is estimated to be 3310MCM, 3535MCM, 3630MCM and 3565MCM for scenarios 1, 5, 6 and 7 respectively, which are less than the mean annual outflow of the lake, 3735MCM.

Table 8-8 Scen-7: Release Schedule to Tis Esat Fall, Beles & Abbay HPs (Worst Conditions)

Months	Release (m3/s)				
	Tis Esat at Chara-Chara (Min)	To Tis Abbay I & II at Chara-Chara (Firm)	To Tis Abbay I & II at Tis Esat	To Beles (Firm)	To Beles HP +Irrigation Including Unregulated
Jan	50	36	51	34	48
Feb	35	36	49	34	49
Mar	35	36	48	34	45
Apr	3	36	48	34	45
May	3	36	48	34	45
Jun	3	36	50	34	45
Jul	3	36	65	34	48
Aug	35	36	78	34	49
Sep	35	36	70	34	57
Oct	35	36	63	34	60
Nov	35	36	58	34	57
Dec	50	36	56	34	52
Sum/Mean	27	36	57	34	50

Figure 8-8 Scen-7: Res Operation Rule Curves for Tis Esat, Beles & Abbay HPs (Worst Conditions)



9. CONCLUSIONS AND RECOMMENDATIONS

9.1 Conclusions

The Lake Tana basin located in the northern portion of the Abbay River basin with estimated drainage area of 15340km² is estimated to have a mean annual inflow of 12051.5MCM. This consists of more than 20% of the Abbay River basin water resources potential. It has an estimated potential of 145000ha (including the Beles basin this potential is estimated to be 268000ha) for the development of irrigated agriculture.

Ethiopian water resources potential, sub divided in to 12 major rivers, has been studied at various levels for the last two to three decades. The Tana basin, as part of the Abbay River basin has been studied by different consultants since 1964. The USBR studies in 1964, the Tana-Beles study by Studio Pietrangeli in 1990, the recently accomplished Abbay River integrated master plan study by BCEOM and associates and Beles basin hydropower development studies by Lahmayer International in 2003 are to mention some.

So far estimation of inflow coming from the Tana basin to the lake reservoir has been conducted applying backward computation techniques of the water balance of the Lake. This computation has resulted that Tana basin has a mean annual inflow of 9380MCM. This research work has, however, attempted to estimate the reservoir inflow by employing conventional methods of rainfall-runoff simulation techniques. Four methods were employed namely, regression analysis, the monthly water balance simulation techniques, the SCS-CN method and the area ratio method. After running modeling of the simulated and observed runoff, the water balance simulation technique best fits for the southern and eastern sub basins and area ratio method is used in the northern sub basins. Accordingly the mean annual inflow is estimated to be 12051.5MCM.

The principal objective of this research work is to run reservoir operation and establish operation rules for Chara-Chara weir. To effect this establishing the water balance of the reservoir is mandatory. This has been performed both at dry periods and all seasons. The water balance made at dry period has clearly indicated the need for all season water balance simulation. While running the

water balance simulation for all seasons, it has been observed that there are some problems in the reservoir evaporation component of the water balance. To reduce errors in using the recorded lake evaporation data, the data obtained at Bahir Dar station was avoided and the research work has decided to compute losses from the water balance equation of the Lake. Accordingly the water balance for the lake has been simulated and the result indicates that 69.2% of the inflow is lost as evaporation and seepage/unaccounted and 31% is lost as an outflow.

Water resources inputs are subject to uncertainties due to the stochastic nature of its components like rainfall. This will have its own impact on the reliability of operation rules that has been established through reservoir simulation techniques. Moreover, the planning horizon for the master plan is taken as 50-years, which is longer than the length of the recorded data available in the basin. To overcome problems associated in this regard, time series analysis for the reservoir inflow has been conducted. 200 realizations have been generated and only 50 realizations were used for simulation purposes as time was the limitation.

Reservoir operation was simulated based on different development scenarios that bear different magnitude of demands to the reservoir. Initially the existing situation has been tested. The current operation rule has been found reliable at 95% by meeting the minimum requirements of the Tis Esat fall and releasing an average firm yield of 95m³/s to Tis Abbay I and II hydropower plants. Moreover, scenario-2, 3 and 4 as developed by the recently accomplished Abbay River basin integrated master plan studies (BCEOM and associates, 1999) have been tested if their demands could be met by the regulatable storage capacity of Lake Tana. The simulation has indicated that the reservoir fails meeting the demand requirements coming from these scenarios.

The research work has developed three scenarios designated as scenario-5,6 and 7, whose conditions are stated in section 7.5.6. Reservoir operation simulated for the stated conditions in these scenarios indicate that the release schedules indicated in section 8.0 are all met at 95% reliability. Furthermore, the research work has established an improved operation rule for the current situation. In the existing situation it is anticipated that 94m³/s could be released to Tis Abbay I & II hydropower plants at 95% reliability. In this research work modifications has been made for the minimum requirements of Tis Esat fall, and regulation is attempted at both the Chara-Chara weir and at the Tis Abbay off take

structure which has increased the efficiency of the modified operation rule by utilizing the spilled water. As a result a firm yield of 100m³/s at 95% reliability has been achieved.

In conclusion these development scenarios bear different benefits. Operating the reservoir at these different operation rules has resulted different outcomes as summarized in Fig 9.1 through Fig 9.3 below. From these three consecutive Figures it is imperative that scenario-6 seems to be more attractive as it generates more power and realizes more irrigation land in the Beles basin both at average and worst conditions. On the other hand scenario-7 seems to be more attractive from social perspectives as it allows irrigated development works in both basins. Fair resources distributions and reasonably equitable sharing of water resources in the two basins is observed while operating the Lake reservoir for conditions set in scenario-7.

Figure 9-1 Energy Production at Different Scenarios for both Average & Worst Conditions

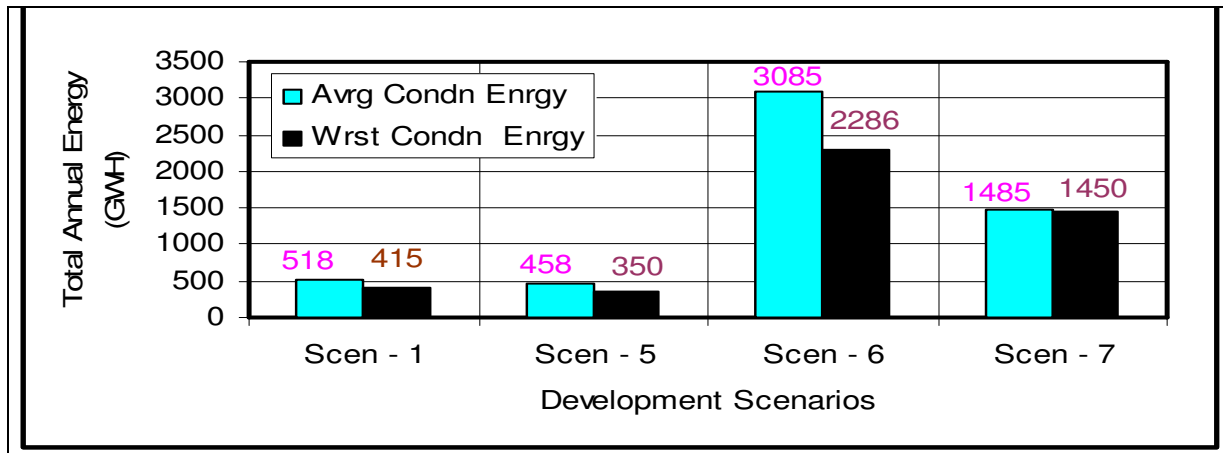


Figure 9-2 Irrigation Development Potential at Different Scenarios for both Average & Worst Conditions

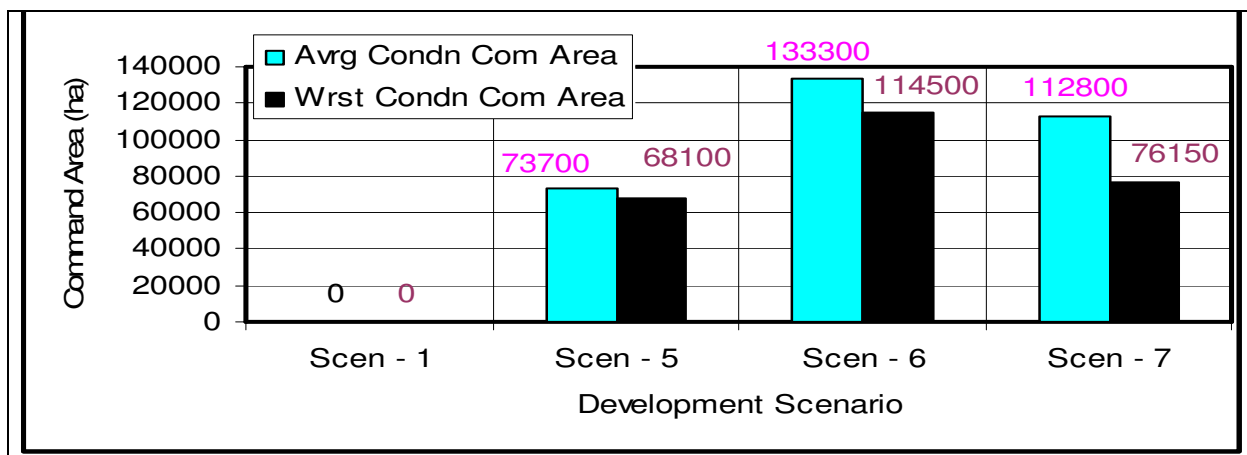
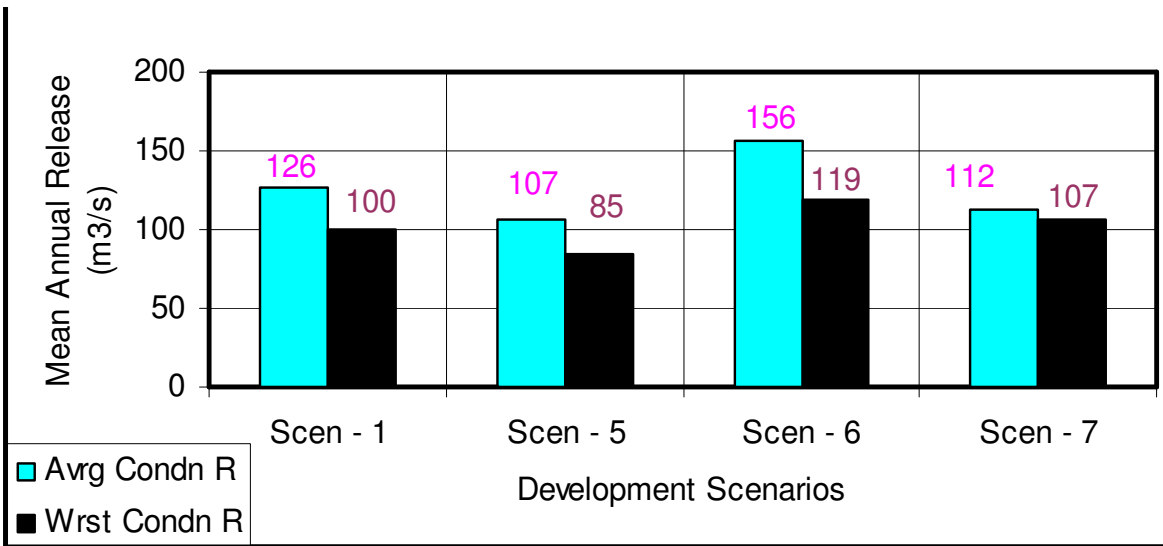


Figure 9-3 Mean Annual Release at Different Scenarios for both Average & Worst Conditions



Selection of the best development scenario is not possible at this level of the research work. Applying simulation techniques only may not be exhaustive reaching the final decision in selecting optimum development scenario. This obviously needs the implementation of optimization techniques. The research work has, therefore, presented these three development scenarios as possible alternative development scenarios and the selection of optimum development scenario to be effected after using optimization techniques.

As a final destination for this research work, limited by time shortages, operation rules for existing condition and the three alternative development scenarios, designated as scenario-5, 6 and 7, at average and worst conditions are developed. While establishing the rule curves and release schedules reservoir resources regulation is made both at Chara-Chara weir and Tis Esat off-take structure. This has been performed to increase the efficiency of the operation rule by further utilizing the spilled water down stream of the Chara-Chara weir.

9.2 Recommendations

In the end the researcher fills that the following recommendation are important for future development of both Tana and Beles basins.

Estimation of the Reservoir Inflow: In the attempt of estimating the reservoir inflow much of the exercise has been made numerically. Observed data has been modeled with the simulated data and the techniques of best fit have been used to estimate reservoir inflows coming from the sub basins of the Lake. This approach has to be supported with field level data collections especially regarding the physical features of each sub basins. In the future much has to be done in this regard and an attempt has to be made to the level of physical modeling at higher research level. The inflow estimated during this research work is limited largely to office level works and in using it the reliability in this regard has to be given due consideration.

Lake Evaporation: - recorded Lake Evaporation at Bahir Dar is observed to have a significant trend. This is largely influenced by the wind conditions recorded at Bahir Dar which is observed to have both trends and shifts significantly. Location of the station might have its own impact as the Bahir Dar meteo station is located in the middle of the town. This situation needs a thorough investigation before using the data as an input for the computation of Lake Evaporation. On the other hand if the situation of negative trend for Lake Evaporation exists as it is observed now, it is important to run a research work on this issue and identify possible reasons associated with it. Moreover, it is advisable that the National Meteorology Service Agency shall implement pitche reading stations at Dek Estifanos, Gorgora and Kunzila.

Future Development Studies: - Development studies conducted so far have the limitations of looking the resource utilization in an integrated manner in the basin. Development plans in the Beles and Tana basin are inter-related as they share the same water resource, the reservoir of Lake Tana. While effecting a development plan in one of these basins it is advisable that the impact of the planned development in one of these basins to the other basin shall be seen and optimum development scenario that benefits the nation shall be planned by effecting simulation and optimization techniques.

Moreover, currently there is an intention of building large reservoirs in the course of Abbay River downstream of the Tana basin. The development of the Tana-Beles basin would have considerable impact on these envisaged reservoirs. This issue has to be seen in such a way that water and land resources envisaged to be developed in the Tana-Beles basin shall be optimized and decisions has to be made based on the optimum benefits that will be resulted from the optimization process.

Furthermore, the impact of developing the Tana-Beles basin to the envisaged d/s reservoirs in the course of the Abbay River shall be investigated especially in terms of abstraction and adequacy of water resources. The ministry of water resources shall give due emphasis to such kind of planning activities while monitoring basin level studies conducted by consultants.

Increasing Efficiency of Reservoir Operation Rules: - In future development activities it is obvious that more optimum operation rules would be established. In the basin five major reservoirs (Megech, Ribb, Gumara, Koga and Gilgel Abbay gravity dams) are planned largely meant for the development of irrigated agriculture. Efficiency of reservoir operation rules at Lake Tana can be enhanced and reliability of reservoir operation at some specified demands/requirements can be increased if systematic utilizations of these reservoirs are developed. It is possible to design these reservoirs to accommodate some floods during peak rainy season and release this water at times the Tana reservoir water surface level starts falling. This effect has dual purposes; first it will substantially reduce the area of flood plains being flooded during wet periods, located down stream of these reservoirs which subsequently reduces the cost of flood mitigation plans that will be implemented for these flood plains. Secondly, these reservoirs will reduce the unregulated spillages at the Chara-Chara weir during wet periods and this part of the water could be utilized for development purposes in the basin. Thus future project designs shall give emphasis to such a kind of integrated multistage reservoir operation techniques in the Tana basin. The reservoirs in the Beles basin could also be utilized for such purposes. For instance more water could be diverted to the Beles 1515 hydropower reservoir during wet periods and released to downstream irrigation development works during dry periods.

Bathymetric Survey: Bathymetric survey for Lake Tana has been conducted in 1988 by Studio Pietrangeli during the study of the Tana-Beles Project (Studio Pietrangeli, 1990). Seventeen years (nearly two decades) has been elapsed since then. It is important that sediment accumulation in the reservoir has to be detected and a survey has to be made. The researcher has the feeling that the MWRs' has to conduct a bathymetric survey for the Lake so that the accumulated sediment can be detected.

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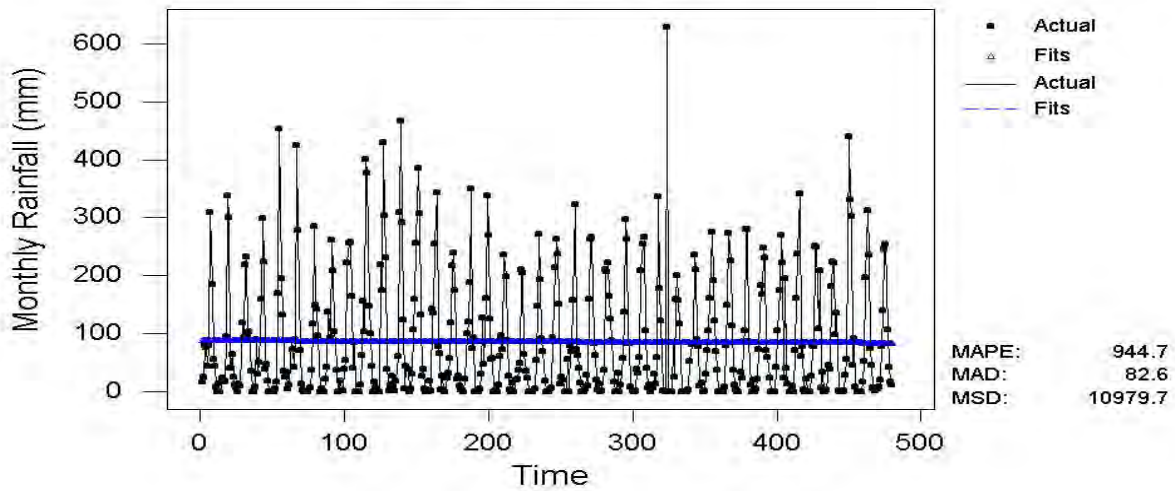
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ANNEX – I – TIME SERIES ANALYSIS OF CLIMATE AND HYDROLOGIC SERIES

Trend Analysis for Rainfall at Gondar Airport

Linear Trend Model
 $Y_t = 87.9927 - 8.67E-03*t$



Trend Analysis for Addis Zemen Rainfall

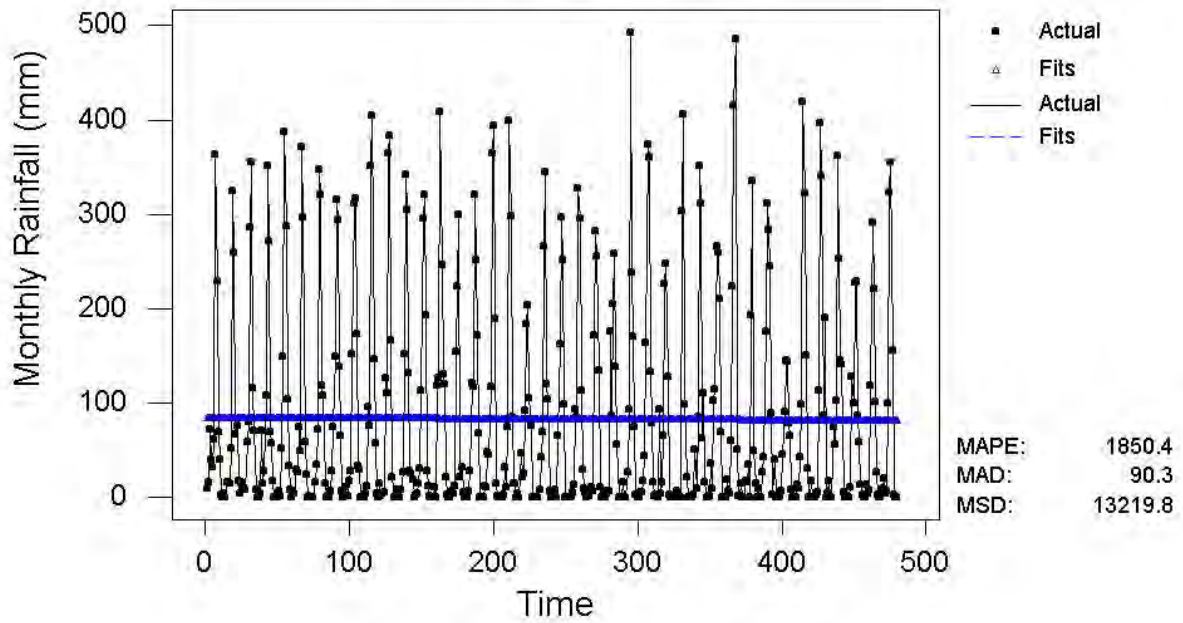
Linear Trend Model
 $Y_t = 68.8439 + 0.154767*t$



Trend Analysis for Rainfall at Yifag

Linear Trend Model

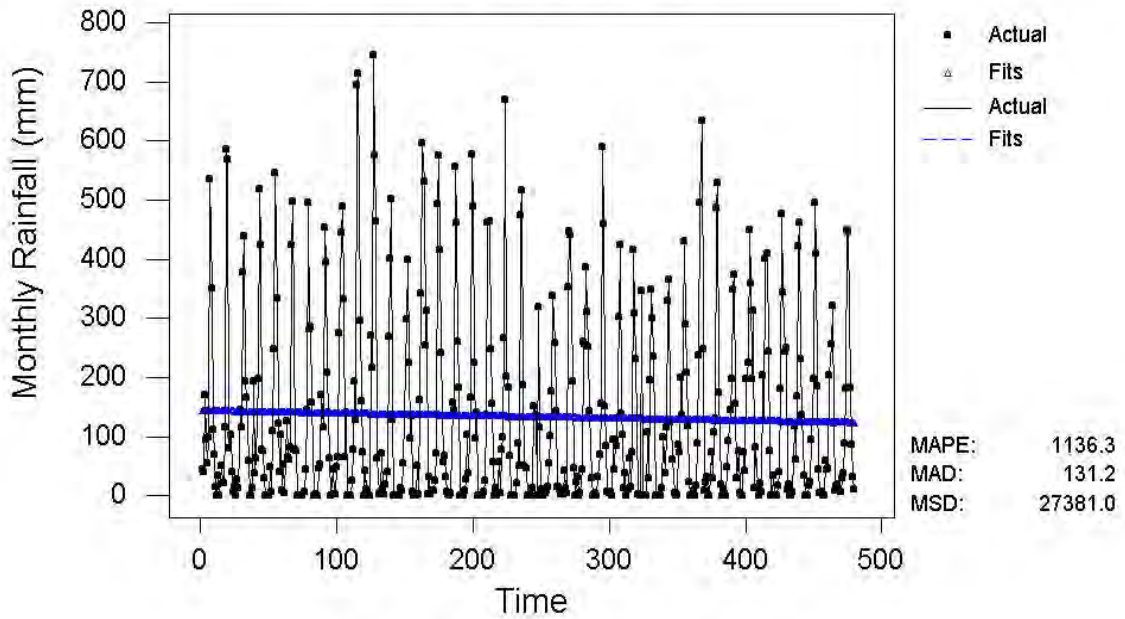
$$Y_t = 84.1403 - 6.36E-03*t$$



Trend Analysis for Rainfall at D Tabor

Linear Trend Model

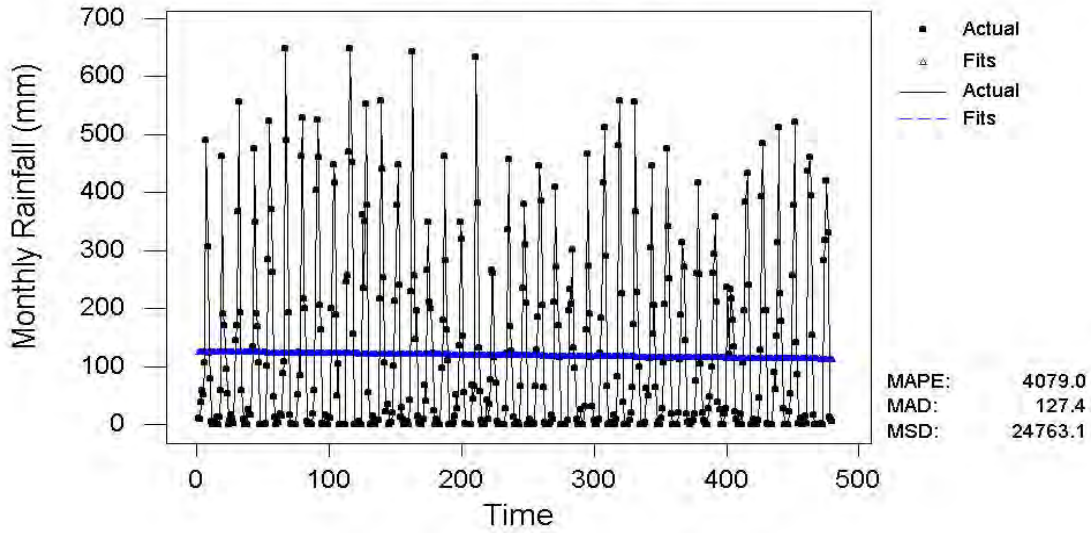
$$Y_t = 143.333 - 4.18E-02*t$$



Trend Analysis for Rainfall at B/Dar Station

Linear Trend Model

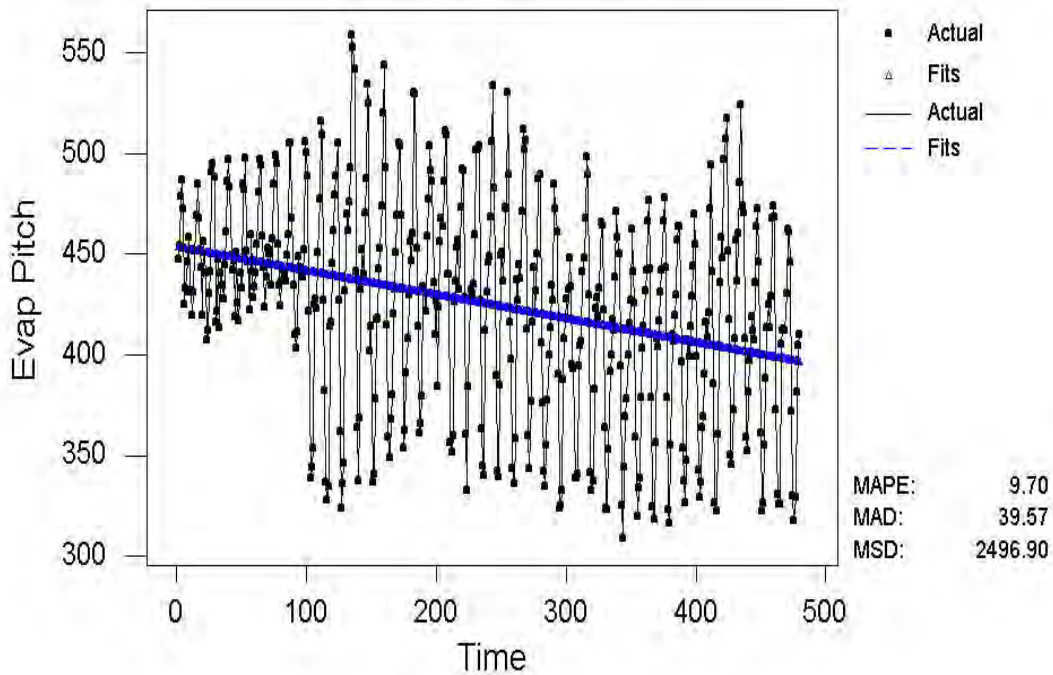
$$Y_t = 125.997 - 2.64E-02*t$$



Trend Analysis for Lake Evap from Pitch at Bahirdar

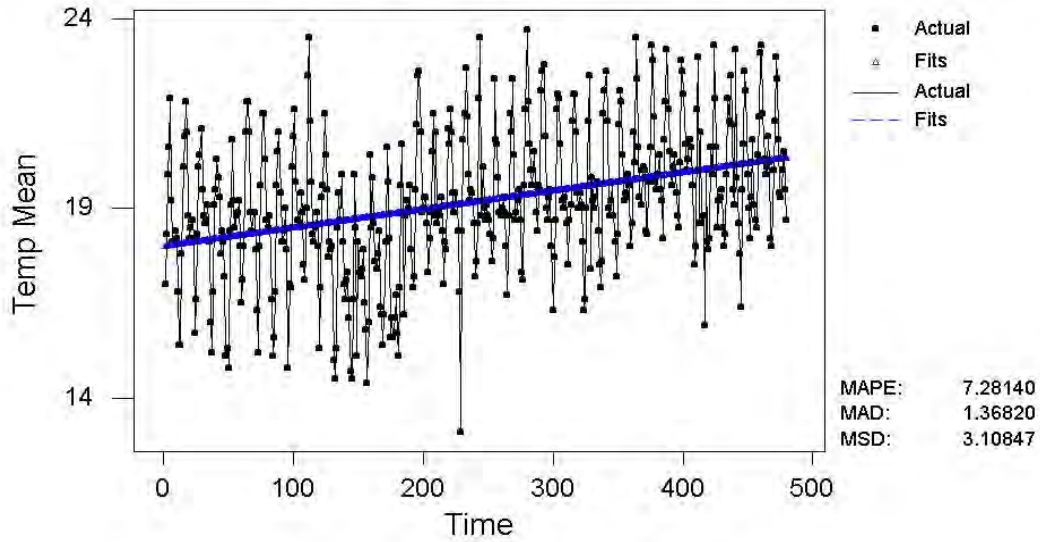
Linear Trend Model

$$Y_t = 453.759 - 0.118776*t$$



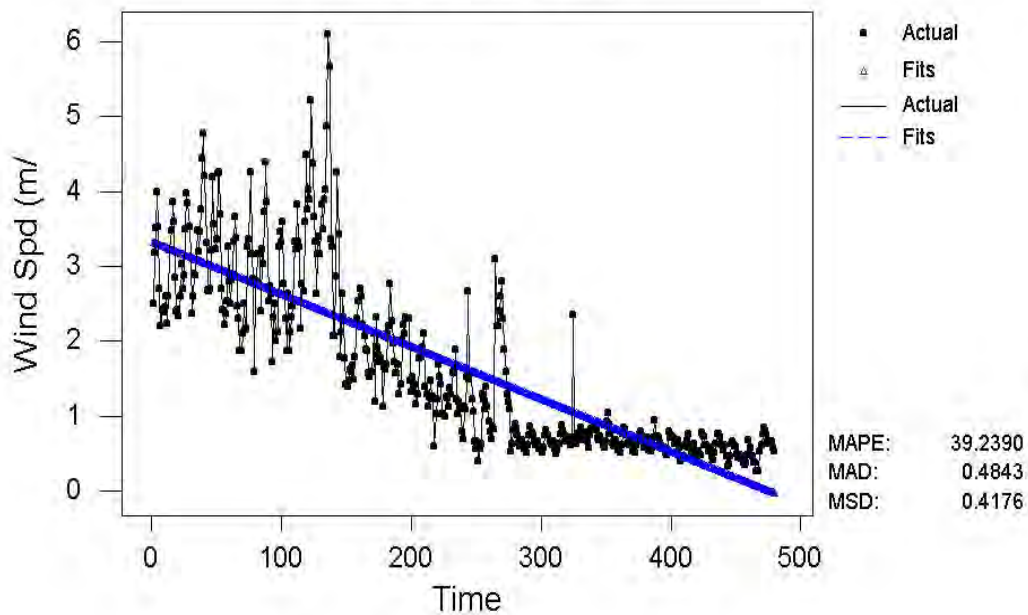
Trend Analysis for Temp Mean

Linear Trend Model
 $Y_t = 18.0002 + 4.86E-03*t$



Trend Analysis for Wind Spd (m/

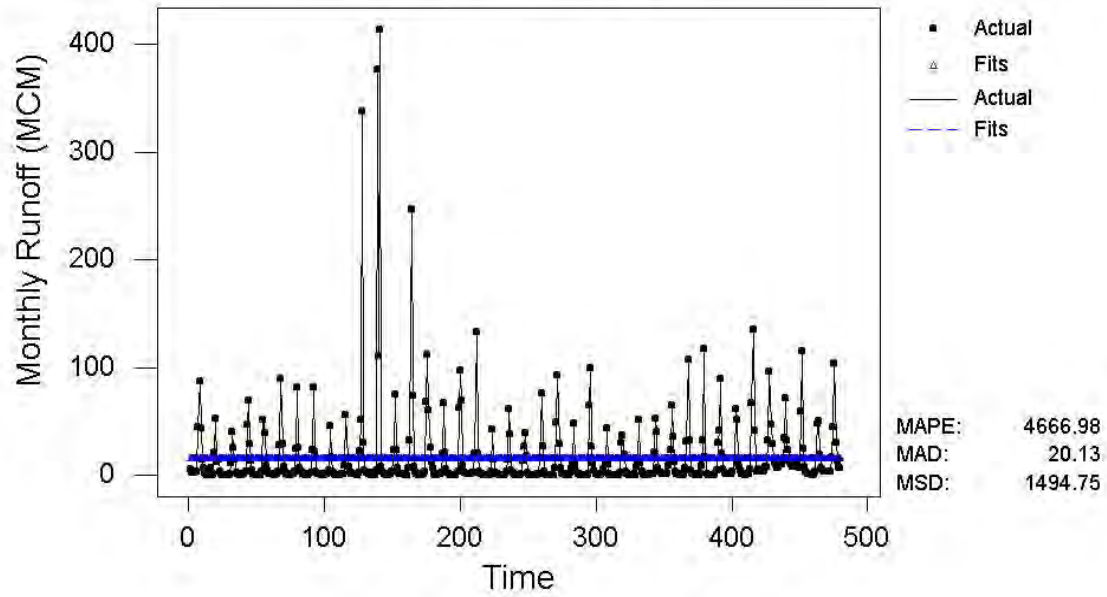
Linear Trend Model
 $Y_t = 3.32974 - 7.00E-03*t$



Trend Analysis for Megech Runoff

Linear Trend Model

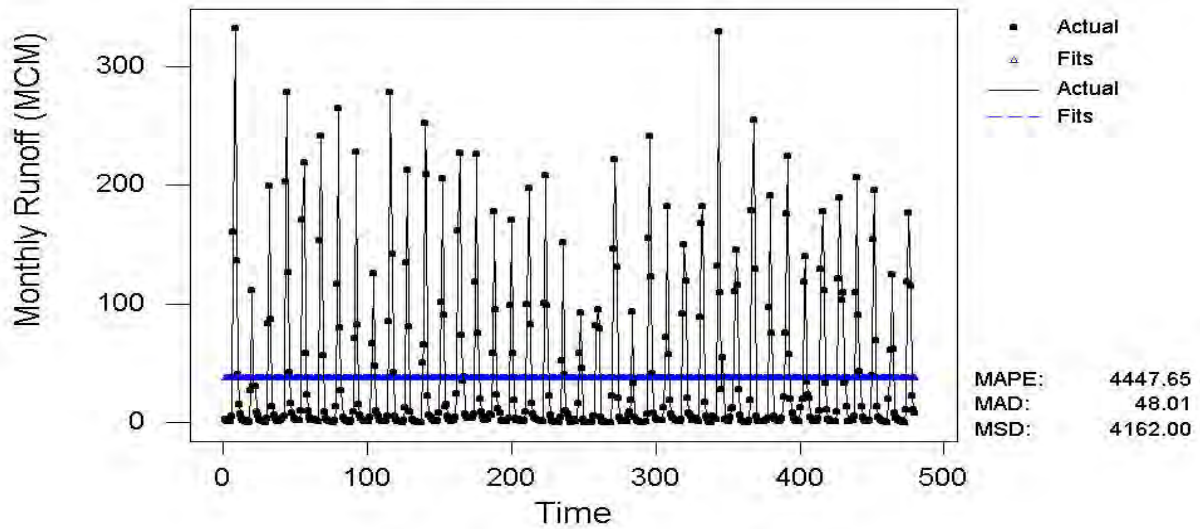
$$Y_t = 15.9047 + 1.78E-04 * t$$



Trend Analysis for Ribb Catchment Runoff

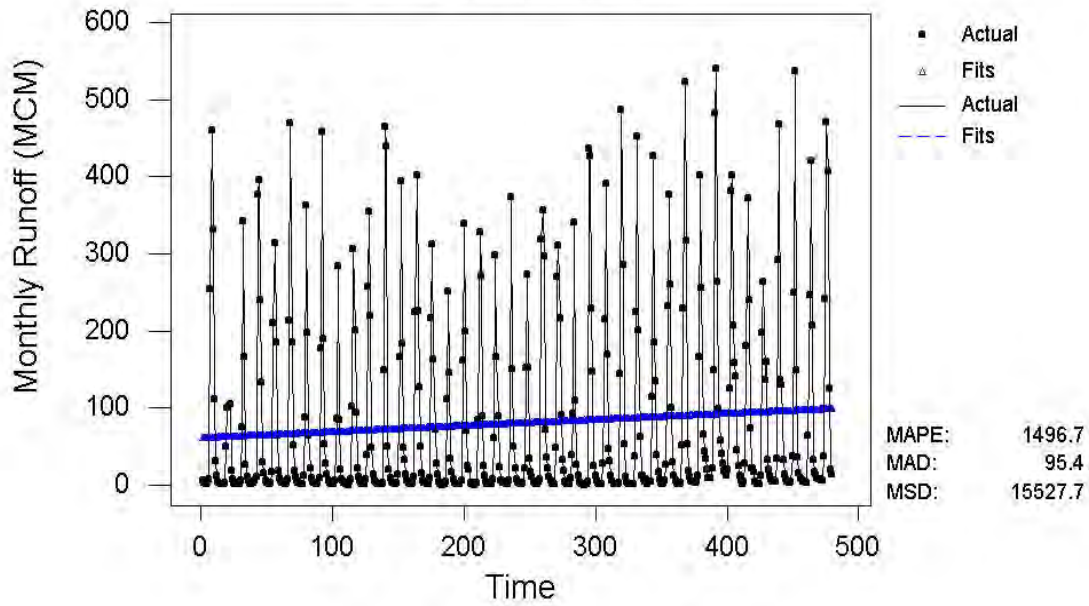
Linear Trend Model

$$Y_t = 38.0177 - 5.69E-04 * t$$



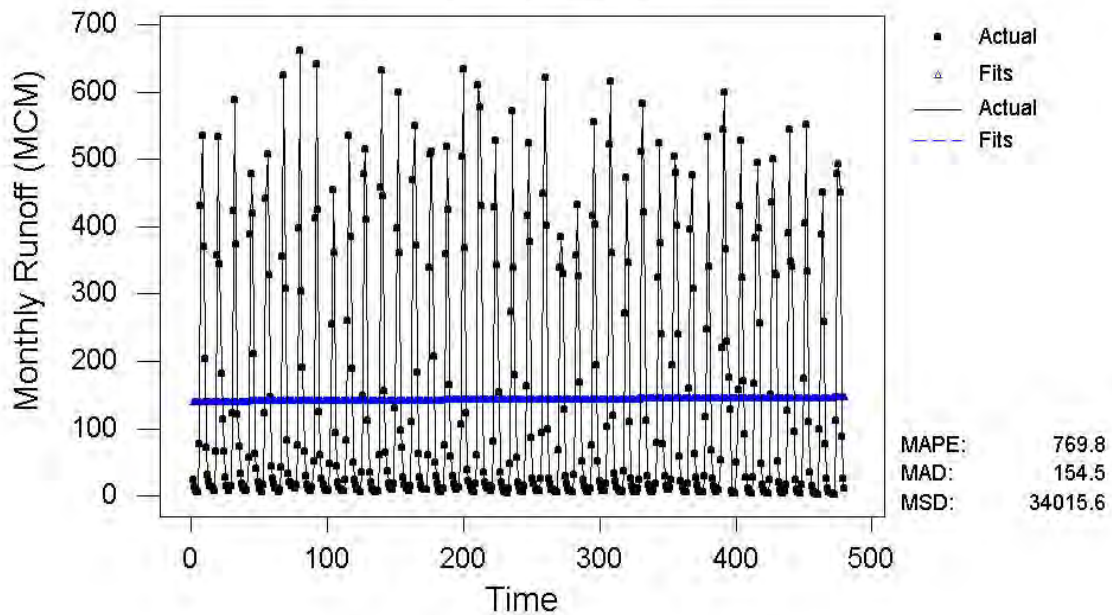
Trend Analysis for Gumara Runoff

Linear Trend Model
 $Y_t = 61.0424 + 7.88E-02*t$



Trend Analysis for Gilgel Abbay Runoff

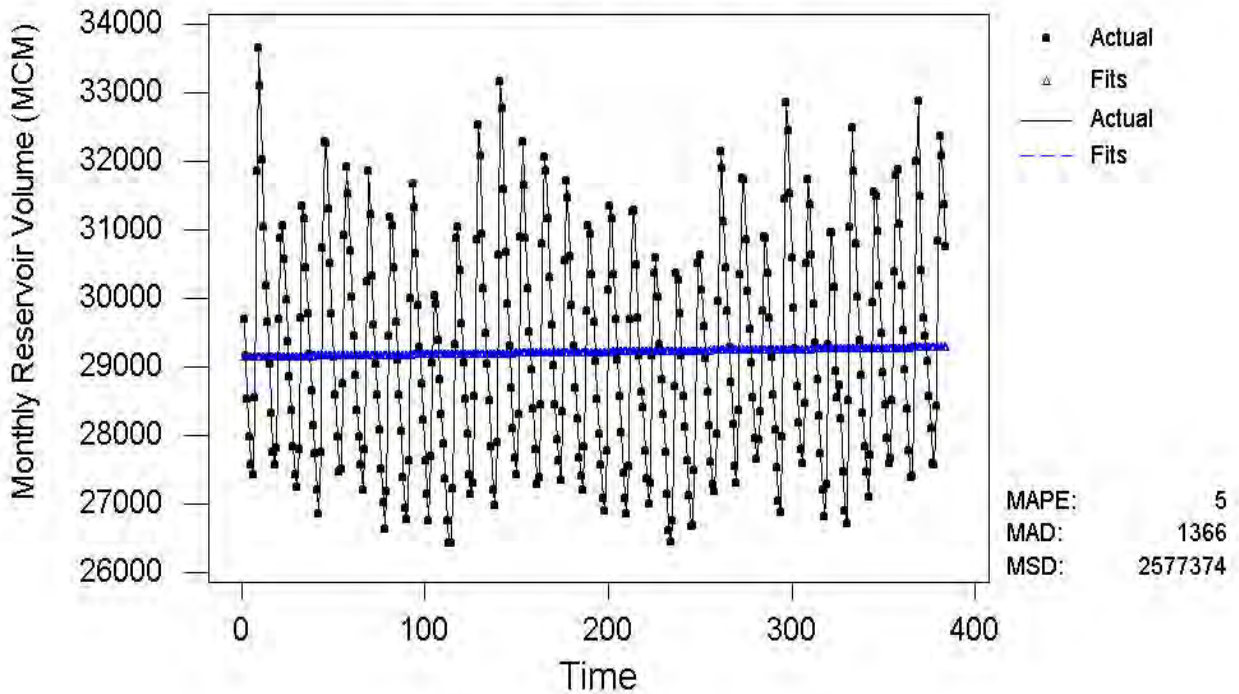
Linear Trend Model
 $Y_t = 139.833 + 1.28E-02*t$



Trend Analysis for Reservoir Volume of Lake Tana Before Commissioning Chara-Chara Weir

Linear Trend Model

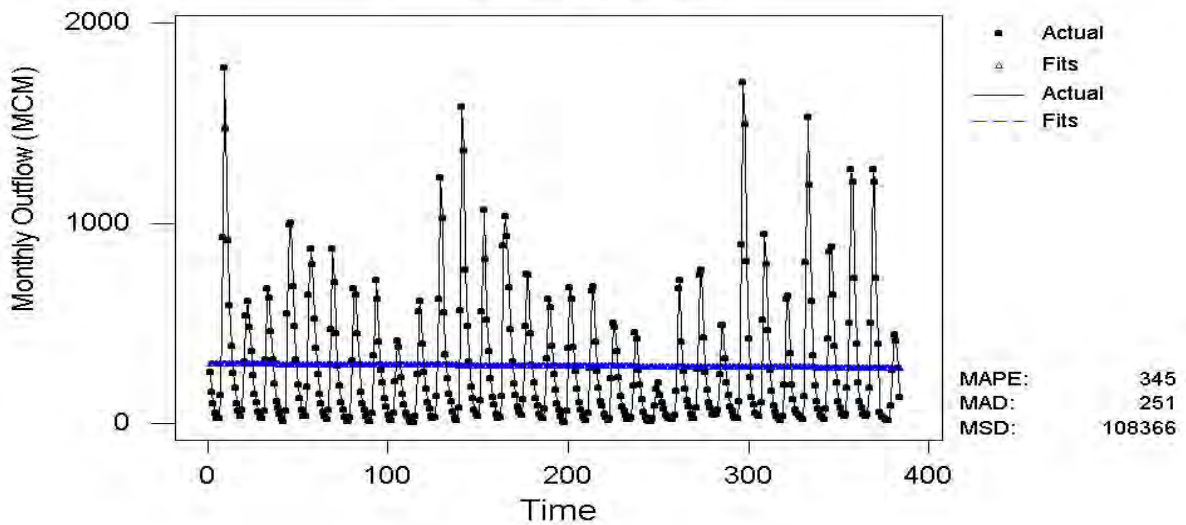
$$Y_t = 29138.6 + 0.375642t$$



Trend Analysis for Lake Outflow Before Commissioning the Chara-Chara Weir

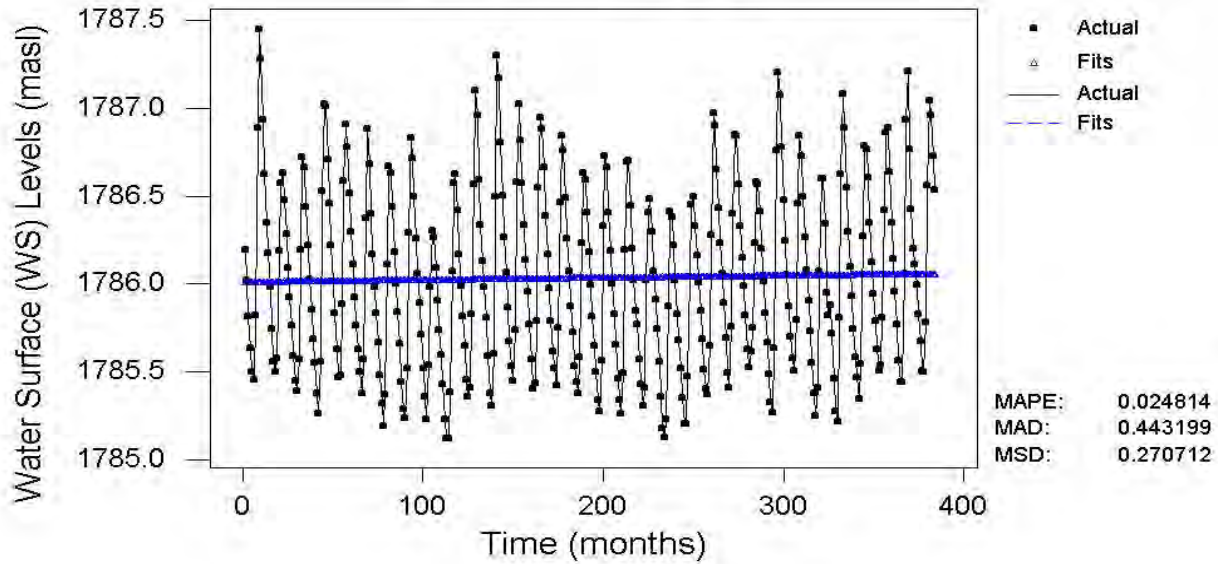
Linear Trend Model

$$Y_t = 298.329 - 5.27E-02t$$



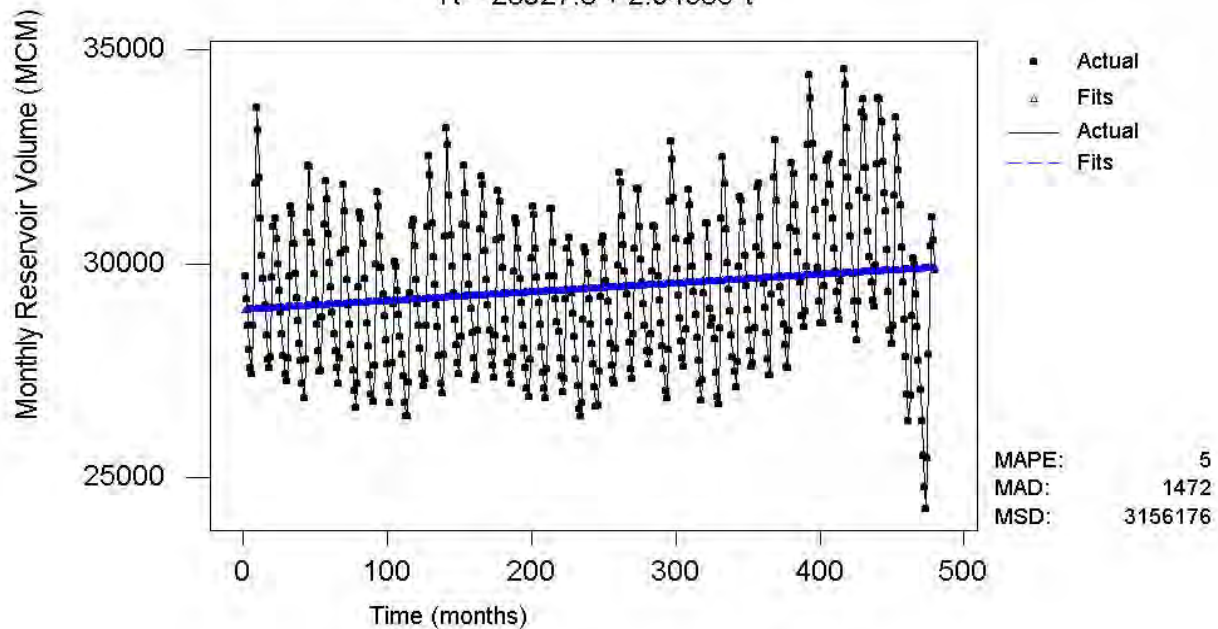
TS Plot for Lake Tana WS Levels Before Commissioning the Chara-Chara Weir

Linear Trend Model
 $Y_t = 1786.01 + 1.23E-04*t$

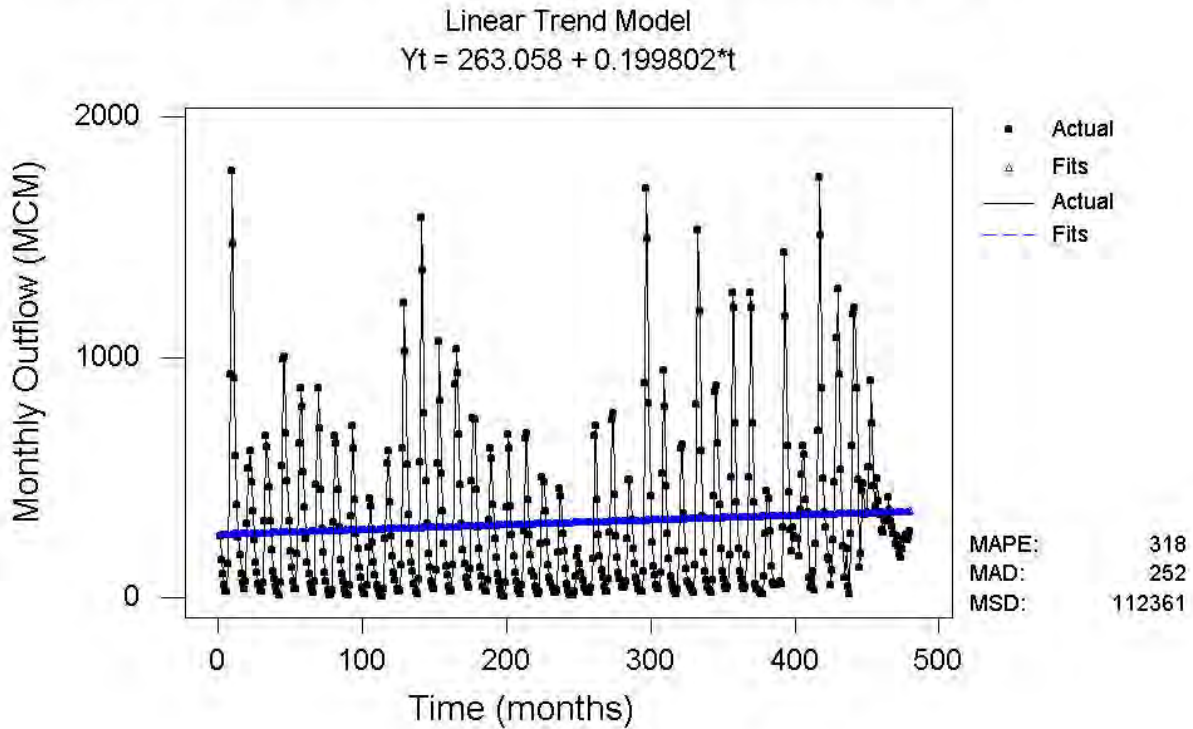


TS Plot for Lake Tana Reservoir Volume After Commissioning the Chara-Chara Weir

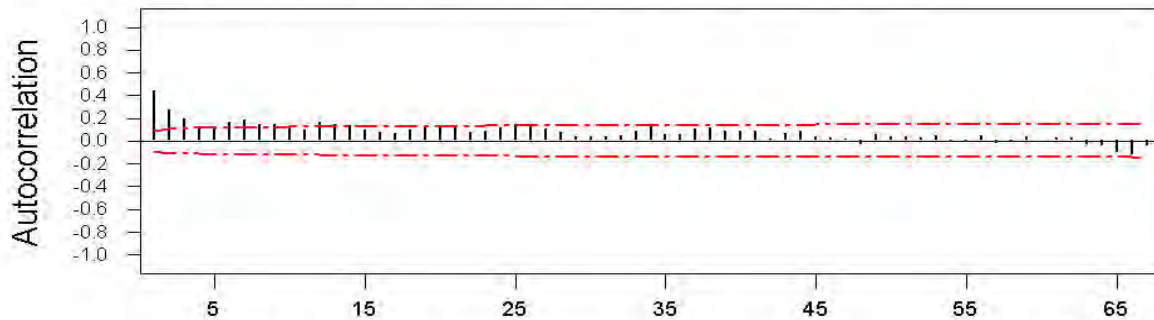
Linear Trend Model
 $Y_t = 28927.8 + 2.04685*t$



TS Plot for Lake Tana Outflow After Commissioning the Chara-Chara Weir

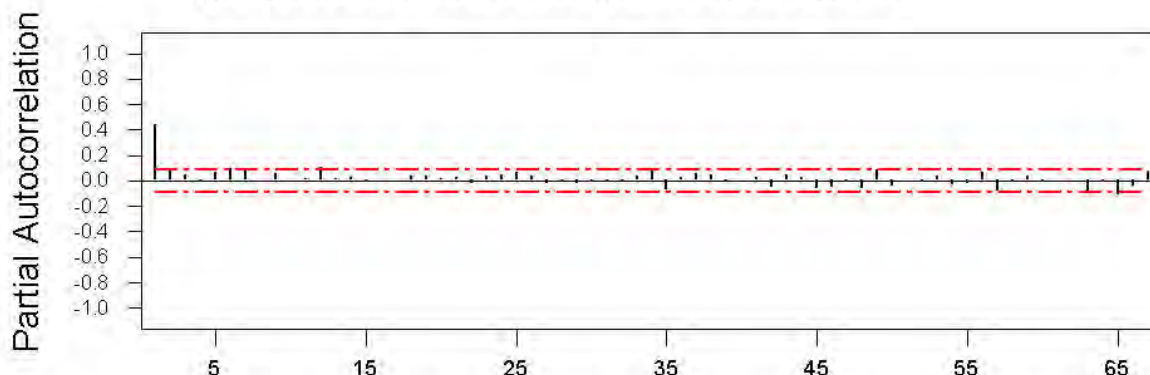


Auto Correlation Function for Standardized Series



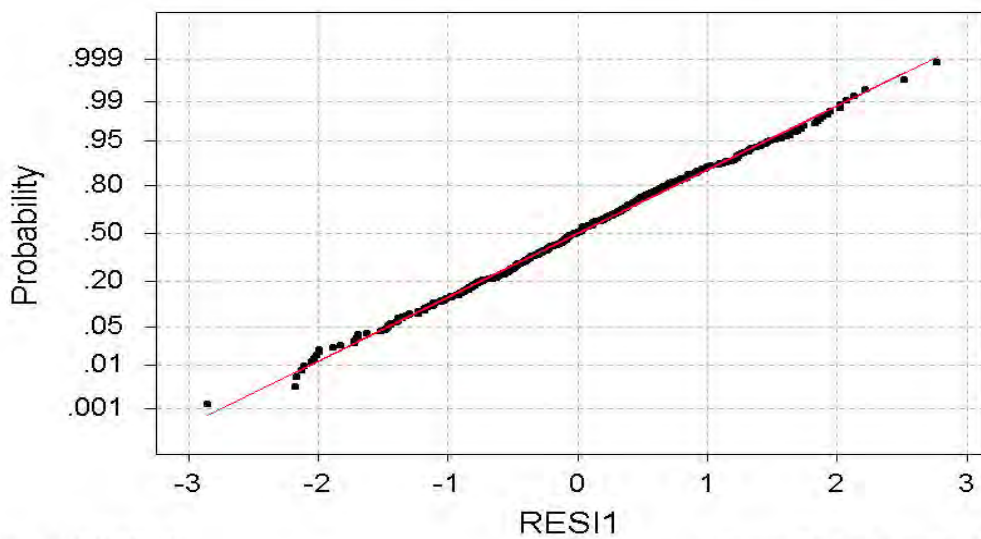
Lag	Corr	T	LBQ	Lag	Corr	T	LBQ	Lag	Corr	T	LBQ	Lag	Corr	T	LBQ	Lag	Corr	T	LBQ
1	0.44	9.66	93.86	16	0.08	1.20	259.13	31	0.03	0.48	329.05	46	0.02	0.27	374.59	61	0.02	0.29	382.24
2	0.27	5.04	129.44	17	0.07	1.03	261.40	32	0.04	0.64	330.10	47	0.02	0.26	374.78	62	0.03	0.41	382.73
3	0.19	3.32	146.54	18	0.09	1.36	265.39	33	0.08	1.18	333.61	48	-0.03	-0.45	375.34	63	-0.03	-0.43	383.28
4	0.11	1.93	152.62	19	0.11	1.70	271.74	34	0.13	1.85	342.36	49	0.05	0.69	376.70	64	-0.04	-0.55	384.18
5	0.12	2.06	159.64	20	0.11	1.66	277.88	35	0.05	0.73	343.74	50	0.03	0.45	377.26	65	-0.10	-1.43	390.23
6	0.16	2.74	172.27	21	0.12	1.79	285.04	36	0.06	0.83	345.51	51	0.04	0.52	378.04	66	-0.13	-1.74	399.28
7	0.18	3.09	188.97	22	0.08	1.13	287.96	37	0.10	1.40	350.62	52	0.03	0.39	378.48	67	-0.04	-0.57	400.27
8	0.14	2.35	198.96	23	0.08	1.24	291.51	38	0.11	1.57	357.12	53	0.05	0.67	379.76				
9	0.15	2.39	209.64	24	0.11	1.63	297.66	39	0.09	1.21	361.02	54	-0.00	-0.04	379.77				
10	0.11	1.81	215.93	25	0.14	2.07	307.75	40	0.08	1.17	364.70	55	-0.02	-0.24	379.93				
11	0.10	1.52	220.39	26	0.15	2.15	318.87	41	0.08	1.13	368.16	56	0.04	0.56	380.83				
12	0.16	2.57	233.33	27	0.10	1.49	324.28	42	0.02	0.22	368.29	57	-0.03	-0.37	381.23				
13	0.14	2.18	242.98	28	0.07	1.08	327.15	43	0.06	0.84	370.25	58	-0.01	-0.19	381.93				
14	0.13	2.04	251.56	29	0.04	0.52	327.83	44	0.08	1.15	373.87	59	0.03	0.47	381.97				
15	0.10	1.46	256.07	30	0.04	0.50	328.46	45	0.03	0.43	374.38	60	0.01	0.11	382.00				

Partial Autocorrelation Function for Standardized Series



Lag	PAC	T	Lag	PAC	T	Lag	PAC	T	Lag	PAC	T	Lag	PAC	T
1	0.44	9.66	16	0.00	0.10	31	-0.02	-0.39	46	-0.05	-1.14	61	0.01	0.14
2	0.10	2.09	17	0.01	0.12	32	-0.01	-0.16	47	-0.00	-0.02	62	0.00	0.09
3	0.05	1.03	18	0.03	0.72	33	0.03	0.65	48	-0.06	-1.35	63	-0.09	-1.94
4	-0.00	-0.10	19	0.03	0.68	34	0.08	1.74	49	0.09	1.91	64	-0.02	-0.39
5	0.06	1.38	20	0.02	0.41	35	-0.07	-1.55	50	-0.05	-0.99	65	-0.11	-2.50
6	0.10	2.13	21	0.03	0.57	36	0.02	0.47	51	0.01	0.13	66	-0.05	-1.04
7	0.08	1.84	22	-0.02	-0.50	37	0.06	1.26	52	-0.02	-0.38	67	0.07	1.62
8	0.00	0.05	23	0.03	0.70	38	0.04	0.91	53	0.03	0.75			
9	0.05	1.11	24	0.05	1.00	39	-0.02	-0.41	54	-0.03	-0.74			
10	0.01	0.12	25	0.06	1.32	40	0.00	0.03	55	-0.02	-0.45			
11	0.02	0.34	26	0.03	0.65	41	0.02	0.50	56	0.06	1.30			
12	0.10	2.29	27	-0.03	-0.57	42	-0.06	-1.25	57	-0.08	-1.84			
13	0.01	0.23	28	-0.01	-0.31	43	0.04	0.98	58	-0.02	-0.34			
14	0.02	0.45	29	-0.03	-0.55	44	0.03	0.59	59	0.04	0.84			
15	-0.02	-0.42	30	-0.01	-0.13	45	-0.06	-1.38	60	-0.01	-0.17			

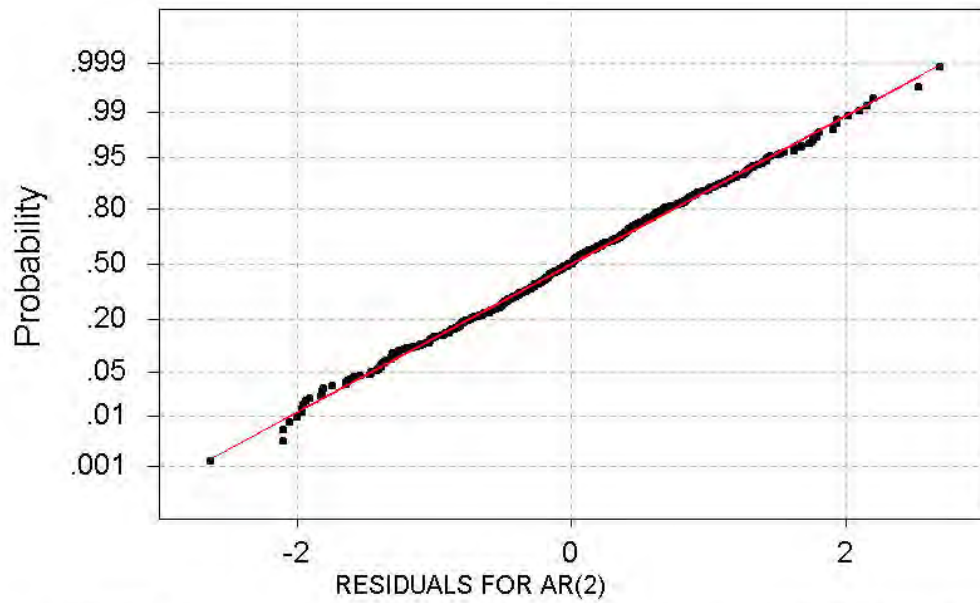
Normality Test for Residuals of AR(1)



Average: -0.0037840
 StDev: 0.883505
 N: 480

Anderson-Darling Normality Test
 A-Squared: 0.393
 P-Value: 0.374

Normality Test for Residuals of AR(2)



Average: -0.0052972
StDev: 0.878335
N: 480

Anderson-Darling Normality Test
A-Squared: 0.345
P-Value: 0.484

**ANNEX –II MODELING OF RECORDED VS SIMULATED RUNOFF
APPLYING SCS-CN METHOD**

ANNEX-II MODELING OF RECORDED Vs SIMULATED RUNOFFS APPLYING SCS-CN METHOD

Fig II-1 Modeling Recorded Vs Simulated Runoff at Megech Catchment Applying SCS-CN Method

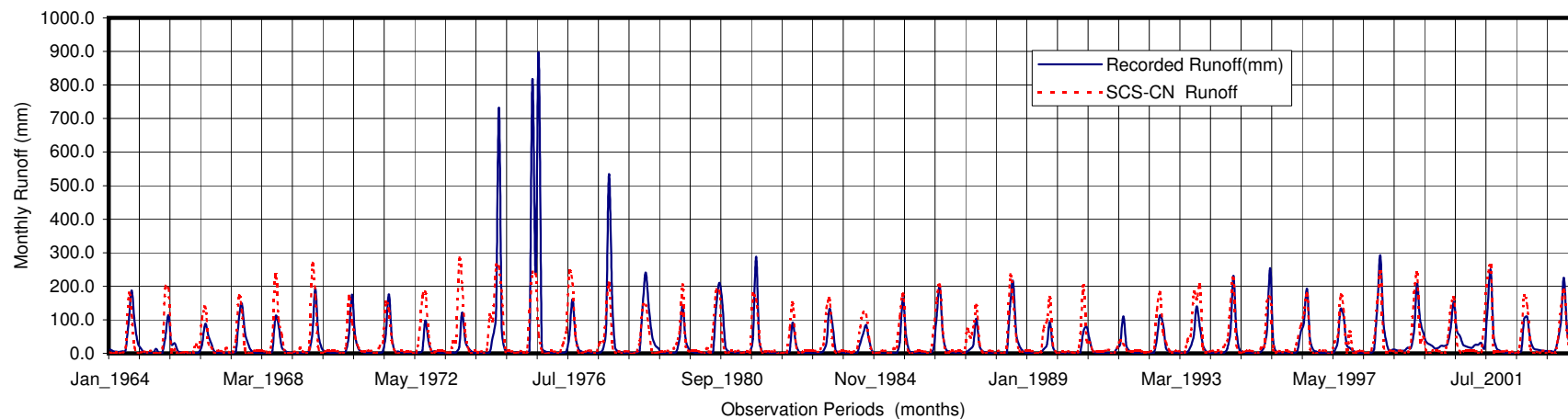


Fig II-2 Modeling Recorded Runoff Vs Simulated Runoff @ Megech Watershed Applying SCS-CN Method

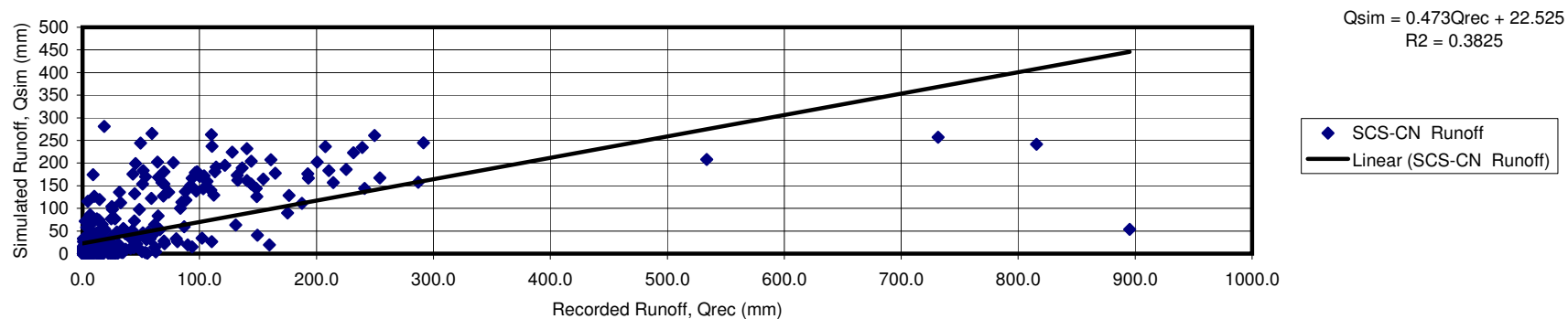


Fig II-3 Modeling Recorded Vs Simulated @ Gumaro watershed Applying SCS-CN Method

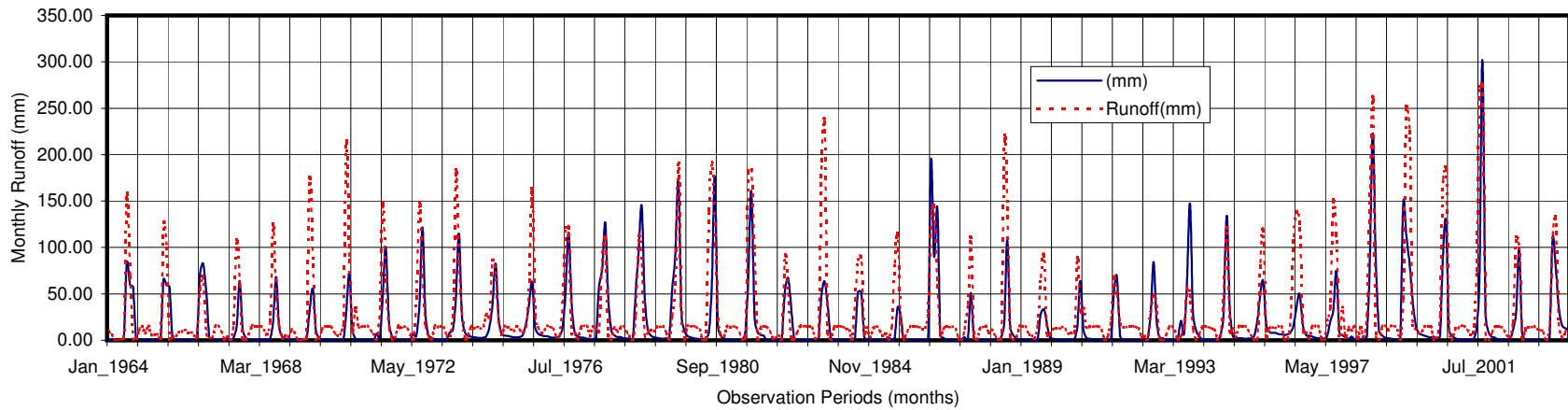


Fig II-4 Modeling Recorded Vs Simulated Runoffs at Gumaro Catchment Applying SCS-CN Method

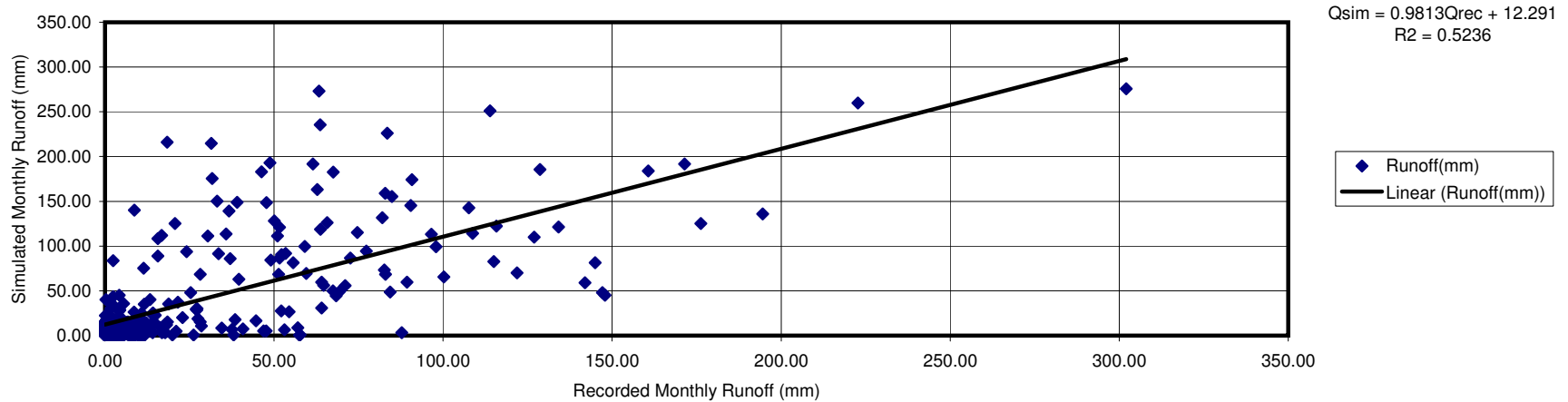


Fig II-5 Modeling Recorded Vs Simulated Runoffs at Garno Catchment Applying SCS-CN Method

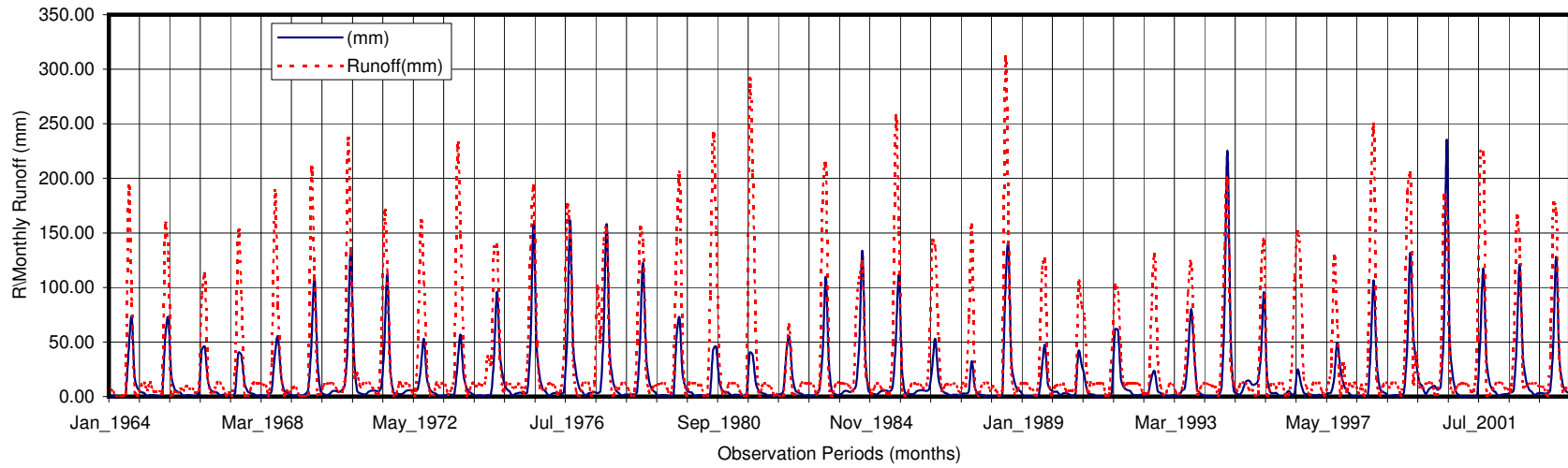
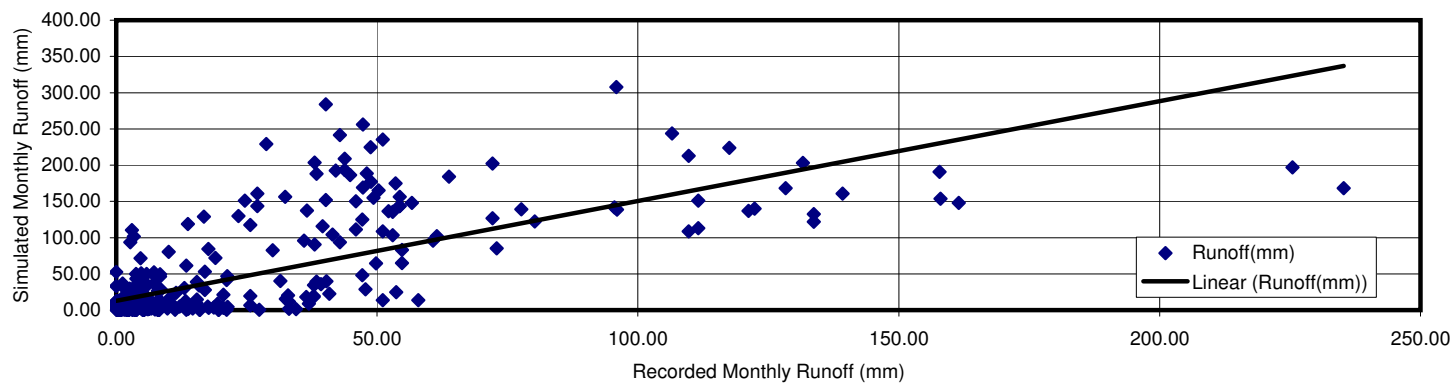


Fig II-6 Modeling Recorded Vs Simulated Runoff at Garno Catchment Applying SCS-CN Method



$$Q_{sim} = 1.377Q_{rec} + 12.738$$
$$R^2 = 0.5408$$

Fig II-7 Modeling Recorded Vs Simulated Runoff at Ribb Catchment Applying SCS-CN Method

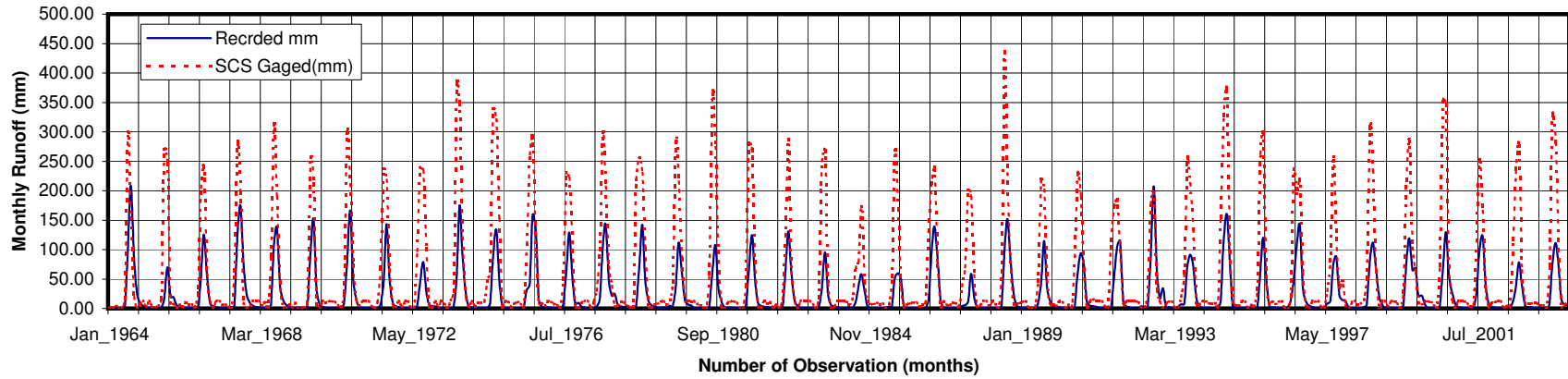


Fig II-8 Modeling Recorded Vs Simulated Runoffs at Ribb Catchment Applying SCS-CN Method

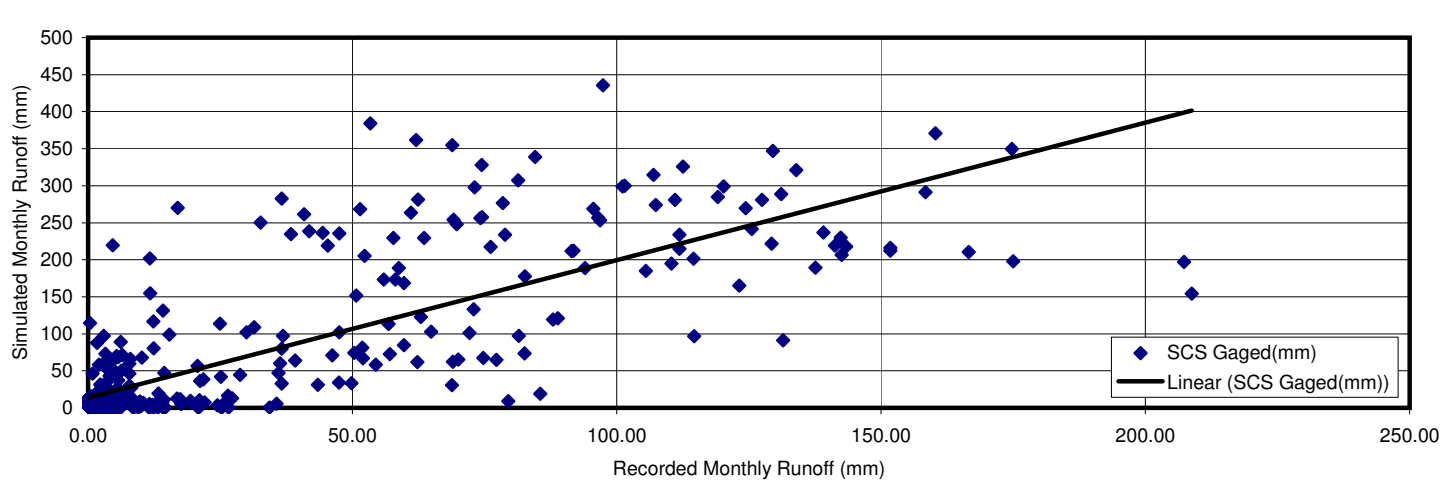


Fig II-9 Modeling Recorded Vs Simulated Runoffs at Gumara Catchment Applying SCS-CN Method

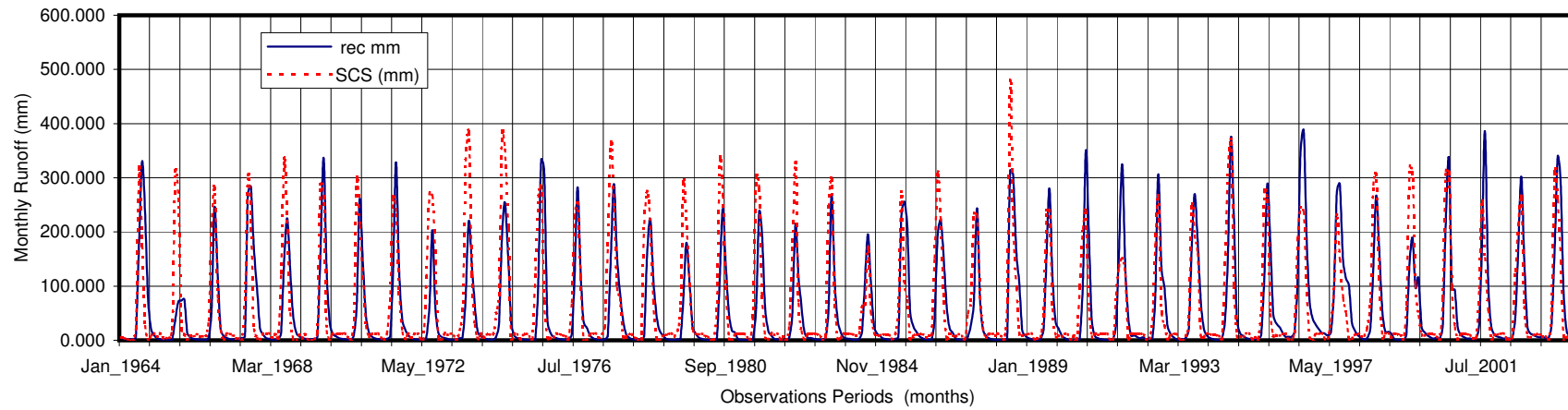


Fig II-10 Modeling Recorded Vs Simulated Runoff at Gumara Catchment Applying SCS-CN Method

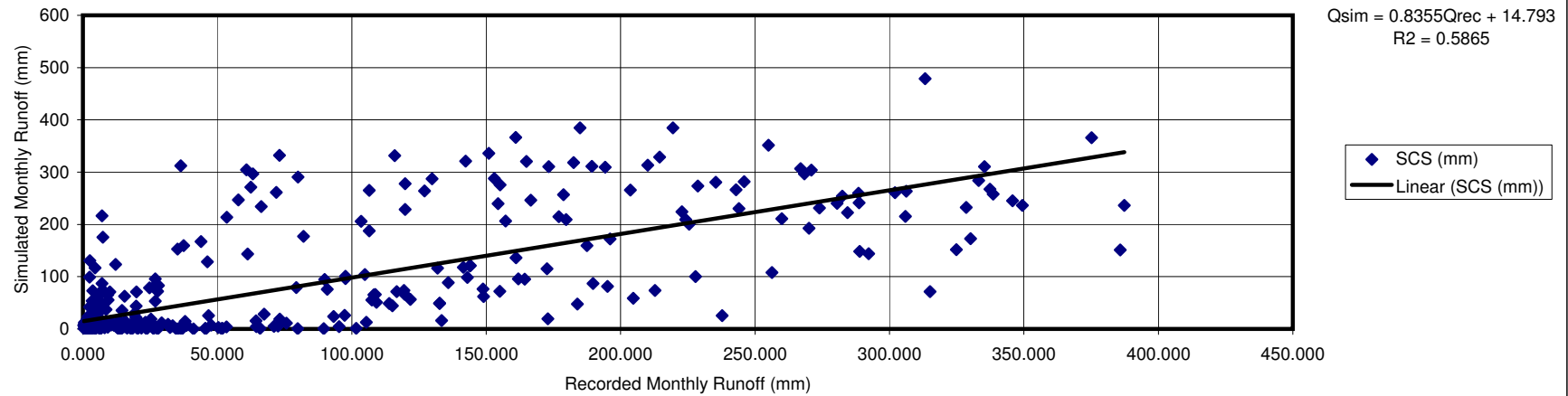


Fig II-11 Modeling Recorded Vs Simulated Runoffs at Gilgel Abbay Catchment

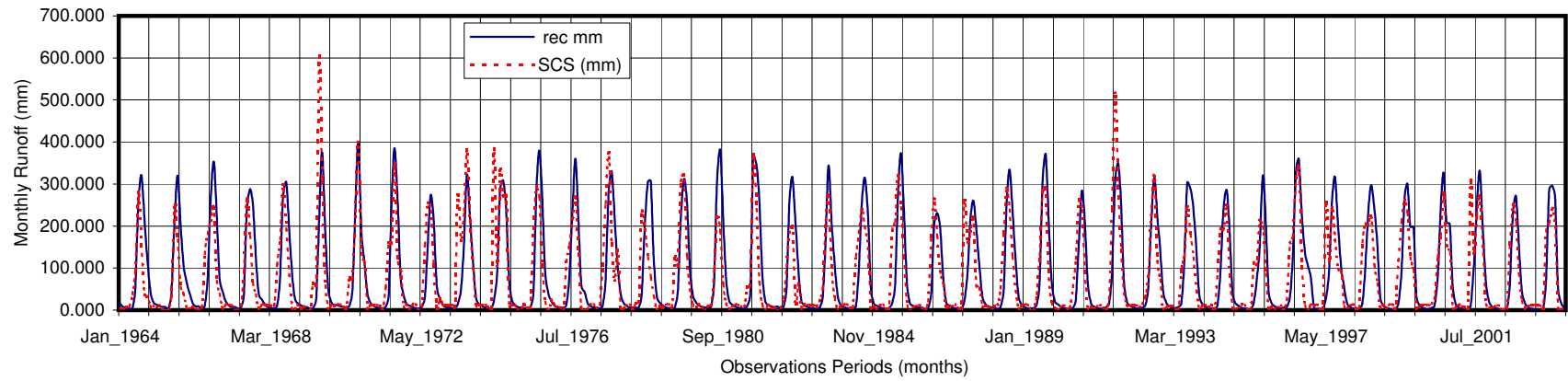


Fig II-12 Modeling Recorded Vs Simulated Runoffs at Gilgel Abbay Catchment Applying SCS-CN Method

$$Q_{sim} = 0.7145Q_{rec} + 17.148$$
$$R^2 = 0.601$$

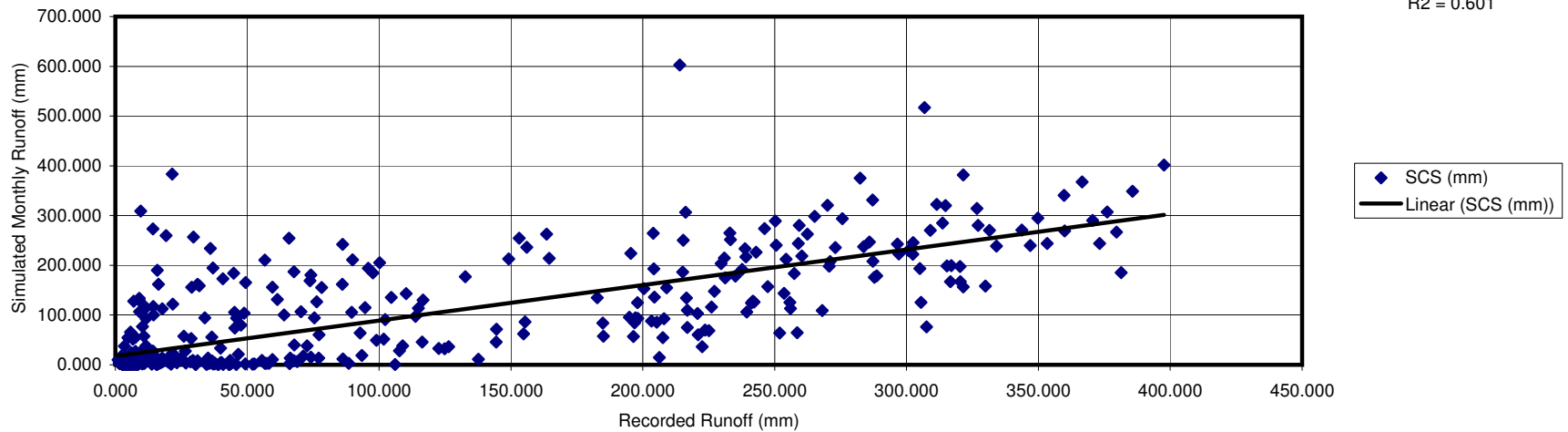


Fig II-13 Modeling Recorded Vs Simulated Runoff at Koga Catchment Applying SCS-CN Method

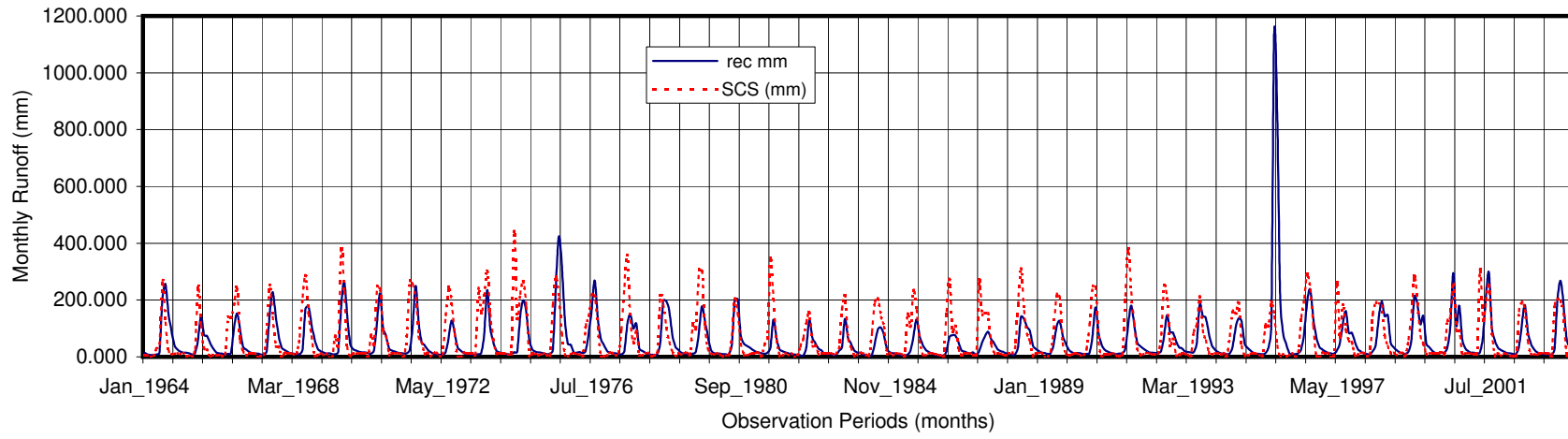
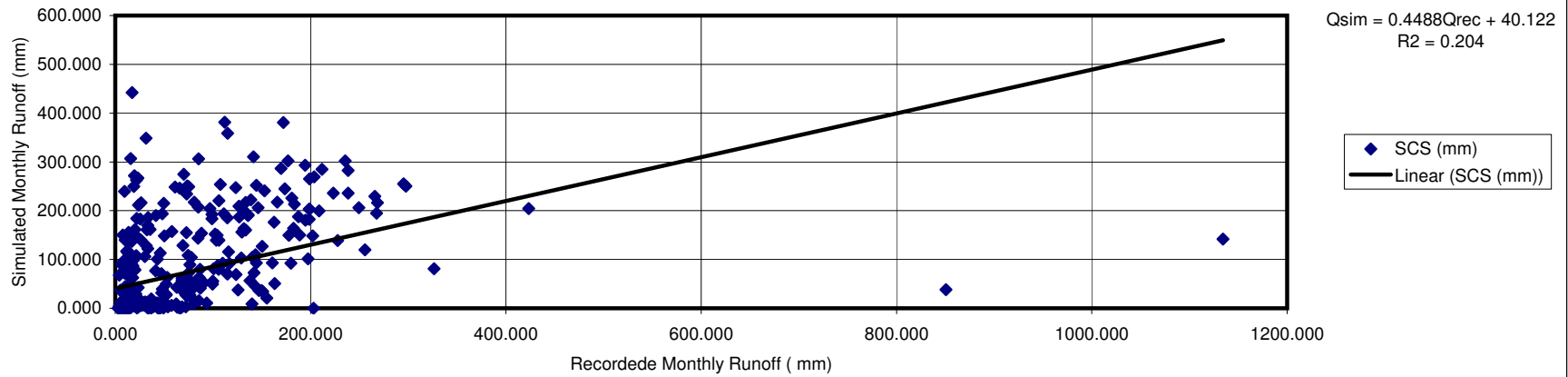


Fig II-14 Modeling Recorded Vs Simulated Runoffs at Koga Catchment Applying SCS-CN Method



ANNEX – III MODELING OF RECORDED Vs SIMULATED RUNOFFS

APPLYING SIMPLIFIED WATER BALANCE SIMULATIONS

ANNEX- III MODELING OF RECORDED Vs SIMULATED RUNOFF APPLYING SIMPLIFIED WATER BALANCE SIMULATIONS

Fig III-1 Rainfall-Runoff Modeling @ Megech Watershed Applying Water Balance Simulation Techniques

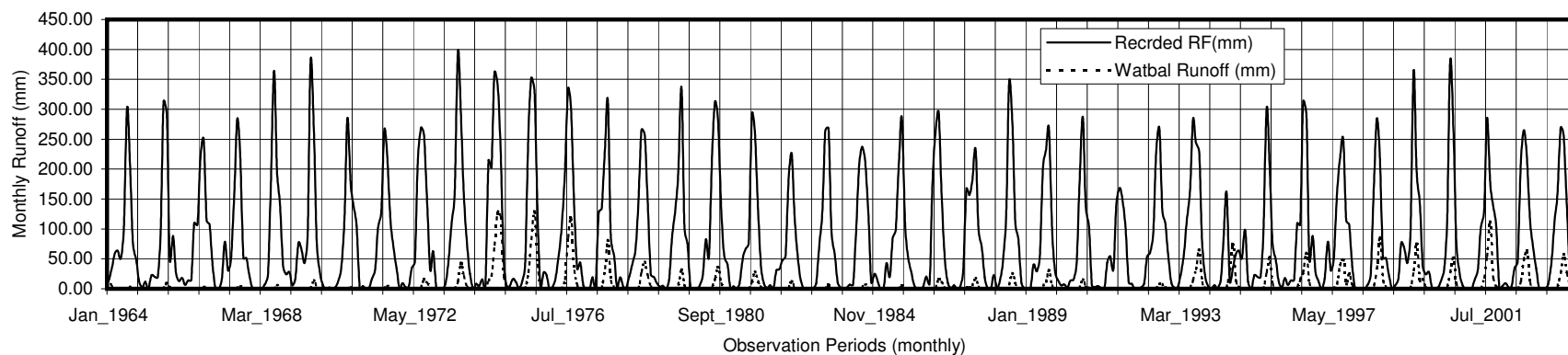


Fig III-2 WATBAL Runoff Estimated Vs Recorded Rainfall at Megech Catchment (After Optimizing Parameters)

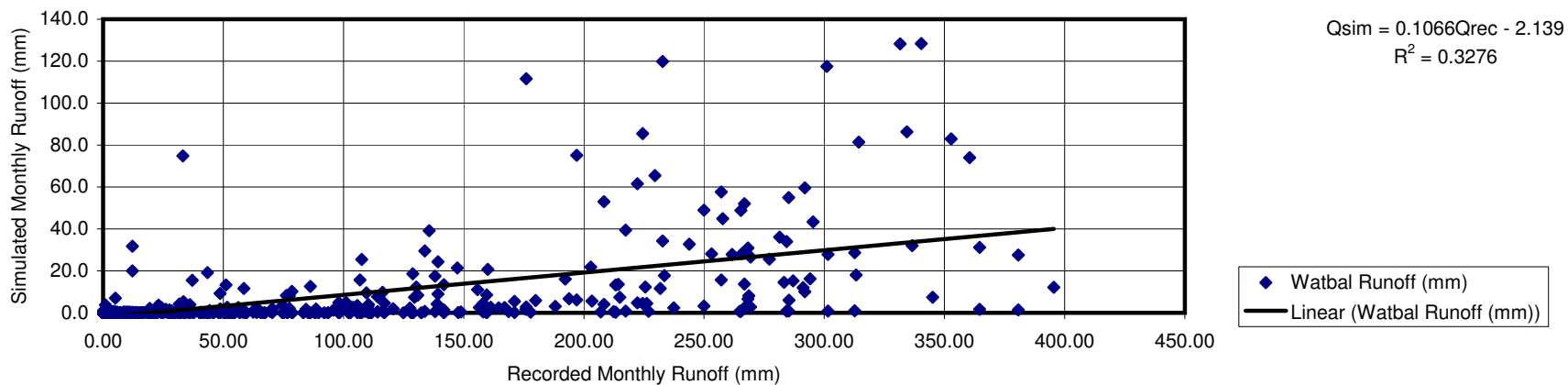


Fig III-3 Rainfall-Runoff Modeling @ Gumaro Watershed Applying Water Balance Simulation Techniques

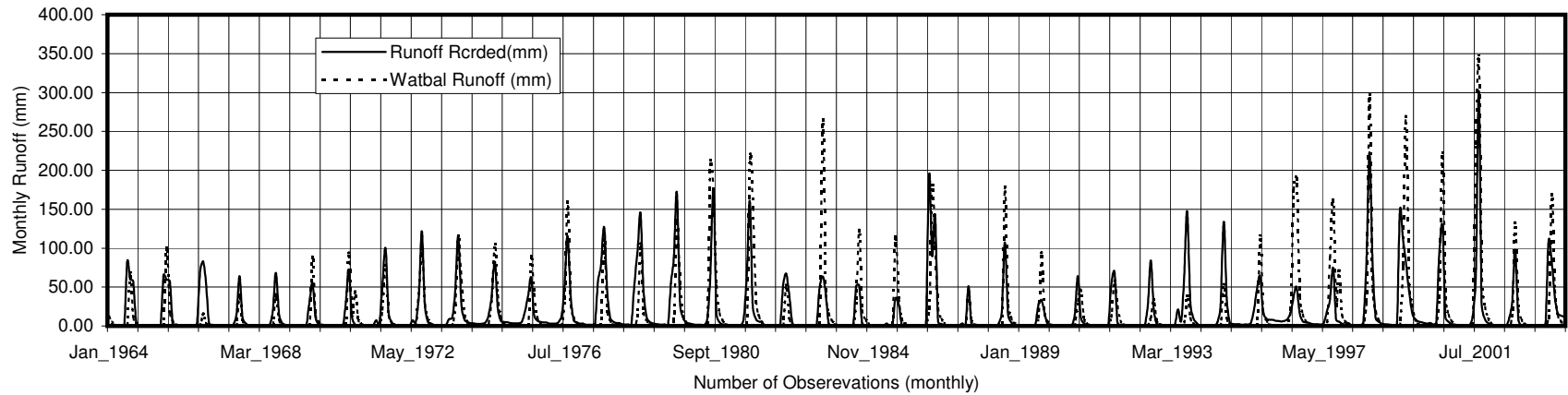


Fig III-4 Simulated Vs Recorded Runoff @ Gumaro: Watbal Method

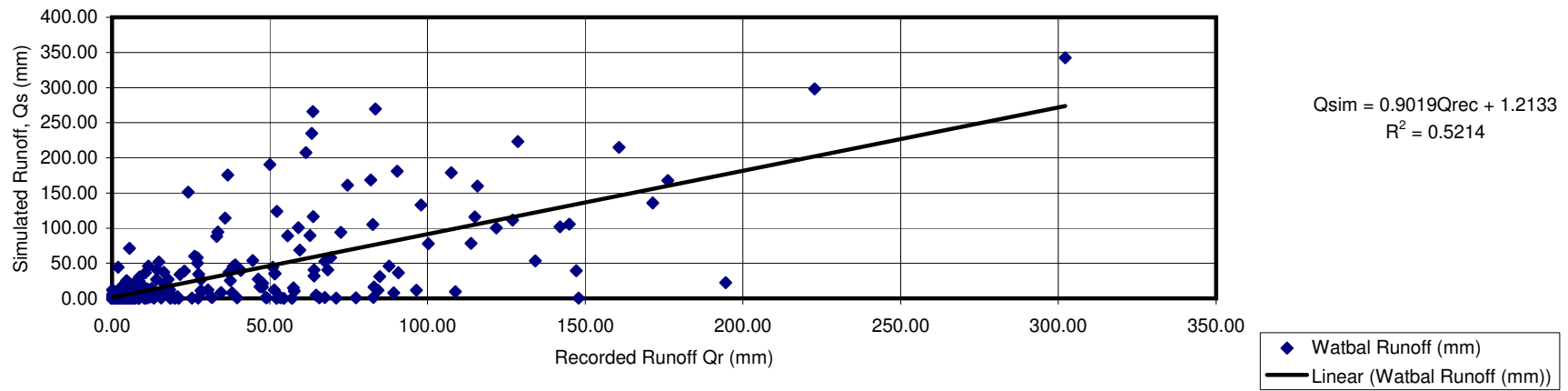


Fig III-5 Rainfall-Runoff Modeling at Garno Catchment Applying Water Balance Simulation Techniques

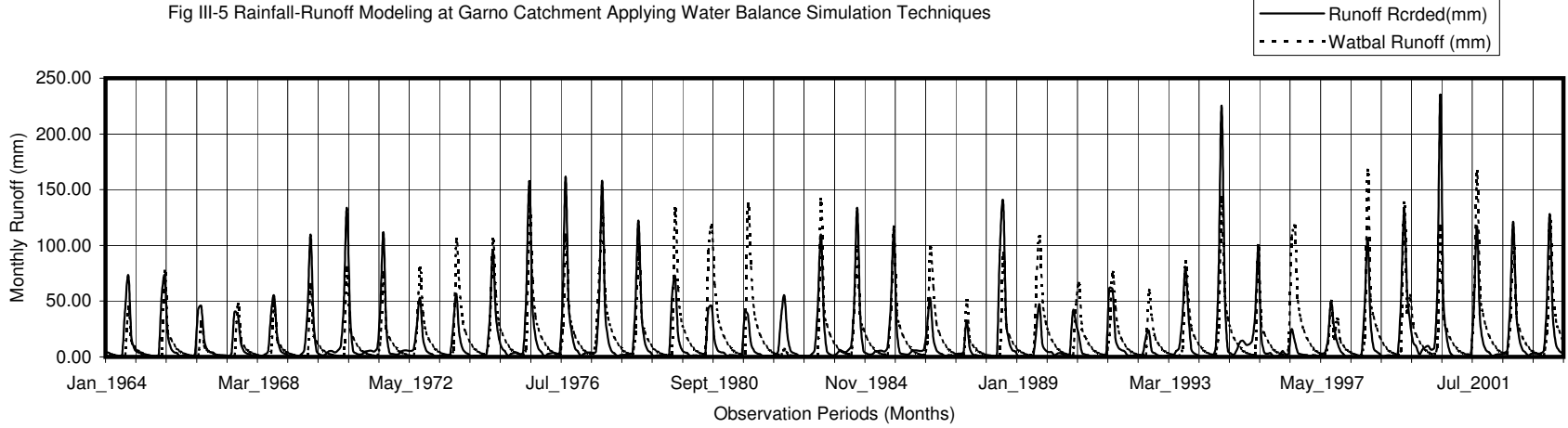


Fig III-6 Simulated Vs Recorded Runoff @ Garno: Watbal Method (After Optimizing Parameters)

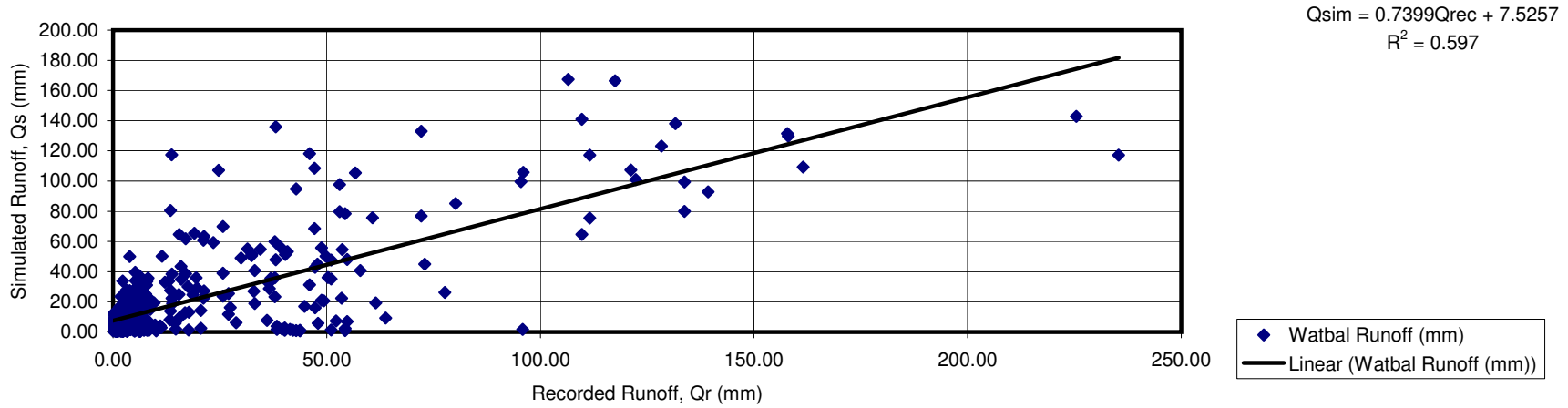


Fig III-7 Rainfall-Runoff Modeling @ Ribb Watershed Applying Waterbalance Simulation Techniques

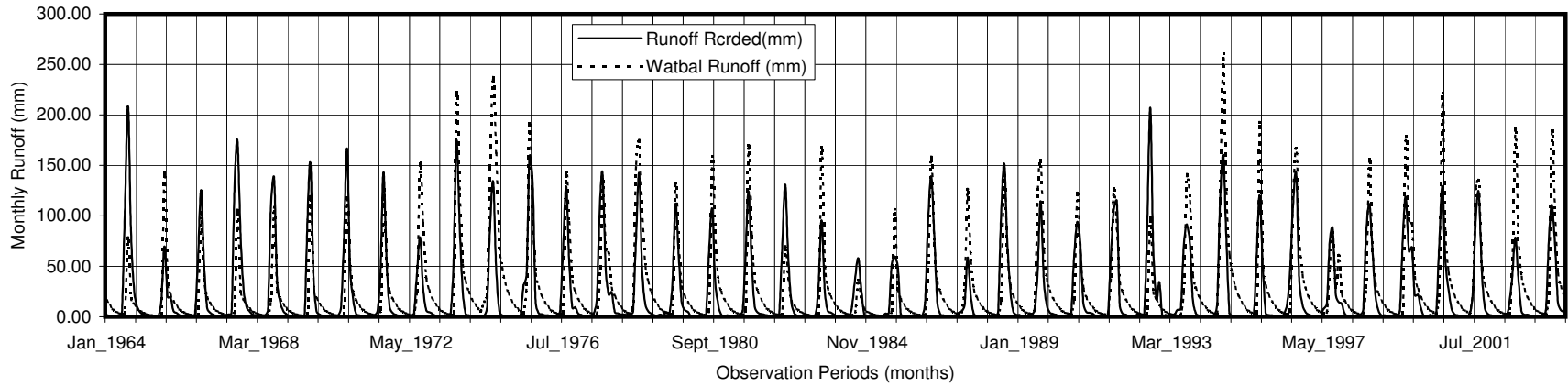


Fig III-8 Simulated Vs Recorded Runoff @ Ribb: Watbal Method

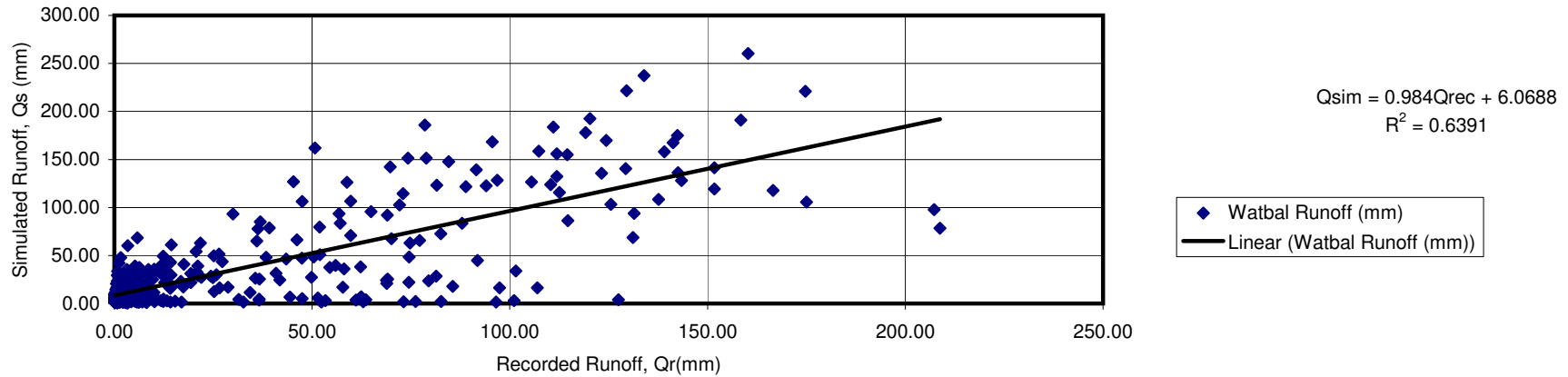


Fig III-9 Rainfall-Runoff Modeling @ Gumara Watershed Applying Waterbalance Simulation

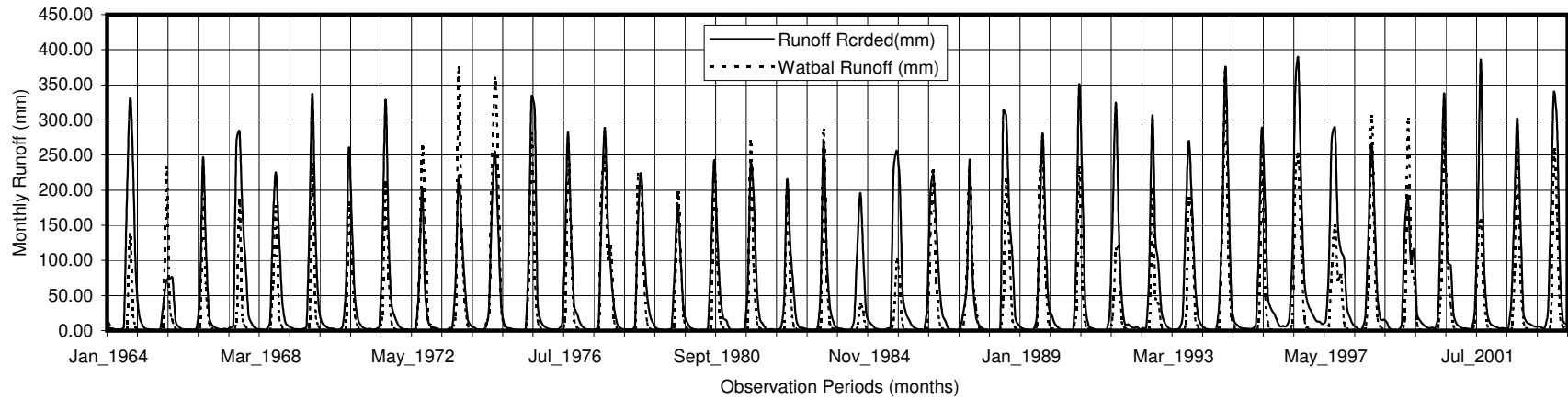


Fig III-10 Simulated Vs Recorded Runoff @ Gumara: Watbal Method

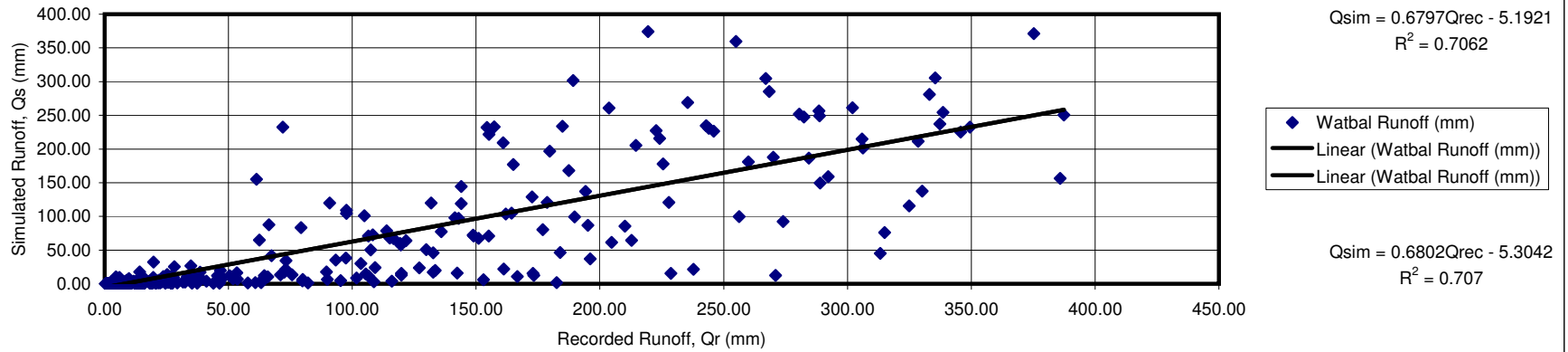


Fig III-11 Rainfall-Runoff Modeling @ Gilgel Abbay Watershed Applying Waterbalance Simulation Techniques

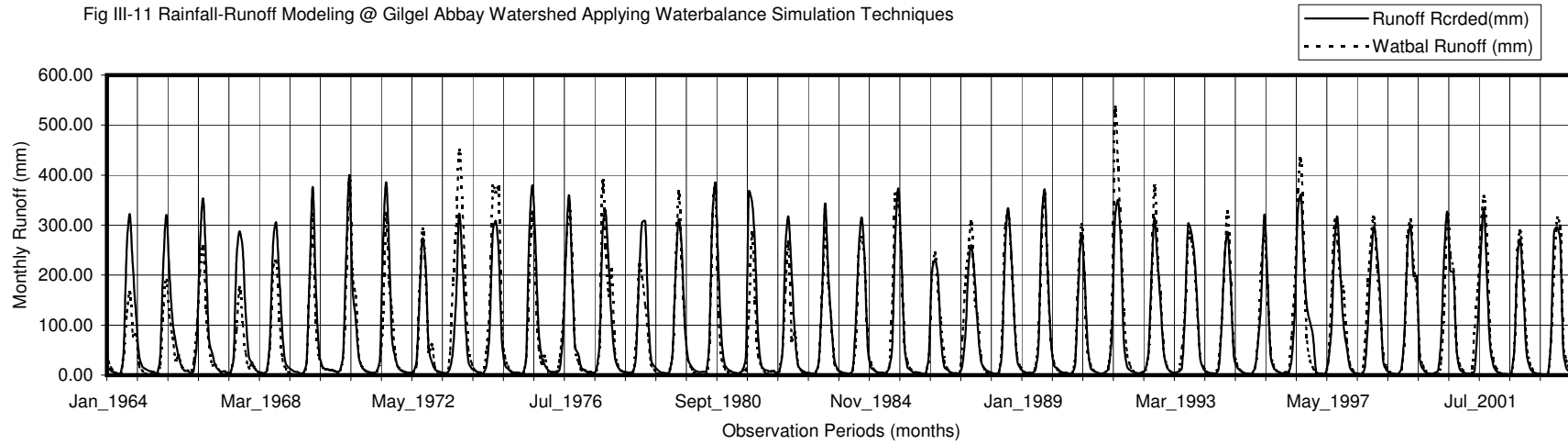
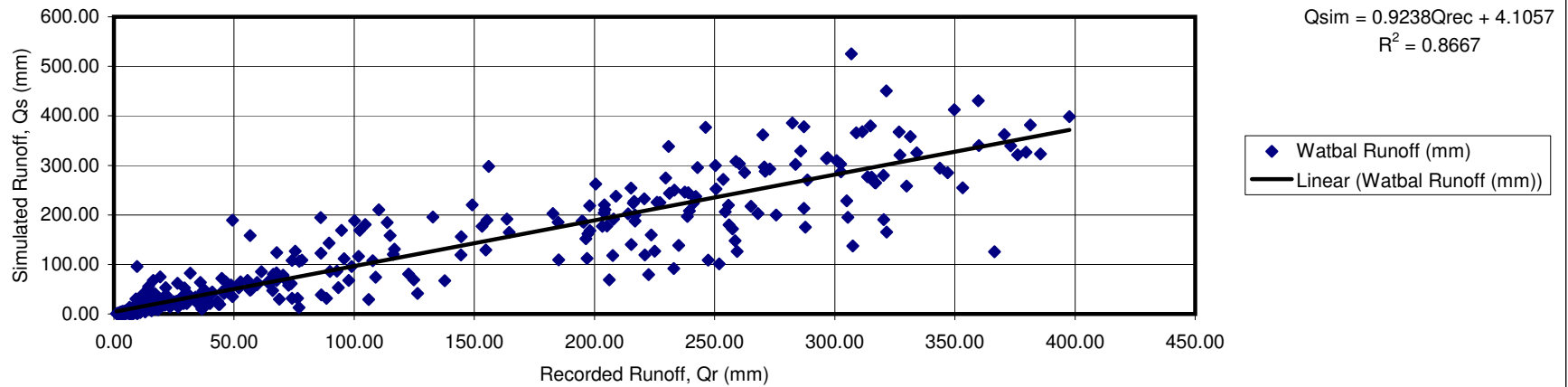


Fig III-12 Simulated Vs Recorded Runoff at Gilgel Abbay: Watbal Method



**ANNEX – IV RAINFALL – RUNOFF MODELING APPLYING SIMPLE LINEAR
REGRESSION TECHNIQUES**

ANNEX - IV RAINFALL-RUNOFF MODELING APPLYING REGRESSION TECHNIQUES

IV-1 North and North-West Sub Basins

IV-1-1 Regression Analysis: Rainfall Vs Runoff Made for Megech Catchment

The regression equation is:

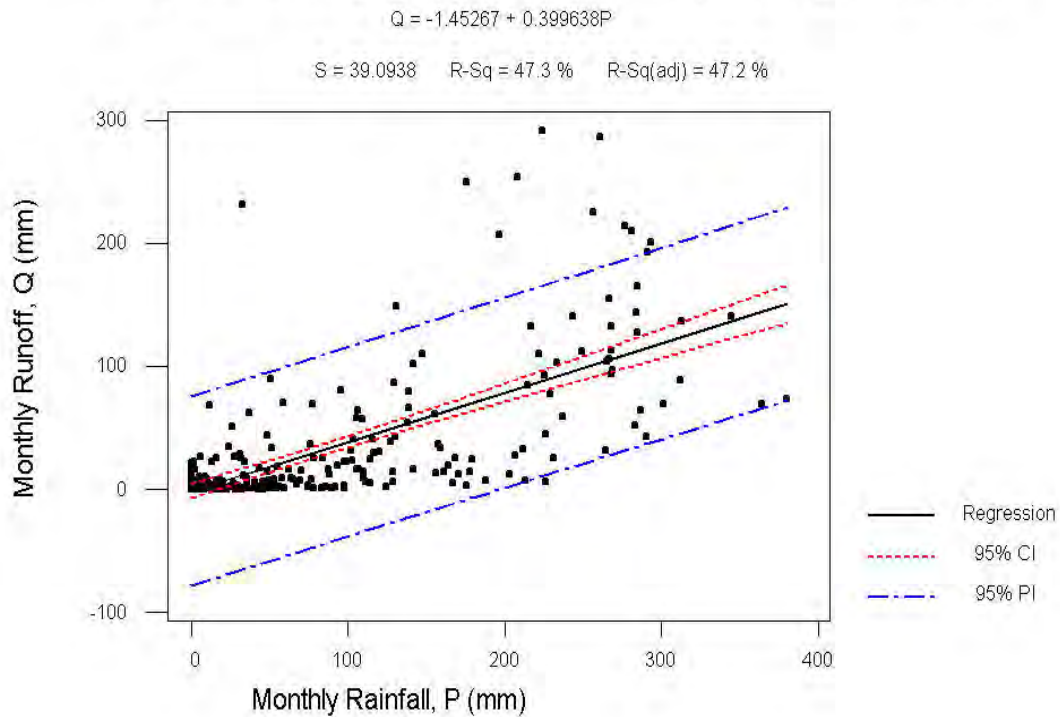
$$Q = -1.45267 + 0.399638P$$

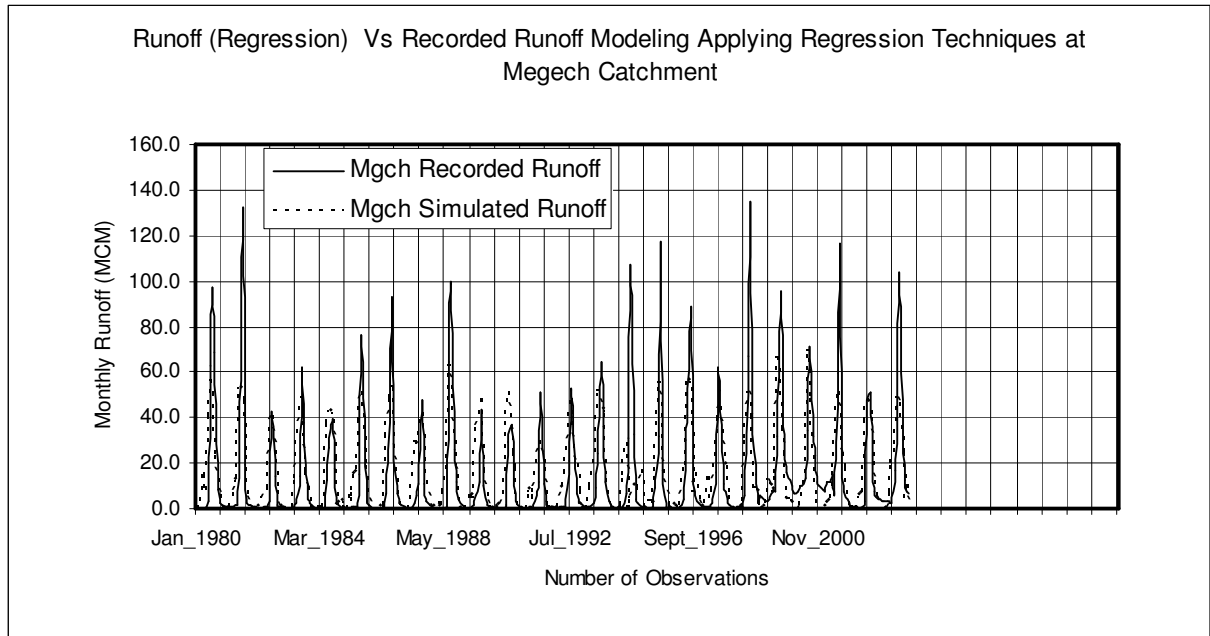
S = 39.0938 R-Sq = 47.3 % R-Sq(adj) = 47.2 %

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	393043	393043	257.173	0.000
Error	286	437100	1528		
Total	287	830143			

Rainfall-Runoff Modeling Applying Regression Techniques at Megech Catchment





IV-1-2 Regression Analysis: Rainfall Vs Runoff Made for Gumaro Catchment

The regression equation is:

$$Q = -1.32537 + 0.249775P$$

S = 31.1525 R-Sq = 36.4 % R-Sq(adj) = 36.1 %

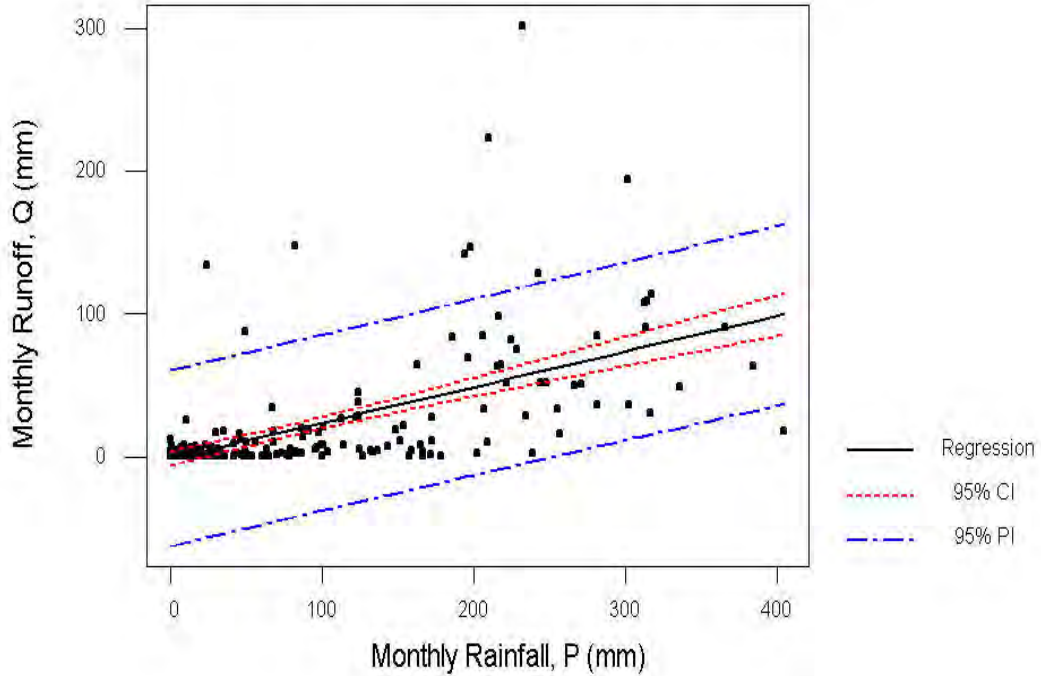
Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	132283	132283	136.307	0.000
Error	238	230974	970		
Total	239	363257			

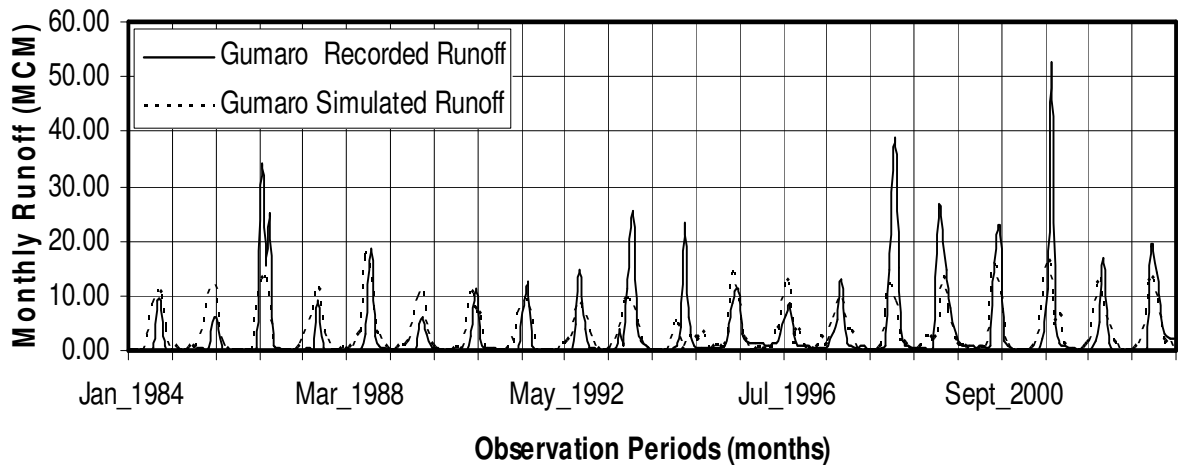
Rainfall-Runoff Modeling Applying Regression Techniques at Gumaro Catchment

$$Q = -1.32537 + 0.249775P$$

S = 31.1525 R-Sq = 36.4 % R-Sq(adj) = 36.1 %



Simulated Runoff Vs Recorded Runoff at Gumaro Catchment



IV-1-3 Regression Analysis: Rainfall Vs Runoff Made for Garno Catchment

The regression equation is:

$$Q = 2.05056 + 0.183461P$$

S = 27.9470 R-Sq = 32.3 % R-Sq(adj) = 32.0 %

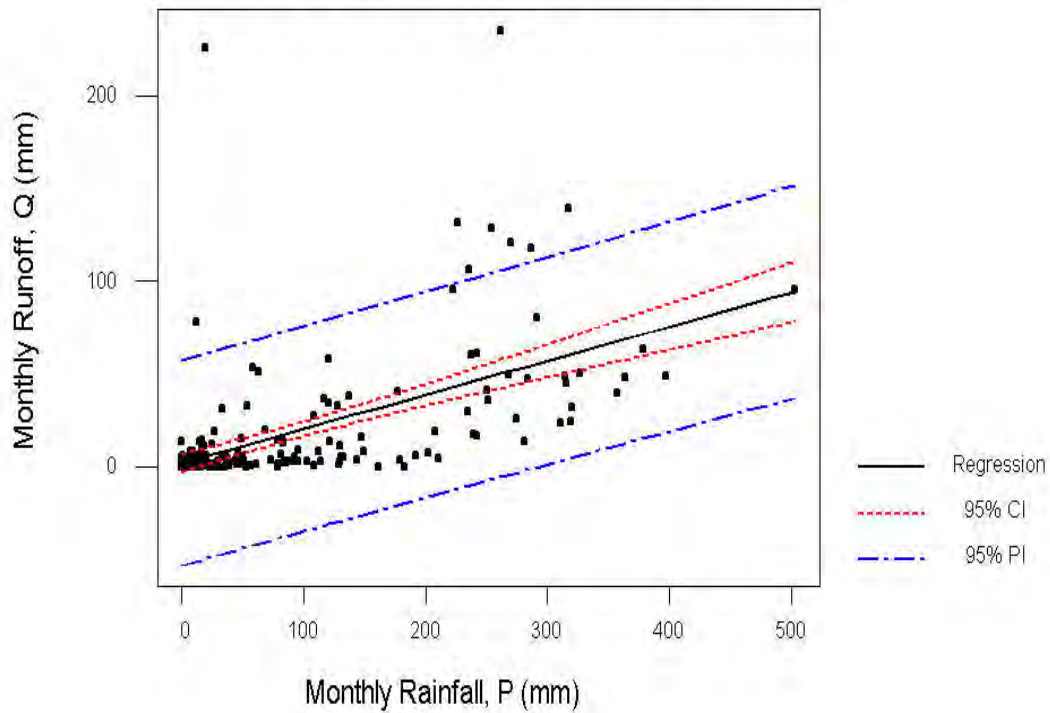
Analysis of Variance

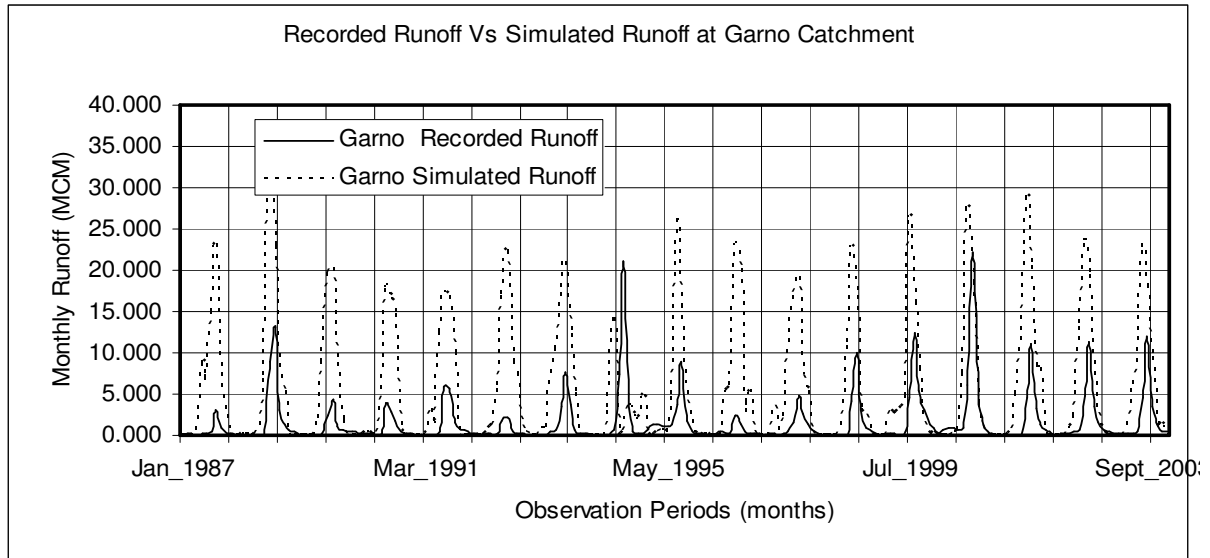
Source	DF	SS	MS	F	P
Regression	1	75237	75237.0	96.3297	0.000
Error	202	157769	781.0		
Total	203	233006			

Rainfall-Runoff Modeling Applying Regression Techniques at Garno Catchment

$$Q = 2.05056 + 0.183461P$$

S = 27.9470 R-Sq = 32.3 % R-Sq(adj) = 32.0 %





IV-2 East and South East Sub Basins

IV-2-1 Regression Analysis: Rainfall Vs Runoff Made for Ribb Catchment

The regression equation is:

$$Q = -0.577116 + 0.238447P$$

S = 24.4108 R-Sq = 61.6 % R-Sq(adj) = 61.5 %

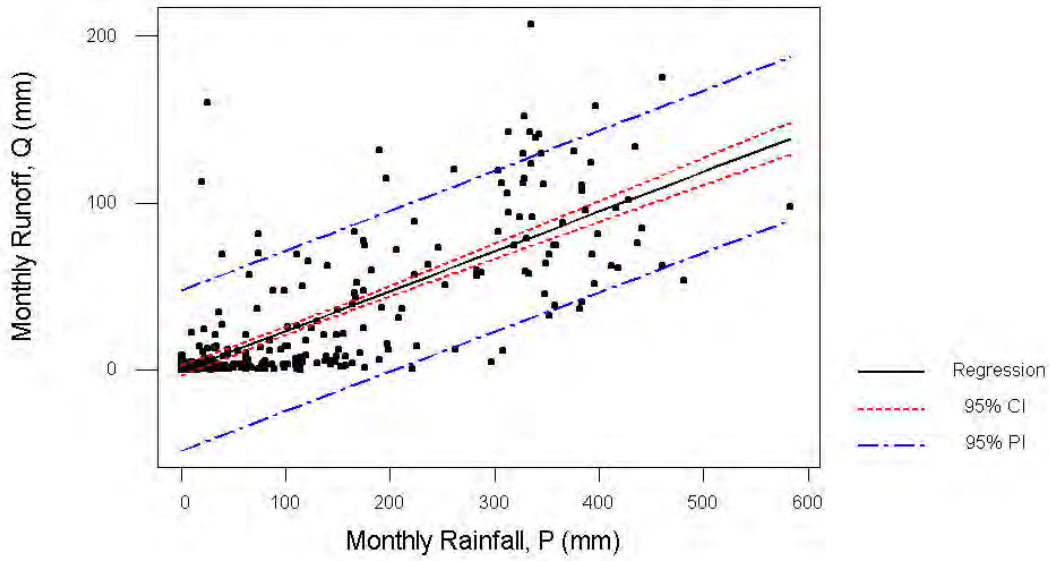
Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	353034	353034	592.453	0.000
Error	370	220477	596		
Total	371	573512			

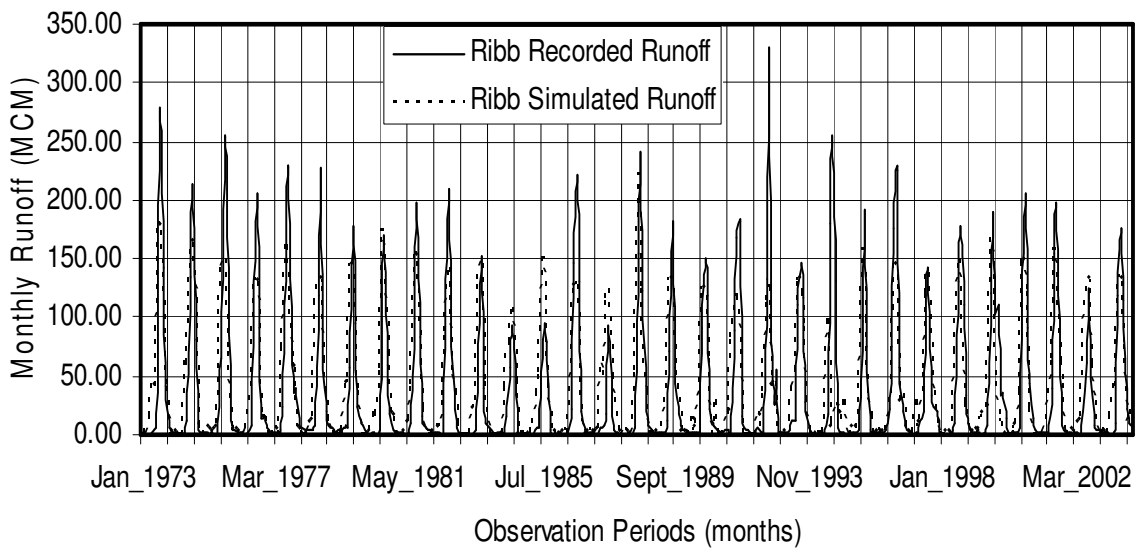
Rainfall-Runoff Modeling Applying Regression Techniques at Ribb Catchment

$$Q = -0.577116 + 0.238447P$$

S = 24.4108 R-Sq = 61.6 % R-Sq(adj) = 61.5 %



Simulated Runoff Vs Recorded Runoff at Ribb Catchment Applying Regression Techniques



IV-2-2 Regression Analysis: Rainfall-Runoff Made for Gumara Catchment

The regression equation is:

$$Q = 4.77102 + 0.526130P$$

S = 59.2385 R-Sq = 58.8 % R-Sq(adj) = 58.7 %

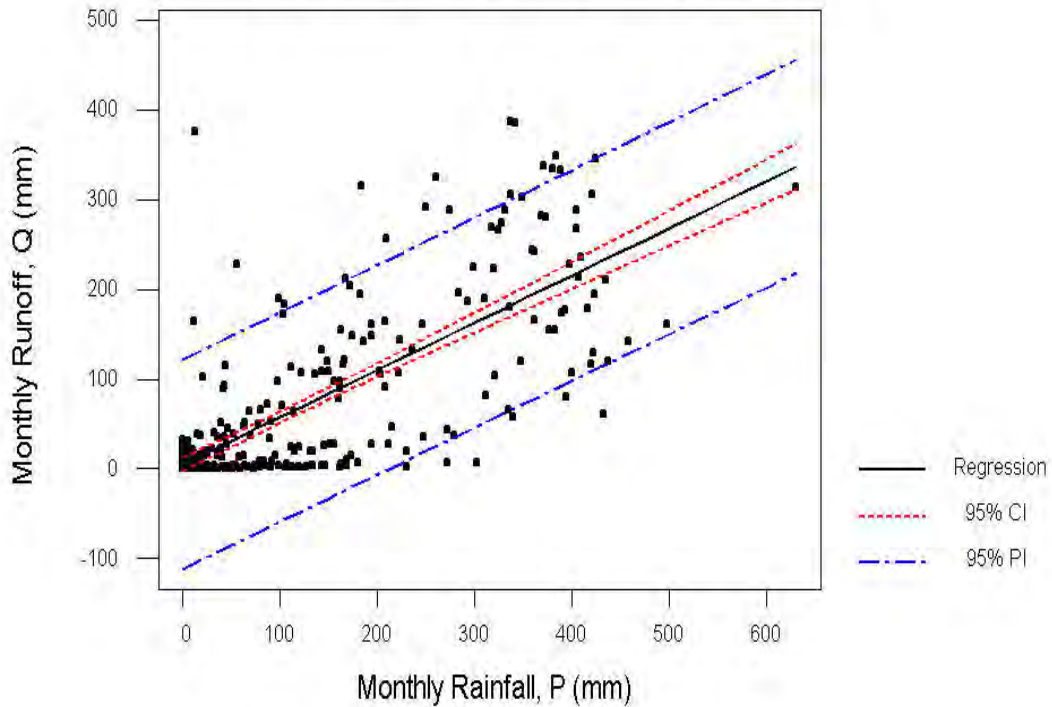
Analysis of Variance

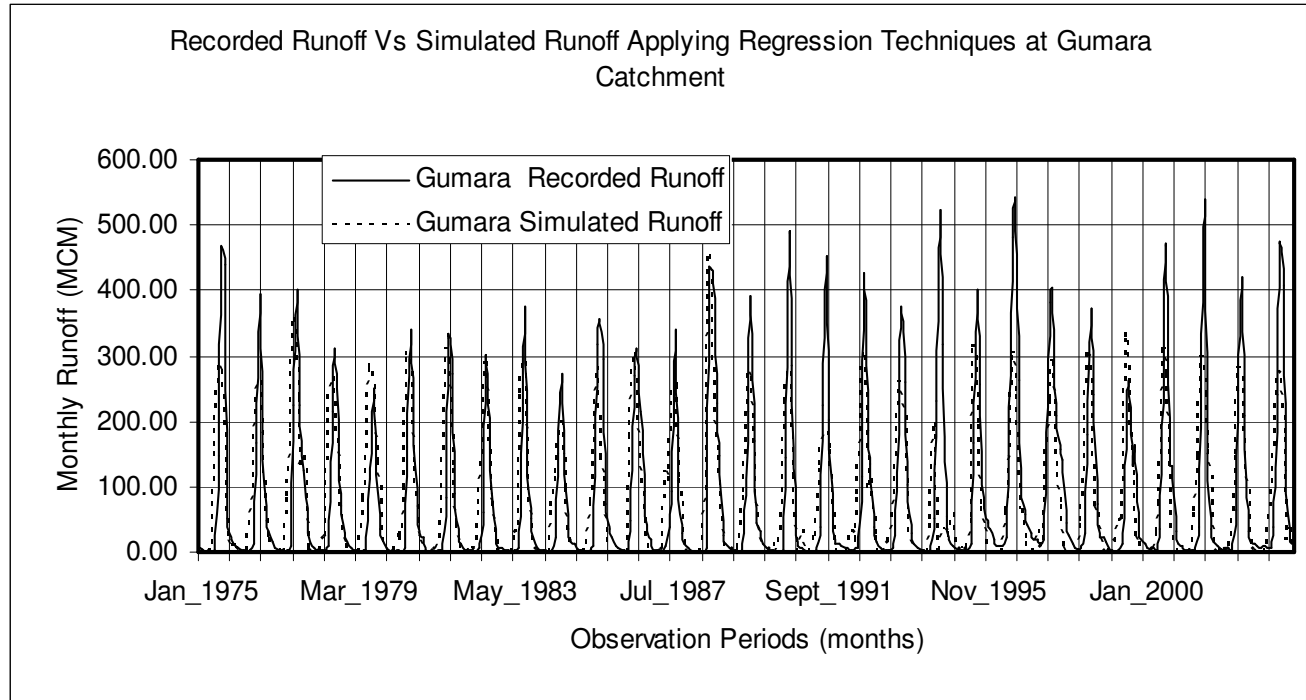
Source	DF	SS	MS	F	P
Regression	1	1735748	1735748	494.628	0.000
Error	346	1214183	3509		
Total	347	2949931			

Rainfall-Runoff Modeling Applying Regression Techniques at Gumara Catchment

$$Q = 4.77102 + 0.526130P$$

S = 59.2385 R-Sq = 58.8 % R-Sq(adj) = 58.7 %





IV-3 South Sub Basins

IV-3-1 Regression Analysis: Rainfall Vs Runoff Made for Koga Catchment

The regression equation is:

$$Q = 18.3794 + 0.269870P$$

S = 76.5962 R-Sq = 21.9 % R-Sq(adj) = 21.6 %

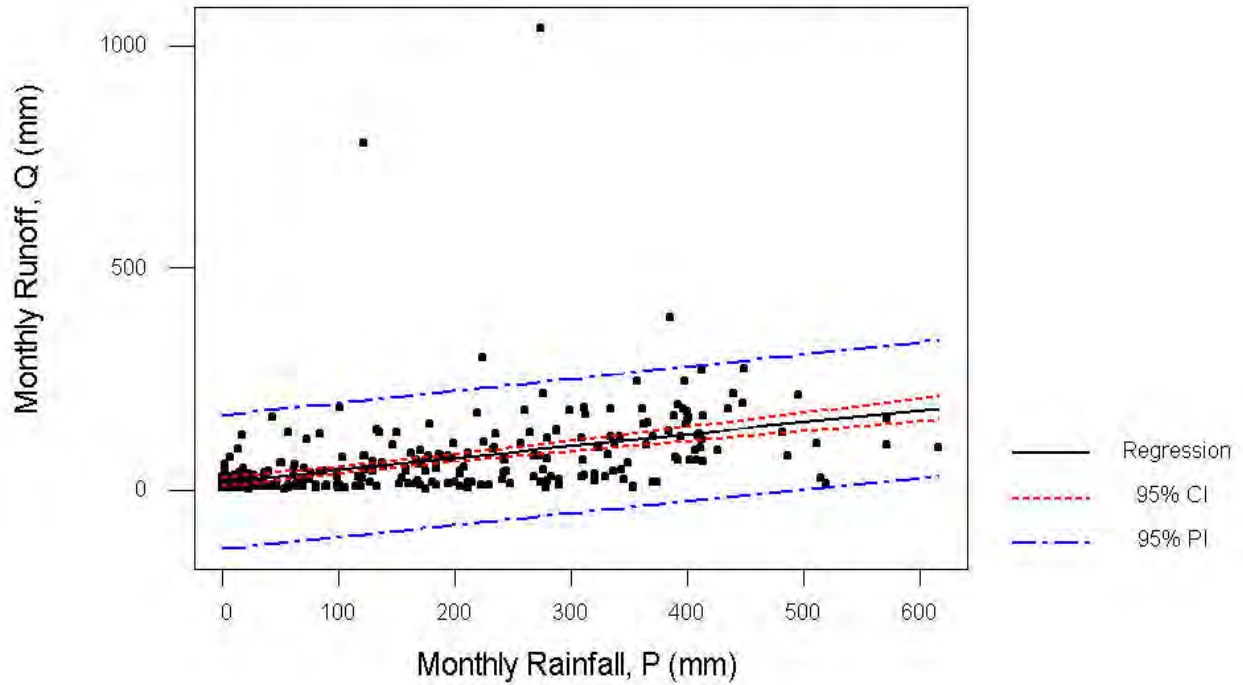
Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	606944	606944	103.451	0.000
Error	370	2170780	5867		
Total	371	2777724			

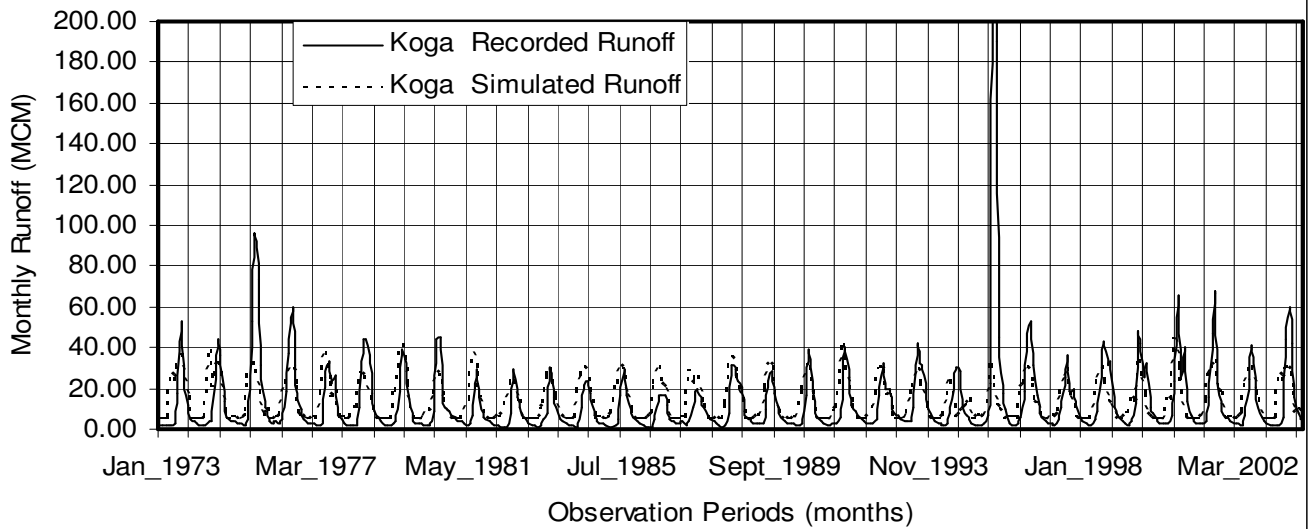
Rainfall-Runoff Modeling Applying Regression Techniques at Koga Catchment

$$Q = 18.3794 + 0.269870P$$

S = 76.5962 R-Sq = 21.9 % R-Sq(adj) = 21.6 %



Recorded Runoff Vs Simulated Runoff at Koga Catchment



IV-3-2 Regression Analysis: Rainfall Vs Runoff Made for Gilgel Abbay Catchment

The regression equation is:

$$Q = 8.79671 + 0.583891P$$

S = 69.2497 R-Sq = 61.1 % R-Sq(adj) = 61.0 %

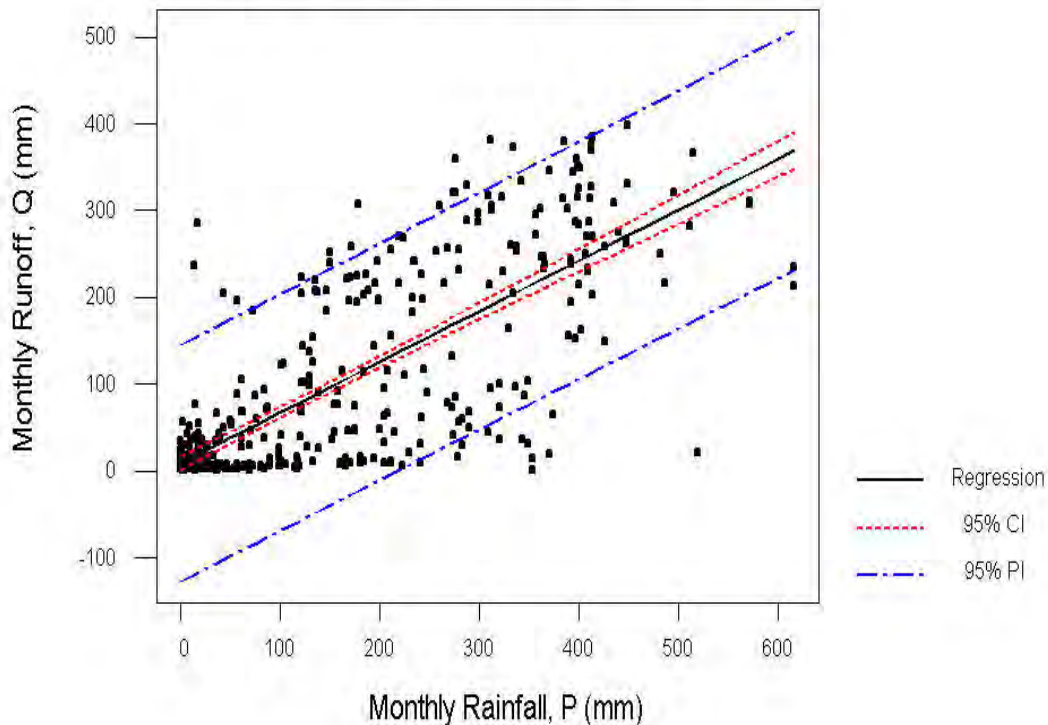
Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	3605046	3605046	751.752	0.000
Error	478	2292260	4796		
Total	479	5897306			

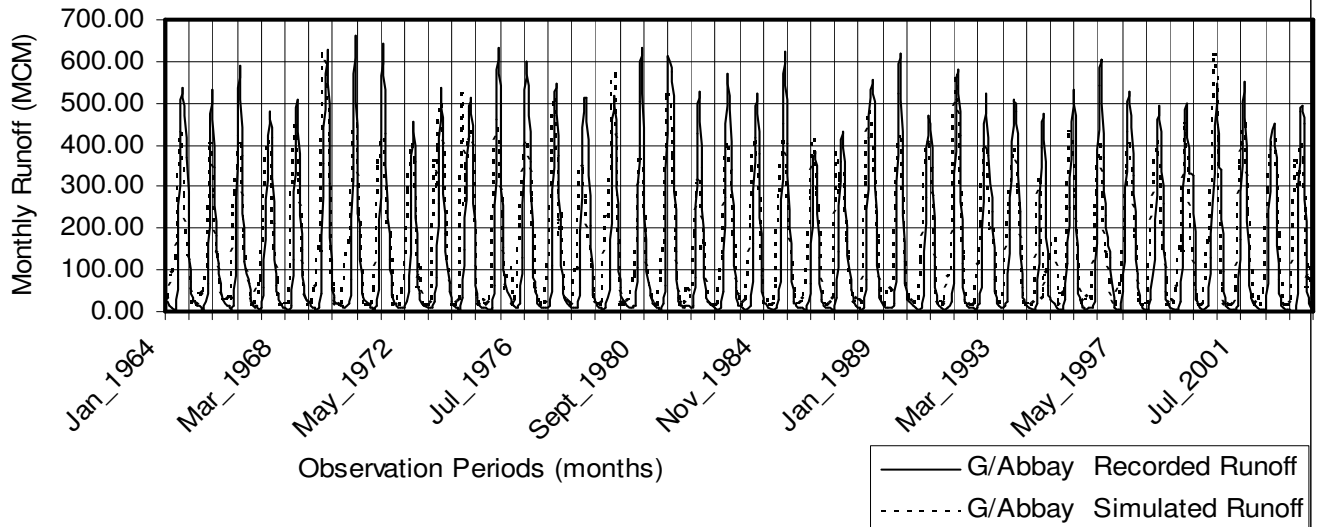
Rainfall-Runoff Modeling Applying Regression Techniques at Gilgel Abbay Catchment

$$GQ = 8.79671 + 0.583891P$$

S = 69.2497 R-Sq = 61.1 % R-Sq(adj) = 61.0 %



Simulated Runoff Vs Recorded Runoff at Gilgel Abbay Catchment Applying Regression Techniques



Table_____ Enjibara Meteo Station Monthly Rainfall (mm)

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
1964	29.7	35.8	171.9	140.0	124.1	394.0	491.4	406.7
1965	20.9	6.4	118.7	77.1	37.8	129.0	429.4	442.0
1966	6.4	41.2	57.0	24.2	175.2	371.1	453.4	451.2
1967	0.0	4.9	64.0	38.4	74.4	259.9	490.8	454.4
1968	0.0	0.0	5.9	6.3	316.3	213.0	529.5	488.1
1969	42.9	16.9	111.3	60.4	113.8	252.7	1334.1	671.8
1970	0.1	0.0	40.1	146.7	151.0	306.8	371.4	1022.1
1971	5.2	0.0	6.4	12.5	57.0	58.0	68.0	902.4
1972	52.2	0.9	0.3	56.0	58.8	329.3	457.6	530.3
1973	0.0	0.0	3.3	19.8	425.1	356.9	449.3	765.1
1974	3.0	2.4	16.2	63.2	265.8	172.6	769.7	477.0
1975	49.7	29.5	0.3	25.7	48.7	375.5	520.1	584.4
1976	0.0	11.7	29.6	76.7	215.7	335.9	400.9	580.2
1977	0.0	0.2	31.8	4.9	185.1	434.7	618.2	389.0
1978	6.4	1.2	61.4	178.8	91.1	437.1	375.8	334.0
1979	28.2	0.3	0.4	16.4	230.0	267.5	502.4	573.0
1980	0.0	17.9	79.6	127.9	96.5	291.0	424.5	440.1
1981	0.0	0.0	14.7	158.5	180.7	168.2	618.2	509.0
1982	29.8	29.1	103.6	32.4	68.3	371.7	493.1	463.4
1983	0.5	2.2	10.0	25.0	100.4	213.4	494.8	565.1
1984	0.0	0.0	25.5	13.2	310.1	318.5	530.8	527.4
1985	5.4	1.3	59.6	81.8	356.0	656.2	729.3	664.8
1986	20.9	0.0	33.1	70.0	286.1	363.8	450.3	555.8
1987	20.9	0.0	33.1	70.0	286.1	363.8	450.3	555.8
1988	8.9	33.4	15.1	9.8	254.6	345.9	452.9	587.4
1989	2.6	1.6	80.9	57.4	221.3	342.3	620.4	693.9
1990	30.4	0.0	45.1	4.2	186.2	221.4	510.2	480.4
1991	20.2	7.5	27.0	107.7	232.5	474.6	1096.9	690.4
1992	0.0	5.7	14.0	164.2	194.7	249.3	367.0	484.1
1993	9.2	11.5	61.6	142.2	212.9	367.2	445.3	535.3
1994	7.0	22.3	0.0	42.6	209.0	435.7	416.1	560.4
1995	0.0	5.9	61.4	45.6	195.5	266.8	411.1	483.6
1996	2.6	8.6	76.6	164.8	289.8	297.8	555.1	792.9
1997	7.2	3.9	49.4	47.6	317.6	376.9	543.1	505.0
1998	13.3	0.9	10.3	30.6	262.5	439.2	401.1	487.0
1999	17.4	0.0	0.4	69.3	295.3	520.0	388.4	497.0
2000	0.0	0.0	6.5	130.8	190.7	293.9	405.4	545.3
2001	0.0	20.0	24.2	68.2	191.0	327.6	417.2	511.5
2002	21.8	2.9	24.7	29.3	93.3	372.9	566.2	500.2
2003	0.2	0.6	4.2	8.3	9.8	378.0	382.9	539.1
Mean	11.6	8.2	39.5	66.2	190.3	328.8	510.8	556.2

Sep	Oct	Nov	Dec	Annual Total
208.8	225.0	18.0	18.0	2263.5
297.7	187.7	223.3	27.9	1997.9
246.9	200.7	50.7	0.0	2078.0
299.5	136.2	119.1	0.0	1941.6
281.4	70.7	34.0	1.3	1946.6
278.6	90.8	4.1	4.0	2981.4
437.4	355.5	41.1	0.7	2873.0
404.3	353.5	13.6	0.0	1881.0
346.8	86.9	334.5	0.0	2253.6
583.6	315.3	14.2	0.0	2932.6
727.9	122.9	1.4	5.9	2627.9
364.2	159.4	96.4	262.4	2516.4
396.2	82.0	111.0	51.8	2291.7
270.5	396.9	67.4	40.7	2439.4
298.8	196.1	89.4	6.6	2076.7
355.7	221.8	0.3	19.0	2215.0
246.7	124.2	35.8	17.6	1901.8
233.8	114.8	70.0	0.6	2068.7
0.0	253.9	26.2	0.3	1871.7
342.1	108.5	78.6	3.0	1943.6
481.5	71.1	30.3	41.8	2350.2
504.4	109.5	139.6	44.2	3352.1
235.0	288.7	25.9	25.8	2355.4
235.0	288.7	25.9	25.8	2355.4
399.3	163.3	29.5	14.6	2314.7
288.3	138.0	34.9	89.9	2571.5
418.3	76.7	22.4	20.1	2015.4
426.1	202.1	3.5	0.9	3289.4
407.9	223.2	62.7	25.5	2198.3
421.6	239.6	56.4	5.0	2507.8
383.4	75.4	37.5	42.3	2231.7
389.4	58.4	12.6	23.3	1953.6
246.5	152.6	9.6	0.0	2596.9
367.4	333.6	272.7	37.2	2861.6
359.7	249.3	46.0	4.9	2304.8
442.0	347.3	92.0	14.5	2683.6
484.9	400.8	62.8	48.4	2569.5
529.0	137.7	43.5	20.8	2290.7
336.6	159.0	39.9	2.5	2149.3
520.1	27.9	59.1	31.9	1962.1
362.4	188.6	63.4	24.5	2350.4