ARBA MINCH UNIVERSITY

SCHOOL OF POST GRADUATE STUDIES

DEPARTMENT OF HYDROLOGY AND WATER RESOURCE MANAGEMENT

INVESTIGATION AND HYDROLOGICAL CHARACTERIZATION OF SURFACE WATER STORAGE OPTIONS IN THE UPPER BLUE NILE

Case Study of Koga and Gomit Dam

By Fuad Abdo Yassin

08/24/2009

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By Fuad Abdo Yassin

A Dissertation Submitted in Partial Fulfillment of the Requirements for the Degree of Master of Science (Engineering) of the Arba Minch University

Arba Minch University

August 2009

CERTIFICATION

The undersigned certifies that he has read the dissertation entitled **Investigation and hydrological characterization of water storage options in the Upper Blue Nile** and hereby recommend for acceptance by the Arba Minch University in partial fulfillment of the requirements for the degree of Master of Science (Engineering).

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Dr. Matthew McCartney

(SUPERVISOR)

Date ____________________________________

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Ato Fisseha Behulu

(Co-SUPERVISOR)

Date ____________________________________

DECLARATION

I, Fuad Abdo Yassin, declare that this dissertation is my own original work and that it has not been presented and will not be presented by me to any other University for similar or any other degree award.

Signature: ______________________________

ABSTRACT

The aim of this study was to summarize potential surface water storage on natural lakes and on existing and planned Irrigations, hydropower and multipurpose projects in the upper Blue Nile (UBN). Daily rainfall runoff modeling and reservoir simulation was conducted using HEC-HMS. The Koga and Gomit storage dams were assessed in terms of Reliability, Resilience and Vulnerability (RRV) performance criteria under both existing and hypothetical future climate conditions.

Existing storage in the UBN comprises natural lakes (28 BCM), as well as artificial storage formed by a weir (9.1 BCM), small (6.1 MCM) and large dams (873.1 MCM). Future storage for ongoing and planned irrigation, hydropower and multipurpose projects totals 79.6 BCM.

A Digital Elevation Model (DEM) of the study area was used to extract the physical characteristics of watersheds using Arc-Hydro and the Geospatial Hydrologic Model Extension HEC-GeoHMS. Then in HEC-HMS, six and four years of hydrological and climatic time series data were used for Koga calibration and validation respectively and two years of reservoir level data was used for Gomit calibration.

Simulation was conducted with two sets of models: first the Deficit–Constant loss model, Snyder UH model and monthly constant base flow model: second the Deficit –Constant loss model, SCS UH model, and monthly constant base flow model.

According to Nash and Sutcliffe Model Efficiency (NSE), Pearson's Coefficient of Determination (R^^{2}) and percent difference for a quantity (D) criteria the first model set was found to be the best model combination. The NSE, R^^{2} and D result for the Koga calibration period were 60.6%, 0.61 and 0.03 and for the validation periods were 61.3%, 0.62 and 0.19 respectively. NSE and R^2 for Gomit were 61.3% and 0.67 respectively. Using the calibrated parameters, the Koga and Gomit reservoirs were simulated on a daily time-step for 20 and 10 years of historical data respectively. This was done, to determine the availability of water to meet the irrigation demand requirements, hydropower requirement (only Koga) and to maintain environmental flow requirements. The simulation of storage gives RRV value of 0.982, 0.024 and 53 for Koga and RRV value of 0.95, 0.0324, and 71 for Gomit.

The effect of hypothetical rainfall changes -20% to +20% on the RRV value of on the Koga and Gomit storage dam were determined.RRV of Gomit varied from 0.874, 0.0164, and 88 to 0.979, 0.055, and 44. Similarly, Koga varied from 0.968, 0.02, and 64 to 0.979, 0.031, and 39.

Acknowledgement

Primarily, I would like to extend my heartfelt acknowledgement for Arba Minch Water Technology Institute who provides me the chance to carry out my graduate study in Arba Minch University.

Furthermore, Special thanks to the International Water Management Institute (IWMI) for giving me the opportunity of doing my dissertation paper under project “Rethinking water storage for climate change adaptation in sub-Saharan Africa “and funding me to do so.

I also forwarded my sincere thanks to my Advisor, Dr. Matthew McCartney, for his dedicated assistance and professional guidance on the entire process of this thesis work. Without him, this research work would not have this final form. In addition, I would like to thank my co-advisor Ato Fisseha Behulu for his wonderful follow up and continuous support.

Finally, my gratitude go to the Ministry of Water Resources, particularly for staff members under the Department of Hydrology and Data Base, GIS and Library, for their considerable support in providing me hydrological data and other relevant reference materials. In addition, my gratitude goes to National Metrological Agency (NMA) who provides me metrological data.

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LIST OF ACRONYMS

UBN	Upper Blue Nile River Basin
WAPCOS	Water and Power Consultancy Services
BCEOM	French Consultants Company
BCM	Billion Cubic Meter
ITCZ	Inter-Tropical Convergence Zone
HEC GEOHMS	Hydrologic Engineering Center Geospatial Hydrologic modeling Extension
HEC-HMS	Hydrologic Engineering Center-Hydrologic Modeling System
DEM	Digital Elevation Model
HEC-DSS	Hydrologic Engineering Center Data Storage System
SCS	Soil Conservation Service
SSR	Sum of squared residual
PEV	Percent error in volume
USACE	United States Army Corps of Engineers
NSE	Nash and Sutcliff Efficiency
Co-SAERAR	Commission for Sustainable Agricultural and Environmental Rehabilitation in Amhara Region
GIS	Geographic Information System
CN	Curve Number
MoWR	Ministry of Water Resources
NMA	National Meteorological Agency
DcSMc	Deficit constant, Snyder and Monthly constant base flow
DcSCSMc	Deficit constant, SCS and Monthly constant base flow
EEPCo	Ethiopian Power Corporations
ETO	Potential Evapotranspiration
FAO	Food and Agriculture Organization
USBR	United State Bureau of Reclamation
WMO	World Meteorological Organization

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CHAPTER ONE

1. INTRODUCTION

1.1 Back Ground

The Blue Nile drains a large area of the Ethiopian Highlands and is the largest tributary of the Nile River, providing a vital source of fresh water to the downstream riparian users, Sudan and Egypt. To date, however, there have been very few published studies on the Upper Blue Nile.

As the world fresh water is becoming scarce and countries are moving from normal to water stressed conditions, it is important to quantify the local, global and regional availability of surface water storage. The availability of water in many countries with shared watercourse is not well quantified. Without adequate knowledge of the surface water storage, sustainable water utilization of shared watercourses will always be constrained by lack of adequate data and information. However, in most instances, quantification of available water from catchments and watersheds of large river basins is costly and time consuming. Therefore, estimation techniques become paramount importance. In view of this study attempted to: i) contribute towards identification and classification of the surface water storage and ii) asses the performance of surface water storage of the Upper Blue Nile (UBN).

Surface water storage is used to store water during periods of excess for use during periods of limited availability In order to mitigate current or future impacts on stream flows, provide new water supply, and potentially improve habitat.

1.2 Potential Surface Water Storage Opportunities

Potential surface water storage includes on-channel and off-channel reservoirs, small impoundments, underground reservoirs and wetlands. *Table 1.1*and *figure 1.1a* and *b*, shows the approach for general classification of storage.

On-channel reservoirs are located on the mainstream of a river or stream and filled by the flow from an upstream watershed. Off-channel reservoirs are located completely off stream and are filled by overland flow or water pumped from a nearby source. Small impoundments in natural depressions, oxbows, or small surface ponds need to be implemented on a basin-wide basis in order to provide the greatest benefit. (*Spokane County, January 2009*)

- *Existing Dams:* like Chara-Chara weir on Lake Tana, Finchaa dam, and small dams for small-scale irrigation schemes.

- *Natural Lakes:* like Lake Tana which is below regulation height of the Chara-Chara weir
- A third potential storage option, that is from new dams, it includes dams that are under construction, and planned dam on planned projects
- Flood Plains
- Other alternatives of surface water storage are wetland or stream restoration.

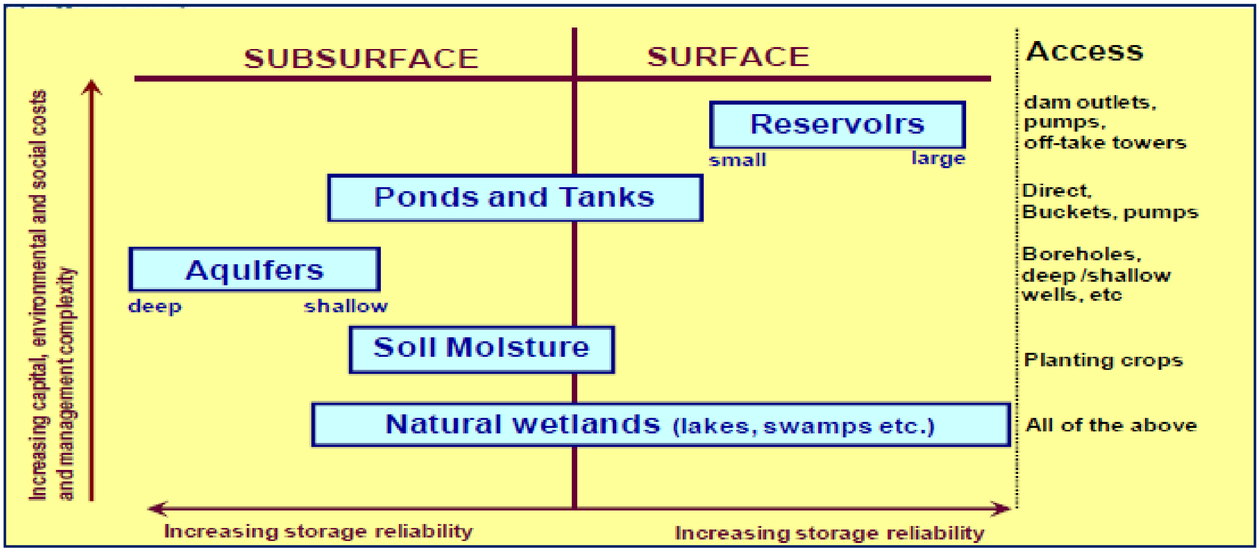
In this study the first three options mentioned above were considered.

Table 1.1 Storage Classifications

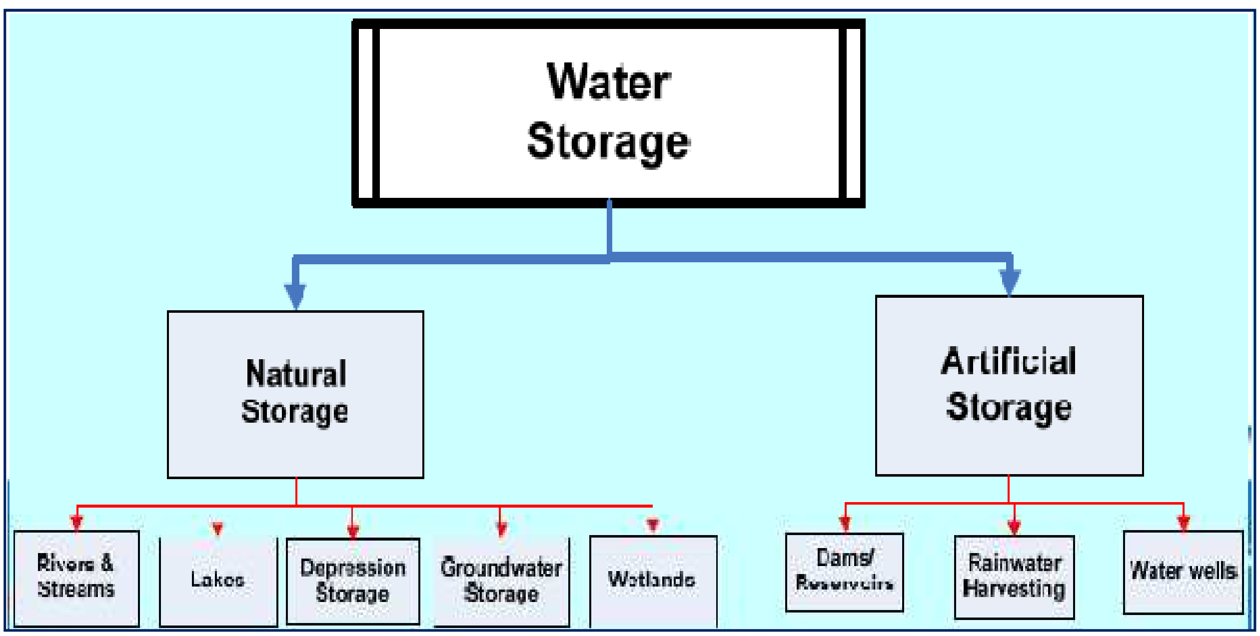
Storage Medium	*Water Source*	
	Rainfall	*Surface Water*
Unsaturated Zone	*Rainwater harvesting through plant spacing, plowing alone the contour , ridges and bunds, and terracing*	*Runoff harvesting from adjacent uncultivated plots, compound areas, roofs, and roads directly onto cropped fields*
Saturated Zone	*Aquifer storage of seepage “losses” from impoundments*	*Aquifer storage from artificial recharge sand dams*
Container	*Runoff harvesting from adjacent uncultivated plots, compound areas, roofs, and roads into a pond, tank, or reservoir*	*Impounding river flow in small, medium , and large reservoirs, both in stream and off channel*

Figure 1.1 a and b approaches for storage classification

a)



b)



1.3 Problem Statement

The availability of surface water storage in different countries with shared watercourse is often not well quantified. Earlier studies in the Blue Nile river basin shows different surface water storage amounts as documented in USBR, WAPCOS, BECOMS, and SMEC etc. Though they have followed different approaches, there are quite considerable differences on the quantity of accessible water resources identified. In addition, the unevenness between supply and demand of water has overstressed the environment. Pressure on water resources in the Blue Nile Basin is likely to increase dramatically in the near future as a result of high population growth in all the riparian states (i.e. Ethiopia and Sudan), and increasing development related water needs. However, in spite of the national and international importance of the region, relatively few studies have been conducted and there is only a limited understanding of the basin's detailed climatic, hydrological, topographic and hydraulic characteristics *(Johnson and Curtis 1994; Conway 1997).*

An increase in rainfall variability translates directly into variation in water availability with potentially adverse impacts on the livelihoods of beneficiaries. Therefore, appropriate determination and documentation of schemes of surface water storage in Blue Nile River Basin with their characterization and performance are indispensable for proper scheduling and consumption of available resources in the context of adaptation to climate change.

1.4 Objectives of the study

1.4.1 General Objective

The foremost objective of the study is to assess the potentials of the different surface water storage types and hydrological characterization of surface water storage in the UBN.

1.4.2 Specific Objectives

- Identify and classify the existing surface water storage schemes in the region
- Characterize and asses the performance of selected water storage types using appropriate hydrological model (s). The layout model used shown in figure 1.2 and its detail description is presented in methodology part (chapter four).
- Develop quantifiable indicators that allow comparison of various storage options and analyze their future trends in terms of performance indices (technical, socio-economical, environmental)

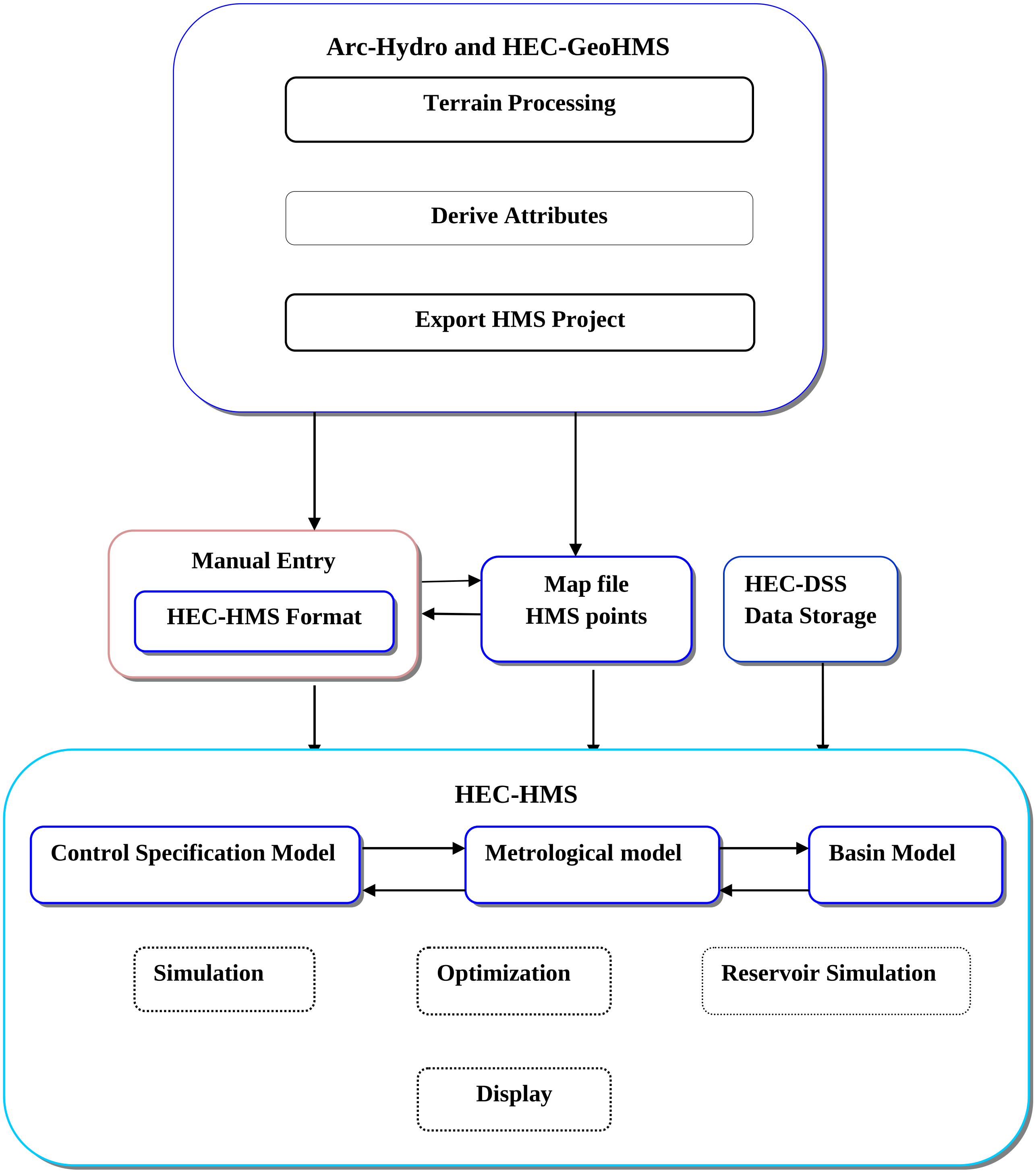


Figure 1.2 Layout of data base and HEC-HMS

CHAPTER TWO

2. DESCRIPTION OF THE STUDY AREA

2.1 Description of Upper Blue Nile

The Upper Blue Nile lies in west Ethiopia between latitudes of 7^{o} 45`N and 12$^{o}$ 46`N; and longitudes of 34^{o} 05'E and 39^{o} 45' E. The basin has a catchment area of about 199,812 km^{2} at the border with Sudan, covering parts of Amhara, Oromiya and Benishangul- Gumuz Regional states. It covers about 17.5 per cent of Ethiopia's land area, about 50% of its total average annual runoff and 25 % of its population.

The Abbay basin accounts for a major share of the country's irrigation and hydropower potential. It has an irrigation potential of 815,581 ha and a hydro potential of 78,820 GWH/yr. The basin has an average annual run-off estimated to 54.8 BCM (Awlachew et.al. 2007).

The basin subdivided into 16 sub basins. (*Figure 2.1*shows Location of the basin)

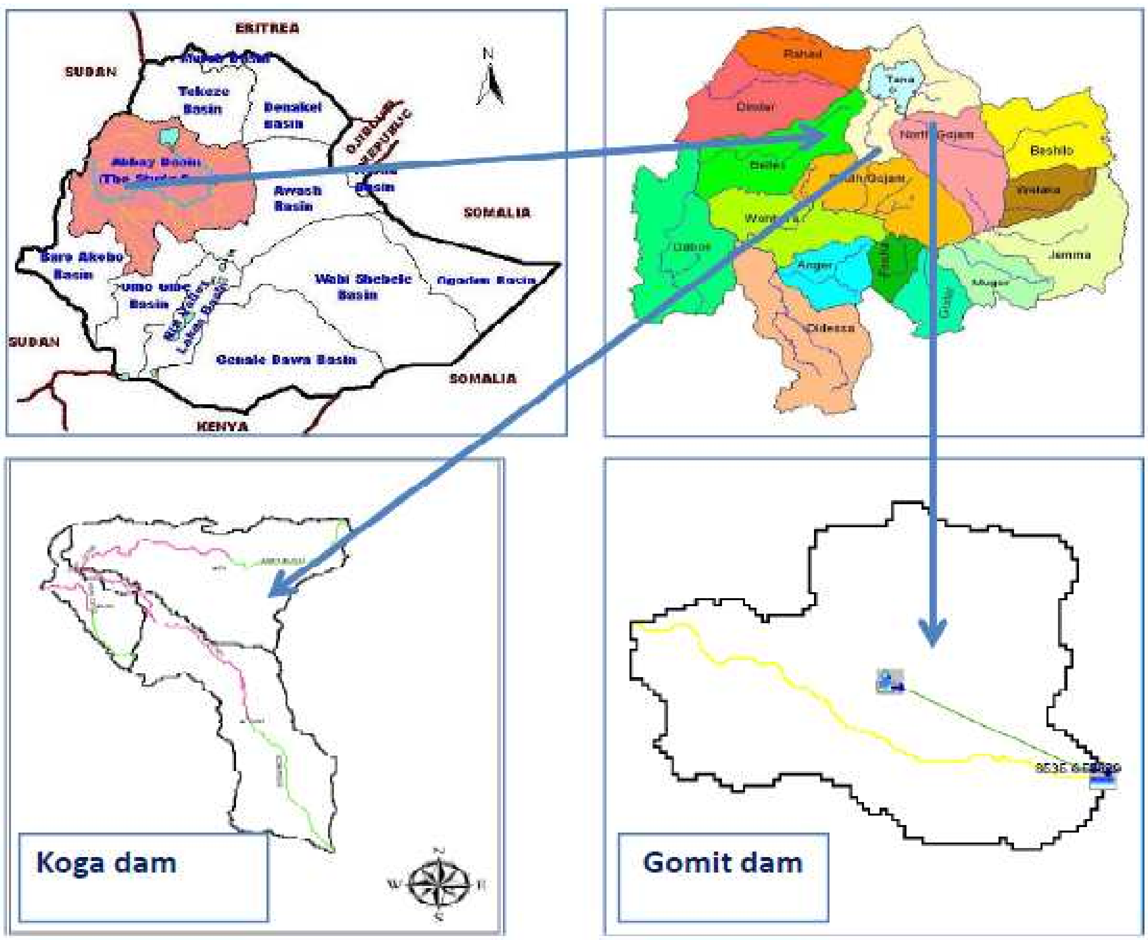


Figure 2.1: Study Area: Top left Ethiopia's River Basins, top right Abbay River Basin with its sixteen subbasins, , bottom left and right Koga and Gomit case study sites respectively.

An altitude ranging from 590 meters to more than 4000 meters dominates the climate of Abbay basin. The influence of this factor determines the variation in local climates ranging from hot to desert-like climate along the Sudan boarder, to temperate on the high plateau, and cold on the mountain peaks. The annual rainfall varies between about 800mm to 2,220 mm with a mean of about 1420mm. *(Master Plan of UBNRB – Main Report, 1999)*

The highest temperatures are observed in the northwestern part of the basin, in parts of Rihad, Dinder, Beles and Dabus sub basins. The maximum temperature being 28^{o}C - 38^{o}C and minimum temperature 15 ^{o}C – 20 ^{o} C. Lower temperatures are observed in the highlands of Ethiopia in the central and eastern part of the basin. The maximum and minimum temperature ranges from 12 ^{o}C – 20 ^{o}C and -1^{o}C to 8^{o}C respectively. *(A. Denekew, Awlachew, January 2009)*

2.2 Physical Features of Gomit

Gomit micro dam irrigation project is located in region, South Gonder zone, Estie woredas, Azigura & Goshibert kebele peasant association, around 10kms away from the woreda town capital, Mekaneyesus. Geographically the area lies on coordinates of 11^{0}33'43'' North & 38^{0}01'20'' East (Figure 2.2 show the dam and irrigation channel). The area has an altitude of 2375 meters above sea level on average. See table 1.1 for general features of the dam.

a)

b)

Figure 2.2: Gomit Dam a) Upstream face of the Gomit dam b) Gomit main and secondary irrigation canal

Table 2.1: Salient Features of the Gomit dam

	Features
Dam type	Zoned earth embankment dam of 20m height and 324m crest length with side slopes of 2:1 and 2.5:1 in u/s and d/s directions respectively
Catchment area	23.43 km^2
Command Area	90ha
Storage features	Normal pool level = 2367 masl Total reservoir volume = 73.964×10^4 m^3 Inundated reservoir area = 22.91 ha
Expected Yield	10.61 Mm^3
Beneficiaries	360 HH
Spilway features	Max design flood = 87.84m^3/s Crest length = 25m
Climate	Mean annual rainfall = 1642.91mm Mean annual air temperature =16.4^{o}c
Sediment load for 23 years	28.11 ha.m = 281100 m^3

Source: Salient Features of Projects Regional Water Resource Bureau, Bahir Dar

The rainfall pattern in the area is characterized by one single rainy season with high amount between June and September. Mean annual rainfall is 1414mm. Daily temperature varies between 14.2 ^{0}C in July and 17.8 ^{0}C on April month. *(Co-SARAR Gomit micro dam irrigation agronomy feasibility report, 2000*)

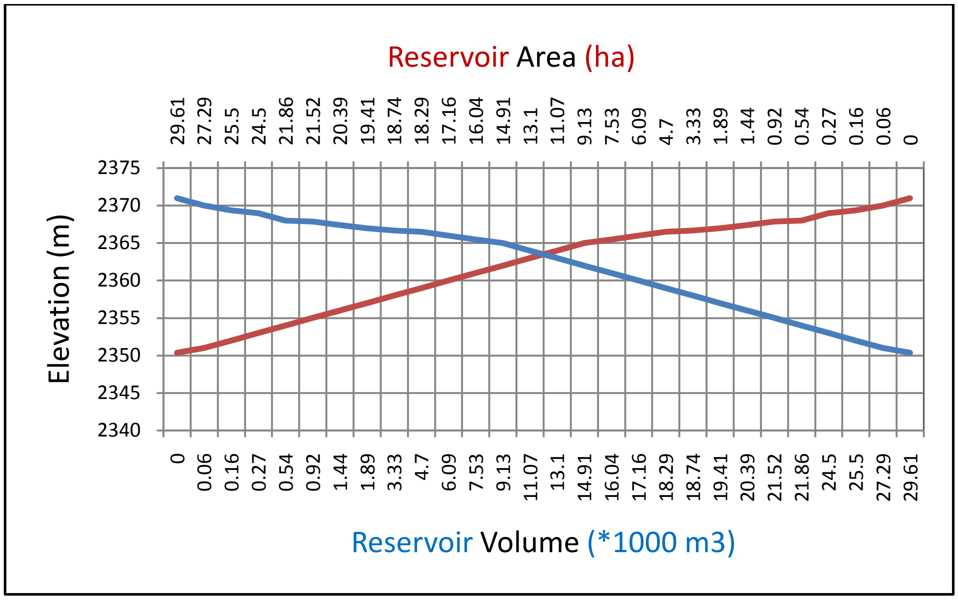
The project area is characterized by mountains, ragged and plain lands amounting 45.3%, 17.0% and 37.6% respectively. Mountainous areas but used for grazing purpose and some used for crop production. With regard to the nature of the command area it is almost gently sloping and regular in its nature having a slope of about 0-4 % approximately.

The soil resource of command area is endowed with deep up to very deep (90-150cm) stone free and a good moisture regime or holding capacity as compared to other area of the project surrounding. Major and dominant soil types identified in the watershed are Calcic Xerosols Eutric Regosols

On the banks of the Gomit river in the reservoir area near to the dam axis water leaks in between the clay soil and rock formation and Gomit River itself has base flow and this flow increase downstream side unit it joins the Wanka River. From the above observation, test pit data and characteristics of the surrounding rock, which is highly vesiculated and weathered basalt rock, and this rock may serve as an aquifer for surrounding area. *(Co-SARAR Gomit micro dam geological feasibility report, 2000*)

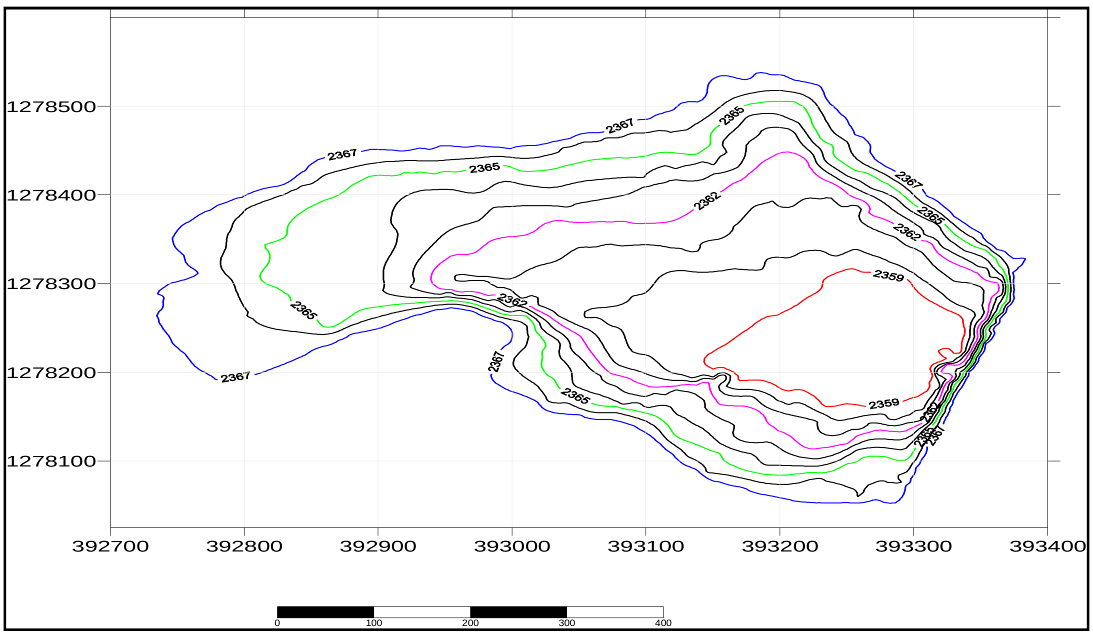
Gomit Dam has a full supply level of 2367 m, and a maximum storage of 73.964×10^4 m^3. *Appendix C.1* and *figure 2.3* shows detail of the reservoir characteristics. Moreover, contour developed from bathymetric data shown in *figure 2.4*.

Figure 2.3: Gomit reservoir characteristics



Source: Salient Features of Projects Regional Water Resource Bureau, Bahir Dar

Figure 2.4: Contour developed from the Bathymetric data



Source: Salient Features of Projects Regional Water Resource Bureau, Bahir Dar

2.3 The Physical Features of Koga Dam

The catchment is located approximately 35km southwest of Bahir Dar, the capital of the west Gojam administrative region, it is situated between 11°10' and 11°32' N and 37°04' to 37°17'E with an altitude range from 1998 (at the dam site) to 3,200 masl. The catchment area to the dam is 170.9 km^2.

The source of the Koga River is close to Wezem, at an altitude of about 3200 m. The river is 64 km long; flowing into the Gilgel Abay River(which is the major inflow to Lake Tana, the source of the Abay River (Blue Nile)) after it crosses the Debre Markos - Bahir Dar road, downstream of the town of Wetet Abay, at an altitude of 1985 m.

Figure 2.5: Koga Dam a) Koga Off-take towers b) Koga main irrigation channel and return flow to stream

a)

b)

The catchment can be divided into two, the upper and the lower catchment. The upper catchment comprises predominantly interfluvial ridges and steep valleys. The land adjacent to the river is steep, with slopes typically ranging from 16% to 40%, but up to 55% in some places. Soils in the upper catchment varied, comprise Luvic Phaeozems, Chromic Cambisols and Lithic Leptosols. Soil erosion is a major problem because of the steep slopes and high rainfall. The lower catchment, where the irrigation scheme is located, comprises a much flatter plateau (locally called the Bojed Plain), with some undulating topography in places and extensive flood plains bordering the Koga River. Soils in the lower catchment comprise primarily Haplic Alisols in the well-drained areas, Eutric Vertisols in the poorly drained plains and Eutric Gleysols in the very poorly drained floodplains of the Koga and its tributaries.

The regional geology comprises flow type rocks of Tertiary origin. The Koga catchment is underlain primarily with basalt interbedded with pyroclastic deposits. Rocky outcrops occur primarily at higher elevations. Most of the catchment covered by highly weathered red clay soils, with alluvial deposits bordering the river at lower elevations (AfDB, 2000).

The climate of the catchment is largely controlled by the movement of air masses associated with the Inter-Tropical Convergence Zone (ITCZ). The dry season occurs between November and April and the wet season between May and October. Typically, about 95% of the annual rainfall occurs in the wet season. In some years, depending on the exact movement of the ITCZ, small rains occur between April and May. Rainfall varies depending on altitude. Mean annual rainfall is approximately 1590 mm, but varies considerably from year to year, with pronounced wetter and drier cycles.

The Koga project comprises the construction of two dams. Currently the project is almost complete and it starts working partially. The main dam is a 21.5 m high earth dam with a length of 1860 m. In addition, an 18.50 m high and 1,106 m long saddle dam about 6km to the northeast of the main dam.(figure 2.5 show Koga dam and main channel) The storage capacity of the reservoir at full supply level (2015.25 masl) is 83.1 Mm^3 (i.e. 71% of the mean annual runoff). The area submerged at FSL is 18.59 km^2. (Details of the reservoir characteristics are given in *Appendix C.*2 and *Figure 2.6*)

The reservoir will provide water for approximately 7000 ha of dry season irrigation and 5,600 ha of wet season irrigation

Figure 2.6: Koga reservoir characteristics

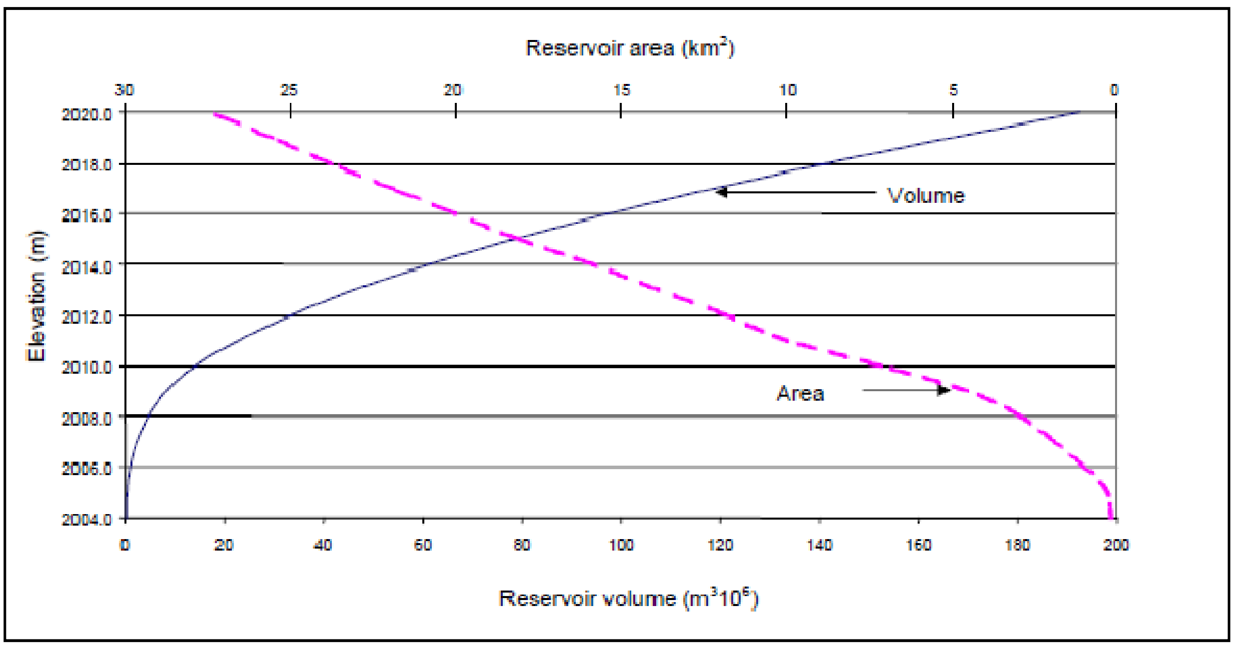


*Table 2.2: Salient Features of the Koga dam**Mott Macdonald (MM) interim Report*

Item	Unit	Koga Main Dam	Koga Saddle Dam
Dam Type		Zoned Earth fill	Modified homogeneous earth fill
Crest elevation	m	2019.5	2019.5
Length of earth dam	m	1730	1162
River bed elevation	m	1998	2011
Max height	m	21	9
Spilway type		overflow ogee type	none
Spilway crest elevation	m	2015.25 (**Crest Length 21.5 m**)	na
spillway gates	m	uncontrolled crest	na
Full supply level (FSL)	m	2015.1	2015.1
Dead storage Level (DSL)	m	2007.5	na
Maximum Water level	m	2016.94	na
Maximum storage	mcm	83.1	na
Live storage	mcm	73.4	na
Maximum Submergence	ha	2041	na
Mean Depth of reservoir	m	4.41	na
Storage volume/Dam volume		145.5	440.6
Irrigation outlet works		1.5-m dia.steel lined conc. Conduit, right abutment	
Diversion work & low level outlet		3-m gated conduit on left bank of river	
Design discharge of outlet works	m3/s	9.1	none
Drainage area about dam site	km2	164.8	na
Catchment yield	mcm	86.72	na
Design flood (inflow to reservoir)	m3/s	1:10000 yr (517)	na
Compensation flow facilities		450 mm dia. Steel pipe & control valve off irr out let	

CHAPTER THREE

3. LITRATURE REVIEW

3.1 POTENTIAL SURFACE WATER STORAGE OPPORTUNITIES ON UBN

3.1.1 Surface Water Storage Option on Existing Dams

Currently only two medium sized hydraulic structures and several micro-earths dam for hydropower irrigation and for small-scale irrigation schemes have been constructed in the Ethiopian Blue Nile catchment. The two dams (i.e. Chara-Chara weir and Finchaa) have better storage opportunities than the micro-earth dam. Features of the storage are shown in *table 3.1.* Chara-Chara weir and Finchaa dam were built primarily to provide hydropower. The combined capacity of the power stations they serve (212MW) represents approximately 30% of the total currently installed power capacity of the country (i.e. 731 MW) *(World Bank, 2006).*

Chara-Chara weir (*figure 3.1) is used* to regulate the water level and outflow of Lake Tana. This regulation originally aimed at a more constant outflow from the lake to increase the hydropower production of the Tis Abbay hydropower plants. The regulation of outflow resulted in a larger seasonal fluctuations in lake level. The weir consists of seven radial sector gates with sill levels at 1782.5 masl and widths of 4.8 m. The concrete spillway has a length of 635 m and the crest level is at 1787 masl. Construction of the weir started in 1994 and the weir, first controlled by two radial gates only, became operational in December 1995. The increased regulation of the Lake Tana's outflow by the Chara-Chara weir enabled the construction of a second power plant (Tis Abbay II), after five additional gates added. The construction of Tis Abbay II started in 1996 and completed in 2001. The minimum operation level is 1784 masl and the maximum operation level is 1987 masl. However, an optional minimum operation level of 1784.75 mentioned, to allow for a minimum draught, needed for navigation in Lake Tana. *(SMEC Main Report, 2007)*

The Lake storage between 1784 and 1787 masl is about 9100 MCM and this storage will reduce by about 25% if the minimum operation level increased to 1784.75. If all gates are opened, the total calibrated discharge at the minimum operation level (1784 masl) is 75 m3/s and at the maximum operation level (spillway level) 490 m3/s *(Salini and Pietrangeli, 2006).*

Figure3.1: Chara-Chara weir

Table 3.1: Water storage options on existing hydropower structure in the Blue Nile catchment

Dam	River	Locations		Reservoir volume (Mm3)	Purpose
		Lat	Long		
Chara-Chara	Abbay	11.6	37.38	The Lake storage between 1784 and 1787 masl is about 9100 MCM	Regulation of Lake Tana outflows for hydropower productions at Tis Abay I and II power stations (installed capacity 84MW)
Finchaa-Amarti	Finchaa			Live storage of 790 MCM	Regulation for hydropower productions (installed capacity 128MW) and sugar cane irrigation (6,205ha).

Irrigation projects classified as small projects have a command area less than 200 ha. The Regional State governments have assumed responsibility for small-scale schemes. Water storage available only from small-scale irrigation from storage reservoirs

In Amhara, five micro-dams and nineteen diversion dams have been constructed over the last ten years or so *(ARS/UNECA, 1996)*. The total command area under small-scale irrigation may reach 20,000-25,000 ha. A few schemes have been constructed with assistance from the ADB/ADF and other external donors. Several studies have reviewed past performance and/or identified further potential (e.g. FAO, 1994) Features of storage opportunities on these micro dams are given in *table 3.2*. SAERAR plans to construct 540 small schemes commanding 65,435 ha over a ten-year period *(ARS/UNECA. 1996).* Emphasis has given to the construction of small dams and associated valley development in drought prone areas of Wello, Shewa and South Gondar. Oromiya has a more modest programme *(RGSO 1995)*, perhaps reflecting its generally better rainfall conditions envisaging the construction of about 180 small schemes covering 19,200 ha over a five year period. Both the Amhara and Oromiya targets are region-wide and the total within the Abbay basin is presumably significantly smaller.

Table 3.2: Water storage options on existing small-scale irrigation schemes in the Blue Nile

Zone	Woreda	Scheme	Command Area (ha)	Reservoir volume (*1000m3)	Water Source
North Gonder	Basonaweran a	Burale	70		Micro-earth Dam
South Gonder	Estie	Gomit	90	739.64	Zoned earth embankment dam
	Fogera	Guanta	60		Micro-earth Dam
	Dera	Shina	60		Micro-earth Dam
	Farta	Selamko	63		Micro-earth Dam
South Wollo	Mekdela	Tebi	200	1000	Micro-earth Dam
West Gojjam	Enargi-Enawga	Abrajit	70	1225.2	Micro-earth Dam

Source: Regional Water Resource Bureau, Bahir Dar

3.1.2. Water Storage Option on Natural Lakes

The only natural Lake of significance size in the UBN is Lake Tana (*Figure 3.2*), Lake Tana is the largest fresh water Lake located in the north western highland plateau of the country (elevation of 1829 m.a.s.l) between 11°35'-12°18'N and 37°01'-37°35'E. It has an average surface area of 3500 sq.km, which is fed by 61 small streams, all very seasonal in the volume of water they carry. They drain a basin of 16,500 km2. The lake has a capacity of 28 billion m3 which is about 52% of the total area of the Lakes in the country. The lake is usually considered as the source of Blue Nile River.

Figure 3.2: satellite image of the Lake.

The lake is 73 km long with a maximum width of 67.7 km a maximum known depth of 14.1 m, a mean depth of 8.5 m. The lake contains several minor and two major islands. These latter, Daga and Dek

Islands in the southern part of the lake are volcanic cones. Small swampy and seasonally flooded alluvial plains border the lake to the north, east and west and in these regions, the lakeshore is flat; elsewhere it is steep and rocky. The lake area enjoys some 2660 hours of sunshine each year, with a mean maximum of 288 hours in January and a mean minimum of 114 hours in July. Mean annual surface water temperatures are between 21.5 and 22.0°C depending upon locality. Winds are generally light.

The Blue Nile carries the overspill of the lake from its southern extremity. Maximum outflow 400 m3/s in September and the average annual overspill estimated at 3.9 billion m3. Precipitation averages 1320 mm/yr, over the lake, with a monthly maximum of 475 mm in July, but by contrast, the December-April period is virtually rainless. Rainfall over the upper catchments may reach 2000 mm/yr while evaporation from the lake margins has been determined as 1836 mm/yr.

Currently, the water level of Lake Tana regulated by the Chara-Chara weir, at the outlet of the Lake close to Bahir Dar town and the natural lake level fluctuation and outflow from the Lake modified.

The weir constructed to enhance energy situation in the country by constructing the second hydropower plant on upper Blue Nile. While like other Lakes in Ethiopia, Lake Tana not protected by law until recently *(Abunie, 2003);* the level of exploitation of the water resources particularly for consumptive use like irrigation remains limited to date. Recently there is extensive study and mobilization activity in the country to develop energy and irrigation sector by utilizing the lake and its tributaries as storage facility for irrigation and hydropower purpose. A notable development is the Tana-Beles growth corridor concept, which is attempting to stimulate Integrated Water Resources Development Program around Lake Tana. The plan include among others a basin transfer scheme from Lake Tana to Beles River Basin for hydropower production, as well as the development of storage dams (for irrigation) on the tributaries of the Lake.

3.1.3. Water Storage in the Future Water Resource Development on Upper Blue Nile Basin

The Nile riparian countries have agreed to collaborate in the development of the Nile water resources to achieve sustainable socio-economical development. There is significant potential for additional exploitation in the basin and our country plans to develop the water resources of the river.

In Ethiopia possible hydropower, irrigation and multipurpose projects have been investigated over a number of years (e.g. Lahmeyer, 1962; USBR, 1964; JICA, 1977; EVDSA, 1980; HALCROW, 1982; WAPCOS, 1990; BCEOM, 1998).

The projects have been classified as pure irrigation projects, pure power projects or multipurpose projects:

- *Irrigation projects* defined as projects where the dam is justified by irrigation requirements. If economically attractive, small hydropower equipment could be installed to turbine the released irrigation flow;
- *Power projects* defined as projects where the reservoir used for regulating the river flows in order to maximize the firm energy. No priority is then given to irrigation;
- *Multipurpose projects* defined as projects where part of the reservoir storage is allocated to satisfy the irrigation requirements and the remaining part to produce power.

Several possible irrigation and power projects in the Abbay basin have been studied at feasibility level other identified projects have been reviewed at a reconnaissance level to obtain a preliminary estimate of their output and cost.

In the Abbay basin, the Master Plan identified around 32 potential irrigation, hydropower and multipurpose projects from these projects there is a possibility of water storage formation of a maximum of 135269.82 Mm3.

The maximum water storage formed around main stream projects comprises around 72% (95600 Mm3) of the total storage in the basin. Didessa sub basin comprised 12.9% (17420 Mm3) and the rest of the basin takes below 5% each (*figure 3.3)*. The detailed results (for all irrigation, power and multi-purpose projects) presented in *Annex A.* It provides curves giving the reservoir characteristics (flooded area and capacity) versus reservoir elevation.

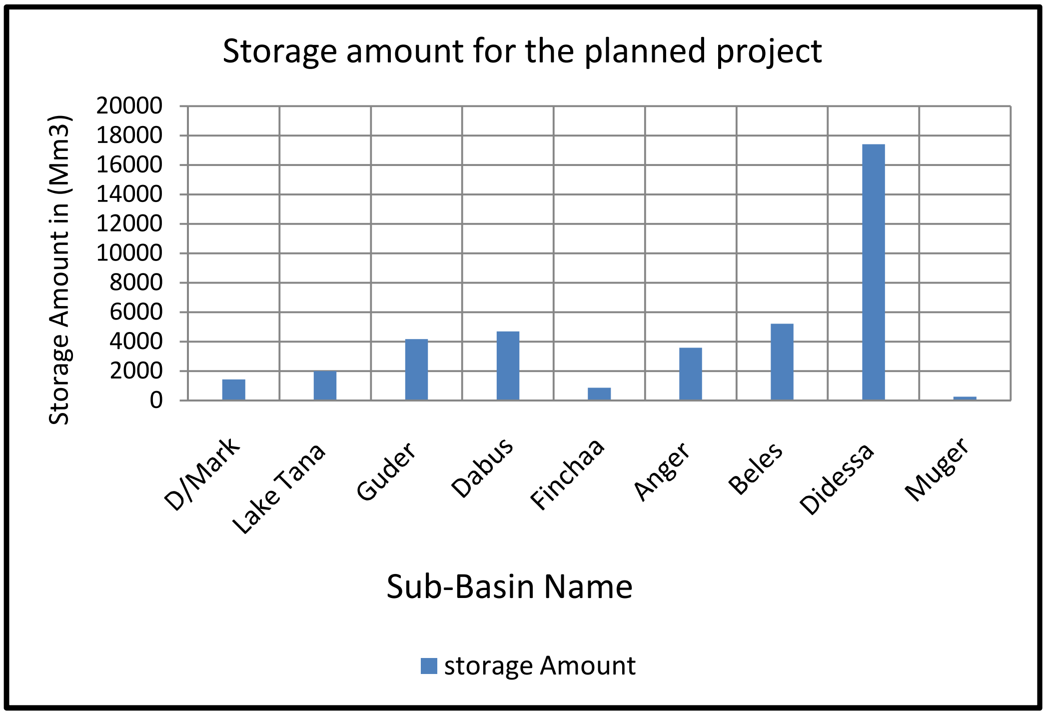


Figure 3.3: Distribution of water storage potential in the Abbay basin

3.1.3.1. Water Storage on planned Irrigation projects

The Master Plan proposed to develop a certain percentage of the identified potential over the 50 years of the Master Plan period. Two alternatives scenarios were proposed for the development of large- and medium-scale irrigation: a "conservative" one aiming at developing 235,000 ha in 50 years (45% of the potential), and an "accelerated" one with 350,000 ha (65% of the potential) *(BCEOM phase 3 main report, 1998).* An analysis of water resources required to support the Ethiopian irrigation development, proposed in the Abbay River Master Plan *(BCEOM, 1998, main report, page 1-76),* indicates that approximately 5,750 Mm3 needed to irrigate between 370,000 and 440,000 ha. This represents approximately 11%-12% of the mean annual flow in-to Sudan.

More recently it has been estimated that the water required for the 220,416 ha of highest priority irrigation would be between 2,200 Mm3 and 3, 830 Mm3 *(Endale, 2006). Figure 3.4* shows all planed irrigation projects with spatial distribution and storage formation scale. (Storage on Angar project 3590Mm^3 is the maximum). According to the phase 2 report of abbay basin studies the projects that are identified and also to be studied at phase three are Gumara (A and B), Megech, Ribb, Gilgel Abbay (A and B), Jema, Negeso, Angar, Galegu, Rahad. Each of these projects have large reservoir with a total maximum storage around 5768.1 Mm3. Additional features like dam location, reservoir elevation with live storage, and irrigable area of irrigation projects are presented in *Annex A.1*.

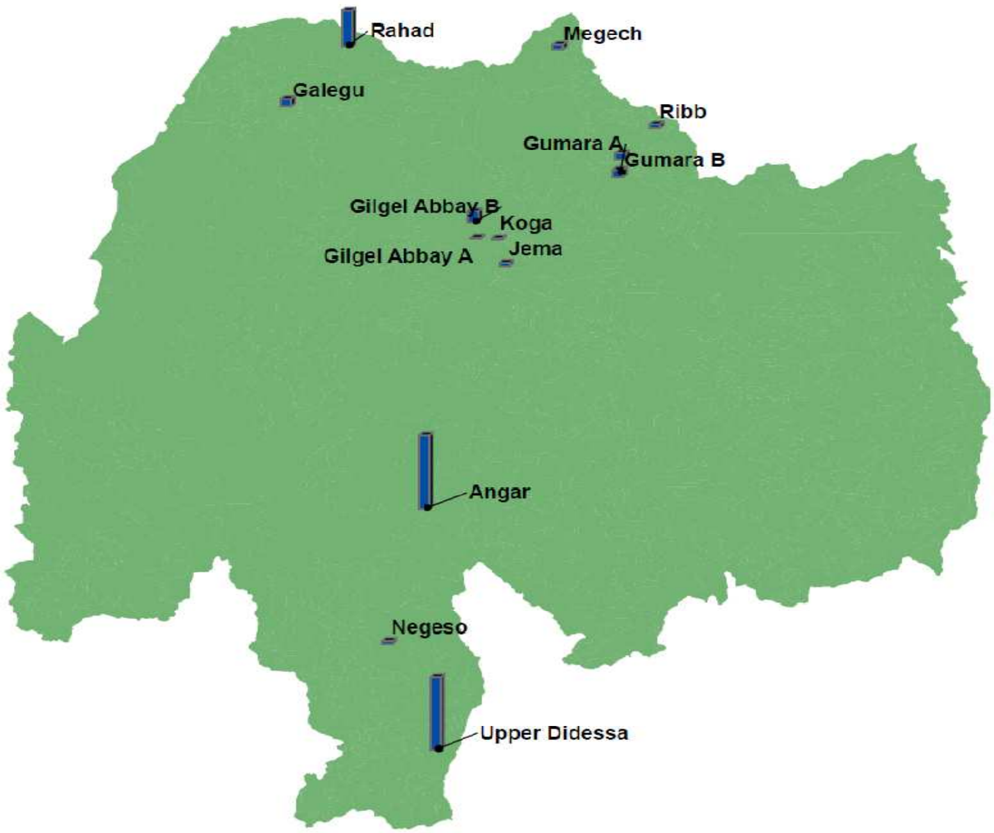


Figure 3.4: Spatial distributions with storage size scale of irrigation projects

3.1.3.2. Water Storage on planned multipurpose projects

The evaluation of multipurpose projects made in a first stage by considering the projects as irrigation dams i.e. by computing the unit cost per stored m3. In a second stage, power equipment introduced with values of installed capacity larger than the irrigation requirements but close to the river natural discharge. *BCEOM, 1998, phase 2, section II VOLUME VI*

According to the phase 2 report of Abbay basin studies the multi-purpose projects that are identified and also to be studied at phase 3 are: Neshe, Upper Guder, Dabana, Lower Dindir, and Nekemte. The total maximum storage which formed by the fore mentioned projects is around 7,869 Mm3, Nekemte project contribute the largest 3,380 Mm3. *Figure 3.5* shows all planed multipurpose projects with spatial distribution and storage scale, In addition, details about the project available on *appendix A.2*

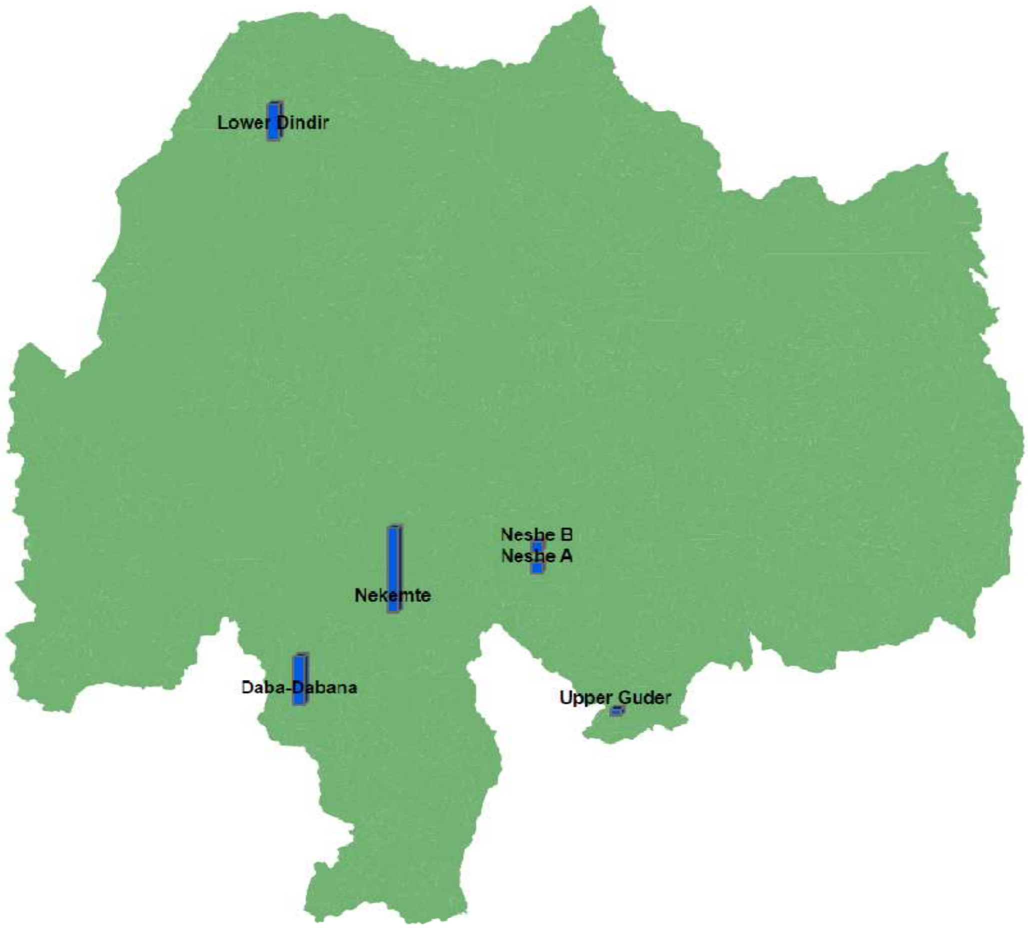


Figure 3.5: Spatial distributions with storage size scale of multipurpose projects

3.1.3.3. Water Storage on planned Hydropower projects

In Ethiopia, 299 hydropower potential sites identified with in 11 river basins. Largest river basin in terms of number of hydropower potential sites as well as technical potential is the Abbay River basin, it has about 79,000GWh/yr, and 49% of potential sites found in the Abbay River Basin, which is around 146 possible sites *[NBCBN-RE Executive Summaries, page -16].*

The main report of Abbay River Basin Integrated Development Master Plan Project, reported that the hydropower resource available in the country is estimated 135,311GWH/yr and found around 26 hydropower potential sites in the Abbay River Basin *[ARBIDMPP, Volume I, main report, page – 14]*. The major hydropower projects currently contemplated in Ethiopia have a combined installed capacity of between 3,643 MW and 7,629 MW. The exact figure depends on the final design of the dams and the consequent head that produced at each. The four largest schemes considered are dams on the main stem of the Blue Nile River. Of these schemes, the furthest advanced is the Karadobi project for which the pre-feasibility study was conducted in 2006 *(Norconsult, 2006)*.

Eleven of the power projects *(figure 3.6)*from the potential sites will form storage and its maximum total storage formation is around 130.483 BCM and power projects on main abbay river takes a large percentage, further features of storage of power project are given in appendix A.3,

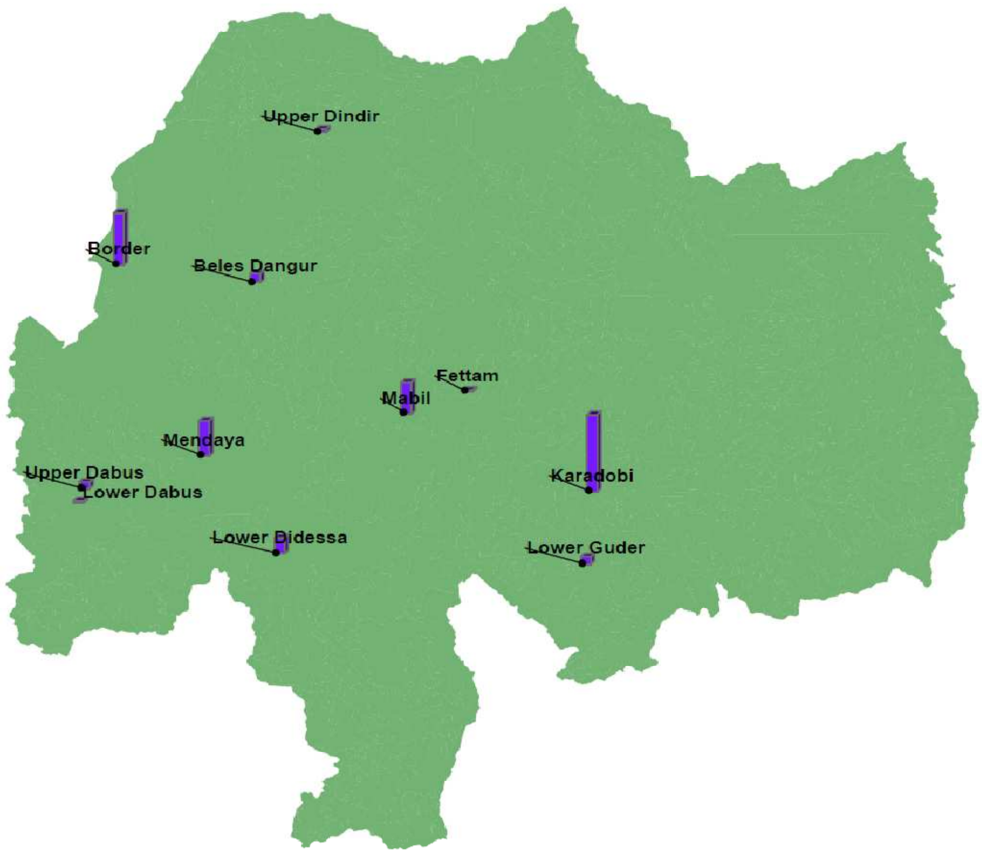


Figure 3.6: Spatial distributions with storage size scale of multipurpose projects

3.2 General Description of all Software used for this study

3.2.1 GIS

With the development of computer science, hydrological models combined with Geographic Information System (GIS) technology. The Arc GIS is one of several Geographic Information Systems (GIS), which is a powerful integrated suite of GIS applications capable of performing advanced mapping, data management and geo processing of spatial data (Weizhe An, 2007).

Making a connection between GIS and HEC GEOHMS and arc hydro, and standard software packages like HEC-HMS, allows the modeler to get the most out of GIS (i.e., to capture the spatial variability of the system) while continuing to work using familiar tools (Weizhe An,2007).

3.2.2 Arc-Hydro

Arc Hydro is an Arc-GIS-based system geared to support water resources applications. It consists of two key components:

- Arc Hydro Data Model
- Arc Hydro Tools

The Arc Hydro tools are a set of utilities developed on top of the Arc Hydro data model. They operate in the Arc-GIS environment. Some of the functions require the Spatial Analyst extension.

The tools have two key purposes. The first purpose is to manipulate (assign) key attributes in the Arc Hydro data model. These attributes form the basis for further analyses. They include the key identifiers (such as HydroID, DrainID, NextDownID, etc.) and the measure attributes (such as Length Down). The second purpose for the tools is to provide some core functionality often used in water resources applications. This includes DEM-based watershed delineation, network generation, and attribute-based tracing (Arc Hydro Tools Overview, 2002).

3.2.3 HEC-GeoHMS

HEC-GeoHMS developed as a tool kit of the geospatial hydrology for engineers and hydrologists with limited GIS experience. The program allow users to visualize spatial information, document watershed characteristics, perform spatial analysis, delineate sub-basins and streams, construct inputs to hydrologic models, and assist with report preparation. Working with HEC-GeoHMS through its interfaces, menus, tools buttons, and context sensitive online help, in a windows environment, allows the user to expediently create Hydrologic Modeling System, HEC-HMS (USACE, 2003).

HEC-GeoHMS version creates background map file, lumped basin model, a grid-cell parameter file, and a distributed basin model, which used by HMS to develop a hydrologic model. The background map file contains the stream alignments, and sub-basins boundaries. The lumped basin model contains hydrologic elements and their connectivity to represent the movement of water through the drainage system. The lumped basin file includes watershed areas and reserves empty fields for hydrologic parameters. To assist with estimating hydrologic parameters, GeoHMS can generate tables containing physical characteristics of steams and watersheds. If the hydrologic model employs the distributive techniques for hydrograph transformation, i.e. ModClark, and grid-based precipitation, then a grid-cell parameter file and a distributed basin model can be generated (USACE, 2003).

3.2.4 HEC-DSS Microsoft Excel Data Exchange Add-In

Used to convert temporal data into HEC-HMS binary format, previously, data from one format would need to enter into another format by hand by each user. Each program would then use separate functions to analyze and graph the data. Therefore time-series and tabular data are not stored in the HEC-HMS dataset; rather, the data are stored in a separate HEC-DSS data file, which accessed by the HEC-HMS model. The database consists of six parts: the A Part *(River basin or project name)*, B Part *(Location of gage identifier)*, C Part *(Data type (e.g. flow, rainfall, etc.))*, D Part *(Starting date)*, E Part *(Time interval of data)*, and F Part *(User defined descriptor of data)*. The data are stored under a unique pathname, which includes all of the parts: */A Part/B Part/C Part/D Part/ E Part/F Part*. Using these parts, it is easy for the user and the model to query and manage the data, especially between models. Long-term data series (years and greater) can be stored in HEC-DSS and multiple model runs can be made in different times within the data series. The data can be accessed by other HEC models.

3.2.5 HEC-HMS Modeling

HEC-HMS (the Hydrologic Engineering Center's Hydrological Modeling System) is the United States Army Corps of Engineers' hydrologic system computer program developed by the Hydrological Engineering Center (HEC). The program simulates precipitation-runoff and routing processes, both natural and controlled. HEC-HMS is the successor to and replacement for HEC's HEC-1 program and for various specialized versions of HEC-1. HEC-HMS improves up on the capabilities of HEC-1 and provides additional capabilities for *distributed modeling* and *continuous simulation* (*USACE, 2000)*.

HMS contains four main components. 1) An analytical model to calculate overland flow runoff as well as channel routing, 2) an advanced graphical user interface illustrating hydrologic system components with interactive features, 3) a system for storing and managing data, specifically large, time variable data sets, and 4) a means for displaying and reporting model outputs. *(Semu, 2003)*

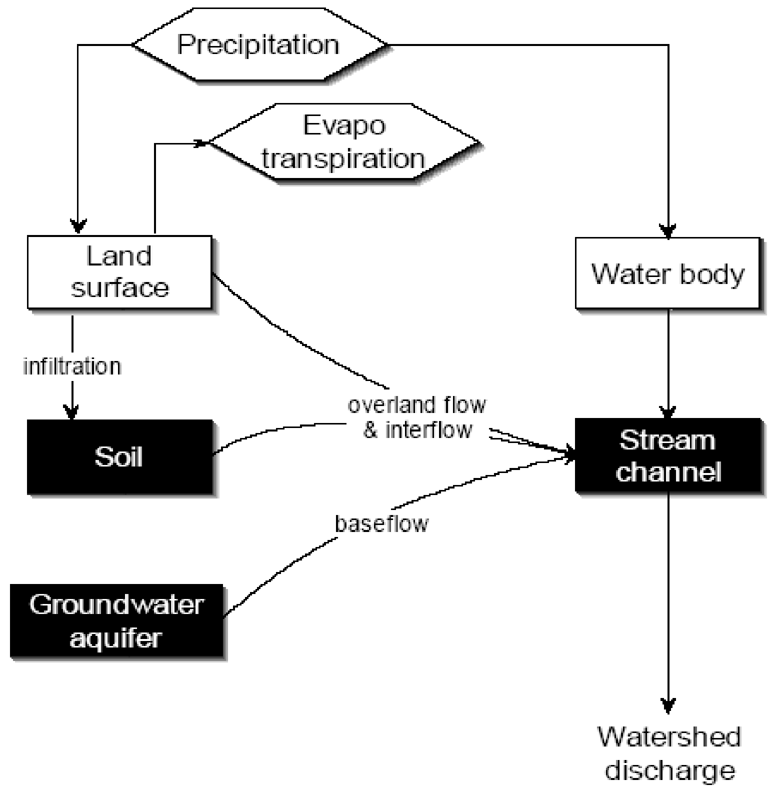


Figure 3.7 Typical HEC-HMS representation of watershed runoff (USACE, 2000)

3.2.5.1 The Analytical Components of HEC-HMS♣

HEC-HMS consists of separate models of the major hydrological processes and transports. It consists of runoff volume models, models of direct runoff (overland flow and interflow), base flow models, channel flow models. HEC-HMS gives flexibility to the user by providing each component with suit of models. The user can choose a suitable combination of models depending on the availability of data, the purpose of modeling and the required spatial and temporal scales. *Appendix B.1* gives categorization of each components of the model. Elaborate discussion of the relevant model components in view of this study given in subsequent sections.

♣ From section 2.3.5.1 to 2.3.5.8, adapted from (USACE, 2000)

3.2.5.2 Runoff-Volume Models

As illustrated by figure 2.1 above, HEC-HMS computes runoff volume by computing the volume of water that intercepted, infiltrated, stored, evaporated, or transpired and subtracting it from the precipitation. Interception and surface storage intended to represent the surface storage of water by trees or grass, local depressions in the ground surface, cracks and crevices in parking lots or roofs, or a surface area where water is not free to move as overland flow. Infiltration represents the movement of water to areas beneath the land surface. Interception, infiltration, storage, evaporation, and transpiration collectively referred to in the HEC-HMS program and documentation as *losses.*

HEC-HMS considers that all land and water in a watershed categorized as either directly connected impervious surface, or pervious surface. Directly connected impervious surface in a watershed is that portion of the watershed for which all contributing precipitation runs off, with no infiltration, evaporation, or other volume losses. Precipitation on the pervious surfaces is subject to losses. HEC-HMS includes seven runoff volume methods specified in *Appendix B.1*. However, only some of the appropriate methods in the perspective of this study described below.

Initial and Constant rate, Deficit and Constant rate Loss models

The underlying concept of the initial and constant-rate loss model is that the maximum potential rate of precipitation loss, f_c, is constant throughout an event. Thus, if *Pi* is the MAP depth during a time interval *t* to *t*+Δ*t*, the excess, Pe_i, during the interval given by:

$$Pei = \begin{cases} Pi - fc & if\ Pi > fc \\ 0 & otherwise \end{cases} \tag{3.1}$$

An initial loss, *Ia*, is added to the model to represent interception and depression storage. Interception storage is a consequence of absorption of precipitation by surface cover, including plants in the watershed. Depression storage is a consequence of depressions in the watershed topography; water is stored in these and eventually infiltrates or evaporates. This loss occurs prior to the onset of runoff. Until the accumulated precipitation on the pervious area exceeds the initial loss volume, no runoff occurs. Thus, the excess given by

$$Pei = \begin{cases} 0 & if\ \sum Pi < Ia \\ Pi - fc & if\ \sum Pi > Ia\ and\ Pi > fc \\ 0 & if\ \sum Pi > Ia\ and\ Pi < fc \end{cases} \tag{3.2}$$

Initial Loss and Constant-Rate

The initial and constant-rate model, in fact, includes one parameter (the constant rate) and one initial condition (the initial loss). Respectively, these represent physical properties of the watershed soils and land use and the antecedent condition.

The constant loss rate can viewed as the ultimate infiltration capacity of the soils. The SCS (1986) classified soils on basis of this infiltration capacity, and Skaggs and Khaleel (1982) have published estimates of infiltration rates for those soils, as shown in Table 2.3. These may used in the absence of better information. Because the model parameter is not a measured parameter, it and the initial condition best determined by calibration.

Table 3.3 SCS soil groups and infiltration (loss) rates (SCS, 1986; Skaggs and Khaleel, 1982)

Soil group	Description	Range of loss rates (in/hr)
A	Deep sand, deep loess, aggregated silts	0.30-0.45
B	Shallow loess, sandy loam	0.15-0.30
C	Clay loams, shallow sandy loam, soils low inorganic content, and soils usually high in clay	0.05-0.15
D	Soils that swell significantly when wet, heavy plastic clays, and certain saline soils	0.00-0.05

The Deficit and Constant-Rate Loss Model

HEC-HMS also includes a quasi-continuous model of precipitation losses, this known as the deficit and constant-rate loss model. This model is similar to the initial and constant-rate loss model, but the initial loss can “recover” after a prolonged period of no rainfall.

To use this model in HEC-HMS, the initial loss and constant rate plus the recovery rate must specify. Then HEC-HMS continuously tracks the moisture deficit, computing it as the initial abstraction volume less precipitation volume plus recovery volume during precipitation-free periods. The recovery rate could estimate as the sum of the evaporation rate and percolation rate, or some fraction thereof.

SCS Curve Number Loss Model

The Soil Conservation Service (SCS) Curve Number (CN) model estimates precipitation excess as a function of cumulative precipitation, soil cover, land use, and antecedent moisture, using the following equation:

$$Pe = \frac{(P - Ia)^2}{P - Ia + S} \tag{3.3}$$

Where: P_e = accumulated precipitation excess at time *t*; *P* = accumulated rainfall depth at time *t*; Ia = the initial abstraction (initial loss); and *S* = potential maximum retention, a measure of the ability of a watershed to abstract and retain storm precipitation. Until the accumulated rainfall exceeds the initial abstraction, the precipitation excess, and the runoff, will be zero.

From analysis of results from many small experimental watersheds, the SCS developed an empirical relationship of *Ia* and *S*:

$$Ia = 0.2\,S \tag{3.4}$$

Therefore, the cumulative excess at time *t* is:

$$Pe = \frac{(p - 0.2\,S)^2}{P + 0.8\,S} \tag{3.5}$$

Incremental excess for a time interval computed as the difference between the accumulated excess at the end of and beginning of the period.

The maximum retention, S, and watershed characteristics related through an intermediate parameter, the curve number (commonly abbreviated *CN*) as:

$$S = \begin{cases} \frac{1000 - 10\,CN}{CN} & (foot\_Pound\ system) \\ \frac{25400 - 254\,CN}{CN} & (SI) \end{cases} \tag{3.6}$$

CN values range from 100 (for water bodies) to approximately 30 for permeable soils with high infiltration rates.

The SCS uses a combination of soil conditions and land-use (ground cover) to assign a runoff factor to an area. These runoff factors, called runoff curve numbers (CN), indicate the runoff potential of an area. The higher the CN, the higher is the runoff potential (USDA SCS (1985a)).

The major factors that determine CN are the hydrologic soil group, cover type, treatment, hydrologic condition, and antecedent runoff condition. Another factor considered is whether impervious areas outlet directly to the drainage system (connected) or whether the flow spreads over pervious areas before entering the drainage system (unconnected). CN values for cultivated agricultural and other agricultural lands presented in *appendix F,* under average antecedent runoff condition with the assumption impervious areas are directly connected.

3.2.5.3 Direct-Runoff Models

Modeling direct runoff is transformation of the excess precipitation into point runoff at a given point outlet. HEC-HMS includes two options, systems type and conceptual type of transformation. The systems type transformation included in HMS consists of *Snyder's unit hydrographs model, SCS UH model, Clark's model*, *Modified Clark's model.* The conceptual model includes only a kinematics wave model of overland flow.

Snyder's UH model

Snyder discovered that the UH lag and peak per unit of excess precipitation per unit area of the watershed related by:

$$\frac{Up}{A} = C\ \frac{Cp}{tp} \qquad (3.7)$$

Where U_p=peak of the standard UH; A= watershed drainage area; C_p= UH peaking coefficient; and C=conversion constant (2.75 for SI or 640 for foot-pound system).

Snyder related parameterized the UH of measured watersheds and related it with measurable watershed characteristics and proposed the following two equations to estimate the UH lag (t_p):

$$tp = CCt\ (LLc)^{0.3} \qquad (3.8)$$

Where, C_t=basin coefficient; L=length of the main stream from the outlet to the divide; L_c=length along the main stream from the outlet to a point nearest the watershed centroid; and C=a conversion constant (0.75 for SI and 1.0 for foot-pound system).

The parameter C_t and C_p best found via calibration, as they are not physically based parameters. Bedient and Huber (1992) reported that C_t typically ranges from 1.8 to 2.2, although it has found to vary from 0.4 in mountainous areas to 8.0 along the Gulf of Mexico.

Alternative forms of the parameter predictive equations proposed.

$$tp = CCt\left(\frac{LLc}{\sqrt{S}}\right)^{N} \qquad (3.9)$$

Where S= overall slope of longest watercourse from point of concentration to the boundary of drainage basin; and N=an exponent, commonly taken as 0.33.

SCS UH model

This is a parametric UH proposed by the Soil Conservation Service (SCS) in 1986. At the heart of the SCS UH model is a dimensionless UH, expresses the UH discharge, Ut, as a ratio to the peak discharge, Up, for any time t, a fraction of Tp, the time to UH peak.

SCS suggests that the UH peak and time of UH peak related by

$$Up = C\,\frac{A}{Tp} \qquad (3.10)$$

Where A= watershed area; and C= conversion constant (2.08 in SI and 484 in FPS). The time of peak (also known as the time of rise) related to the duration of the unit of excess precipitation as:

$$Tp = \frac{\Delta t}{2} + tlag \qquad (3.11)$$

Where t= the excess rainfall duration and tlag= the basin lag, defined as the time difference between the center of mass of rainfall excess and the peak of the UH.

The lag time tag given as:

$$tlag = max\left[\frac{Lw^{0.8}\left[\frac{1000}{CN-9}\right]^{0.7}}{31.67\ S^{0.5}}, 3.5\ \Delta t\right] \qquad (3.12)$$

Where Δt is the computational time interval, CN is average curve number for the watershed, S is the slope of the longest flow path (%) and L is the length of the longest flow path (ft).

3.4.5.4 Base flow Models

HEC-HMS includes three models for modeling the base flow.

Constant Monthly

This is the simplest base flow model in HMS. It represents base flow as a constant flow; this may vary monthly. This user-specified flow added to the direct runoff computed from rainfall for each time step of the simulation.

Exponential Recession Method

This explains the drainage from natural storage in a watershed. It defines the relationship of Q_t, the base flow at any time t, to an initial value as:

$$Qt = Qo\ K^{t} \qquad (3.13)$$

Where Qt is the base flow at time t; Qo is initial base flow (at time zero); and K is an exponential decay constant. The contribution decays exponentially from the starting flow. As implemented in HMS, K defined as the ratio of base flow at time t to the base flow one day earlier. The parameters of this model include the initial flow, the recession ratio, and the threshold flow. The starting base flow is an initial condition of the model.

3.4.5.5 Channel Flow

The channel routing models available in HMS includes *Lag*; *Modified Pulls*, *Muskingum*, *Kinematic wave*, and *Muskingum Cunge*. Only lag methods used for this study and discussed below.

Lag Model

This is the simplest of HEC-HMS routing models. With it, the outflow hydrograph is simply the inflow hydrograph, but with the ordinates translated (lagged in time) by a specified duration. The flows not attenuate, so the shape is not changed. Mathematically, the downstream ordinates computed as:

$$Ot = \begin{cases} I(t) & t \leq lag \\ I(t-lag) & t \geq lag \end{cases} \qquad (3.14)$$

Where O_t, is outflow hydrograph ordinate at time t; it is inflow hydrograph ordinate at time t; and lag is time by which the inflow ordinates are to be lagged.

3.2.5.6 Reservoir in HMS

A reservoir is an element with one or more inflow and one computed outflow. Inflow comes from other elements in the basin model. If there is more than one inflow, all inflow added together before computing the outflow. It assumed that the water surface in the reservoir pool is level. Several methods are available for defining the storage properties of the reservoir. The element used to model reservoirs, lakes, and ponds

Three different routing methods are available. The first one *Outflow Curve* routing method designed to represent the reservoir with a known storage-outflow relationship. The second method *Outflow Structure* route method designed to represent individual components of the outlet works. The final method uses a *specified release* and computes the storage that would result.

In order to specify the storage characteristics for the reservoir, it will depend on the routing method selected. The Outflow Curve routing method can accept three different forms of storage characteristics: storage-discharge, elevation-storage-discharge, or elevation-area-discharge. The Outflow Structures route method can accept two different forms of storage characteristics: elevation-storage, or elevation-area. The Specified Release route method can accept two different forms of storage characteristics: elevation-storage, or elevation-area.

In addition, the selection of routing method also changes choice available in storage method, selection list. For outflow curve routing method only initial condition (elevation, storage or discharge) appear in selection list, for *Outflow Structures* routing initial condition, spillways, auxiliary, outlets, evaporation, dam seepage, tailwater rating curve, release, dam tops, and pumps selection option will be available and most of them are optional. Finally, the specified released method maximum release and maximum reservoir capacity are available.

3.2.5.7 Model Calibration and Verification

Calibration

Model calibration is a systematic process of adjusting model parameter values until model results match acceptably the observed data. The objective function described by the quantitative measure of the match. In the precipitation-runoff models, this function measures the degree of variation between the observed and the computed hydrographs. The calibration process finds the optimal parameter values that minimize the objective function. Further, the calibration estimates some model parameters that cannot estimate by observation or measurement, or have no direct physical meaning. Calibration can be either manual or automated (optimization). Manual calibration relies on user's knowledge of basin physical properties and expertise in hydrologic modeling. In the automated calibration model parameters iteratively adjusted until the value of the selected objective function is minimized (CFCAS, 2004).

The latest version of HEC-HMS model includes optimization manager that allows automated model calibration. There are five objective functions available in the optimization manager *(CFCAS, 2004):*

- Peak-weighted root mean square error (PWRMSE): Using a weighting factor, the PWRMSE measure gives greater overall weight to error near the peak discharge.
- Sum of squared residual (SSR): The SSR measure gives greater weight to large errors and lesser weight to small errors (USACE, 2001):

$$SSR = \sum_{t=1}^{N} (Qot - Qmt)^2 \qquad (3.17)$$

- Sum of absolute residuals (SAR): The SAR function gives equal weight to both small and large errors.
- Percent error in peak flow (PEPF): The PEPF measure only considers the magnitude of computed peak flow and does not account for total volume or timing of the peak:
- Percent error in volume (PEV): The PEV function only considers the computed volume and does not account for the magnitude or timing of the peak flow.

Two search methods are available in HEC-HMS model for minimizing the objective functions defined above (USACE, 2001):

- The univariate gradient method (UG): The UG method evaluates and adjusts one parameter at a time while holding other parameters constant.
- The Nelder and Mead method (NM): The NM method uses a downhill simplex to evaluate all parameters simultaneously and determine which parameter to adjust.

Initial values of parameters that are subject to automated calibration are required to start an optimization process. The HEC-HMS model has default hard constraints that limit the range of optimized within reasonable physical intervals. Values within hard constraints do not cause numeric instabilities or errors in computations. Soft constraints can be defined by the user and allow limiting the range of values within the wider range of hard constraints.

Verification

Model verification is the process of testing model ability to simulate observed data other than used for the calibration, with acceptable accuracy. During this process, calibrated model parameters are not subject to change, their values kept constant. The quantitative measure of the match is again the degree of variation between computed and observed hydrographs.

3.2.6 Model Performance

In addition to evaluation of performance model in HEC-HMS, other efficiency criteria such as coefficient of determination, R^2 [Nash and Sutcliff (NSE), 1970] and percent difference D. were used.

The r^2 coefficient and NSE simulation efficiency measure how well trends in the measured data are reproduced by the simulated results over a specified period and for a specified time step. The range of values for r^2 is 1.0 (best) to 0.0

The r^2 coefficient for n time steps calculated as:

$$r^2 = \frac{\left[\sum_{i=1}^{n}(Qsi-\overline{Qs})(Qoi-\overline{Qo})\right]^2}{\sum_{i=1}^{n}(Qsi-\overline{Qs})^2\sum_{i=1}^{n}(Qoi-\overline{Qo})^2} \qquad (3.22)$$

Where: *Qsi* is the simulated value, *Qoi* is the measured values, $\overline{Qs}$ is the average simulated value, $\overline{Qo}$ is the average measured value

The NSE simulation efficiency for n time steps calculated as:

$$\text{NSE}=\left[1-\frac{\sum_{i=1}^{n}(Qsi-Qoi)^2}{\sum_{i=1}^{n}(Qoi-\overline{Qo})^2}\right] \qquad (3.23)$$

Where: *Qsi* is the simulated value, *Qoi* is the measured values, $\overline{Qs}$ is the average simulated value

The statistical index of modeling efficiency (NSE) values range from 1.0(best) to negative infinity.

The percent difference for a quantity (D) over a specified period with total days calculated from measured and simulated values of the quantity in each model time step as:

$$D = 100\left[\frac{\sum_{i=1}^{n} Qoi - \sum_{i=1}^{n} Qsi}{\sum_{i=1}^{n} Qoi}\right] \qquad (3.24)$$

Where: *Qsi* is the simulated value, *Qoi* is the measured values

A value close to 0% is best for D. A negative value indicates model over estimation and a positive value indicate model under estimation.

3.2.7 Reservoir Performance

A quantitative measure of performance of water resource systems is useful in assessing the operational strategies of the potential future dam projects. Hashimoto et al. (1982) suggested the use of indices of reliability, resiliency, and vulnerability, for classifying and assessing the performance of water resource systems. The simulation for both Koga and Gomit reservoir was undertaken by considering long term series with their irrigation water release and environmental flow release. Then the simulation was used for characterization of both storage based on the above performance indices that are reliability, resilience and vulnerability.

Reliability is a measure of frequency or probability that a system is in a satisfactory state meeting a given criterion. Resiliency generally indicates a measure of how quickly a system recovers from failure once failure has occurred. Vulnerability is defined as (1) the maximum duration of system failure; and (2) the cumulative maximum magnitude of water shortage during a system failure. The computational scheme for these indices in this study was done by defining a (dead storage) storage criterion (C) as the minimum required storage, the simulated daily storage (X_t) at time t can be classified as a satisfactory state (S) or a failure state (F), i.e.

$$\text{If} \quad X_t \geq C \quad \text{then} \quad X_t \,\varepsilon\, S \quad \text{and} \quad Z_t = 1 \qquad (3.25)$$
$$\text{Else} \quad X_t \,\varepsilon\, F \quad \text{and} \quad Z_t = 0$$

Where: Zt is a generic indicator variable, the dead storage of the total storage used as a criterion and, thus, system failure occurs when storage is below the criterion on any given day. Another indicator, Wt, which represents a transition from F to S, is defined as:

$$Wt = \begin{cases} 1, & Xt \,\varepsilon\, F \text{ and } Xt+1 \,\varepsilon\, S \\ 0, & Otherwise \end{cases} \qquad (3.26)$$

If the periods of Xt in F are defined as U1, U2,…, UN where N is the number of F periods, then reliability, resilience, and vulnerability indices during the total time period (T) can be defined as:

$$Reliablity = \frac{\sum_{i=1}^{T} Zi}{T} \qquad (3.27)$$

$$Resiliency = \frac{\sum_{i=1}^{T} Wt}{T - \sum_{i=1}^{T} Zt} \quad (3.28)$$

$$Vulnerability\ Time = \ max\{U1, U2, \dots., UN\} \quad (3.29)$$

These indices were previously used to evaluate reservoir operations (Hashimoto et al. 1982; Moy et al. 1986) and water distribution systems (Zongxue et al. 1998); manage water quality of a river (Maier et al. 2001) as well as assessing climate change impacts on water resource systems (Fowler et al.2003).

CHAPTER FOUR

4. METHODOLOGIES AND PROCEDURES

This chapter explains the procedure used to meet the objectives of the study.

- Terrain preprocessing using DEM, ARC-GIS and Arc-Hydro tool for preparation of spatial hydrographic features, used as an input to HEC-GeoHMS.
- Curve Number (CN) Grid generation using land use and soil data of the study areas.
- HEC-GeoHMS data processing for watershed delineation and for the generation of a basin model file and importing it in-to HEC-HMS
- Calibration and validation of rainfall runoff modeling, generating volume of discharge and the runoff hydrographs of the study area using HEC-HMS using historical data.
- Reservoir simulation in HEC-HMS and checking reliability, resilience and vulnerability of reservoirs for irrigation, hydropower and downstream release

4.1 Terrain Preprocessing

The purpose of terrain preprocessing was to perform an initial analysis of the terrain and to prepare the dataset for further processing. A Digital Elevation Model (DEM) of the study area is required as input for terrain preprocessing: a DEM is a grid in which each cell assigned the average elevation on the area represented by the cell. The DEM must be in ESRI GRID format. There are several tools available for terrain pre-processing. In this research, Arc Hydro tools (version that works with Arc-GIS 9.2) was used to process a 90-meter DEM to delineate watershed, sub-watersheds, stream network and some other watershed characteristics that collectively describe the drainage patterns of a basin. The results were used to create input files for HMS hydrologic models.

The steps for the preprocessing of arc hydro are

- *DEM reconditioning:* The DEM Reconditioning function modifies Digital Elevation Models (DEMs) by imposing linear features onto them (burning/fencing).
- *Fill sinks:* The Fill Sinks function fills sinks in a grid. If a cell surrounded by higher elevation cells, the water is trapped in that cell and cannot flow. The Fill Sinks function modifies the elevation value to eliminate these problems.
- *Flow direction:* takes a grid ("Hydro DEM" tag) as input, and computes the corresponding flow direction grid ("Flow Direction Grid" tag). The values in the cells of the flow direction grid indicate the direction of the steepest descent from that cell.

- *Flow Accumulation:* takes as input a flow direction grid. It computes the associated flow accumulation grid ("Flow Accumulation Grid" tag) that contains the accumulated number of cells upstream of a cell, for each cell in the input grid.
- *Stream definition:* takes a flow accumulation grid as input and creates a Stream Grid ("Stream Grid" tag) for a user-defined threshold. This threshold is defined either as a number of cells (default 1%) or as a drainage area in square kilometers.
- *Stream segmentation:* creates a grid of stream segments that have a unique identification. A segment may be either a head segment, or a segment between two segment junctions.
- *Catchment grid delineation:* creates a grid in which each cell carries a value (grid code) indicating to which catchment the cell belongs. The value corresponds to the value carried by the stream segment that drains that area, defined in the input Link grid.
- *Catchment polygon processing:* takes as input a catchment grid and converts it into a catchment polygon feature class ("Catchment" tag)
- *Drainage line processing:* converts the input Stream Link grid into a Drainage Line feature class. Each line in the feature class carries the identifier of the catchment in which it resides.
- *Drainage point processing:* allows generating the drainage points associated to the catchments.
- *Longest flow path for catchments:* generates the longest flow path for each catchment in the input Catchment feature class.
- *Slope:* allows generating the slope grid in percent for a given DEM.
- *Slope greater than 30:* allows generating a grid where the cells having a slope greater than or equal to 30% have a value of 1, and all the others 0. It requires as input a slope grid containing the slope in percent.
- *Slope greater than 30 and facing north:* allows generating a grid where the cells having a slope greater than or equal to 30% and facing north have the value 1. All other cells take the value 0.
- *Weighted flow accumulation:* used to compute the runoff or the load for each cell. This function takes as input a flow direction grid and a weight grid. It computes the associated weighted flow accumulation grid ("Weighted Flow Accumulation Grid" tag) that contains the accumulated values (weight) of cells upstream of a cell, for each cell in the input flow direction grid.

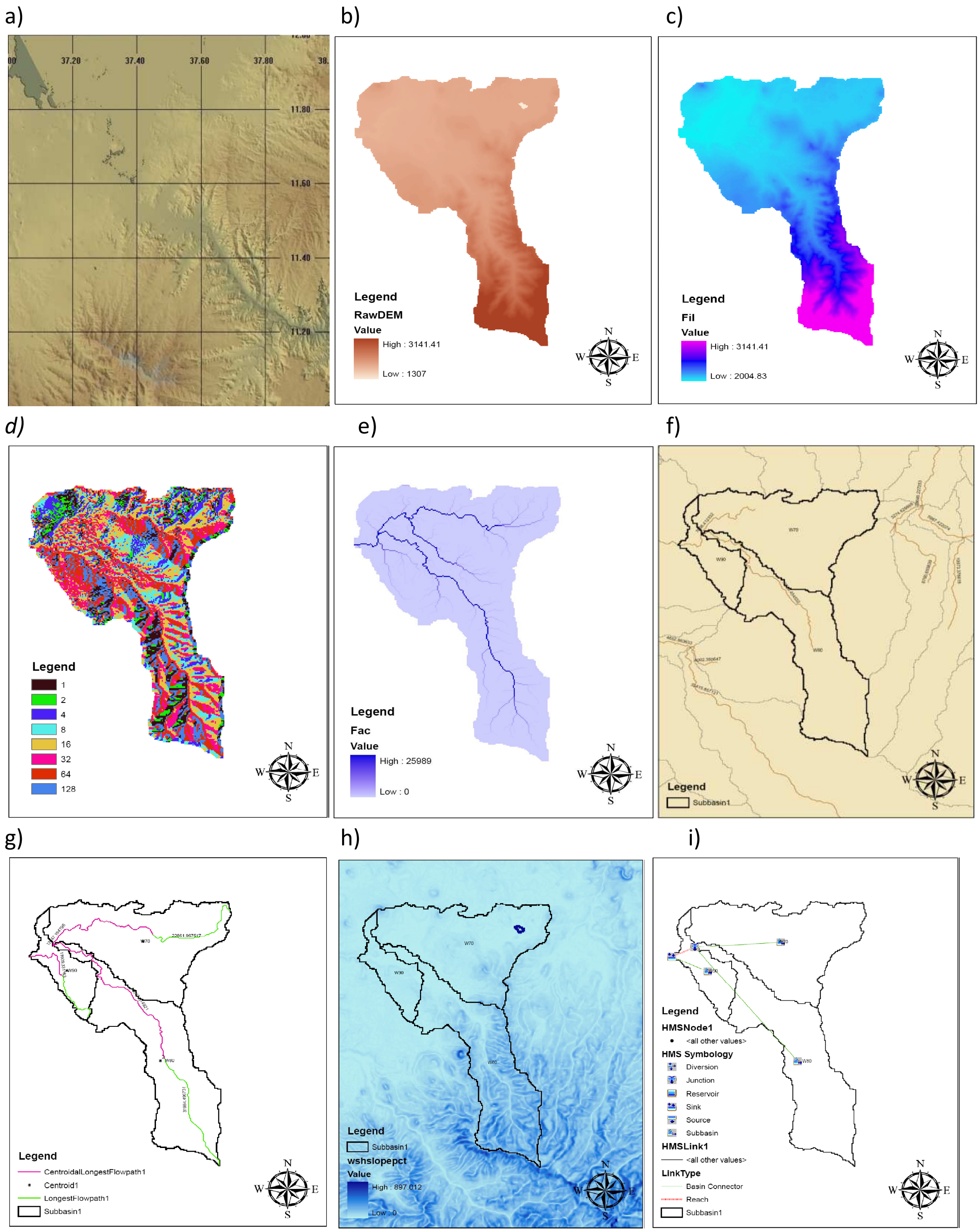


Figure 4.1: Terrain preprocessing for Koga catchment a) unprocessed DEM b) Clipped DEM of the area c) Filled DEM d) Flow Direction grid e) Flow accumulation grid f) Catchment polygon g) centroidal and longest flow path h) Slop grid I) HMS

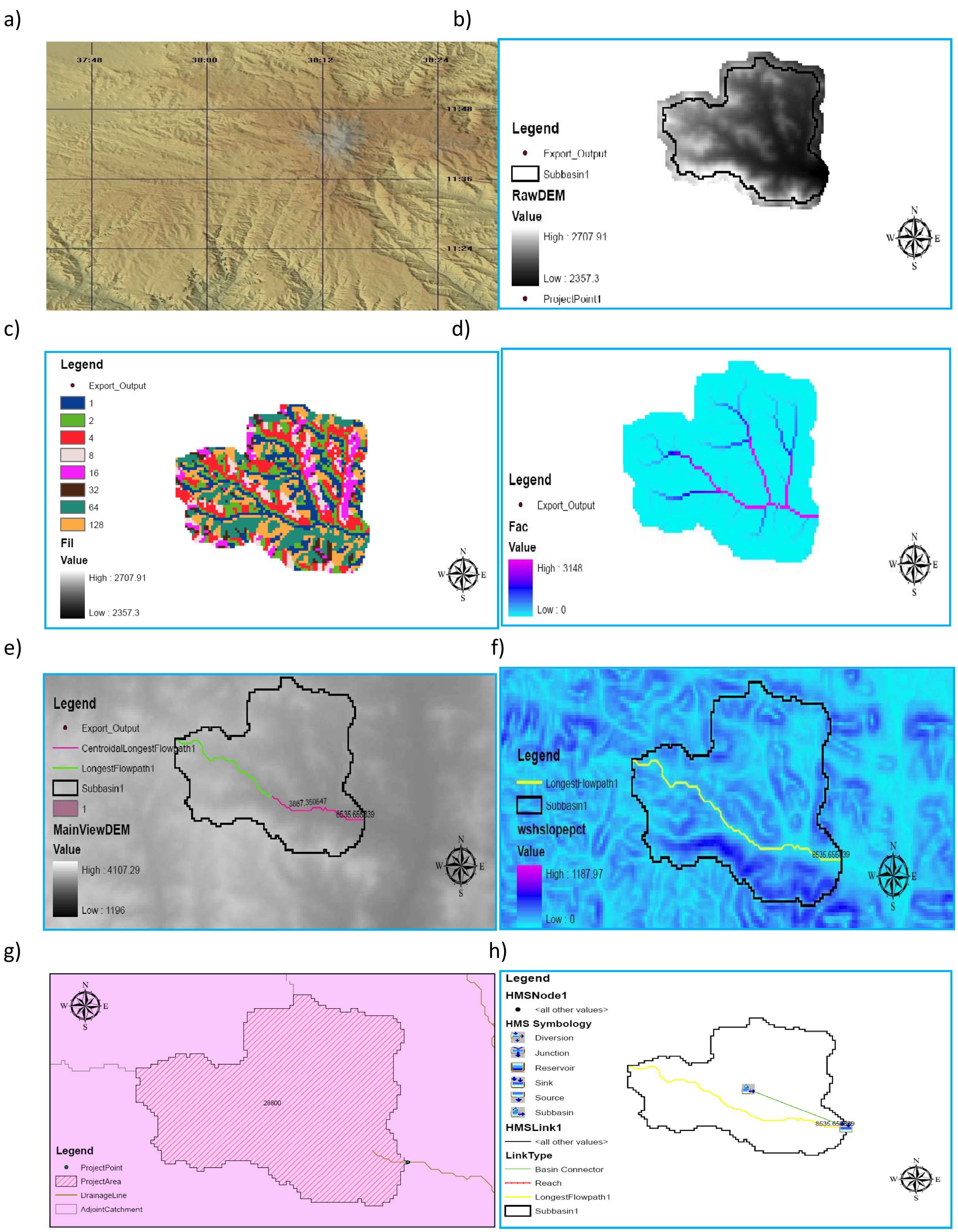


Figure4.2: Terrain Preprocessing for Gomit catchment a) unprocessed DEM b) Clipped DEM of the area c) Flow Direction grid d) Flow accumulation grid e) centroidal and longest flow path f) Slop grid g) Catchment polygon h) HMS

4.2 Generation of SCS Curve Number Grid

SCS curve number grid (CN grid) is used by many hydrologic models to extract the curve number for watersheds, Soil and land use data are used to create a curve number grid using HEC-GeoHMS 4.2 (ArcGIS 9.2 version).

Clipped Soil and land use from ETHIO-GIS (Figure 5.1 and 5.2, in chapter five) were joined to create Unioned Land Use feature by using the analyst tools in Arc-GIS. Then after preparation of a look-up table that will have curve numbers for different combinations of land uses and soil groups (SCS Curve number from TR55 Manual used). Finally, HEC-GeoHMS 4.2 uses the spatial features in conjunction with the look-up table to create curve number grid (Figure 4.3 and 4.4). (Attribute table and CN look up table available in the appendix C.3 and C.4)

Figure 4.3: Koga CN grid

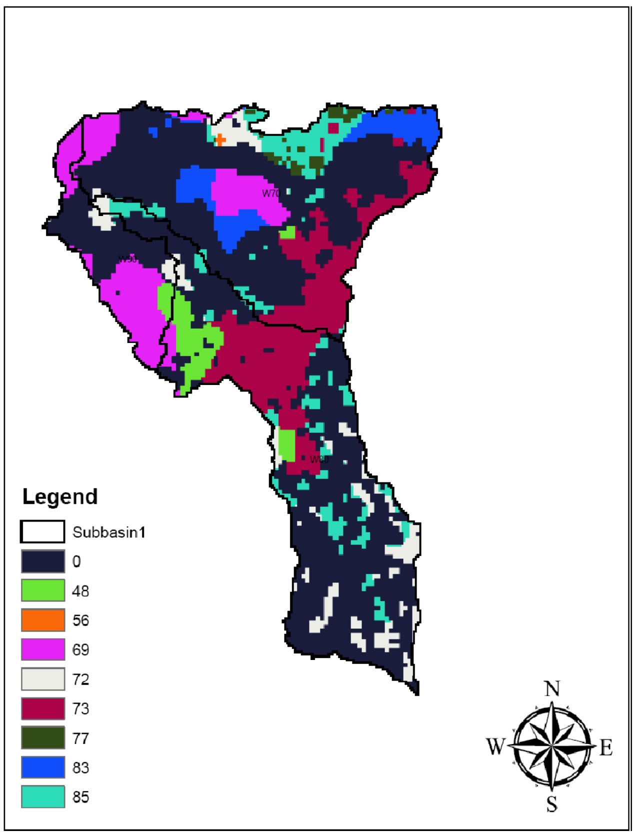
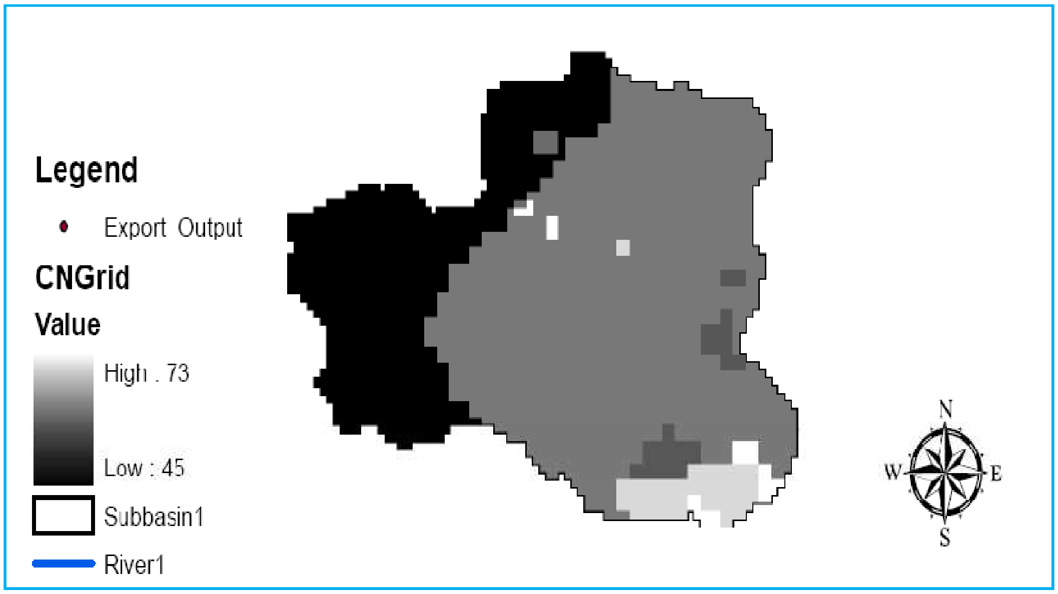


Figure 4.4: Gomit CN grids



4.3 Basin Model Development Using HEC-Geo-HMS

4.3.1 Hydrographic Features

One of the main input parameters for GeoHMS processing is spatial hydrographic features. The GeoHMS tool is designed to have the output files from the Arc Hydro terrain preprocessing tools as inputs. These Hydrographic features, which are already executed using Arc Hydro are flow direction grid (Fdr), flow accumulation grid (Fac), stream grid (Str), stream link grid (Lnk),catchment grid (Cat),curve number grid, slope grid.

4.3.2 GeoHMS Data Processing

The point of the extensive data preprocessing using Arc-Hydro was to create input files for the GeoHMS tools. GeoHMS uses the output files from Arc Hydro and automatically create *subbasins*, *longest and centroidal flow paths*, *basin centroid and other watershed properties*. Additionally, parameters such as slope, length and average curve number are assigned to flow lines and basins. In general, GeoHMS uses spatial analyst tools to convert geographic information into parameters for each of the basins and flow lines. These parameters are used to create a HEC-HMS model that can be used within the HEC-HMS program. *Table 4.1a) to c)* basin model prepared in HEC-GeoHMS *(Basin model representations of the catchment in HEC-GeoHMS shown on figure 4.5 and figure 4.6)*

Figure 4.5: HMS representation of Koga catchment

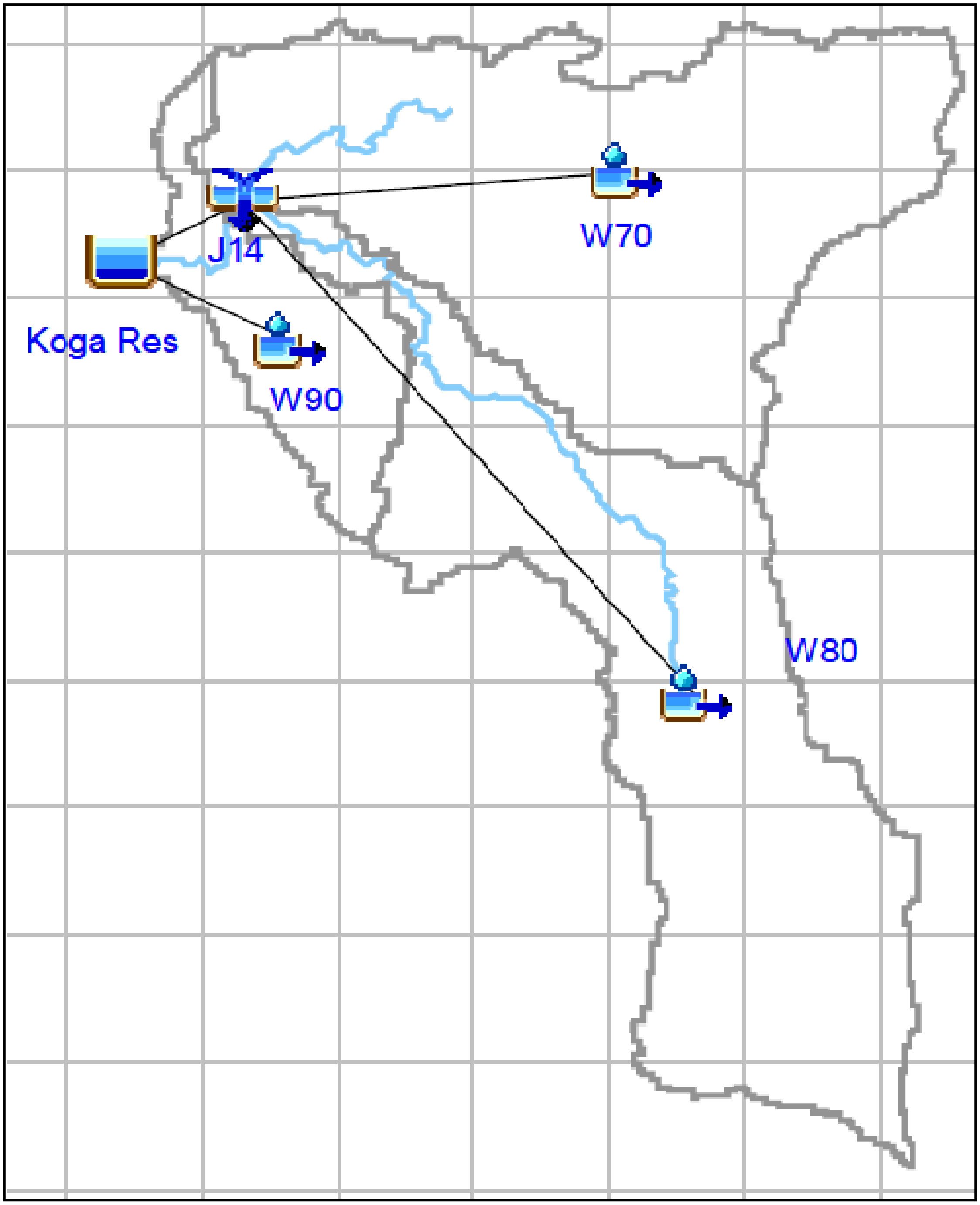


Figure 4.6: HMS representation of Gomit catchment

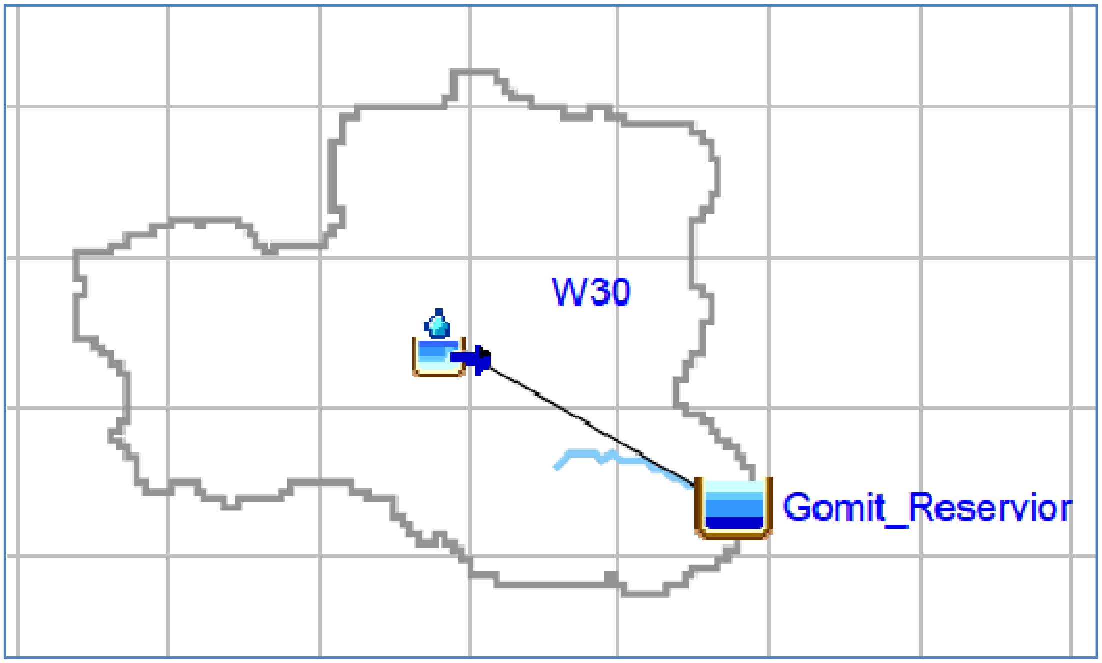


Table 4.1 Gomit basin characteristics

Basin Name	Area HMS	Centroidal FL(m)	Longest FL(m)	Elev U/s(masl)	Elev D/s(masl)	Slope
Gomit	24.9564	3867.35	8535.65	2649.35	2357.3	0.03

Table 4.2 a) and b) Koga basin characteristics

Sub Basin NAME	Shape Length	Shape Area	Basin Slope	Area HMS	Longest FL	Centroidal FL	Centroidal Elevation
W70	65880	92105100	5.00225	92.105	22861.968	12647.195	2087.264
W80	82440	89456400	15.59100	89.456	31984.497	19537.815	2156.585
W90	37980	22145400	2.33371	22.145	11009.331	5043.557	2037.069

River Name	ElevUP HMS	ElevDS HMS	RivLen HMS	Slope
R40	2022.201	2008.804	7668.412	0.001747
R50	2008.804	2003.990	3297.792	0.001460
R60	2129.991	2008.804	19556.455	0.006197

4.4 HEC-HMS model Development

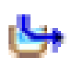
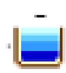
After converting data from a geographic to a hydrologic data structure in the HEC GeoHMS the next step was configuration of the HMS model. HEC-HMS is a graphical user interface model that requires the construction of three-model components and data manager that are required for a run: Basin Model, Meteorological Model, and Control Specification Model.

4.4.1 Basin Model

The basin model represents the spatial configuration of the watershed. The basin model, for instance, contains information relevant to the physical attributes of the model, such as basin areas, river reach connectivity, or reservoir data. The basin model of Koga and Gomit catchment imported that developed in the previous section. Once imported in HEC HMS, the watershed elements can be modified, added or removed. In the basin model, individual hydrologic elements can be connected in a network imitating basin hydrologic structure. HEC-HMS allows seven different watershed elements for construction of the basin model: sub-basins, reach, junction, source, sink, reservoir and diversion.

The Koga and Gomit basin contains different hydrologic elements but both of them have Subbasin, reservoir and outlet junction, in addition Koga has reach element. Individual hydrologic element labels used are shown below with their description

Table 4.3: HMS element

Hydrologic Element		Description
Subbasin		Used to represent the physical watershed
Reach		Used to convey (route) stream flow downstream in the basin model
Reservoir		Used to model the detention and attenuation of hydrograph caused by a reservoir or detention pond
Junction		Used to combine flows from upstream reaches and sub-basins
Diversion		Used for modeling streamflow leaving the main channel.

On the basis of the available data and evaluation of model components, simulation was undertaken with two model sets:

i) Combinations of *Deficit Constant loss*, *Snyder unit hydrograph* and *monthly constant baseflow* models

ii) Combinations of Deficit –Constant loss model, SCS UH model, and monthly constant base flow model.

To model the runoff processes in each sub-basin it was necessary to establish initial values for 9 parameters: 4 for the deficit and constant-rate loss model, 2 for Snyder's model, 2 for SCS model and 1 for the routing Lag model. Some parameters were imported from the basin model (e.g. basin lag) and others were entered based on type of soil class and acceptable ranges. (*Acceptable ranges of parameters of each model category available in appendix B.2.)*

4.4.2 Meteorological Model

The meteorological model in HEC-HMS is the major component that is responsible for the definition of the meteorological boundary conditions for the subbasins. It includes precipitation, evapotranspiration and snowmelt methods to be used in simulations. In the present version HEC HMS 3.3 there are four methods in the HMS model to distribute observed rainfall over the basin: user hyetograph, user gage weighting, inverse-distance gage weighting, and gridded precipitation. The user specified precipitation method was used in the model simulations. For precipitation gage input data the most representative rain gages among nearby station for Koga and Gomit catchments were selected using the Thessien polygon method. Koga used stations at Merawi and Adet and for the Gomit basin one station at Mekane Yesus was used. All data transfer was achieved using HEC-DSS.

4.4.3 Control Specification Model

The Control Specification Model specifies the start and end of the computation period and the computation time interval. Since the available data was daily the computation time interval of this study was one day. The computation period was divided into a calibration and a validation period. Finally the model was used for reservoir simulation.

4.4.4 Model Parameter Calibrations and Validations

Each method in HEC-HMS has parameters and the initial values of these parameters need to entered as input to the model to obtain the simulated runoff hydrographs. Some of the parameters were estimated by observation and measurements of stream and basin characteristics, but some of them cannot be estimated. When the required parameters cannot be estimated accurately, the model parameters are *calibrated,* i.e. in the presence of rainfall and runoff data the *optimum* parameters are found because of a systematic search process that yield the best fit between the observed runoff and the computed runoff. This systematic search process is called *optimization.* Optimization begins from initial parameter estimates and adjusts them so that the simulated results match the observed streamflow as closely as possible.

In this study, Nelder and Mead search algorithm was selected to move from the initial estimates to the final best estimates by considering the sum squared residuals objective function.

Koga watershed uses six years of data from 2001 to 2006 for calibration and four years of data from 1996 to 1999 for validation. Manual and automatic parameter adjustment was used for optimization of observed and simulated flow data. In contrast because of lack of data only calibration could be conducted for the Gomit watershed. This was undertaken using two years of reservoir level data from August 2006 to July 2008. Manual parameter adjustment was used for optimization of observed and simulated reservoir level. Most of the initial parameters used based on the watershed characteristics.

4.4.5 Model Performance

The performance of a model must be evaluated on the extent of its accuracy, consistency and adaptability *(Goswami et al., 2005).* A forecast efficiency criterion is therefore necessary to judge the performance of the model. Assessing performance of a hydrologic model *(Krause et al., 2005)* requires subjective and/or objective estimates of the closeness of the simulated behavior of the model to observations.

4.4.6 Calibration and Validation Performance

In this study, the objective function used for measuring the goodness of fit between the computed and the observed hydrographs is Sum of Squared Residuals with Nelder Mead search algorithm. HEC-HMS computes the percent errors in peaks and volumes and gives these values in the optimization result tables automatically. These two values used as goodness-of-fit criteria between observed flow and the simulated flows. Additionally, three statistical criteria were used to evaluate the calibrated model performance:

i) Pearson's Coefficient of Determination (R^2)

ii) Nash and Sutcliffe Model Efficiency (NSE) [Nash and Sutcliffe, 1970] and

iii) Percent difference D.

These were computed externally.

4.4.7 Reservoir Simulation

In HEC HMS the reservoir element used to assign for both Koga and Gomit reservoirs instead of outlets and all flow coming from upstream subbasin, consider as inflow to reservoir. Reservoir element for Koga were considered only during the reservoir performance simulation period, not the calibration and validation period (outlet element considered for this period) because the dam is not constructed during validation and calibration period. However, for Gomit, the reservoir element considered for both case.

For both Gomit and Koga reservoirs the routing method selected was *Outflow Structures*. In addition, data for elevation-storage-area, spillway, release (for irrigation and environmental), monthly reservoir evaporation were entered.

Finally, reservoir simulation was undertaken using the optimized parameters, long-term historical rainfall data and by assuming the reservoir was full initially. The simulation period for Koga was from 1983 to 2004 and for Gomit from 1996 to 2006.

The performance of the reservoirs was evaluated based on reliability, resiliency and vulnerability (RRV) performance indices. Base line condition selected to decide whether the reservoir is in safe or failure state is dead storage level for irrigation and environmental release. Dead storage level for Koga and Gomit are 2007.5 and 2361.589 masl respectively.

Koga hydropower potential of 32 Kilo Watt (KW) was investigated during feasibility study, it is generate by using compensation flows discharge from the reservoir with head range of 15.5 m to 8.5 m (reservior fluctuates from EL 2015 to EL 2008.5) assuming turbines are connected to low level outlet. The RRV of reservoir also evaluated for hydropower generation using minimum required reservior elevation of 2008.5 masl.

4.4.8 Climate Scenarios

The climate in most of the Upper Blue Nile River Basin is likely to become wetter and warmer in the 2050s (2040-2069).The potential changes in mean annual precipitation from six GCMs range from -11% by CSIRO to 44% by CCSR/NIES with a change of 11% from the weighted average scenario. *(Kim, U; Kaluarachchi, J. J.; Smakhtin, V. U. 2008)*

The average changes of climate variables and runoff from the six sub-basins are shown in Figure 4.7. Compared to the southwest of the UBN, the northeast shows a more pronounced increasing trend in precipitation and a less pronounced increasing trend in temperature. These trends result in a noticeable increase in runoff in the northeast compared to the southeast. It is, therefore, possible to suggest that water availability will most likely improve in this area. *(Kim, U; Kaluarachchi, J. J.; Smakhtin, V. U. 2008)*

In this study, climate scenario considered to look at the change in values of performance indices by increasing and decreasing each daily rainfall hypothetically. Since, Koga and Gomit catchment located in subbasin 6 as per figure 4.7, by 2050 the precipitation increased by 15 to 20%.

Therefore, hypothetical 20% increase of daily rainfall was assumed as the upper limit. As mentioned above the mean annual precipitation potentially decrease by -11% but the lower limit of -20 % used in order to see performance indices sensitivity.

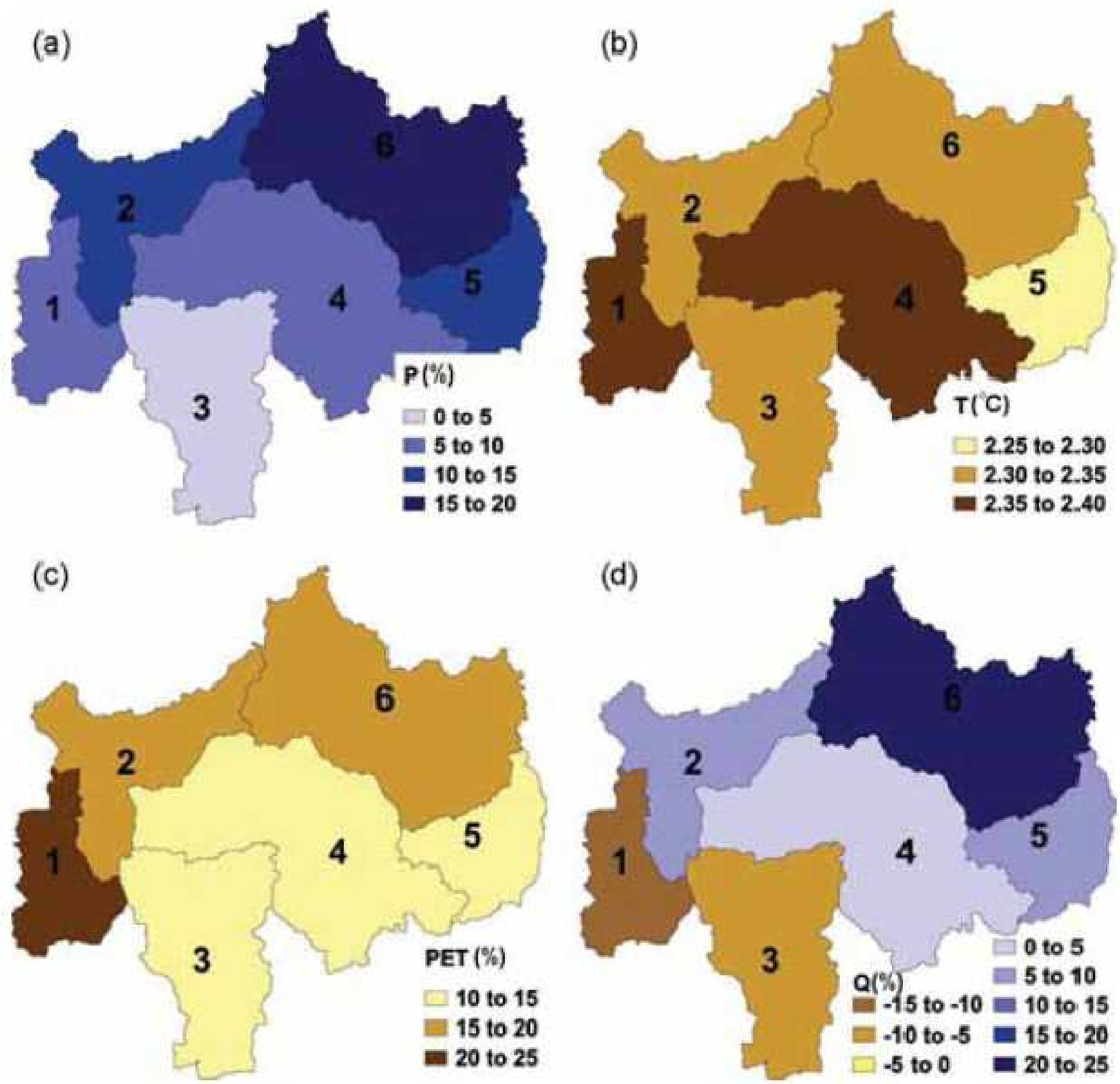


Figure 4.7: Spatial distribution of the average annual changes in climate variables and runoff under the weighted scenario for the 2050s: (a) precipitation, (b) temperature, (c) potential evapotranspiration, and (d) runoff.

CHAPTER FIVE

5. DATA AND ANALYSIS

The purpose of this chapter is to bring all the available data and select relevant information for the analysis. The data sets DEM, Hydrological, Meteorological data, Land use, Land cover and Soil maps collected.

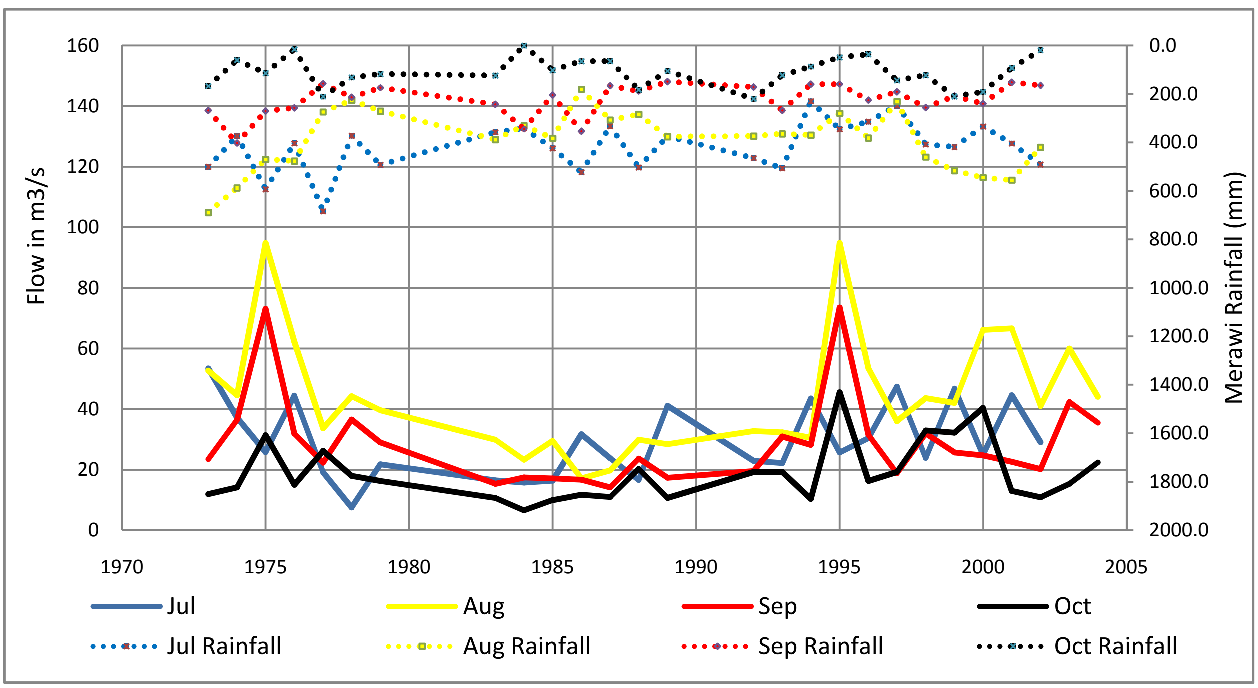
5.1 Hydrological Data

Twenty years of daily flow data for nine stations for Koga, Gomit and nearby catchments were collected from the Hydrology Department in the Ministry of Water Resources (MoWR). The name and location of hydrological station is available in *Appendix A.1*

Flow in the Koga River is measured at Merawi (37° 02' E and 11° 22' N). Data for this station are available from January 1973. A gauge was installed at the proposed dam site in 2003, but at present, no data are available for it at the Ministry of Water Resources (MoWR). However, in the past, data from the gauging station at the site was used to develop a relationship between there and the gauge at Merawi *(Mott MacDonald, 2004)*.

As shown figure 5.1, the Flow at Merawi shows different behavior year to year

Figure 5.1: Monthly flow year-to-year variation



As the Koga dam site is situated about 20kms upstream of the gauging station, discharge data obtained at the gauging station were adjusted to dam site. In this respect, an adjustment factor for the difference in the catchment areas at the gauging station and the dam site considered. This is assuming that the catchment area is hydrologically homogeneous and the variability of rainfall over the catchment is negligible. The adjustment factor (*f_Koga*) obtained as follows

$$f\_Koga = \frac{Ads}{Ags} = \frac{203}{244} = 0.831$$

Where *Ads* is catchment area of dam site in km2 and *Ags* is catchment area of gauging station in km2

At the Gomit dam, there is no historical measured flow data at the dam site. However, there are two nearby stations, the first at Wanka $11^{0}37'$N and $38^{0}04'$E near Istay town, it's catchment area 110 km2 and it has available daily data from 1987 to 2003 with some gaps, the second at Chena $11^{0}37'$N and $38^{0}02'$E near Istay with catchment area 32.5 km2, it has available daily data from 1985 to 2007 with some gaps. The gaps for both stations were filled by using long term daily average flow.

The flow series at the Gomit dam site obtained by adjusting flow data at Chena using area ratio method adjustment factor (f _Gomit) 0.77. (Chena selected because it is near to the dam site than Wanka)

$$f\_Gomit = \frac{Ads}{Ags} = \frac{25}{32.5} = 0.77$$

Where *Ads* is catchment area of dam site in km2 and *Ags* is catchment area of gauging station in km2

5.2 Meteorological Data

Fifteen years of daily data for 10 stations (six station near Koga catchment and four stations for Gomit catchment) were collected from National Meteorological Agency (NMA).The location of meteorological stations and the type of data collected is available in *Appendix A.2*. Average annual rainfall for all stations is shown in *figure 5.1*

Thessien polygon created in the ARC-GIS for both Koga and Gomit, for Koga, Adet and Merawi stations considered, for Gomit only Mekane Yesus station considered. Mean monthly rainfall and evaporation data are presented in *Table 5.2* and *5.3*

Merawi meteorological station available data is limited to the period from 1981 to 1995. The station did not operate between the beginnings of 1996 up to December 2004. The available data period for Adet is from 1986 to 2007.Mekane Yesus station available data is from 1994 to 2007. For the all stations there are large data gaps within the periods of record, therefore it needs data filling and extension.

Figure 5.2: Average annual rainfalls

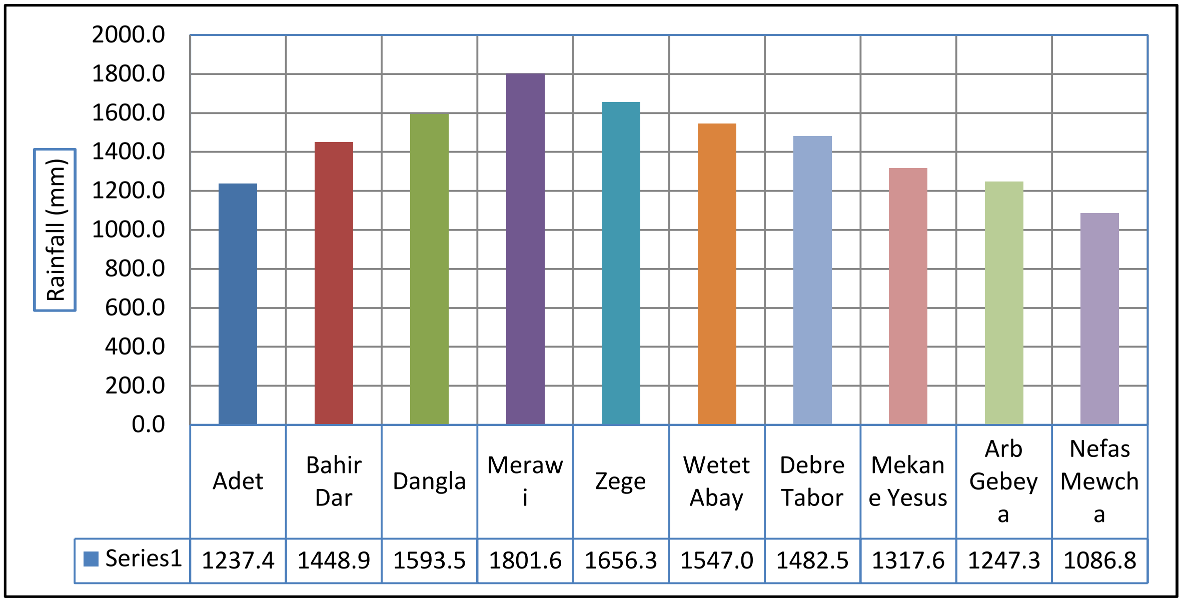


Table 5.1: Evaporation and rainfall

	Koga		Gomit	
	ET_0 (mm/month)	Rainfall (mm/month)	ET_0 (mm/month)	Rainfall (mm/month)
January	105	3.2	114.7	7.8
February	109	1.7	120.4	12.7
March	143	10.1	148.8	45.3
April	147	30.6	144	41.2
May	140	102.7	130.2	85.6
June	117	227.8	105	156.6
July	100	445.3	74.4	457
August	100	406.7	74.4	434.3
September	103	219.7	99	164.9
October	116	102.2	114.7	62.9
November	107	23	105	27.9
December	103	5.3	102.3	12.9

Table 5.2: open water evaporation

	Open Water Evaporation(mm/month)												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Koga MM	121	124	157	163	151	127	109	103	112	135	124	116	1542
Koga FS	114	118	155	159	154	128	107	109	117	131	117	109	1516
Gomit	126	132	164	158	143	115	82	82	109	126	115	113	1465

5.3 Missing Data Filling

Simple normal ratio method was used to fill stations with missing data.

Normal ratio method are expressed by the following relationship

$$px = \frac{1}{n}\left(\frac{px}{p1} * p1 + \frac{px}{p2} * p2 + ,,,,,,,,,, + \frac{px}{pn} * pn\right)$$

Where

P^X missing value of precipitations

PX average value of rainfall for the station in equation for recorded Period.

P1-----Pn any value of neighboring stations.

p1 -----Pn rainfall of neighboring station during missing period

n ----- Number of stations used in the computations

5.4 Checking Consistency and Homogeneity

A time series observational data is relatively consistent and homogenous if the periodic data proportionally behaves comparable similar pattern. This proportionality tested by double - mass analysis. The principle of double mass analysis is to plot accumulated values of the station under investigation against accumulated value of another station, or accumulated values of the average of other stations, over the same period. Through the double mass curve, inhomogeneities in the time series (in particular jumps) can be investigated. For example, those originating from a change in observer, in rain-gauge type, etc. These indicate in double mass plot, showing an inflection point in the straight line. The data series, which is inconsistent, adjusted to consistent values by proportionality. Double mass curve plot made for all ten stations near to Koga and Gomit catchments *figure 5.2* to *5.3* shows only for Merawi and Mekane Yesus. For the rest station available in *Appendix E.1*. From the double mass curve figure the stations are consistent each other.

Figure 5.2: Merawi Double mass curves

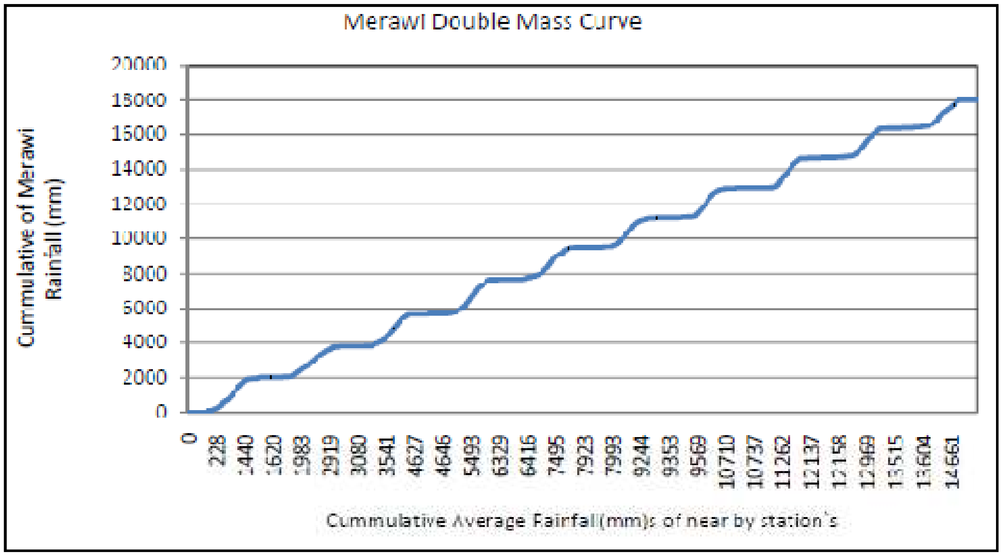
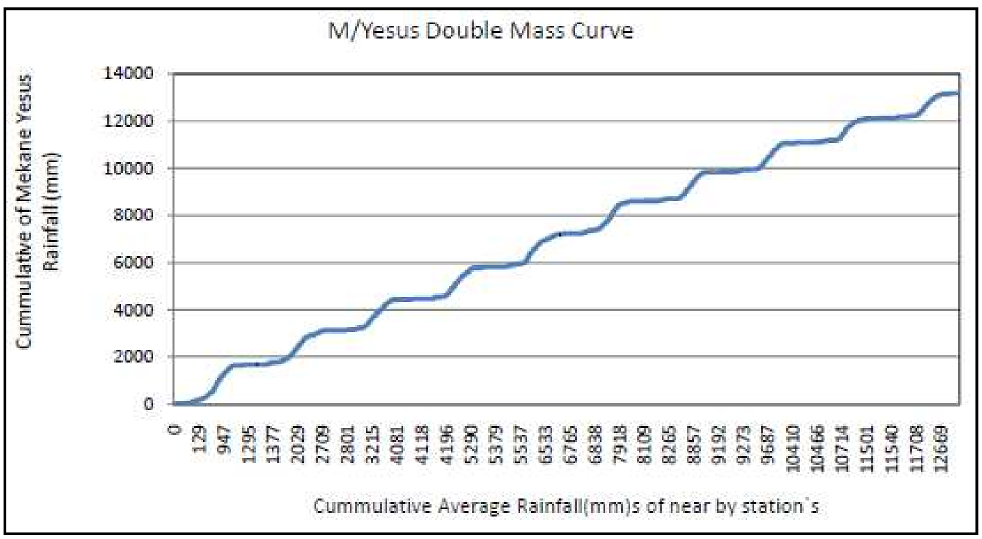


Figure 5.3: Mekane Yesus Double Mass curve



5.5 Irrigation and Downstream Release Data

The gross crop water requirements used for Gomit and Koga reservoir simulations are shown in *table 5.3* and *5.4, t*heir command area are 90ha and 7000ha respectively.

Total gross annual irrigation requirement Koga 1358 mm for irrigation efficiency of 50% and Gomit irrigation 470 mm for irrigation efficiency of 40.5%

The environmental flow from feasibility study (FS) is used for this study and it is presented in *table 5.4* with long-term average downstream flow. There is no environmental release by FS in the month of June to September, presumably because the period through the rainy season should have sufficient water directly from rain and local runoff downstream of the dam. In addition there will be return flows from irrigation system via drainage networks to the river.

Table 5.3: Gomit Crop water requirements

(NIR: Net Irrigation Requirement, GIR: Gross Irrigation Requirement)

Crop Type	Crop water requirements (wet season) (mm/month)						
		Area (ha)	Jan-Aug	Sep	Oct	Nov	Dec	Total
Wheat	NIR		0	16.1	21.5	0	0	37.6
	GIR (35%)	31.5	0	5.64	7.53	0	0	
Field Peas	NIR		0	12.4	31.3	0	0	43.7
	GIR (15%)	13.5	0	1.86	4.7	0	0	
Flax	NIR		0	14.7	49.8	6	0	70.5
	GIR (15%)	13.5	0	2.2	7.47	0.9	0	
Garlic	NIR		0	15.6	27.3	0	0	42.9
	GIR (20%)	18	0	3.12	5.46	0	0	
Barley	NIR		0	16.1	21.5	0	0	37.6
	GIR (15%)	13.5	0	2.42	3.23	0	0	

Crop Type	**Crop water requirements (Dry season)(mm/month)**										
		Area (ha)	Jan	Feb	Mar	Apr	May	Jun-oct	Nov	Dec	Total
Wheat	NIR		43.7	114.5	140.4	126.3	21	0	0	0	445.9
	GIR (35%)	31.5	15.3	40.08	49.14	44.21	7.35	0	0	0	
Fenugreek	NIR		43.4	109.6	133.3	108.9	0	0	0	0	395.2
	GIR (15%)	13.5	6.51	16.44	20	16.34	0	0	0	0	
Barley	NIR		104.3	134.5	126	30.2	0	0	0	39.1	434.1
	GIR (35%)	31.5	36.5	47.07	44.1	10.57	0	0	0	13.68	
Garlic	NIR		113.6	131.4	73.7	0	0	0	14	58.3	391
	GIR (15%)	13.5	17.04	19.71	11.05	0	0	0	2.1	8.74	

Source: Co-SARAR Gomit micro dam irrigation agronomy feasibility report, 2000

Table 5.4: Koga crop water requirements

Gross Crop Water Requirements *(mm)*												
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
FS	99	184	258	149	0	0	0	0	0	89	111	44	934
MM	109	237	329	237	24	0	0	0	87	207	106	22	1358
	Environmental Flow Release *(m^3/s)*												
FS d/s Release	0.4	0.4	0.3	0.26	0.3	0	0	0	0	1	0.6	0.3	3.56
Long term average d/s flow	0.45	0.37	0.3	0.26	0.3	0	0	0	0	1.8	0.99	0.64	5.11

Source: Feasibility Study (FS), Annex I, Table I 4.2(a) and (b) and Mott Macdonald (MM) Table 4.14 interim Report

5.5 DEM (Digital Elevation Model)

The DEM 90*90 of Ethiopia obtained from Ministry of Water Resource was used to delineate the study area. The DEM was processed according to the location of the study area. The full process of the DEM is described in the methodology.

5.6 Land Use, Land Cover, Soils

The soil and land use data of Ethiopia obtained from Ministry of Water Resource was used to clip soil and land use grid of the study area.

5.6.1 Koga Soil and Land use

Major and dominant soil types identified in the watersheds are chromic vertisols, Dystric gleysols, Pellic vertisols, Eutric nitisols, chromic cambisols, chromic luvisols, and Leptosols.*(fig 5.4 and Table 5.3)* The most dominant soil types are chromic vertisols, Dystric gleysols, and Pellic vertisols.

Figure 5.4: Koga soil grids

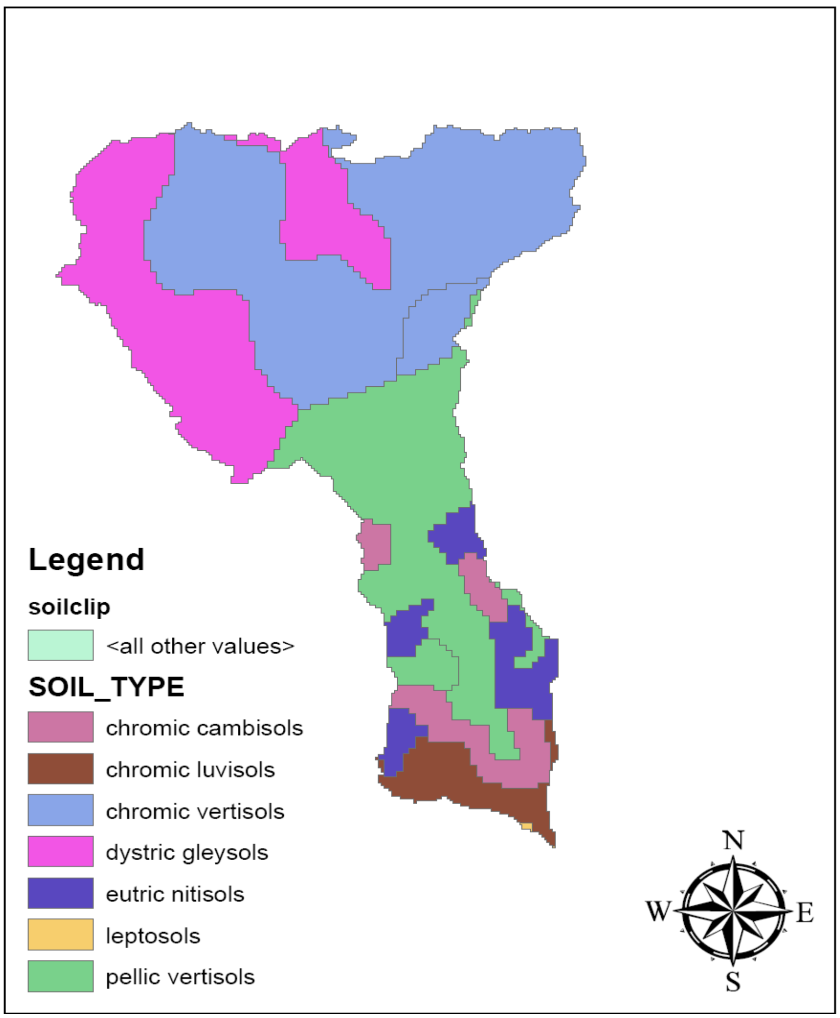


Table 5.5: Koga Soil data

No	SOIL_TYPE	Area(km2)	Total Watershed %
1	Chromic vertisols	54.15	26.58
2	Dystric gleysols	56.86	27.91
3	Pellic vertisols	51.41	25.24
4	No data	2.19	1.07
5	Eutric nitisols	13.57	6.66
6	Chromic cambisols	14.01	6.88
7	Chromic luvisols	11.39	5.59
8	Leptosols	0.13	0.06
Total		203.71	100.00

The land cover for the Koga basin is mainly characterized by dominantly cultivated, and grassland, Shrubland, Wetland and plantation according to the Ministry of Water Resources (Ethiopia) land cover classification *figure 5.5*.

Figure 5.5: Koga land use grid

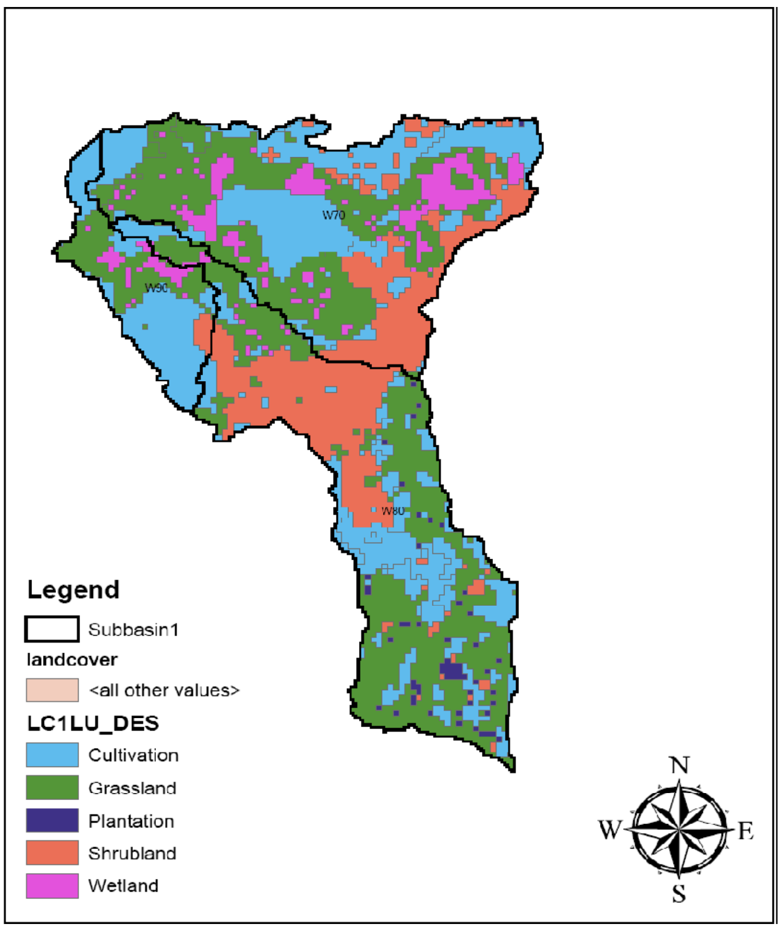


Table 5.6: land Use grids

No	LC_TYPE		Area *(km2)*	Total Watershed %
1	Cultivation	Cultivated Land; Rainfed; Cereal Land Cover System; lightly stocked	9.37	4.60
		Cultivated Land; Rainfed; Cereal Land Cover System; moderately stocked	29.68	14.57
		Cultivated Land; Rainfed; Cereal Land Cover System; unstocked (woody pl)	29.15	14.31
2	Grassland	Grassland; moderately stocked	0.92	0.45
		Grassland; unstocked (woody plant)	41.93	20.59
		Grassland; unstocked (woody plant),Wetland; Seasonal Swamp / Marsh	44.01	21.61
3	Shrubland	Shrubland; Dense (>50% woody cover),Woodland; Open (20-50% tree cover)	1.53	0.75
		Shrubland; Open (20-50% woody cover)	0.84	0.41
		Shrubland; Dense (>50% woody cover)	33.63	16.51
4	Wetland	Wetland; Perennial Swamp / Marsh	9.76	4.79
5	Plantation	Forest; Plantation forest; Open (20-50% crown cover)	2.87	1.41
Total			203.70	100.00

5.6.2 Gomit Soil and Land Use

Major and dominant soil types identified in the watershed are Calcic Xerosols Eutric Regosols (fig 5.6 (a) and *table 5.7*).

Figure 5.6: Gomit watershed Soil and land use grid

a) Soil grid B) Land use grid

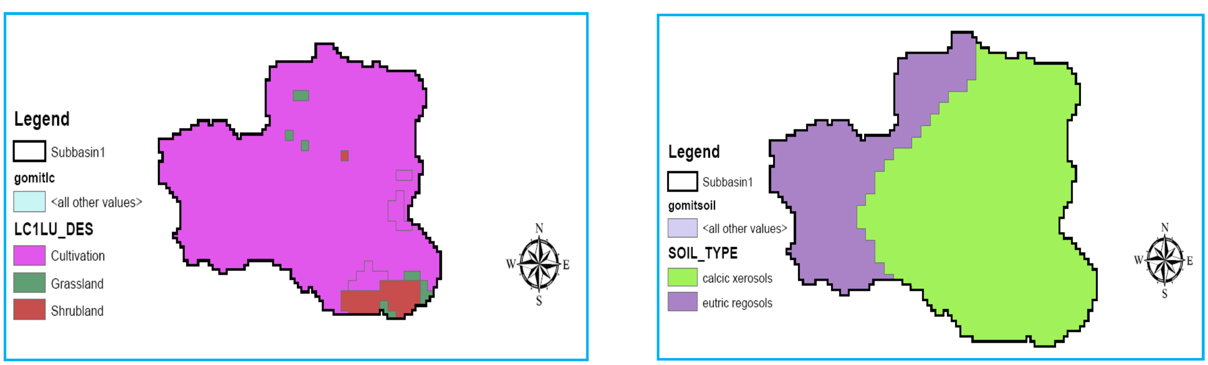


Table 5.7: Gomit Soil

No	SOIL_TYPE	Soil Code	Area(Km^2)	Total Watershed %
1	Calcic Xerosols	B	17.756	69.77
2	Eutric Regosols	A	7.694	30.23
Total			25.450	100

The land cover for the Gomit basin is mainly characterized by dominantly cultivated, and grass land, and Shrubland (fig 5.7 (b) and table 5.8). The cultivated land takes 91.42 % of the total catchment area.

Table 5.8: Gomit Land use

S.no	Land Use	Area(ha)	Total Watershed %
1	Cultivated Land; Rainfed; Cereal Land Cover System; lightly stocked	2326.54	91.42
2	Cultivated Land; Rainfed; Cereal Land Cover System; unstocked (woody pl)	74.09	2.91
3	Grassland; lightly stocked	17.14	0.67
4	Grassland; unstocked (woody plant)	16.55	0.65
5	Shrubland; Open (20-50% woody cover)	110.69	4.35
Total		2545	100

CHAPTER SIX

6 RESULT AND DISSCUSION

6.1 HEC-HMS Results

The rainfall runoff modeling for both Koga and Gomit watershed was conducted using two transformation methods. The first combination was Deficit constant loss, Snyder unit hydrograph transformation and monthly constant base flow (DcSMc) and the second combination was Deficit constant loss, SCS unit hydrograph transformation and monthly constant base flow (DcSCSMc). The SCS loss (curve number) method was tried in the above two combination but the result was very weak so it was not considered, this could be due to the low resolution of soil and land use grid, this loss method is not effective for long-term simulation in addition this loss method not be effective for Ethiopia it is developed for USA.

6.1.1 Calibration and Verification Result

Daily and monthly discharge data at the Koga dam site from 1996 to 2006 was used for model calibration (2001 to 2006) and validation (1996 to 1999) of Koga dam watershed. The latest data were used for calibration because most of the data for this period is not in filled.

Summary results in HEC HMS for a combination DcSMc shown on table 6.1, in addition three Calibration performance result, are shown in *figure 6.1 and 6.3*. The first performance evaluation Nash and Sutcliffe Model Efficiency (NSE) *[Nash and Sutcliffe, 1970*] for daily stream flow calibration is 0.606 and 0.881 for monthly Calibration. The second performance evaluation result that is Pearson's Coefficient of Determination (R^2) gives 0.61 and 0.883 for daily and monthly calibration. The third performance evaluation result, volumetric fit (D), gives 0.01 % for daily and 2.8 % for monthly.

Table 6.1 Koga objective function result

Measure	Simulated	Observed	Difference	Percent Difference
Volume (mm)	7854.716	8025.447	-170.73	-2.13
Peak Flow (M^3/S)	33.416	86.419	-53.003	-61.3
Time of Peak	27-Aug-06	00:00	26-Aug-06	00:00
Time of Center of Mass	1-Sep-01	02:16	11-Aug-01	13:06

Model validation for this study was used to determine the effectiveness of the parameterization and calibration methodologies. The selected validation period was before the respective calibration period. Daily and Monthly validation result for three-efficiency evaluation (figure 6.2 and 6.4) are 0.622 and

0.882 for NSE, 0.63 and 0.919 for R^2, and 0.17 % and 1 % for D. These values are higher than the ones obtained through the model calibration process, this improvement occurred possibly due to Merawi rainfall data, during calibration the data is both filled and observed but during validation the filled data used. However, the improvement shows the model is capable of making accurate predictions for periods outside a calibration period and no need of doing recalibration process.

The result for the second combination DcSCSMc shows better calibration and validation result in R^2. It varies from 0.60 to 0.601 respectively.

Generally, the model under estimates peak flow for all daily simulation period however, for monthly it underestimates considerably only for year 2006. The volumetric fit shows very good fit of observed and simulated flow for both monthly and daily, even though the under estimation is greater for monthly simulation.

The transferred flow data from the Chena station did not give better result in any of performance evaluation criteria therefore two years of Daily Gomit reservoir level data from May 2006 to July 2008 were used for model calibration.

Calibration summary result for a combination DcSMc are shown in *table 6.2* and the other results of model performance (*figure 6.5 and 6.6*) gave NSE of 0.64 and R^2 of 0.67 for daily comparisons and NSE of 0.785 and R^2 of 0.795 for monthly comparisons. The daily and monthly reservior simulation graph *(figure 6.5)* shows some timing gap in the rise of the reservior water surface specially the daily simulation. This may be due to non-availability of measured rainfall near the reservior within the catchment.

Table 6.2 Gomit calibration summery table

Gomit Summery Table	
Peak inflow	9.830 (m^3/S)
Peak outflow	10.106 (m^3/S)
Total inflow	822.312 (mm)
Total outflow	815.122 (mm)
Date/Time of Peak Inflow	28-Jun-06
Date/Time of Peak Outflow	28-Jun-06
Peak Storage	1094.986 (1000 m^3)
Peak Elevation	2367.386 (m)

Figure 6.1 Calibration of observed and simulated daily and monthly flow hydrograph of Koga watershed at dam site, Period (2001-2006)

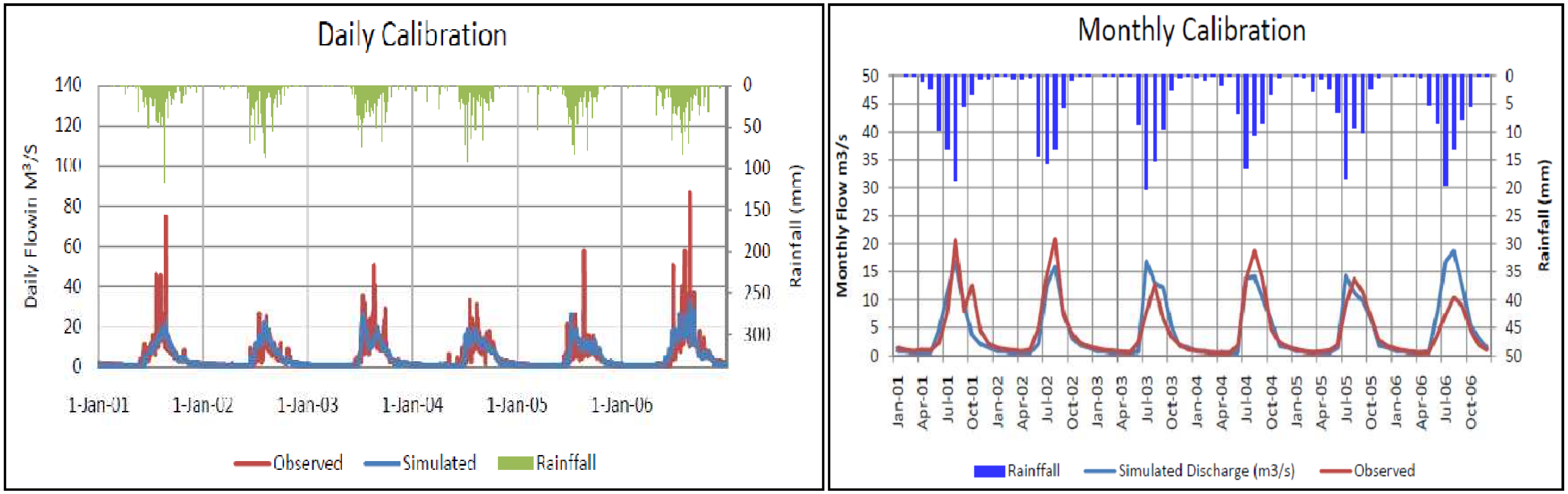


Figure 6.2 Validation of observed and simulated daily and monthly flow hydrograph of Koga watershed at dam site, Period (1996-1999)

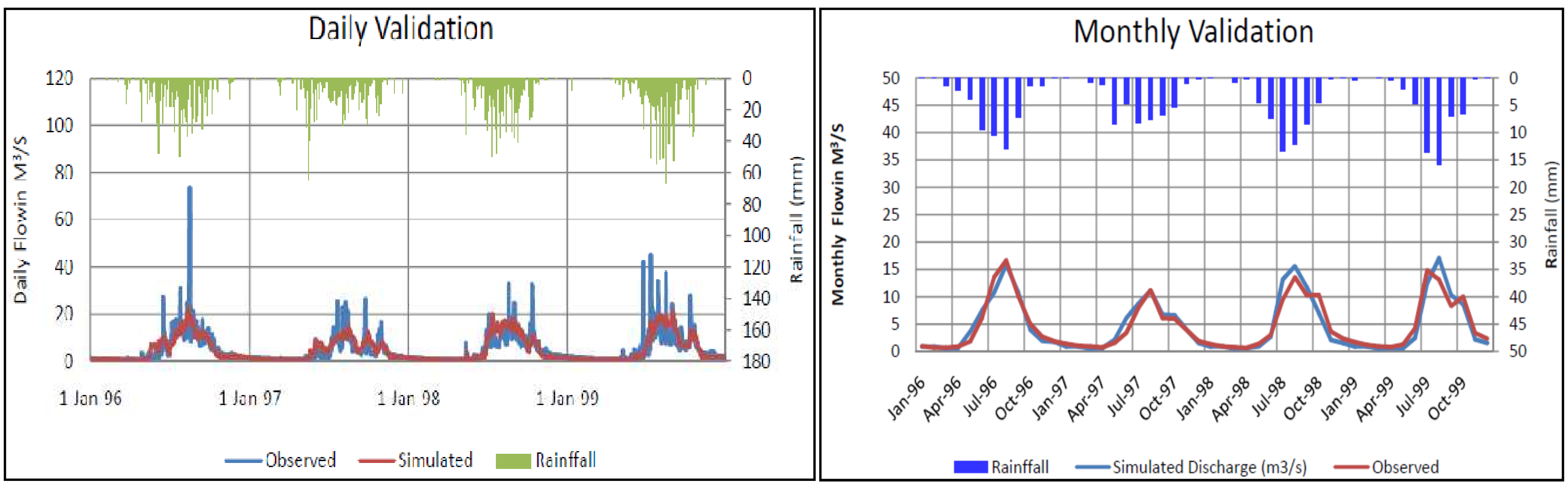


Figure 6.3 Scatter plot of observed and simulated discharge for Koga watershed at dam site, Period (2001-2006)

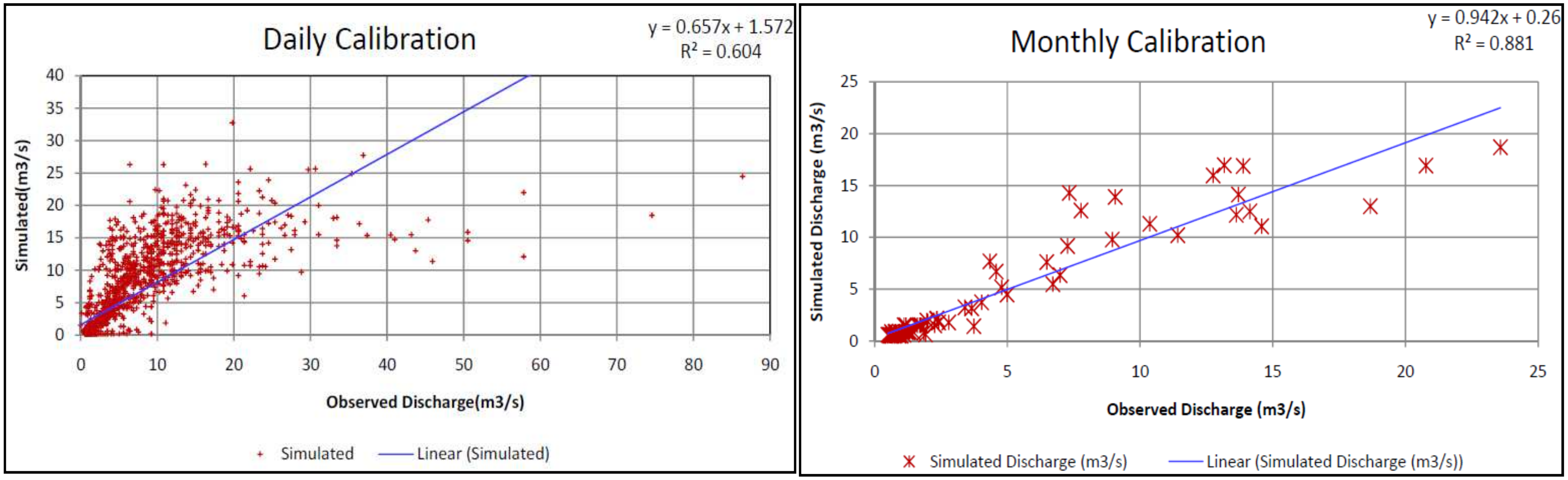


Figure 6.4 Scatter plot of observed and simulated discharge for Koga watershed at dam site, Period (1996-1999)

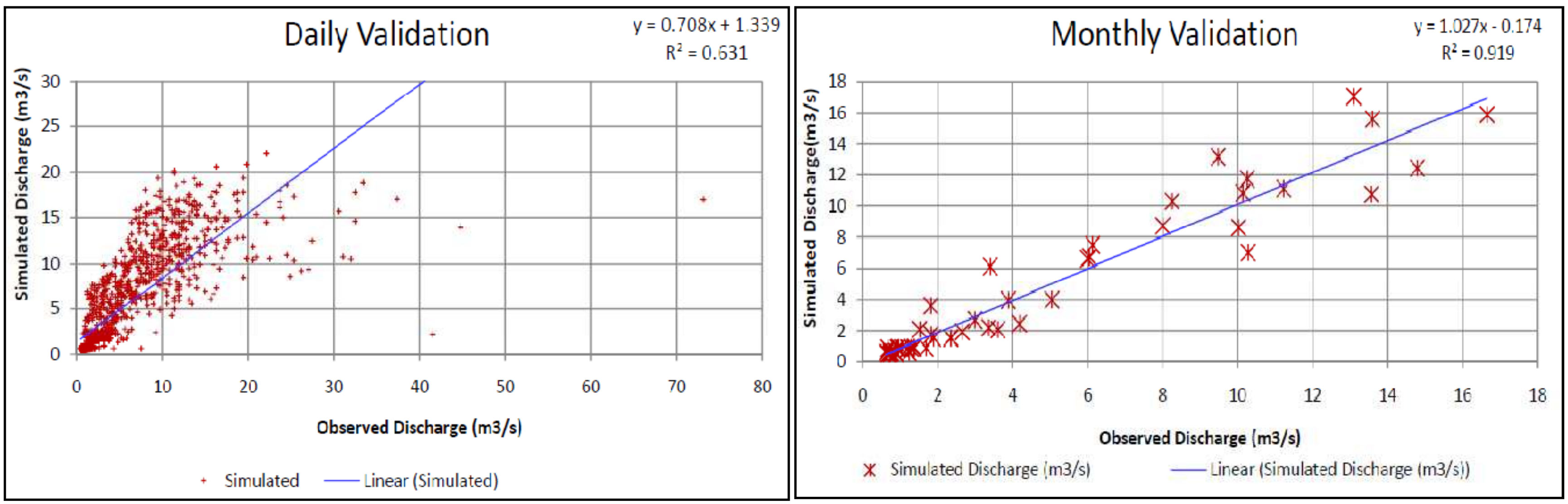
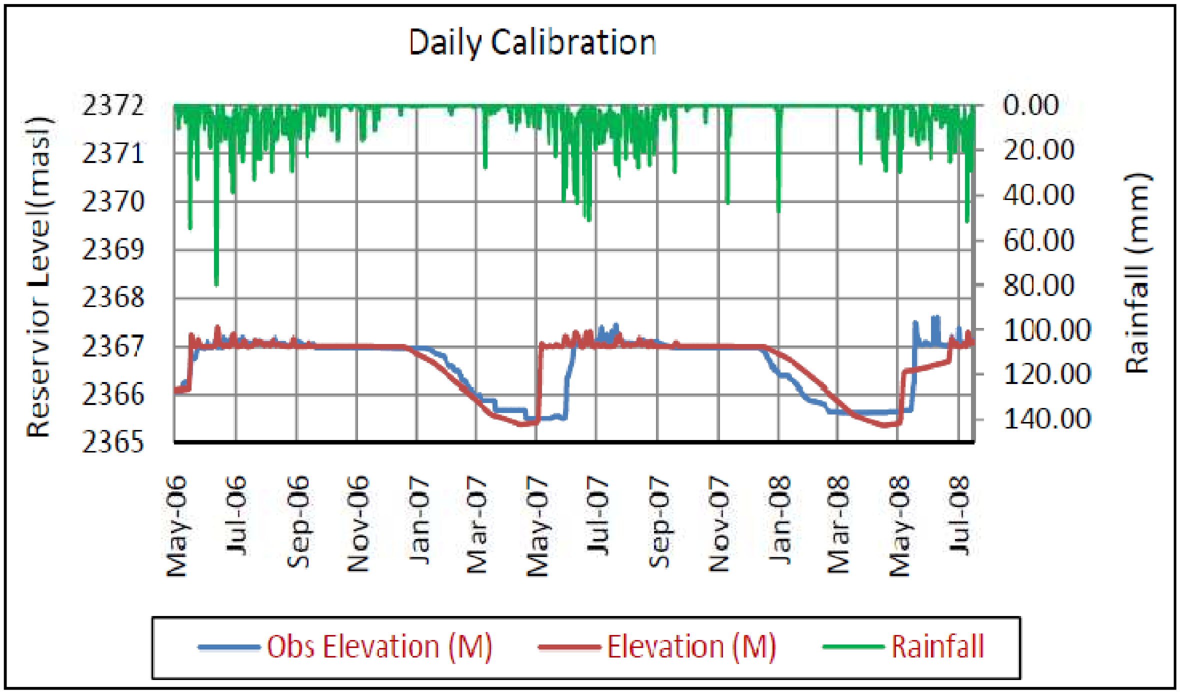
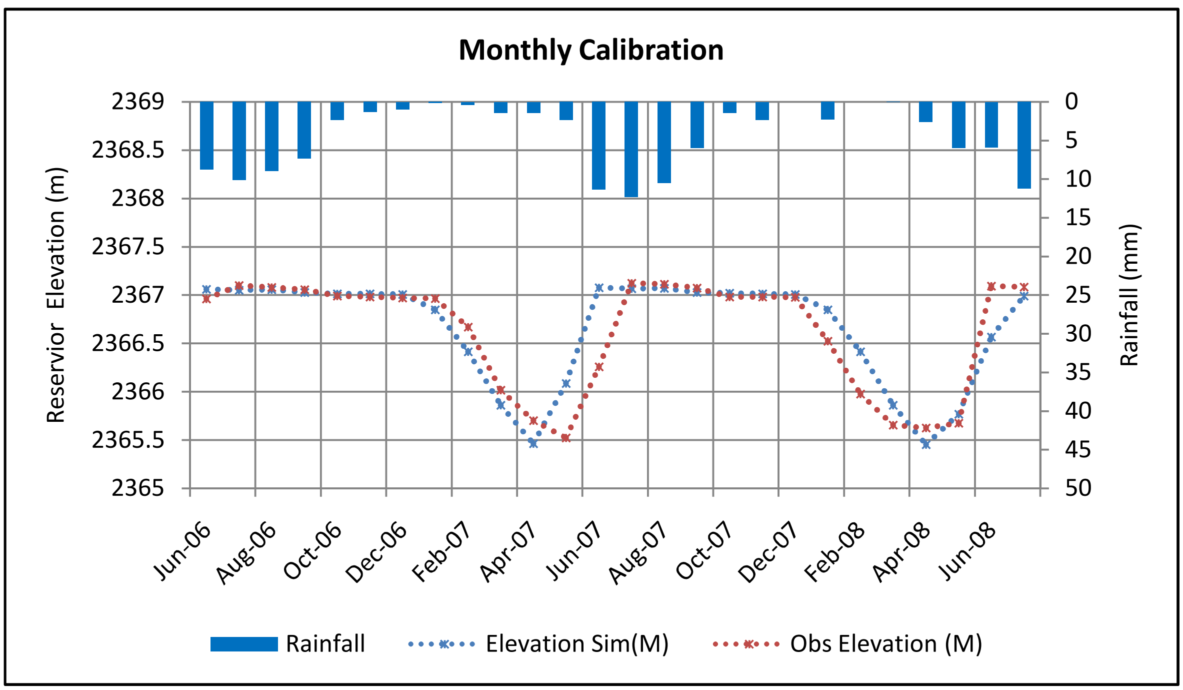


Figure 6.5 Gomit reservoir level daily and monthly calibrations





6.1.2. Reservoir Simulation

6.1.2.1. Koga reservoir simulation

Koga reservoir simulation in HEC-HMS (*figure 6.6*) for rainfall (RF) data from 1987 to 2006, irrigation demand and downstream release for the same period, Gives reliability, resiliency and vulnerability (RRV) results which is presented in *Table 6.3* using a baseline criterion of dead storage level of 2007.5masl. The result shows the maximum day in which the irrigation demand may not fulfilled within the simulation period is 37 day.

In addition, the simulation was also used to check the RRV of storage for minimum power generation using base line of minimum elevation of 2008.5 masl for power generation. The results presented in *Table 6.4;* it shows the reservior fail to generate power for a maximum of 66 day. Since baseline elevation for hydropower is above irrigation baseline, the reliability is less than that of irrigation.

The hypothetical RF change scenarios from -20% to +20% used to check effect on RRV for irrigation and hydropower requirement, *Table 6.3* and *6.4* show change of RRV values. Vulnerability of irrigation is more sensitive than resilience and reliability to RF change (e.g. 10% increment of rainfall reduces vulnerability of irrigation more than by half) but RF change effect is lesser on RRV of reservoir for hydropower . The simulation period for -20% RF changes shortened to April 1991 because the reservior is empty at this point.

The percentage increase of RF by 20% makes the minimum reservior storage level above dead storage level (2007.5 masl) and RRV values of reservior for irrigation reaches the optimum but RRV values of reservior for hydropower will not reach the optimum, even it will fail to meet minimum power demand for a maximum of 58 day.

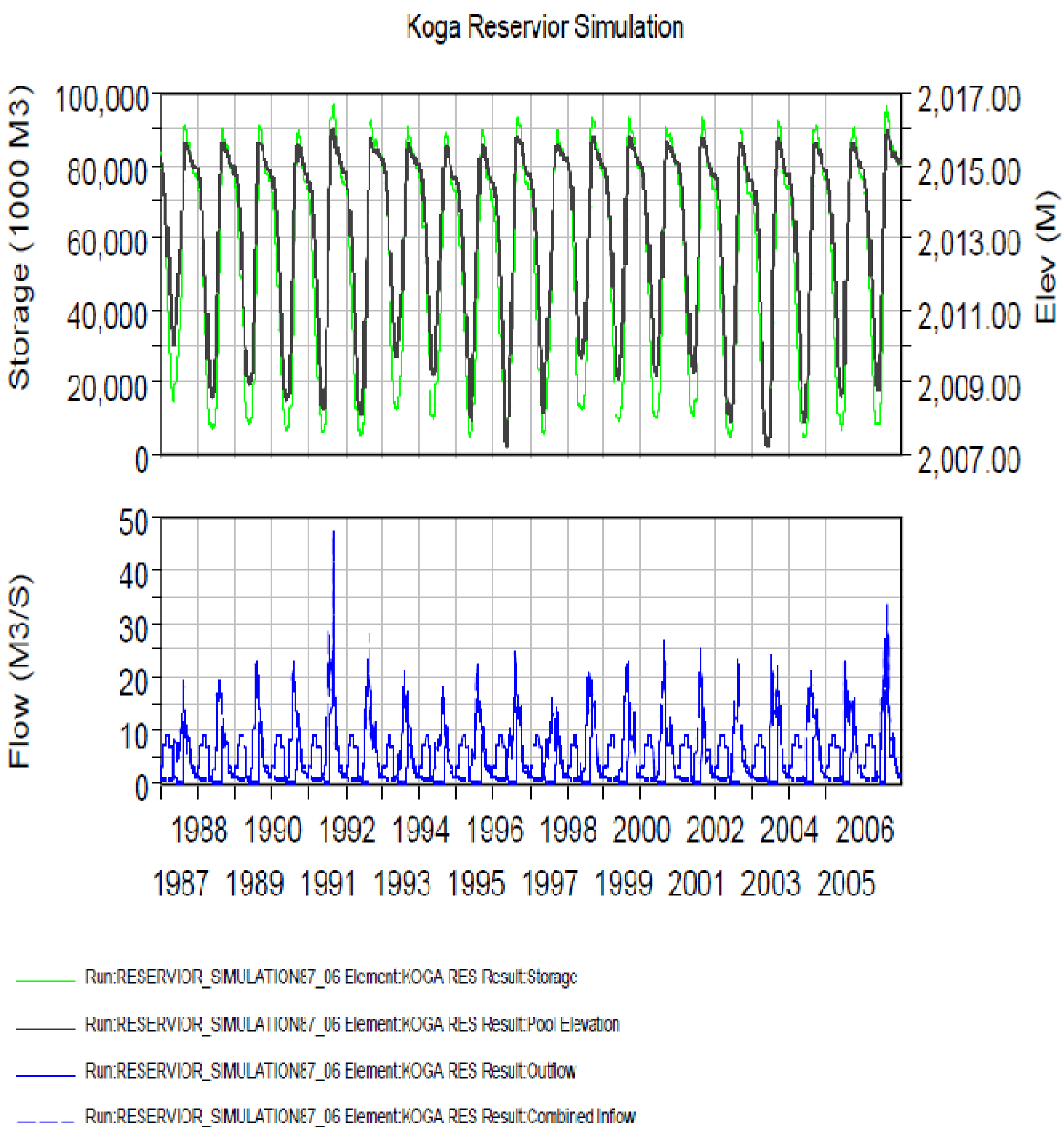
Table 6.3: Reservior simulation result for Irrigation over the period 1987 to 2006

Rainfall	Resilience	Reliability	Vulnerability day (month)
Observed Rainfall *(from 1987-2006)*	0.037	0.992	37
-20% *(Jan,1987-Apr,1991)*	0.142	0.991	9
-10% *(Jan,1987-Dec,2006)*	0.036	0.985	49
+10% *(Jan,1987-Dec,2006)*	0.1	0.998	10
+20% *(Jan,1987-Dec,2006)*	1	1	0

Table 6.4: Reservior simulation result for Hydropower

Rainfall	Resilience	Reliability	Vulnerability (month)
Observed Rainfall *(Jan,1987-Dec,2006)*	0.023	0.948	66
-20% *(Jan,1987-Apr,1991)*	0.019	0.867	76
-10% *(Jan,1987-Dec,2006)*	0.020	0.927	69
+10% *(Jan,1987-Dec,2006)*	0.026	0.959	64
+20% *(Jan,1987-Dec,2006)*	0.033	0.975	60

Figure 6.6: Koga HEC-HMS reservior simulation



6.1.2.2. Gomit reservoir simulation

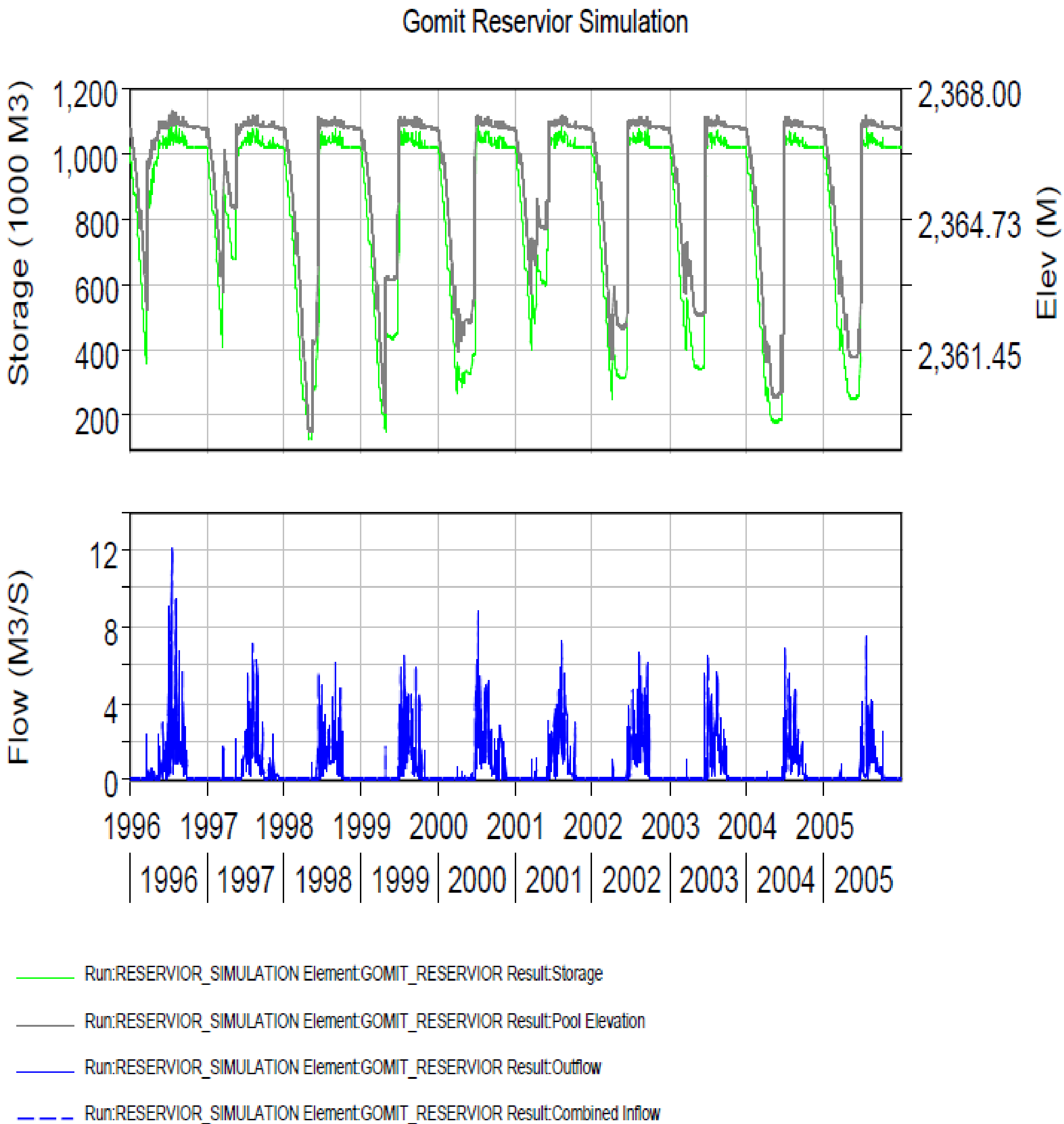
Gomit reservoir simulation result in HEC-HMS (*figure 6.7*) for rainfall data from 1996 to 2005 and irrigation demand release for the same period. This gives reliability, resiliency and vulnerability results as presented in *table 6.5, b*ased on baseline criterion of Dead storage Level 2361.589 masl. In addition, the minimum reservior storage is 0.133 Mm^3 with minimum elevation of 2359.457 masl. The reservoir fails to meet irrigation requirement for 71 day, this is the maximum failure period than other failure.

The hypothetical rainfall change scenarios from -20% to +20% used to check its effect on RRV for irrigation performance, *table 6.5* show changes of RRV. RF change by +20% considerably increase RRV specially resiliency and vulnerability, maximum failure of reservoir to meet irrigation requirement under normal RF (71 day) reduce to 44 day however RF change by -20% increase this failure days to 88. The reliability is more sensitive to reduction of RF.

Table 6.5: Gomit reservior simulation result for Irrigation

Irrigation	Resilience	Reliability	Vulnerability
Observed Rainfall *(from 1996-2005)*	0.032	0.950	71
-20%	0.016	0.874	88
-10%	0.020	0.900	86
+10%	0.039	0.965	60
+20	0.055	0.979	44

Figure 6.7: HEC-HMS output graph of Gomit reservior simulation over the period 1996 to 2005



CHAPTER SEVEN

CONCLUSION AND RECOMMENDATION

7.1 Conclusion

Based on consideration of all storage opportunities on existing, planned, and ongoing (irrigation, hydropower and multipurpose projects), the storage option on the Upper Blue Nile Basin is well distributed except the eastern part. The ongoing projects concentrate around Lake Tana sub basin. Storages on small-scale projects are not well summarized due to less organized information.

The HEC-HMS program was selected for the current study due to its versatility, capability for reservior simulation, automatic parameter optimization and its connection with GIS through HEC-GeoHMS. This model was used to simulate the hydrological characteristics of Gomit and Koga dam located in the Lake Tana subbasin and north Gojjam subbasin. The selection of the simulation period for hydrologic modelling was conditioned by the extension and quality of available rainfall data. The direct runoff model was selected to estimate the total water volume available for runoff. The surface runoff analysis was carried out using Snyder's and SCS model. The simulation of baseflow was conducted using a monthly constant model. The flow routing was modelled by means of the Lag model. The initial values of parameters were obtained using different formulas, which are indirectly related to watershed characteristics. The Thessien polygon method was used to identify the meteorological stations that best represent each subbasin.

The Gomit watershed parameters not verified due to the shortness of reservior level data. The Koga watershed parameters were calibrated and validated using observed flow at Merawi. The analysis of goodness of fit was carried out qualitatively, by means of comparisons between simulated and observed hydrographs, and quantitatively, based on the calculation of the Nash–Sutcliffe efficiency coefficient (NSE), person coefficient of determination (R^2) and percent difference (D) at two different time scales: daily and monthly. The best adjustments were obtained at a monthly scale, but D had better result on daily scale. The NSE, R^^{2} and D result for the Koga calibration period were 0.60 (0.88), 0.61(0.88) and 0.01(2.8) and for the validation were 0.62(0.88), 0.63(0.91) and 0.17(1) respectively. The calibration result for Gomit were NSE 0.64(0.785) and R^2 0.67(0.795). The values in bracket are for monthly time scale.

The evaluation of RRV on daily time step gives best represent the reliability and vulnerability but not the resiliency (its values is very low) because the reservior will not able to recover rapidly from failure to safe state on daily time step, instead reservoir translate to safe state after continuous failure state.

The reliability (under observed RF) of Koga reservoir to irrigate 7000 ha and to generate 0.3 MW are 0.992 and 0.948 and reliability of Gomit reservoir to irrigate 90 ha is 0.95, these values shows both reservoirs are efficient for the intended purpose. The resiliency of both reservoirs is below 0.04, it is small compared to its optimal value that is 1, and this is due to the simulation period as explained above. Lastly, vulnerability of Koga reservoir for a simulation period (20 year) is 37 day for irrigation and 66 day for hydropower; these failures are the maximum for 20 years.

RRV of reservior for hypothetical RF (change of RF by -20% to +20%); RRV of Koga for irrigation reaches optimal value for RF increment by 20%, but reservoir fail for 60 days to meet hydropower release. The reduction of RF by 20% makes the reservior to reach its minimum level HEC-HMS continue simulation until it reach the bottom of the reservior and it will stop then after.

Gomit reservior failure period vary from 44 to 88 day (reliability from 0.979 to 0.874) for RF change of RF from -20% to +20% and for simulation period of ten year. The reservoir resists the RF variation the in better manner.

7.2 Recommendation

Variability of flow data at Merawi shows different statistics year to year. Therefore, for better result in calibration and validation it needs good observed meteorological data within the watershed. This happened in the result of Koga and Gomit, both uses station that is out of the watershed. Therefore, Well-distributed meteorological station needed within the catchment.

In addition, during site visits, reservior regulation for Gomit dam is not efficient it affects the believability of reservior level data that means during reservior level calibration specified irrigation release considered but in actual case this not what happened. Therefore measuring of flow at the reservior outlet is indispensable.

Reservior out flow rule curve is not available, only irrigation and environmental flow requirement data available, the out flow rule curve good for better reservior simulation otherwise, HEC-HMS reservior simulation stops when the reservior is empty.

Detail base flow and reservior sedimentation study needed for better estimation of sensitivity of reservior on RRV. For instance, the base flow considered is constant, it has no relation to rainfall variation and also it covers some percentage of the irrigation demand. Therefore The Gomit reservior resist the RF variation effect.

Koga and Gomit reservoirs show variation on RRV for irrigation and hydropower production for hypothetical RF. In this study, the hypothetical RF used is percentage decrease and increase of RF; it only brings variation of RF amount not timing effect. Climate change study on these reservior is very important for their sustainable management.

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APPENDICES

APPENDIX A: Location of Meteorological station

Station Name	LAT	LONG	EASTING	NORTHING	ALTITUDE_masl
Dera Hamusit	11.7667	37.3833	323836	1301142	1900.0
Mekane Eyesus	11.6500	38.0667	398263	1287903	400.0
Nefas Mewcha	11.7333	38.4500	440067	1297008	3000.0
Arb_Gebeya(Dera)	11.5167	38.8833	487277	1272996	2300.0
Debretabor	11.8833	38.0333	394718	1313718	2690.0
Bahir Dar	11.59968	37.41666	327365	1282652	1770.0
Merawi	11.41666	37.15000	298152	1262582	2110.0
Wetet.Abay	11.36666	37.05000	287200	1257122	1830.0
Addet	11.26969	37.46999	332988	1246123	2080.0
Dangla	11.11666	36.41666	217803	1229995	2000.0
Zege	11.72968	37.29999	314727	1297105	1820.0

APPENDIX B: Storage projects features

APPENDIX B.1: List of Projects

Project	*Objective*	*Project status*			
		in operation	*already studied*	*identified*	*phase 3*
Gumara A	IR			■	
Gumara B	IR				
Ribb	IR				■
Megech	IR			■	
Gilgel Abbay A	IR				■
Gilgel Abbay B	IR				■
Upper Beles	PW		■		
Beles Dangur	MP			■	
Koga	IR	■			
Jema	IR		■		
Middle Birr	IR		■		
Chemoga Yeda	PW		■		
Lah SHP (1)	PW				■
Fettam	PW				■
Chagni SHP (1)	PW				■
Aleltu	PW		■		
Upper Guder	MP				■
Lower Guder	PW			■	
Finchaa – Amarti	MP	■			
Neshe	MP			■	
Upper Diddessa	MP			■	
Dabana	MP			■	
Negeso	IR			■	
Angar	IR			■	
Nekemte	MP			■	
Lower Diddessa	PW			■	
Upper Dindir	PW			■	
Lower Dindir	MP			■	
Galegu	IR			■	
Rahad[1]	IR			■	
Upper Dabus	PW			■	
Lower Dabus	PW			■	
Dabus SHP (1)	PW				■
Karadobi	PW			■	
Mabil	PW			■	
Mendaia	PW			■	
Border	PW			■	

[1] For all irrigation projects, and Rahad is one of them, the Consultant tried to check whether HP as a by-product from irrigation could be attractive. Rahad rated capacity would be about 20 MW with a very high cost because the head is limited (about 60 m) with a very wide valley (about 2 km wide for a 50 m high dam). Power is thus not attractive but the fact that Rahad considered, as an irrigation project is more a result of the analysis than a basic data.

Appendix B.1: Proposed Irrigation projects on the UBNB

S.no	*PROJECTS*	*Dam site Location*		*Res.elev. masl*	*Mean flow Mm3*	*Capacity Mm3*	*Flooded Area (ha)*	*Max. Irrig. ha*
		LAT	*LONG*					
1	GUMARA A	11.755	37.805	1940 1950 1960	235	134 223 333	779 991 1200	13976
2	GUMARA B	11.738	37.790	1960 1970 1980	248	136 218 317	740 901 1090	13976
3	RIBB	12.038	37.990	1905 1915 1925	454	49.5 99.5 173	412 611 895	19625
4	MEGECH	12.522	37.467	1920 1935 1950	203	51 124 260	334 672 1160	7311
5	GILGEL ABBAY A*	11.356	37.026	1920 1922 1924	1766	331 470 641	625 772 937	12069
6	GILGEL ABBAY B	11.456	37.005	1880 1890 1900	2 200	80 216 419	1090 1670 2452	11508
7	KOGA *(almost finished)*	11.351	37.134	2015.25	8672	83.1	2041	6000
8	JEMA	11.191	37.175	2110 2120 2130	175	54 99 163	366 545 737	7786
9	GALEGU	12.171	35.991	770 785 800	196	69 187 374	576 1010 1480	9860
10	NEGESO	8.858	36.540	1970 1975 1980	188	56 107 177	831 1210 1600	22815
11	ANGAR	9.688	36.740	1385 1410 1420	541	555 1653 3583	2930 5960 9580	14,450
12	UPPER DIDDESSA	8.203	36.803	1400 1410 1420	1712	1140 2160 3490	8460 11800 14700	14280

Source: (BCEOM, phase 2, section III VOLUME II)

*(*Gilgel Abbay-A is much less attractive than Gilgel Abbay B and would be filled by sediment before 50 years),*

Appendix B.2: Proposed multipurpose projects on the UBNB

S.no .	*PROJECTS*	*Dam site location*		*Mean flow Mm3*	*Res.elev. masl*	*Capacity Mm3*	*Flooded Area (ha)*	*Max. Irrig. ha*	*P (MW)*
		Lat	*Long*						
1	UPPER GUDER	8.858	37.667	183	2425 2430 2435	27 100 244	858 2193 3638	4896	10.4
2	NESHE A	9.751	37.253	103	2215 2220 2225 2230	114 205 323 464	1530 2090 2610 3020	7217	19.2
3	NESHE B	9.757	37.254	103	2210 2215 2220 2225	76 151 258 398	1720 1810 2490 3090	7217	19,2
4	DABANA	8.918	36.008	1609	1340 1350 1360 1370	921 1193 1523 1923	2810 4700 6630 8430	16388	41.6
5	NEKEMTE	9.425	36.500	1937	1300 1310 1320 1330	276 771 1710 3340	3390 6800 12300 20900	11220	16
6	LOWER DINDIR	12.016	35.873	2009	750 755 760 765	537 755 1040 1430	3800 4960 6320 8040	49555	50

(source: BCEOM, 1998, phase 2, section III VOLUME II)

Appendix B.3: Major planned hydropower schemes on UBNB

S.no	*Name*	*Location*		*Res. elev.*	*Capacity Mm3*	*Flooded Area(ha)*	*Anticipated capacity (MW)*
		Lat	*Long*				
1	Karadobi	9.853	37.688	1075 1100 1150 1175	6000 11600 28100 38900	18600 25900 40100 46700	660-1,580
2	Mabil	10.317	36.668	860 880 900 920	1600-4000 4700-7050 8700-11100 13800-16200	13000 17700 22900 28000	510-1,400
3	Mendaia	10.066	35.558	720 730 740 750	4800-7100 7300-9700 10300-12700 13800-16200	23400 27500 33000 38600	980-1,700
4	Border	11.208	35.090	570 580 590 600	1810-5110 6800-10100 13200-16500 21000-24300	42400 56800 71600 85000	750-1,780
5	Beles Dangur	11.105	35.838	830 835 845 850	2530 2960 3930 4470	8150 8900 10500 11400	104-143
6	Fettam	10.451	37.005	1955 1960 1965 1970	125 312 595 972	2810 4700 6630 8430	94-139
7	Lower Didessa	9.483	35.971	970 980 1 000 1 010	3220 4290 6910 8490	9380 11400 14900 16800	190-400
8	Lower Guder	9.420	37.653	1360 1380 1400 1410	709 1606 3006 3926	3420 5670 8430 10000	30-82
9	Lower Dabus	9.833	34.870	1335 1340 1345 1350	385 608 888 1223	3880 5040 6160 7100	164-212
10	Upper Dabus	9.871	34.901	1365 1370 1375 1380	423 983 1963 3483	7970 14900 24700 36300	152-193
11	Upper Dindir	12.002	36.200	950 960 970 980	465 803 1270 1890	2790 4000 5410 7000	15-37.5

Source: (BCEOM, 1998, table 6.1- 6.2)

APPENDIX C: HEC-HMS Features

Appendix C.1: HEC-HMS model components and categorization

MODEL	CATEGORIZATION
RUNOFF-VOLUME MODELS	
Initial and constant-rate	Event, lumped, empirical, fitted parameter
SCS curve number (CN)	Event, lumped, empirical, fitted parameter
Girded SCS CN	Event, distributed, empirical, fitted parameter
Green and Ampt	Event, distributed, empirical, fitted parameter
Deficit and constant rate	Continuous, lumped, empirical, fitted parameter
Soil moisture accounting	Continuous, lumped, empirical, fitted parameter
Girded SMA	Continuous, distributed, empirical, fitted parameter
DIRECT-RUNOFF MODELS	
User-specified Unit hydrograph	Event, lumped, empirical, fitted parameter
Clark's UH	Event, lumped, empirical, fitted parameter
Snyder's UH	Event, lumped, empirical, fitted parameter
SCS UH	Event, lumped, empirical, fitted parameter
ModClark	Event, distributed, empirical, fitted parameter
Kinematic wave	Event, lumped, conceptual, measured parameter
BASE FLOW MODELS	
Constant monthly	Event, lumped, empirical, fitted parameter
Exponential recession	Event, lumped, empirical, fitted parameter
Linear reservoir	Event, lumped, empirical, fitted parameter
ROUTING MODELS	
Kinematic wave	Event, lumped, conceptual, measured parameter
Lag	Event, lumped, empirical, fitted parameter
Modified Puls	Event, lumped, empirical, fitted parameter
Muskingum	Event, lumped, empirical, fitted parameter
Muskingum-Cunge standard section	Event, lumped, quasi-conceptual, measured parameter
Muskingum-Cunge 8-point section	Event, lumped, quasi-conceptual, measured parameter
Confluence	Continuous, conceptual, measured parameter
Bifurcation	Continuous, conceptual, measured parameter

Appendix C.2: Calibration parameter constraints

Modeling	Model	Parameter	Unit	Minimum	Maximum
Runoff Volume	Initial and constant-rate loss	Initial Loss	mm	0	500
		Constant loss rate	mm/hr	0	300
	Deficit and Constant rate loss	Initial deficit	mm	0	500
		Maximum deficit	mm	0	500
		Deficit recovery factor	-	0.1	5
	SCS loss	Initial abstraction	mm	0	500
		Curve number	-	1	100
Direct Runoff Transformation	Snyder's UH	Lag	hour	0.1 hr	500
		Cp		0.1	1
	SCS UH	Lag	minute	0.1	30000
	Clark's UH	Time of concentration	hour	0.1	500
		Storage coefficient	hour	0.1	1
Base Flow	Exponential Recession	Initial base flow	m^3/s	0	100000
		Recession factor		0.000011	-
		Flow-to-peak ratio		0	1
Lag routing	Lag	Lag	min	0	30000

APPENDIX D

Appendix D.1: Gomit Elevation, Area and Capacity Curves

Elevation(m)	Reservoir Area(ha)	Storage(Ha.m)	Cumulative Storage (Ha.m)	Remark
2350.36	0	0	0	Bed Level
2351.0	0.06	0.02	0.02	
2352.0	0.16	0.11	0.13	
2353.0	0.27	0.22	0.35	
2354.0	0.54	0.41	0.76	
2355.0	0.92	0.74	1.5	
2356.0	1.44	1.18	2.68	
2357.0	1.89	1.67	4.35	
2358.0	3.33	2.61	6.96	
2359.0	4.7	4.02	10.98	
2360.0	6.09	5.4	16.38	
2361.0	7.53	6.82	23.20	
2362.0	9.13	8.33	31.53	
2363.0	11.07	10.11	41.64	
2364.0	13.10	12.10	53.74	
2365.0	14.91	14.01	67.75	
2365.5	16.04	7.74	75.49	
2366.0	17.16	8.3	83.79	
2366.5	18.29	8.86	92.65	
2366.7	18.74	3.71	102.08	
2367.0	19.41	5.72	102.08	
2367.4	20.39	7.96	110.04	
2367.86	21.52	9.64	119.68	F.R.L
2368.0	21.86	3.04	122.72	
2369.0	24.5	23.18	145.9	
2369.36	25.5	9.00	154.9	M.R.L
2370.0	27.29	16.89	171.79	
2371.0	29.61	28.45	200.24	

Appendix D.2: Koga Elevation, Area and Capacity Curves

Koga Main Dam Reservoir Area and Volumes				
Contour	Feasibility Study [1]		Current Study(MM)	
	Area(ha)	Volume($m^3/10^6$)	Area(ha)	Volume($m^3/10^6$)
2004	18	0.20	18.5	0.2
2005	39	0.50	31.4	0.4
2006	94	1.10	98.2	1
2007	185	2.40	190.4	2.4
2008	298	4.80	291.8	4.8
2009	435	8.50	452.2	8.4
2010	683	14.00	713.8	14.2
2011	932	22.10	995.3	22.9
2012	1106	32.20	1184	33.8
2013	1345	44.50	1388.2	46.4
2014	1544	58.90	1583.4	61.5
2015	1724	75.20	1807.7	78.5
2016	1906	93.40	1999.4	97.6
2017	2072	113.30	2188.4	118.6
2018	2236	134.80	2378.1	141.5
2019	2400	158.00	2554.2	166.2
2020	2582	182.90	2739.7	192.7
Source: (1) FS Annex, Figure 16.1				

Appendix D.3: Koga CN LOOKUP table

LUVALUE	LANDUSE	A	B	C	D
24	Cultivated Land; Rainfed; Cereal Land Cover	55	69	78	83
9	Cultivated Land; Rainfed; Cereal Land Cover	58	72	81	85
6	Grassland; unstocked (woody plant)	49	69	79	84
142	Shrubland; Open (20-50% woody cover)	35	56	70	77
8	Grassland; unstocked (woody plant)	49	69	79	84
131	Shrubland; Dense (>50% woody cover)	30	48	65	73
3	Forest; Plantation forest; Open (20-50% cover	45	58	72	79
1	Wetland; Perennial Swamp / Marsh	100	100	100	100
25	Wetland; Seasonal Swamp / Marsh	100	100	100	100
5	Cultivated Land; Rainfed; Cereal Land Cover	55	69	78	83
4	Shrubland; Dense (>50% woody cover)	30	48	65	73

Appendix D.4: Gomit CN LOOKUP table

LUVALUE	LANDUSE	A	B	C	D
15	Cultivated Land; Rainfed; Cereal Land Cover System; lightly stocked	45	58	72	79
89	Grassland; unstocked (woody plant)	57	73	82	86
142	Shrubland; Open (20-50% woody cover)	43	65	76	82
9	Cultivated Land; Rainfed; Cereal Land Cover System; unstocked (woody pl)	30	55	70	77
101	Grassland; lightly stocked	49	69	79	84

Appendix E: Optimized Parameter Results

Appendix E.1: Koga Optimized Parameter Results

Deficit & Constant Loss, Snyder UH model

Element	Parameter	Units	Initial Value	Optimized Value	Objective Function Sensitivity
W70	Constant Rate	MM/HR	1.6	1.6982	-0.02
W70	Initial Deficit	MM	0.366	0.3969	0
W70	Maximum Deficit	MM	80.03	79.902	0
W70	Snyder Peaking Coefficient		0.99	0.998	0
W70	Snyder Time to Peak	HR	12.129	12.245	0
W80	Constant Rate	MM/HR	0.12611	0.12744	-0.02
W80	Initial Deficit	MM	1.6736	1.8263	0
W80	Maximum Deficit	MM	140.05	140.57	-0.03
W80	Snyder Peaking Coefficient		0.152	0.1	0
W80	Snyder Time to Peak	HR	14.982	15.345	0
W90	Constant Rate	MM/HR	0.61508	0.52474	0
W90	Initial Deficit	MM	1.5007	1.7452	0
W90	Maximum Deficit	MM	79.901	79.868	0
W90	Snyder Peaking Coefficient		0.99	0.998	0
W90	Snyder Time to Peak	HR	7.739	7.9153	0
R50	Lag	MIN	24.931	25.41	0

Appendix E.2: Koga Optimized Parameter Results

Deficit & Constant Loss, SCS UH model

Element	Parameter	Units	Initial Value	Optimized Value	Objective Function Sensitivity
R50	Lag	MIN	210	209.88	0
W70	SCS Lag	MIN	3490	3490.4	-0.02
W80	SCS Lag	MIN	1760	1759.9	-0.02
W90	SCS Lag	MIN	937	937.25	-0.11
W70	Constant Rate	MM/HR	0.1	2.3482	0.03
W70	Initial Deficit	MM	1	1.0614	0
W70	Maximum Deficit	MM	60	59.5	0
W80	Constant Rate	MM/HR	0.1	2.1245	-0.08
W80	Initial Deficit	MM	1	2.0395	0
W80	Maximum Deficit	MM	60	62.453	0
W90	Constant Rate	MM/HR	0.1	0.0067936	0
W90	Initial Deficit	MM	1	0.61176	0
W90	Maximum Deficit	MM	60	58.163	0.01

Appendix E.3: Gomit Optimized Parameter Results

Deficit & Constant Loss, Snyder UH model

Parameter	Initial Value	Optimized Value	Sensitivity
Initial Deficit (MM)	10	10	0
Maximum Storage (MM)	40	30	0
Constant Rate (MM/HR)	0.5	0.45	0.08
Lag Time (HR)	3.2	3.2	0
Peaking Coefficient	0.8	0.85	0

Appendix F Curve Number

Appendix F.1: Runoff curve numbers for other agricultural lands 1/

Cover description: Cover type	Hydrologic condition	Curve numbers for hydrologic soil group: A	B	C	D
Pasture, grassland, or range—continuous forage for grazing. 2/	Poor	68	79	86	89
	Fair	49	69	79	84
	Good	39	61	74	80
Meadow—continuous grass, protected from grazing and generally mowed for hay.	—	30	58	71	78
Brush—brush-weed-grass mixture with brush the major element. 3/	Poor	48	67	77	83
	Fair	35	56	70	77
	Good	30 4/	48	65	73
Woods—grass combination (orchard or tree farm). 5/	Poor	57	73	82	86
	Fair	43	65	76	82
	Good	32	58	72	79
Woods. 6/	Poor	45	66	77	83
	Fair	36	60	73	79
	Good	30 4/	55	70	77
Farmsteads—buildings, lanes, driveways, and surrounding lots.	—	59	74	82	86

1 Average runoff condition, and $I_a = 0.2S$.

2 *Poor:* <50%) ground cover or heavily grazed with no mulch.
Fair: 50 to 75% ground cover and not heavily grazed.
Good: > 75% ground cover and lightly or only occasionally grazed.

3 *Poor:* <50% ground cover.
Fair: 50 to 75% ground cover.
Good: >75% ground cover.

4 Actual curve number is less than 30; use CN = 30 for runoff computations.

5 CN's shown were computed for areas with 50% woods and 50% grass (pasture) cover. Other combinations of conditions may be computed from the CN's for woods and pasture.

6 *Poor:* Forest litter, small trees, and brush are destroyed by heavy grazing or regular burning.
Fair: Woods are grazed but not burned, and some forest litter covers the soil.
Good: Woods are protected from grazing, and litter and brush adequately cover the soil.

Appendix F.2: Runoff curve numbers for cultivated agricultural lands 1/

Cover description			Curve numbers for hydrologic soil group			
Cover type	Treatment 2/	Hydrologic condition 3/	A	B	C	D
Fallow	Bare soil	—	77	86	91	94
	Crop residue cover (CR)	Poor	76	85	90	93
		Good	74	83	88	90
Row crops	Straight row (SR)	Poor	72	81	88	91
		Good	67	78	85	89
	SR + CR	Poor	71	80	87	90
		Good	64	75	82	85
	Contoured (C)	Poor	70	79	84	88
		Good	65	75	82	86
	C + CR	Poor	69	78	83	87
		Good	64	74	81	85
	Contoured & terraced (C&T)	Poor	66	74	80	82
		Good	62	71	78	81
	C&T+ CR	Poor	65	73	79	81
		Good	61	70	77	80
Small grain	SR	Poor	65	76	84	88
		Good	63	75	83	87
	SR + CR	Poor	64	75	83	86
		Good	60	72	80	84
	C	Poor	63	74	82	85
		Good	61	73	81	84
	C + CR	Poor	62	73	81	84
		Good	60	72	80	83
	C&T	Poor	61	72	79	82
		Good	59	70	78	81
	C&T+ CR	Poor	60	71	78	81
		Good	58	69	77	80
Close-seeded or broadcast legumes or rotation meadow	SR	Poor	66	77	85	89
		Good	58	72	81	85
	C	Poor	64	75	83	85
		Good	55	69	78	83
	C&T	Poor	63	73	80	83
		Good	51	67	76	80

[1] Average runoff condition, and I_a=0.2S

[2] Crop residue cover applies only if residue is on at least 5% of the surface throughout the year.

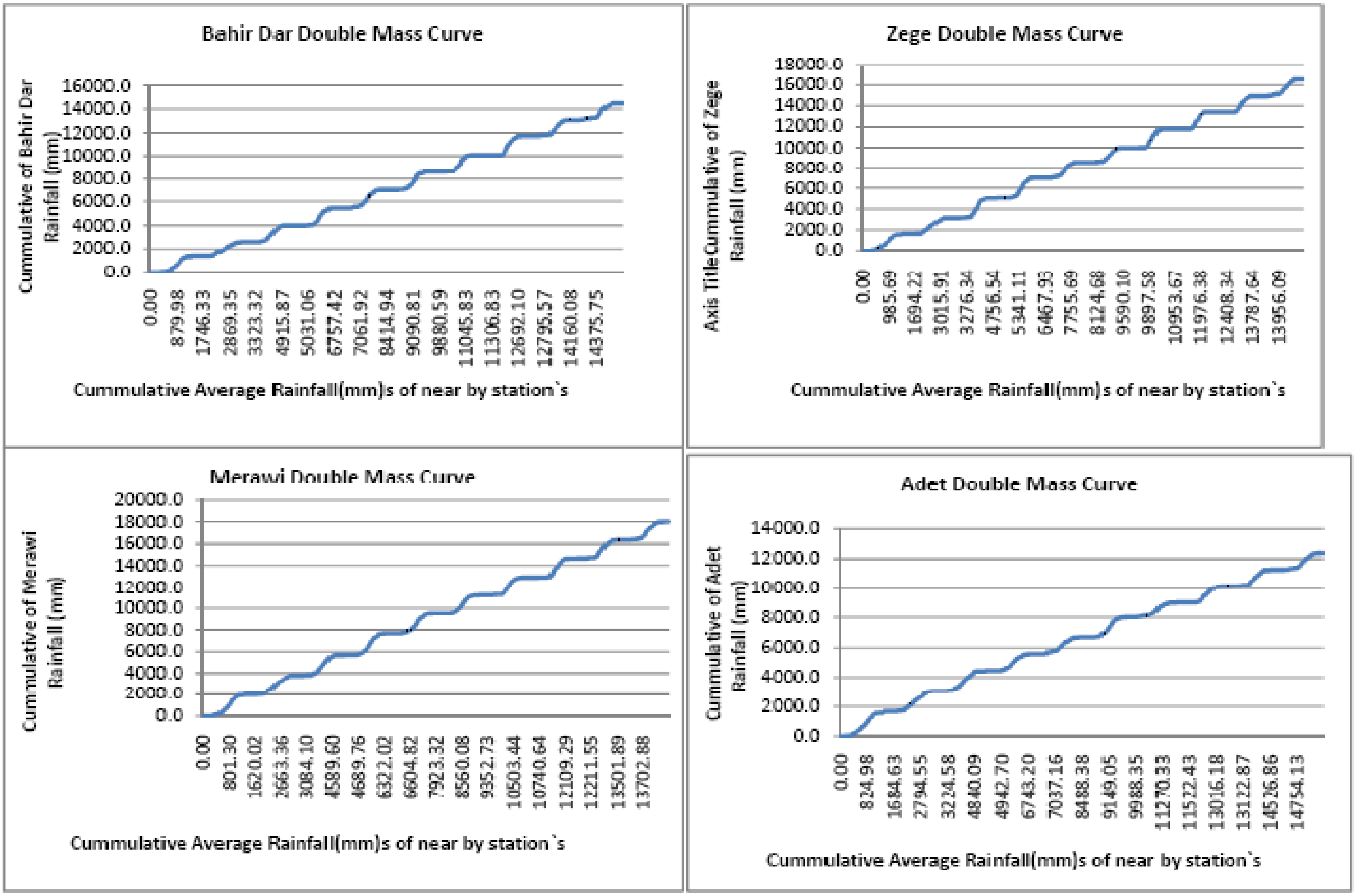
[3] Hydraulic condition is based on combination factors that affect infiltration and runoff, including (a) density and canopy of vegetative areas, (b) amount of year-round cover, (c) amount of grass or close-seeded legumes, (d) percent of residue cover on the land surface (good ≥ 20%), and (e) degree of surface roughness.

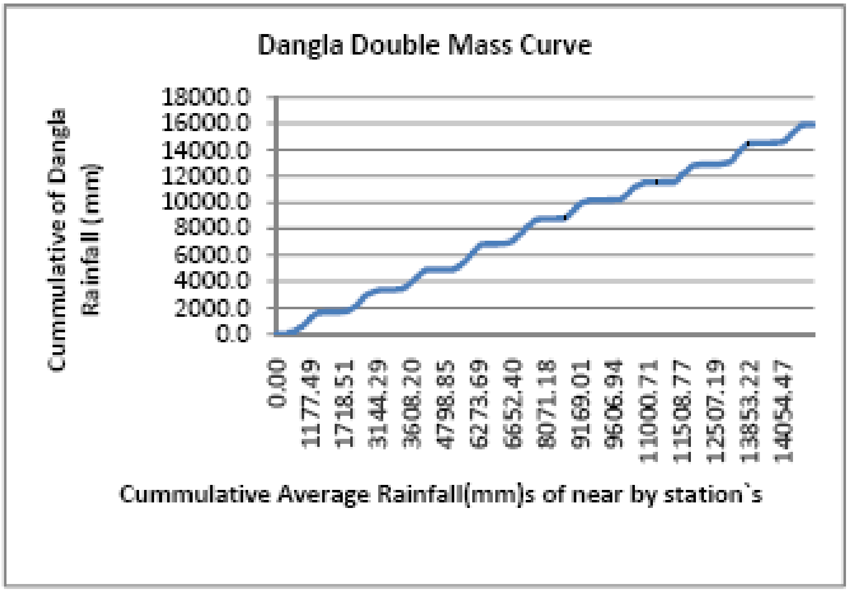
Poor: Factors impair infiltration and tend to increase runoff.

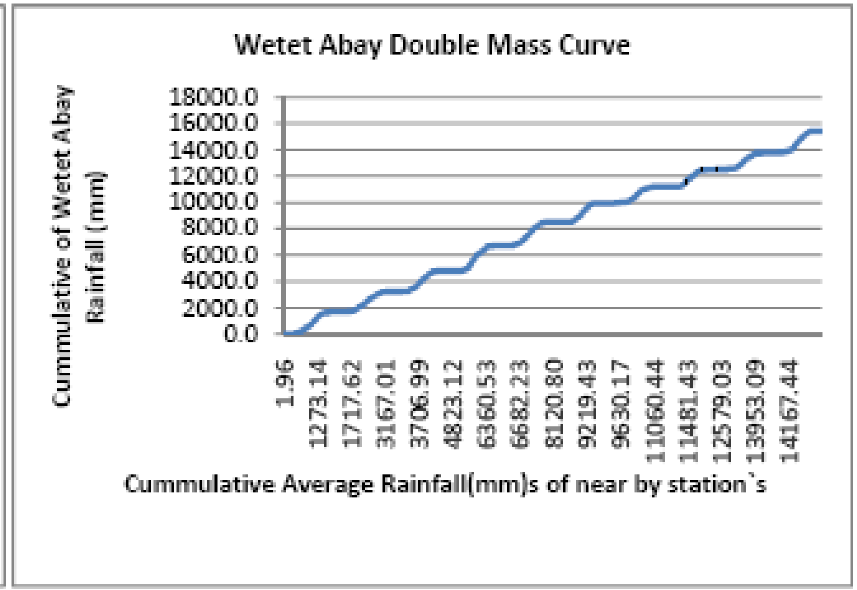
Good: Factors encourage average and better than average infiltration and tend to decrease runoff.

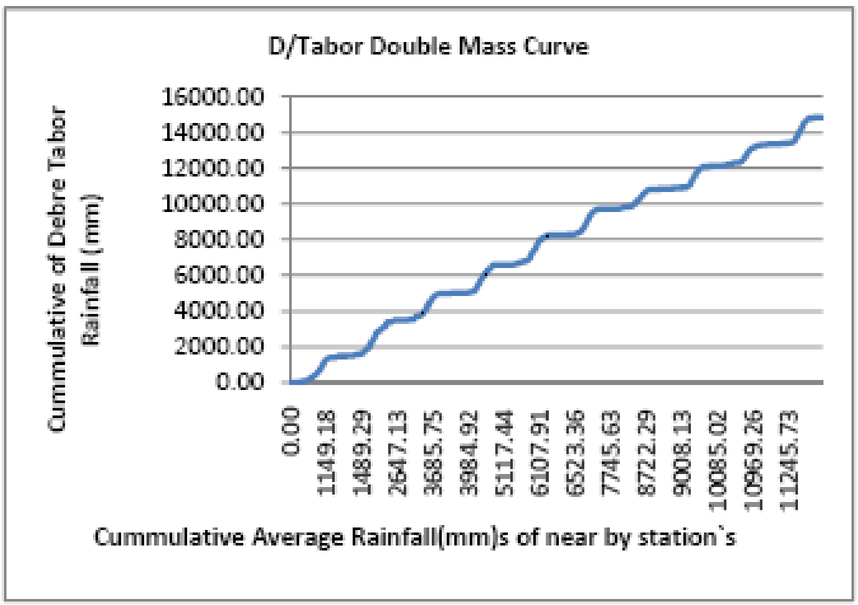
APPENDIX G

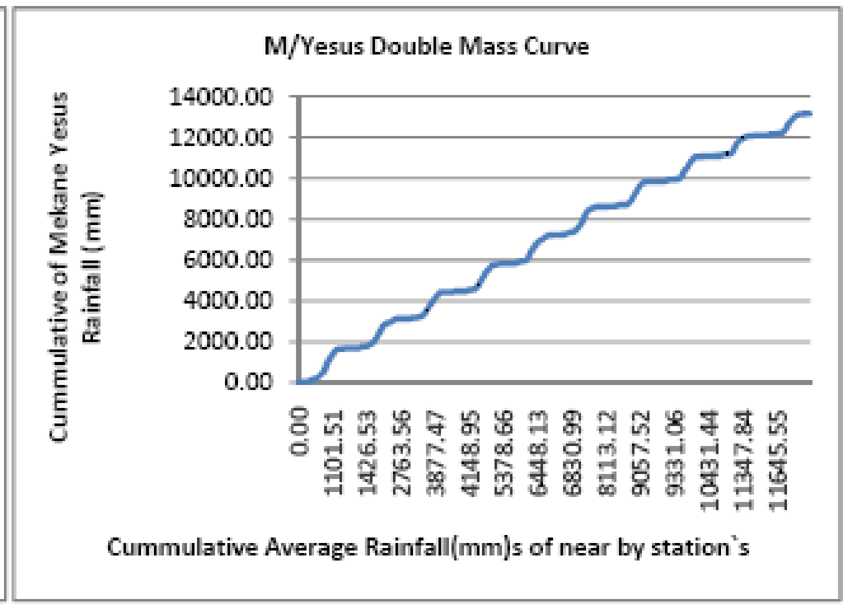
Appendix G.1: Double mass curve plots of the stations

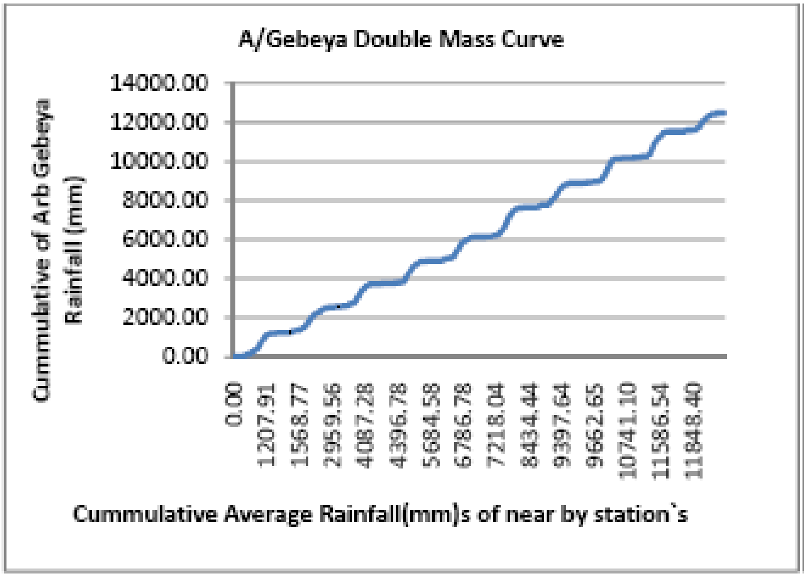


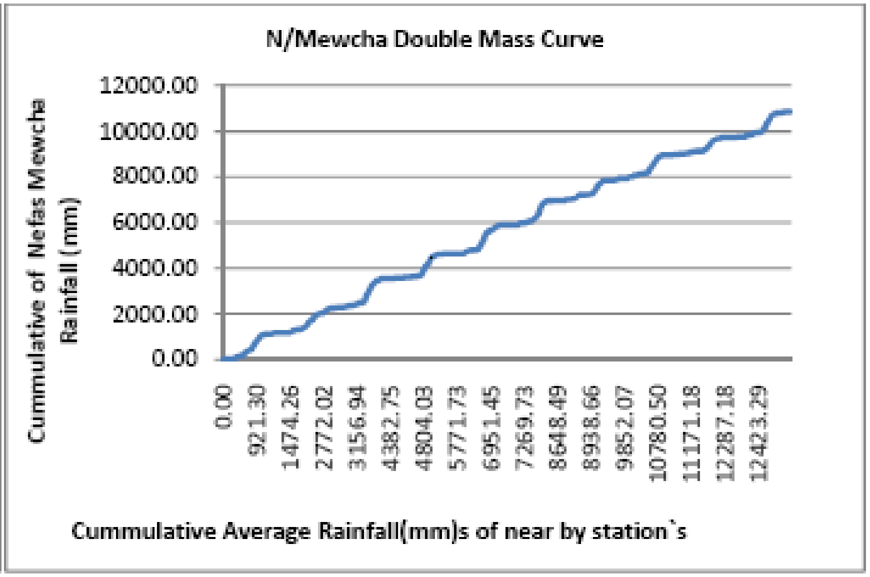

Dangla Double Mass Curve
Cummulative of Dangla Rainfall (mm)
18000.0
16000.0
14000.0
12000.0
10000.0
8000.0
6000.0
4000.0
2000.0
0.0
0.00
1177.49
1718.51
3144.29
3608.20
4798.85
6273.69
6652.40
8071.18
9169.01
9606.94
11000.71
11508.77
12507.19
13853.22
14054.47
Cummulative Average Rainfall(mm)s of near by station`s


Wetet Abay Double Mass Curve
Cummulative of Wetet Abay Rainfall (mm)
18000.0
16000.0
14000.0
12000.0
10000.0
8000.0
6000.0
4000.0
2000.0
0.0
1.96
1273.14
1717.62
3167.01
3706.99
4823.12
6360.53
6682.23
8120.80
9219.43
9630.17
11060.44
11481.43
12579.03
13953.09
14167.44
Cummulative Average Rainfall(mm)s of near by station`s


D/Tabor Double Mass Curve
Cummulative of Debre Tabor Rainfall (mm)
16000.00
14000.00
12000.00
10000.00
8000.00
6000.00
4000.00
2000.00
0.00
0.00
1149.18
1489.29
2647.13
3685.75
3984.92
5117.44
6107.91
6523.36
7745.63
8722.29
9008.13
10085.02
10969.26
11245.73
Cummulative Average Rainfall(mm)s of near by station`s


M/Yesus Double Mass Curve
Cummulative of Mekane Yesus Rainfall (mm)
14000.00
12000.00
10000.00
8000.00
6000.00
4000.00
2000.00
0.00
0.00
1101.51
1426.53
2763.56
3877.47
4148.95
5378.66
6448.13
6830.99
8113.12
9057.52
9331.06
10431.44
11347.84
11645.55
Cummulative Average Rainfall(mm)s of near by station`s


A/Gebeya Double Mass Curve
Cummulative of Arb Gebeya Rainfall (mm)
14000.00
12000.00
10000.00
8000.00
6000.00
4000.00
2000.00
0.00
0.00
1207.91
1568.77
2959.56
4087.28
4396.78
5684.58
6786.78
7218.04
8434.44
9397.64
9662.65
10741.10
11586.54
11848.40
Cummulative Average Rainfall(mm)s of near by station`s


N/Mewcha Double Mass Curve
Cummulative of Nefas Mewcha Rainfall (mm)
12000.00
10000.00
8000.00
6000.00
4000.00
2000.00
0.00
0.00
921.30
1474.26
2772.02
3156.94
4382.75
4804.03
5771.73
6951.45
7269.73
8648.49
8938.66
9852.07
10780.50
11171.18
12287.18
12423.29
Cummulative Average Rainfall(mm)s of near by station`s