

**ADDIS ABABA UNIVERSITY
ADDIS ABABA INSTITUTE OF TECHNOLOGY
SCHOOL OF GRADUATE STUDIES**

**WATER USE AND OPERATION ANALYSIS OF WATER RESOURCE
SYSTEMS IN OMO GIBE RIVER BASIN**

M.Sc. Thesis

Daniel Asefa

May 2011

Addis Ababa



**ADDIS ABABA UNIVERSITY
ADDIS ABABA INSTITUTE OF TECHNOLOGY
SCHOOL OF GRADUATE STUDIES**

**Water Use and Operation Analysis of Water
Resource Systems in Omo Gibe River Basin**

**Submitted in partial fulfillment for the Degree of Masters of Science in Civil
Engineering
(Major in Hydraulic Engineering)**

**By Daniel Asefa
Addis Ababa
May 2011**

Declaration and Copyright

I, Daniel Asefa Alene, declare that this is my own original work and that it has not been presented and will not be presented to any other University for similar or any degree award.

Signature

This dissertation is a copyright material protected under the Berne Convention, the Copyright Act, 1999 and other international and national enactments in the behalf, on the intellectual property. It may not be produced by any means in full or in part, except for short extracts in fair dealing, for research or private study, Critical scholarly review or disclosure with an acknowledgement, without written permission of the School of Graduate Studies, on the behalf of both the author and the Addis Ababa University

Acknowledgement

My deep appreciation goes to my advisor Dr.In.Dereje Hailu of Addis Ababa University for his encouragement, advice, support and, his valuable guidance and lectures throughout the course of this study and, above all his unselfish contribution to this thesis. His trust and confidence makes me to work on my interest topic.

I would like to acknowledge the Ethiopian Electric Power Corporation (EEPCO) particularly Ato Daniel; Ministry of Water and Energy Resource MoWE particularly hydrology and hydropower department, GIS department and Library, for their appreciable support in providing me hydrological data and other reference materials; and the Ethiopia Meteorological Service Agency for providing me the relevant data and information required free of charge.

My deepest thank is to my beloved parents. Their unconditional love, inspiration and encouragement always surround me, support me, and give me strength to go through my study.

A special group of friends also supported me through their friendship and professional help. Among them I would like to mention: Abdrhaman B., Ahmed A., Abayne A., Bogale T. and Biruk A

Above all, sincere thanks go to the Almighty God and his mother saint Virgin Mary for making this thesis success. This day God what you have done for me is really beyond what I can imagine and I have dreamt. Indeed, thanks for everything You have been doing for me.

Abstract

In this study, HEC-ResSim (Hydrologic Engineering Center-Reservoir System Simulation) model was used to simulate water use and operation of existing, ongoing and planned hydraulic infrastructures, and irrigation schemes in Omo Gibe river basin. For these purpose five different water resource scenarios were simulated viz. Scenario-T, Scenario-A, Scenario-B, Scenario-C and Scenario-D. Scenario-T was first set up to simulate gauged flow routing without taking into account effects of development and a good agreement was observed between simulated and measured flow at Karadus station. The Nash-Sutcliffe efficiency criterion obtained for the catchment was 0.782. Following this, the model was configured to simulate the recent and proposed development interventions on water resource. Scenario-A result showed that an average annual energy of 780GWh/year and 1911GWh/year are produced by Gibe I and Gibe II respectively when they are operated in tandem. Equivalent storage distribution was also examined among reservoirs in the entire simulation period. The current study, HEC-ResSim simulation in scenario B, has discovered that long term effects of operation of Gibe III power plant would increase the dry season outflow and decrease in flood season outflow from the Omo-Gibe river system. An average increase of 130% in mean monthly inflows from November to June and decrease of 25% in mean monthly inflows from July to October was observed at Karadus. But the mean annual outflow from the basin at Karadus will be decrease by 1.14%. Simulation of Gibe III power plant produced an average annual energy of 6,488GWh/year and power of 758.94MW. The firm energy and power that can be guaranteed 90% of the time are 5885GWh/year, 625.0MW respectively. The average energy obtained is close with the study made by EEPCO. The firm energy obtained is also similar and greater than the energy obtained during reservoir operation studied by EEPCO.

Due to upstream regulation i.e. intervention the proposed power plants, Gojeb and Hallele Warabesa stage I and II, in the upstream Omo-Gibe basin under scenario D can increases firm energy production of Gibe III power plant to 6023GWh (2.75%) per year with same reliability and the average annual energy can also increase to 7587 GWh per year (by 15.66%). Moreover, during scenario D simulation annually about 1.87BCM volume of water will be diverted into irrigation site under full irrigation development (142,000ha) and the annual volume of water from Omo-Gibe river system below the proposed irrigation sits will decrease by 14.15%.

Keywords: *Firm Energy, HEC-ResSIM, Reservoir Operation, Simulation scenario, Karadus, and Reservoir Network*

Dedication

This work is dedicated solely to my mother
Abeba Yemataw, my aunt Messeret and uncle Sisay

Table of Contents

Declaration and Copyright	I
Acknowledgement.....	II
Abstract	III
Dedication	IV
Table of Contents	V
List of figures	VIII
List of tables.....	X
1.0 INTRODUCTION.....	1
1.1 Background	1
1.2 Problem Statement	3
1.4 Objectives of the study.....	4
1.5 Structure of the Thesis.....	4
2.0 LITREATURE REVIEW.....	6
2.1 Technologies for Decision Making in Water Management.....	6
2.2 Reservoir/River System modeling.....	7
2.2.1 General	7
2.2.2 Simulation	8
2.2.3 Optimization.....	9
2.4 Review of river basin simulation models	9
2.4.1General	9
2.5 Introducing HEC-ResSim.....	12
2.5.1 HEC-ResSim Environment for Model Building	13
2.6 Reservoir Operation Rules	15
2.6.1 Reservoir Operation rule in HEC-ResSim	17
2.6.2 Tandem operation rule in HEC ResSim	18
2.6.3 Implicit and Explicit system storage balance	18
2.7 Previous Studies in the Basin	19
2.7.1 Omo-Gibe river basin Integrated development master plan Study	19
2.7.2 Preliminary priority sites for hydropower in Omo-Gibe river basin	20
2.7.3 Planned Water resource development	21
2.8 Irrigation Potential and Development in the lower Omo- Gibe basin.....	24
2.8.1 History of Irrigation Development in lower Omo-Gibe Basin.....	24
2.8.2 Lower Omo-Gibe Basin Irrigation Potential sites.....	25

3.0	DESCRIPTION OF THE STUDY AREA	27
3.1	Location of Omo-Gibe Basin	27
3.2	Climate and Rainfall Features	28
3.3	Topography	29
3.4	Hydrography and drainage subasins	30
3.5	Land use	31
3.6	Lake Turkana	31
3.6.1	Geographical Location and physical description	31
3.7	Existing Hydropower Schemes on the Omo-Gibe River Basin	32
4.0	METHODOLOGY	40
4.1	General	40
4.2	Data Collection and Analysis	41
4.2.1	General	41
4.3	Hydrological data	41
4.3.1	Hydrological data analysis	43
4.4	Meteorology Data	45
4.4.1	Meteorology Data Analysis	46
4.4.2	Runoff from the intervening (residual) catchment	52
4.5	Transfer of data to dam site and river confluence	54
4.5.1	Transfer of gauged data using area ratio method	54
4.6	Meteo Climatic Data	56
4.6.1	Evaporation	56
4.7	Hydropower related data	57
4.7.1	Reservoir physical characteristics and Power plant data	57
4.8	Irrigation and Ecological Water demand data	57
4.8.1	Irrigated Agriculture water demand data	57
4.8.1	Ecological required flow	60
5.0	BUILDING HEC- ResSim FOR OMO GIBE BASIN	61
5.1	Overview	61
5.2	HEC-ResSim Model Framework of Omo Gibe River Basin	61
5.2.1	Watershed Network Setup	61
5.2.2	Reservoir Network setup	63
5.2.3	HEC-ResSim model elements	66
5.2.4	Operational parameters	71

6.0	RESULTS AND DISCUSSION	75
6.1	Simulation in HEC-ResSim.....	75
6.2	Scenario modeling and graphic outputs	76
6.2.1	Simulation for testing the model	76
6.2.2	Simulation in Scenario A	78
6.2.3	Simulation in Scenario B.....	83
6.2.3	Simulation in Scenario C.....	97
6.2.4	Simulation in Scenario D	102
7.0	SUMMARY, CONCLUSION AND RECOMMENDATION	107
7.1	Summary and conclusion	107
7.2	Recommendation.....	110
	REFERENCES	111
	APPENDIX	114
	APPENDIX-A Measured and Generated Stream Flow Data	114
	APPENDIX-B Graphs Plotted to Test Homogeneity of the Stations.....	114
	APPENDIX-C Graphs Plotted To Check Consistency of the Stations	114
	APPENDIX-D Physical and Power plant characteristics of hydropower dams.....	114
	APPENDIX-E Standard Graphic Output of HEC-ResSim Model.....	114

List of figures

Figure 2-1 Water use in a river basin; the case of Omo-Gibe basin	6
Figure 2-2 ResSim module concept (HEC-2003)	13
Figure 2-3 Reservoir pool	15
Figure 2-4 Reservoir operation rule curves for multi-purpose reservoir	17
Figure 2-5 Small scale pumped irrigation site at Lobet Dasenech Wereda	26
Figure 2-6 Recession cultivation site at Dasenech-Tobacco field	26
Figure 3-1 Study Area; Omo-Gibe River Basin.....	27
Figure 3-2 Mean monthly temperature in the basin	28
Figure 3-3 Mean monthly rainfall in the basin.....	29
Figure 3-4 DEM of the study area.....	30
Figure 3-5 Photograph view of Gibe I dam and reservoir.....	33
Figure 3-6 Elevation-Area- Storage curve of Gibe I reservoir.....	33
Figure 3-7 Photograph view of Gibe II power house and penstocks	34
Figure 3-8 Location of Gibe I, II, III and other cascade projects planned in Omo Gibe basin....	39
Figure 4-1 Stream flow gauging stations	42
Figure 4-2 Metrological gauging stations	45
Figure 4-3 Homogeneity test for Kumbi, Abelti, and Sekoru and Saja school stations.....	47
Figure 4-4 Homogeneity test for Atnago, Dilela, Welkite, Gibe farm stations	48
Figure 4-5 Consistency Test for Assendabo, Jima and metesso stations.....	50
Figure 4-6 Consistency Test for Abelti Sekoru and Kumbi stations.....	50
Figure 4-7 Theissen polygon for the intervening basin.....	52
Figure 4-8 Inflow time series at dam sites	55
Figure 4-9 Lake evaporation from previous studies.....	56
Figure 4-10 Total crop water requirements.....	59
Figure 5-1 ResSim Watershed setup of Omo Gibe basin.....	62
Figure 5-2 Reservoir System Network for scenario D.....	70
Figure 5-3 Storage capacity and surface area at different elevation for Gibe III reservoir.....	71
Figure 5-4 Spillway maximum outflow capacity for Gibe III dam.....	72
Figure 5-5 Bottom duct capacity for Gibe III dam.....	72
Figure 5-6 Gibe III plant intake maximum capacity	73
Figure 6-1 Comparison between measured and simulated time series at Karadus	76
Figure 6-2 Comparison of measured and simulated hydrograph at Karadus.....	77
Figure 6-3 Reservoir System Network for Scenario A	78
Figure 6-4 Simulated Gibe I Pool, level, Inflow and outflow at scenario A.....	79
Figure 6-5 Simulated Gibe II pool level, inflow and outflow at scenario A.....	79
Figure 6-6 Guide curve for Gibe II pool	80
Figure 6-7 Simulated Gibe I power plant operation at scenario A.....	81
Figure 6-8 Simulated Gibe II power plant operation at scenario A	81
Figure 6-9 Global energy duration curve for Gibe I and II power plant at scenario A.....	82
Figure 6-10 Global turbined flow duration curve at Gibe I and II tail race at scenario A	82
Figure 6-11 Reservoir System Network for Scenario B	83
Figure 6-12 Simulated pool level, inflow and outflow for Gibe III reservoir during scenario B ..	84
Figure 6-13 Year Max-Min- Mean pool level (simulated Guide curves) at scenario B	85
Figure 6-14 Global pool duration curve for Gibe III reservoir at scenario B	85
Figure 6-15 Energy generated using HEC-ResSim and EEPKO and Kifle (2009) studies	87
Figure 6-16 Simulated Gibe III power plant operation during scenario	87
Figure 6-17 Global energy duration curve at Gibe III power plant during scenario B.....	88

Figure 6-18 Global power duration curve at Gibe III power plant during scenario B.....	88
Figure 6-19 Flow hydrograph before and after gibe III downstream of the dam.....	90
Figure 6-20 Inflow hydrograph at Karadus before and after scenario B	91
Figure 6-21 Cumulative volume at Karadus before and after scenario B.....	91
Figure 6-22 Global turbined flow duration curve at Gibe III tail race at scenario B.....	94
Figure 6-23 Comparison of regulated flow with maximum diversion requirement at scenario B	95
Figure 6-24 Hydrographs of the Omo river before and after scenario B below Karadus.....	96
Figure 6-25 Cumulative flow volume of the Omo river before and after scenario B.....	96
Figure 6-26 Reservoir System Network for Scenario B	97
Figure 6-27 Simulated Gibe III power plant operation at scenario C.....	98
Figure 6-28 Pool level, inflow and outflow for Gibe III reservoir at Scenario B and C.....	99
Figure 6-29 Max-Min-Mean water level (Guide curves) at scenario C.....	99
Figure 6-30 Inflow hydrograph at Gibe III dam site for scenario B and C.....	100
Figure 6-31 Hydrograph of the Omo river before and after scenario C below Karadus.....	101
Figure 6-32 Cumulative flow volume of Omo river before and after scenario C.....	101
Figure 6-33 Monthly plant factor for Gibe III power plant simulated for each scenario.....	102
Figure 6-34 Max-Min- Mean pool level (Guide curves) for Gibe III reservoir at scenario D....	103
Figure 6-35 Cumulative flow volume of Omo river before and after scenario D.....	104
Figure 6-36 Hydrographs before and after HP developments at Karadus	104
Figure 6-37 Cumulative flow volume Omo river before and after HP developments.....	105
Figure 6-38 Time series at abelti station before and after scenario D.....	105
Figure 6-39 Hydrograph at abelti before and after senario D	106
Figure 6-40 Inflow at Gibe III dam site at Scenario B, C and D	106

List of tables

Table 2-1 River basin simulation models and descriptions.....	10
Table 2-2 Priority sites for hydropower development in omo gibe basin.....	20
Table 2-3 Halele Warabesa stage I hydropower project silent features.....	22
Table 2-4 Halele Warabesa stage II hydropower project silent features.....	23
Table 2-5 Gojeb OM19 hydropower project silent features	24
Table 2-6 Irrigation potential sites in the lower Omo Gibe basin OGRBIDMP (1996).....	25
Table 3-1 Gibe III hydropower project silent features (EEPSCO, 2007).....	37
Table 4-1: Summary of selected Hydrometric stations.....	43
Table 4-2 Correlated equations between stations for filling missing data	44
Table 4-3: Summary of selected rainfall stations.....	46
Table 4-4 Unit hydrograph ordinates developed for abelti sub- catchment, Kemal (2007).....	52
Table 4-5 Mean Monthly inflow at dam sites	55
Table 4-6 Energy generation requirement in GWh for existing and proposed power plants.....	57
Table 4-7 Crop water requirement based on no effective rainfall (mm/day).....	58
Table 4-8 Existing and potential irrigation schemes in lower omo region	59
Table 4-9 Minimum environmental flow release from existing and planned dams in m ³ /sec.....	60
Table 5-1 Summary of the likely development scenarios in omo gibe basin	65
Table 6-1 Simulated Gibe III power plant parameters in HEC-ResSim	86
Table 6-2 Gibe III power plant and reservoir characteristics between years 1985-2006.....	89
Table 6-3 Natural and regulated flow at Karadus and Gibe III dam site	92
Table 7-1 Annual average energy ,firm energy and power of Gibe III power plant.....	108

Abbreviations

DEM	Digital elevation Model
EEPCO	Ethiopian electric Power Corporation
ET _o	Potential Evapotranspiration
FSL	Full supply level
Fig	Figure
GIS	Geographic information system
HEC	Hydraulic engineering center
HEC-ResSim	Hydraulic engineering center reservoir simulation
HEC-DSS	Hydraulic engineering center data storage service
ha	Hectare
km	Kilometer
Km ²	kilometer square
l/s	Liter per second
MoWE	Ministry of water and energy
Max	Maximum
Min	Minimum
MOL	Minimum operating Level
masl	meter above sea level
mm	millimeter
Mm ³	million cubic meters
MW	Mega watt
MWh	Mega watt hour
NMA	National meteorological Agency
OMGRB	Omo-Gibe river basin
OMGRBIDMP	Omo-Gibe river basin integrated development master plan
RCC	Roller Compacted concrete
RN	Reservoir network
SC	Scenario

1.0 INTRODUCTION

1.1 Background

“Water is essential for life”. We are all aware of its necessity, for drinking, providing food, for washing, etc., in essence for maintaining our health and dignity. Water is also required for providing many industrial products, for generating power, and for moving people and goods, all of which are important for the functioning of a modern, developed and developing society. In addition, water is essential for the integrity and sustainability of the earth’s system (The United Nations-World water development report, 2003). However, water availability is very much concerned in the last decades. Demand and competition for water resources continue to grow almost everywhere. The main reason can be explained by the increase of the world population leading to higher demand on water for activities such as agriculture, industry energy supply etc., in addition the decrease of water quality due to such activities .

Today, water resources development and management remain at the heart of the struggle for sustainable development, growth, and poverty reduction. This has been the case in all industrial countries, most of which invested heavily on both water infrastructure and institutions, and it is the case in all developing countries, most of which have not invested sufficiently in water infrastructure and institutions. In some developing countries, such as Ethiopia, the unmet challenge of managing our water legacy is almost without precedent (World Bank, 2006). Unless we are able to do so, sustainable growth and poverty eradication cannot be achieved

Ethiopia has twelve major river basins, including the Blue Nile. Its riparian systems, combined with its eleven major lakes, make Ethiopia the ‘water tower’ of Northeast Africa. However, the country cannot fully mitigate the impact of hydrological variability through water infrastructure and management investments alone. It is estimated that artificial reservoir storage in Ethiopia is about 43 cubic meters per capita in contrast to 750 cubic meters per capita in South Africa (World Bank, 2006). Many field studies reveal that Ethiopia stands second in hydropower potential next to the Congo Republic and according to recent studies hydropower potential of the country is estimated to be 160,000 GWh/year (World Energy Council, 2007). However the per capita electricity consumption will still remain among the lowest in the world.

Based on the present indicative information sources, the potential irrigable land is about 3.7 million hectares. Estimates of the irrigated area presently vary, but it ranges between 150,000 and 250,000 hectares which is less than five percent of potentially irrigable land (World Bank, 2006; Awulachew *et al.* 2007) and showing that water resources have yet made little contribution towards the development of irrigated agriculture. Nowadays, the exploitation of hydropower potential has been recognized by the Ethiopian government as a key issue in the economic development of the country. To meet the strong increase of energy demand in future years, the Ethiopian government has undertaken a series of actions for the construction of power plants particularly on the rivers of omo gibe river basin as a cascade hydropower. However, implementation of such a complex system needs good management and allocation of the basin water and should be based on an insight into the evolution of past water use, as well as an understanding of current demand and an awareness of possible future trends. Moreover, being able to assess the ability of the basin to satisfy its future water demands using computer based decision support Systems (DSS) is crucial in order to plan for the future and make wise decisions.

Basin-scale analyses are often undertaken using one of two types of models: one is to simulate water resources behavior in accordance with a predefined set of rules governing water allocations and infrastructure operations, or the other is to optimize and select allocations and infrastructure based on an objective function and accompanying constraints. Often the assessment of system performance can best be addressed with simulation models, whereas, optimization models tend to be more useful when system improvement is the main goal.

Simulation based water allocation models use mass balance principles to allocate resources in a river system, as in ARSP (Acres International Corporation), MIKE BASIN (Danish Hydraulic Institute), WEAP (Stockholm Environmental Institute), RIBASIN (Delft Hydraulics) etc. and many of them are customized for the particular system, but there is also substantial usage of public domain, general-purpose models such as HEC-5 which is being updated as HEC- ResSim (Hydrologic Engineering Center-Reservoir System Simulation) developed by the US Army Corps of Engineers to include a windows-based graphical user interface (HEC, 2003; Wurbs, 2005). Hence, the aim of this research is to configure and simulate the present and likely future water resource systems of Omo Gibe river basin using HEC-ResSim model.

1.2 Problem Statement

Like many river basins in Ethiopia, water resources in the Omo Gibe river basin are not fully developed and optimally allocated yet. And also no great research effort has been put into evaluation of the developed master plan under updated models for water allocation or other purpose. In recent years like 2006 floods caused the death of hundreds people, thousands of animals and displaced a population of about 15,000 living in lower omo. Millions of US\$ of works were needed to rehabilitate Health, Education, Shelter, Water and Sanitation, Agriculture, Livestock, Fishing, Roads, etc which were washed away. Access to water supply varies from 3.8 to 69% depending on the location with the average being 24% for urban and 6% for rural areas. In addition farmers in lower omo depends on upstream rainfall and most of whom remain poor, deprived of basic needs and vulnerable to the droughts and floods that are likely to become more frequent.

Power interruption is common in years of severe drought over the country and shortages in water disrupt power plant operation in this basin. For example, the 2008–9 droughts caused a power interruption that was lasted for about four months with a one-day-per-week complete interruption throughout the country; hampering all business and economic activities. The crisis has also reached a critical point that blackouts occurred every other day with the water level in the currently operating hydropower generation dams going down by an average of one to two centimeters every day.

However, the government having recognized the power shortage and its role in the economic development of the country is developing and planning a number of hydropower projects especially in Omo Gibe basin (Gibe II, III, IV, V, Gojeb and Hallele-Warabesa). On the contrary, different international organizations, environmentalists and journalist have been lobbying to block the construction of these massive projects, particularly Gibe III project, and blazing misleading news to the world. Especially BBC's documentary on Mar 25, 2009 saying "...the water war", "the river that divides Ethiopians..." and "Hard conversation questions; the Gibe III dam must be stopped" by an environmentalist Richard Leakey are good examples.

Consequently the complexities involved in water allocation and use of Omo Gibe river basin and any river basin in the world require a holistic approach to the planning and management of its water resources to achieve an optimal utilization that is at the same time sustainable, efficient, and equitable.

1.4 Objectives of the study

General objectives

To simulate water use and operations of existing, ongoing and planned water resource development projects at Omo Gibe river basin using HEC-ResSim (Hydrologic Engineering Center –Reservoir System Simulation) model

Specific objectives

- ✚ To construct and set up a river/reservoir simulation model for the existing Omo Gibe river basin using the HEC-ResSim model.
- ✚ To simulate Gibe III power plant operation and evaluate long term operation effect on hydrologic regime of Omo River and planned irrigation schemes in lower Omo.
- ✚ To evaluate effects of various upstream planned hydropower reservoirs Hallele, Warabesa and Gojeb OM19 on Gibe III power plant.
- ✚ To establish operational characteristics, tandem rule, for the existing, on-going and planned cascaded hydropower reservoirs

1.5 Structure of the Thesis

Simulating a river basin including allocation and operation of water resource systems is described in this report and overview for the subsequent chapters is presented as follow:

Chapter 2 is the literature review and talks about methods how to manage water resources at a river basin scale and general river/reservoir simulation and operation techniques. The chapter reviews the available simulation models and describes the HEC-ResSim model, its characteristics and applications. Besides, the general condition and previous studies conducted in the basin are broadly discussed in the chapter.

Chapter 3 gives a description of the study area, including the main characteristics of the Omo Gibe river basin including the location, rainfall characteristics, land use, topography and drainage sub basins. The chapter also discusses about the location, physical and operational characteristics of the existing hydropower plants and reservoirs

Chapter 4 describes methods and materials taken to achieve the objectives of the thesis. The chapter focuses on hydrological, meteorology, operational and physical data collection and analysis.

Chapter 5 deals with how HEC-ResSim model was built for Omo Gibe river basin and how information was used and analyzed. The chapter that follows this presents simulation results and discussion of the thesis which is also followed by conclusion and recommendation chapters, reference and the appendix sections.

2.0 LITREATURE REVIEW

2.1 Technologies for Decision Making in Water Management

River basin management involves the development, conservation, control, regulation, protection, allocation, and beneficial use of water in streams, rivers, lakes, and reservoirs. Public recreation, water quality, erosion and sedimentation, and protection and enhancement of fish, wildlife, and other environmental resources are important considerations in managing reservoir/river systems. A typical water use in a river basin is shown below in Fig 2.1, the case of Omo Gibe river basin current water use. However, due to the complexity of river basin systems, it is not very easy to satisfy a large number of possible design and operating policies. Very often there is no assurance that the best combination of policies and structural measures can be found, especially when the river basin is large with a large number of reservoirs (or reservoir systems) and a large variety of short- and long-term interests that have to be satisfied. These management requirements translate into a need for Computer based Decision Support Systems (DDS) that can provide balanced use of water as well as allow the decision maker to easily modify operating policy and physical and economic characteristics of a particular river basin.



Figure 2-1 Water use in a river basin; the case of Omo-Gibe basin

Computer based Decision Support Systems (DSS) are being used worldwide in order to manage more wisely our water resources. Simonovic (1996) presents the role of DSS in achieving a sustainable use of water resources: “A Decision Support System allows decision-makers to combine personal judgment with computer output, in a user machine interface, to produce meaningful information for support in a decision-making process. Such systems are capable of assisting in solution of all problems (structured, semi structured, and unstructured) using all information available on request. They use quantitative models and database elements for problem solving. They are an integral part of the decision-makers approach to problem identification and solution”. According to him a DSS must help decision makers at the upper levels, must be flexible and respond to questions quickly, must provide for “what if” scenarios and must consider the specific requirements of the decision makers. Particularly water allocation models are being widely used in order to assess the impacts of future development trends, water management strategies, climate change, etc on the availability of water resources

2.2 Reservoir/River System modeling

2.2.1 General

Goodman (1984) defines systems analysis as “in a generic sense, systems analysis can refer to any orderly and scientific approach to problem solving. It includes traditional engineering methods and more recently developed mathematical methods in the field of operations research”. A very large number of publications on applying systems analysis techniques to reservoir operation problems have appeared in the literature. They are all searching for a proper system analysis to solve for the best or optimum solution. Water resource system operation is usually analyzed using mathematical models, rather than with physical models. Mathematical modeling is an essential tool in modern water resources planning and management. Reservoir system analysis models can be categorized or classified in various ways. Popular operations research techniques include optimization methods, simulation, queuing theory, network flow theory, and game theory. Among these, optimization and simulation (prescriptive and descriptive) are extensively used in water resources problem.

Simulation models are descriptive, and demonstrate what will happen if specified decisions are made. Optimization models are generally viewed as being prescriptive. However, a descriptive reservoir system simulation model may incorporate an optimization algorithm. Likewise, a simulation model may be embedded within a prescriptive optimization model. Often the assessment of system performance can best be addressed with simulation models, whereas, optimization models tend to be more useful when system improvement is the main goal. However the most effective strategy for analyzing river/reservoir operation problems may involve various combinations of optimization and simulation models.

2.2.2 Simulation

Simulation is a modeling technique that is used to predict the behavior of the system under a given set of conditions, representing all the characteristics of the system largely by a mathematical or algebraic description (cited in Yeh, 1985). Simulation models are used to evaluate the consequences of a set of decisions (what-if analysis) over a hydrologic period of interest. The operation rule in a complex system involving many projects and purposes of development in a river basin system may be tested with the aid of simulation models. In a pure simulation model, reservoir releases are determined by a set of predetermined operating rules. Through a series of simulations these rules can be modified and improved until model results are judged acceptable. A reservoir system simulation model is based on a mass-balance accounting procedure for tracking the movement of water through a reservoir-stream system, and performed by repeatedly solving the storage equation for a reservoir (inflow minus outflow equals change in storage) over a certain period. In a general form, the mass balance or quantity equation for reservoirs can be formulated as:

$$S_t = S_{t-1} + I_t - R_t - L_t \dots \dots \dots 3.1$$

Where:

S_t is the reservoir storage at the end of time e step t

S_{t-1} is the reservoir storage at the beginning of time step t

I_t is the inflow into the reservoir at time step t

R_t is the release for demands at time step t

L_t is the loss or water wasted from the reservoir at time step t.

2.2.3 Optimization

In a broad sense, optimization includes human judgment, use of simulation and/or optimization models, and use of other decision support tools. However, the term optimization is often used synonymously with mathematical programming to refer to a mathematical formulation in which a standard algorithm is used to compute a set of decision variable values that minimize or maximize an objective function subject to constraints. Optimization models automatically search for an optimum set of decision variable values (Wurbs, 2009).

Typical reservoir objective functions to be maximized or minimized could be a quantitative measure of an objective such as economic benefits and cost, water availability and reliability and hydroelectric power generation. Decision variables might be targets and release rates. Constraints typically include physical characteristics of the reservoir system, such as maximum and minimum storage, maximum and minimum releases, and regulatory or policy requirements (minimum in stream flows, restrictions on allocations and transfers etc.), and mass balances.

According to Yeh (1985) development of optimization techniques for planning, design, and management of complex water resources systems are among the important advances made in the field of water resources engineering. Simulation models are effective tools for evaluating water resource systems and provide the response of the system for certain inputs. However, optimization (mathematical programming) models are more efficient to find an optimum decision for system operation meeting all system constraints while maximizing or minimizing some objective.

2.4 Review of river basin simulation models

2.4.1 General

In spite of the development and growing use of optimization techniques, simulation models remain the primary tool for river basin planning and management studies in practice. Simulation models have been routinely applied for many years by water resources development agencies responsible for planning, construction, and operation of reservoir projects. The following table contains programs designed to simulate water development and management policies in river basins.

They are generic in that they are designed to be applicable to a wide variety of specific river basin water resource system configurations, institutional conditions, and management issues.

Table 2-1 River basin simulation models and descriptions

Short Name	Descriptive Name	Model Development Organization
HEC-5	Simulation of Flood Control and Conservation Systems	USACE Hydrologic Engineering Center http://www.hec.usace.army.mil/
HEC-ResSim	Reservoir System Simulation	USACE Hydrologic Engineering Center http://www.hec.usace.army.mil/
ARSP	Acres Reservoir Simulation Program	Acres International, BOSS International http://civilcentral.com/html/arsp_tech_info.html
MIKE BASIN	GIS-Based Decision Support for Water Planning & Management	Danish Hydraulic Institute http://www.dhisoftware.com/mikebasin/
WEAP	Water Evaluation and Planning	Stockholm Environment Institute, http://weap21.org

HEC-5

The program simulates the sequential period-by-period operation of a multiple-purpose reservoir system for inputted sequences of unregulated stream flows and reservoir evaporation rates. Multiple reservoirs can be located in essentially any stream tributary configuration. The program uses a variable time interval. For example, monthly or weekly data might be used during periods of normal or low flows in combination with daily or hourly data during flood events. The user specifies the operating rules in HEC-5 by inputting reservoir storage zones, diversion and minimum instream flow targets, and allowable flood flows.

ARSP

The Acres Reservoir Simulation Program (ARSP) was developed by Acres International Corporation. The original model was developed to assess alternative operation policies for a 48-reservoir multiple-purpose water supply, hydropower, and flood control system in the Trent River Basin in Ontario, Canada. The ARSP network flow programming based model simulates multi-purpose, multi-reservoir systems. Operating policies are defined by prioritizing water demands. Monthly, weekly, daily, or hourly time steps may be used. The software assigns upper and lower bounds and cost functions to the network flow paths for the network flow programming formulation based on the input provided by the user.

WEAP

The Water Evaluation and Planning (WEAP) System was developed and is distributed by the Stockholm Environmental Institute Boston Center at the Tellus Institute located in Boston, Massachusetts. WEAP is a reservoir/river/use system water balance accounting model that allocates water from surface and groundwater sources to different types of demands. The modeling system is designed as a tool for maintaining water balance databases, generating water management scenarios, and performing policy analyses

MIKE BASIN

MIKE BASIN runs within and is an extension to ArcView which is a geographical information system (GIS) software product available from ESRI (Environmental System Research Institute). MIKE BASIN integrates GIS capabilities with reservoir/river system modeling. Features also facilitate interconnected use of Microsoft Excel with MIKE BASIN. The model simulates multi-purpose, multi-reservoir systems based on a network formulation of nodes and branches. Although the time step is user-selected, solutions are stationary for each time station without flow routing dynamics. Thus, a monthly time step is common. Time series of inflows from catchments to each branch of the stream system are normally provided as input. However, the model can also be connected to watershed precipitation-runoff capabilities provided by the MIKE11.

HEC-ResSim

The Hydrologic Engineering Center (HEC) of the U.S. Army Corps of Engineers has developed a new reservoir simulation model, HEC-ResSim, as the successor to the well-known HEC-5.

HEC-ResSim uses an original rule-based approach to mimic the actual decision-making process that reservoir operators must use to meet operating requirements for flood control, power generation, water supply, and environmental quality. Parameters that may influence flow requirements at a reservoir include time of year, hydrologic conditions, water temperature, and simultaneous operations by other reservoirs in a system. Basic reservoir operating goals are defined by flexible at-site and downstream control functions and multi-reservoir system constraints. As HEC-ResSim has evolved, advanced features such as outlet prioritization, scripted state variables, and conditional logic have made it possible to model more complex systems and operational requirements, as a result of unique features mentioned it is primarily selected for this study.

2.5 Introducing HEC-ResSim

ResSim has a graphical user interface (GUI) and utilizes the HEC Data Storage System (HEC-DSS) for storage and retrieval of input and output time-series data. ResSim is used to simulate reservoir operations including all characteristics of a reservoir and channel routing downstream. The model allows the user to define alternatives and run their simulations simultaneously to compare results. Network elements include reservoirs, routing reaches, diversions, and junctions. In ResSim, watersheds include streams, projects (i.e. reservoir, levees), gage locations, impact areas, time-series locations and hydrologic and hydraulic data for that specific area. Schematic elements in ResSim allow you to represent watershed, reservoir network and simulation data visually in a geo-referenced context that interacts with associated data.

2.5.1 HEC-ResSim Environment for Model Building

The model allows the user to define alternatives and run simulations simultaneously to compare results. Schematic elements in HEC-ResSim allow the representation of watershed, reservoir network and simulation data visually in a geo-referenced context that interacts with associated data. Additionally, HEC-ResSim is compatible with ArcGIS shape files, which can be used as a background layer and facilitate the better representation of the physical system. HEC-ResSim is unique among reservoir simulation models because it attempts to reproduce the decision making process that human reservoir operators must use to set releases.

The program represents the physical behavior of reservoir systems with a combination of hydraulic computations for flows through control structures, and hydrologic routing to represent the lag and attenuation of flows through segments of streams. It represents operating goals and constraints with an original system of rule-based logic that has been specifically developed to represent the decision-making process of reservoir operation. Watershed boundaries, reservoirs, channel networks, diversions, etc. can be superimposed over the shape file. The HEC-ResSim program is divided into three modules (Fig 2.2) which are respectively, the watershed setup, the reservoir network definition and the simulation scenario management

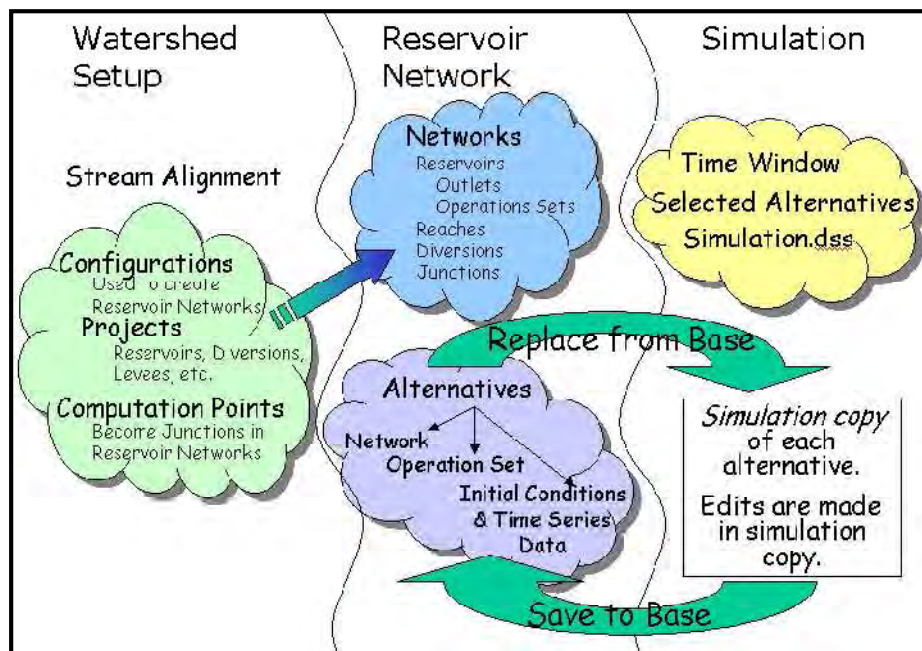


Figure 2-2 ResSim module concept (HEC-2003)

Watershed module

The purpose of this module is to provide a common framework for watershed creation and definition. A watershed is associated with a geographic region for which multiple models and layers of information (idem, area coverage in ArcGIS) can be configured. A watershed may include all of the streams, projects, e.g., reservoirs, levees, gage locations, impact areas, time-series locations, and hydrologic and hydraulic data for a specific area. All of these details together, once configured, form a watershed framework.

Reservoir network module

The purpose of the Reservoir Network module is to isolate the development of the reservoir model from the output analysis. This module facilitates the creation of the network schematic, the description of the physical and operational elements of the reservoir model, and the definition the management alternatives to be analyzed. Reservoirs are further divided into multiple technical elements such the pool, the dam, and one or more outlets. The criteria for reservoir release decisions are drawn from a set of discrete pool heights, power production levels and release rules. Reservoirs are connected to the river network as well diversions or junctions.

After completing the connection network schematic, physical and operational data for each network element are defined. Management alternatives are created to compare results using different model schematics, i.e. physical properties, operation sets, inflows, and/or initial conditions.

Simulation scenario management

The purpose of the Simulation module is to isolate the output analysis from the model development process. Once the reservoir model is complete and the alternatives have been defined, the Simulation module enables the model to test various river flow hypotheses.

2.6 Reservoir Operation Rules

Reservoir operation rules provide a guideline for answering the questions on how the storage should be managed, more in particular given a certain status of the reservoir how much water should be released during the coming time step. Reservoir management requires the creation of “a set of operation (or regulation or release) procedures, rules, schedules, policy or plans that best meet a set of objectives”. Typically, reservoir operating rules guide release decisions. Operational decisions involve allocation of storage capacity and water releases between reservoirs and between uses in different time periods. The wide variety of regulation policies presently in use consist of operating rules which specify ideal pool levels or zones, and specify what to do if reservoir storage deviates from those levels or zones.

Typically reservoir storage capacity is subdivided in several zones or pools, such as inactive-, conservation-, flood control- and surcharge zone. (See Figure 2.3)

Inactive pool: also called dead storage, this level indicates the lower operation limit, water releases are normally not made below this level. The dead storage level may be fixed by the invert of the lowest outlet, or in the case of hydroelectric power, by conditions of operation efficiency for the turbine.

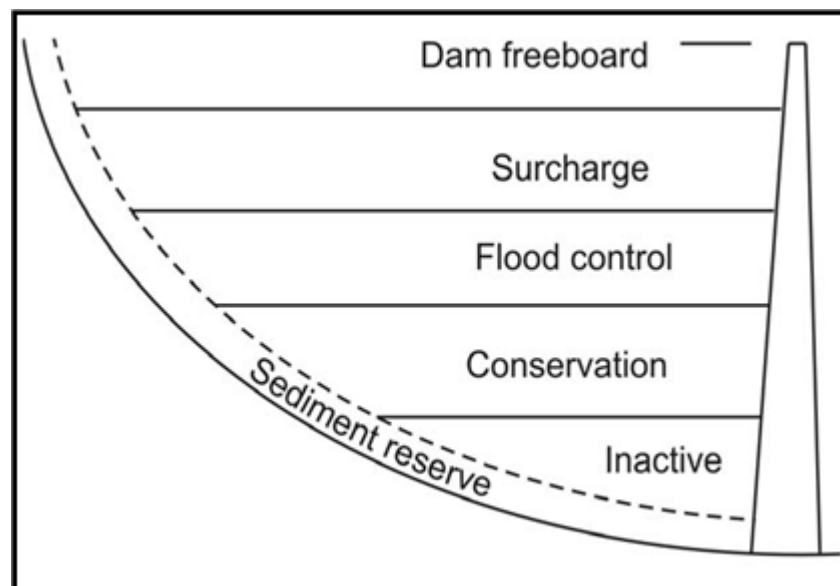


Figure 2-3 Reservoir pool

Conservation pool: This is defined as the storage zone between the flood control pool and the inactive pool, searching for the target level for maximum average energy generation trying to obtain the optimum balance over time between creation of head and avoidance of spilling. This target level is not relevant if there is no hydropower station.

Flood control pool: this zone serves for flood control purposes. It lies between the maximum reservoir level and the maximum level of the conservation pool. This storage space should be kept as empty as technically possible, so that by storing the water in the reservoir incoming floods are attenuated and thus avoid downstream damage.

The desirable reservoir storage or elevation at various times of the year may be shown by a rule curve. The terms rule curve or guide curve are typically used to denote operating rules which define ideal or target storage levels and provide a mechanism for release rules to be specified as a function of storage content. Rule curves may be expressed in various formats such as water surface elevation or storage volume versus time of the year (Wurbs, 2009).

Rule curves have one advantage, this is simplicity for the operator of the dam, but also have many disadvantages. Some of these are that they disregard present circumstances of weather and watershed conditions, and lack of a clearly defined objective function. Fig 2.4 presents an example of such rule curves; the rule curves divide the live storage into various storage zones.

The upper zone serves flood control purposes. It lies between the maximum reservoir level and the flood control curve. This storage space should be kept as empty as technically possible, so that by storing the water in the reservoir incoming floods are attenuated and thus downstream damage is avoided. The flood control curve can be put at the full reservoir storage level, when the reservoir does not have a flood control function. The storage curve (target curve) for maximum average energy generation, which is defined in the storage zone between the flood control and firm storage curves, presents the optimum balance over time between creation of head and avoidance of spilling.

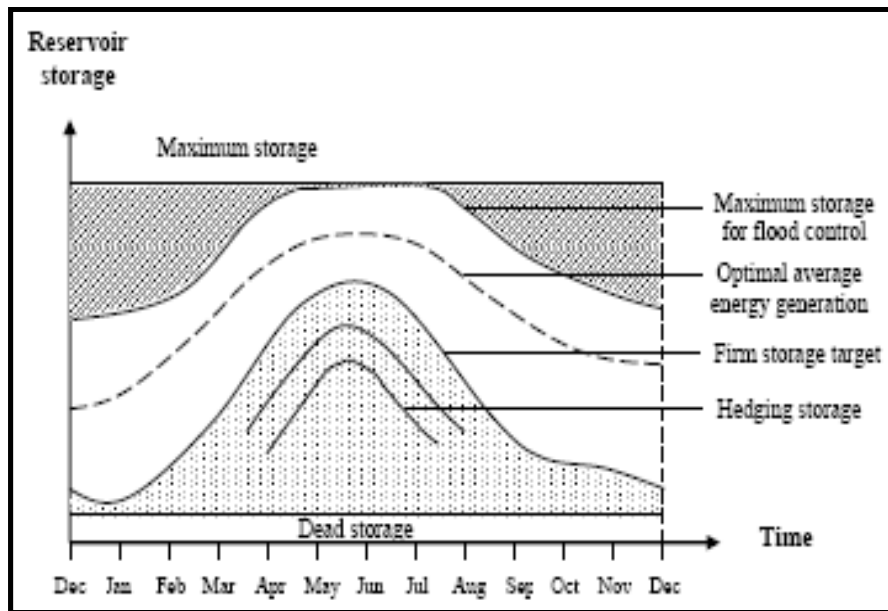


Figure 2-4 Reservoir operation rule curves for multi-purpose reservoir

Reservoir Operation Rule Curves for a Multi-purpose Reservoir

This curve is not relevant if there is no hydropower station. The firm storage curve and the dead storage level define the lowest zone. The firm storage curve indicates the amount of water, which should be kept in storage in order to be able to supply the demands during critical dry situations, in particular the demand for the generation of firm energy. The dead storage level indicates the lower operation limit, water releases are normally not made below that level. The dead storage level may be fixed by the invert of the lowest outlet, or in the case of hydroelectric power, by conditions of operation efficiency for the turbine. It may also provide a portion of the sediment reserve, head for hydroelectric power, and water for recreation and fish habitat.

2.6.1 Reservoir Operation rule in HEC-ResSim

A reservoir in HEC-ResSim must have a target elevation. A reservoir's target elevation, represented as a function of time, is called its Guide Curve. It is the dividing line between the upper zones of the reservoir (typically called the flood-control pool) and the lower zones (typically called the conservation pool).

The release decision logic in HEC-ResSim starts and ends with the guide curve. When the reservoir's pool elevation is above the guide curve ("in flood control"), the reservoir wants to release more water than is entering the pool; when below guide curve ("in conservation"), and the reservoir wants to release less water than is entering the pool. All operating rules and physical limitations act as constraints upon the reservoir's ability to meet the goal of returning the pool to its guide curve elevation. Without rules, the reservoir will be constrained only by physical capacity of the outlets to get to and stay at the guide curve elevation (HEC, 2003).

2.6.2 Tandem operation rule in HEC ResSim

Tandem operation is the method in HEC reservoir simulation model that used to analyze the reservoir operation in the system and the storage distribution among the reservoirs on the same stream. When a Tandem reservoir system is defined, the model determines the amount of release from the upper reservoir in order that the downstream reservoir is operating towards a storage balance. For every decision interval an end-of- period, storage is first estimated for each reservoir based on the sum of the beginning of period storage and period average inflow value, minus all potential outflow volumes. The estimated end of date storage for each reservoir is computed to a desired storage that is determined by using a system storage balance scheme.

The priority for release is then given to the reservoir that is furthest above the desired storage. When a final release decision is made, the end of period storage is recomputed. Depending on other constraints or higher priority rules, system operation strives for a storage balance such that the reservoirs have either reached their guide curve or they are operating at the desired storage (HEC, 2007).

2.6.3 Implicit and Explicit system storage balance

The implicit and explicit system storage balances are the default and the user defined desired storage balances in system reservoirs, respectively. The methods are applied to both tandem and parallel system operations. The implicit method is automatically created by the model when a reservoir system is established by either of the system operation methods.

Thus, the desired storage for each reservoir is determined through an implicit balance line, which is simply a linear relationship between the storage at each reservoir and the system storage. For each reservoir, the balance line hinges on the intersection of the reservoir empty storage and system empty storage, reservoir-guide curve storage and the system-guide curve storage, and reservoir full storage and system full storage.

The explicit method is optional and allows the user to define a desired storage balance in the reservoir system. The user can further modify the implicit balance lines explicitly to characterize the desired storage distribution using one or more system zones (i.e., adding one or more special division of the conservation pool in both of the reservoirs) and placing inflection points along the balance line. The inflection points effectively transfer the implicit balance line into explicit curves (HEC, 2007).

2.7 Previous Studies in the Basin

2.7.1 Omo-Gibe river basin Integrated development master plan Study

The Omo-Gibe River Basin Development Master Plan Study was carried out under the support of the government of Ethiopia between 1993 and 1996 with external assistance provided by the African Development Bank. The multi-disciplinary study team comprised more than 30 national and international experts provided by a consortium led by Richard Wood roffe and Associates and Mascott Ltd, together with professional and technical counterpart staff from the ministry of water resources.

The aim of the study was to prepare a master plan for the Omo-Gibe Basin that makes optimum use, both at a regional and national level, of all physical, human and animal resources, with the minimum possible adverse environmental impact. One objective of the study has also been to define and prepare sustainable and implementable projects, mainly hydropower and agricultural, which optimally exploit, in terms of social, economic financial and environmental needs and constraints of the natural resources of the area. The study has assessed surface water resource of the basin using a rainfall-runoff model, preliminary hydropower and large scheme irrigation sites.

2.7.2 Preliminary priority sites for hydropower in Omo-Gibe river basin

The master plan study made has assessed preliminary hydropower, irrigation and tourism potential of the basin. The study also identified a preliminary 21 priority sites for hydropower development in Omo-Gibe River Basin.

Table 2-2 Priority sites for hydropower development in omo gibe basin

River	Site Reference	Location Northing (deg,min,sec)	Location Easting	River Bed Level	Normal Water Level	Dam Crest length (m)	Average flow (m ³ /s)	Head (m)	Power (MW)
Gilgel	OM1*	07-52-20	37-24-00	1390	1438	200	64.6	138	87.4
Gibe	OM2	8-11-30	37-25-00	1200	1300	500	68.8	100	87.4
Gibe	OM 3	08-35-00	37-16-00	1500	1600	500	80.7	400	316.3
	OM 4*	8-15-00	37-30-00	1130	1200	400	205.7	100	501.6
	OM 5	8-1-00	37-35-45	1000	1100	300	230.9	100	225.7
	OM 6	07-56-00	37-30-00	900	1000	600	352.8	100	345.7
Wabe	OM 7	8-21-30	38-05-40	1900	2000	500	8.2	100	8
	OM 8	8-20-00	38-01-30	1800	1900	750	11.7	100	1.5
	OM 9	8-16-20	37-52-25	1700	1800	500	16.5	100	16.2
	OM 10	8-14-00	37-44-00	1600	1700	1000	23.4	500	114.7
Omo	OM 11	7-12-30	37-27-00	800	900	400	376.4	100	269.1
	OM12*	07-55-20	37-25-40	690	800	750	452.8	100	443.7
	OM 13*	06-37-45	37-04-00	600	700	600	507.8	100	497.6
	OM 14	6-27-30	36-25-00	500	600	700	558.8	100	547.6
	OM 15*	6-22-00	36-04-20	470	500	500	617.6	50	302.6
	OM 16	6-02-40	35-59-00	440	450	500	617.6	25	151.3
	OM 21	07-19-00	37-25	810	910	-	-	100	
Gojeb	OM 17	07-33-50	36-07-30	1510	1550	300	16.3	250	39.9
	OM 18*	7-23-50	36-33-20	1200	1300	550	48.9	200	75
	OM 19*	7-13-50	36-53-30	1000	1100	500	68.1	100	66.7
	OM20*	7-16-25	37-12-00	915	1000	400	84.4	100	82.9

This is most useful data, although it has been modified further during planning and engineering period as;

DS4	Dam site 4	Gilgel-gibe I Hydropower site (near OM1*)
DS8	Dam site 8	Gilgel-Gibe II Hydropower site (near OM1*)
DS14	Dam site 14	Gibe III Hydropower site(near OM12*)
OM13	Dam site 13	Gibe IV Hydropower site(near OM12*)
OM15	Dam site 15	Gibe V Hydropower site (near OM 15*)
OM 19*	Dam site	Gojeb Hydropower dam site

2.7.3 Planned Water resource development

Halele –Warabesa Stage I

The Halele-Werabesa Stage I Hydropower Project comprises a large earth core, rock fill dam and an underground power scheme at Halele. The power scheme comprises a short 360 m headrace arrangement of inclined shaft and tunnel, an underground powerhouse accommodating 2 x 48 MW Francis turbine generator units, a tailrace surge chamber and a 5 km tailrace tunnel. The scheme exploits a total head of 103 m to generate 460 GWh of firm energy per year. This energy will be fed into the 230 kV national grid by a 30 km transmission line tying in to the existing Gilgel Gibe to Gedo line. The Halele-Werabesa Stage I Hydropower Project is feasible from the technical, economic and environmental viewpoints. There are no legal obstacles to its development. Such a worthwhile scheme, which will bring net benefits to the nation in general and the local communities in particular, should be implemented at the earliest possible date. The principal technical characteristics of the project are included in Table 2.3

Table 2-3 Halele Warabesa stage I hydropower project silent features

Halele Dam, hydrology and Reservoir	
Catchment area	6126 km ²
Mean inflow	78.4 m ³ /s
Main Dam Type	zoned earth fill/rock fill
Height	85 m
Total storage at FSL	3,300 million m ³
Active storage	2,900 million m ³
Dead storage	400 million m ³
Reservoir surface area at FSL	280 km ²
Spillway type	Side channel, free overflow, chute, flip bucket
Routed PMF peak discharge	754 m ³ /s
Power plant	
Powerhouse type	Underground
Turbine number and type	2, Francis
Total installed capacity	96 MW
Rated head	89.1 m
Rated total flow	124 m ³ /s
Firm energy production	460 GWh/year

Hallele –Warabesa Stage II

The project area is located some 200km (air distance) east-south-east of Addis Ababa. The scheme, including the reservoir and power waterways, extended over a corridor some 25km long. The approximate centroid of the project area lies at altitude 8⁰24' north and longitude 37⁰23' east. The Halele-Warabesa Stage II hydropower project comprises a medium sized composite dam (Roller-Compacted concrete central block, rock/clay, rock fill embankment flanks) and an underground power scheme.

The power scheme comprise along 4,260m headrace tunnel ,a 77m high surge shaft ,a steeply inclined 295m long pressure shaft ,a 230m long high pressure headrace tunnel ,an underground power house accommodating 4x81.5MW Francis turbine generator unites , a tailrace surge chamber and a 4090m long tailrace tunnel.

The scheme exploits a total gross head of some 313m to generate 1570GWh of firm energy per year. As its name implies, Halele-Werabesa Stage II scheme will be the second development in cascade.

Table 2-4 Halele Warabesa stage II hydropower project silent features

Warabesa Dam, hydrology and Reservoir	
Catchment area	6,692 km ²
Mean inflow	87.8 m ³ /s before Halele
Main Dam Type	RCC with clay core rock fill t flanks
Height	45 m
Total storage Volume at FSL	184 million m ³
Active storage	108 million m ³
Capacity at minimum operating level	78 million m ³
Reservoir surface area at FSL	13.4 km ²
Spillway type	Free overflow built on RCC dam with crest ogee,
Routed PMF peak discharge	1,194 m ³ /s
Power plant	
Powerhouse type	Underground
Turbine number and type	4, Francis
Total installed capacity	326 MW
Rated head	296 m
Rated total flow	124 m ³ /s
Firm energy production	1570 GWh/year

Gojeb OM19 hydropower project

The proposed OM19 hydropower dam project is located in the Omo-Gibe river system, which drains an area of 79,000 km² in south-west Ethiopia before discharging into Lake Turkana in Kenya. The dam site is situated in the middle reaches of the Gojeb river, a principal tributary of the river Omo, and has a catchment area of 5,390 km². The project involves the construction of a rock fill dam across the Gojeb river and a downstream power house. The principal technical characteristics of the project are presented in Table 2.5

Table 2-5 Gojeb OM19 hydropower project silent features

Hydrology	
Catchment Area (km ²)	5,390.0
Mean Annual inflow (Mm ³)	2,720.0
10,000 year return period flood (m ³ /s)	1,706.0
Probable Maximum Flood (m ³ /s)	2,230.0
Reservoir	
Maximum Retention Level (masl)	1,110.0
Minimum Operating Level (masl)	1,067.5
Total Storage (Mm ³)	997.0
Live Storage (Mm ³)	757.0
Power Generation	
Firm Energy (GWh/yr)	364.0
Plant Load factor	0.60
Dependable Capacity (MW)	70.0
Installed Capacity (MW) (3x50 MW units)	150.0
Minimum head (m)	70.0
Maximum head (m)	111.0

2.8 Irrigation Potential and Development in the lower Omo- Gibe basin

2.8.1 History of Irrigation Development in lower Omo-Gibe Basin

The Omo-Rate farm was originally called The Tringole state farm and was established by the Ethio-Korea Agricultural development venture project. The project was designed for cotton production and the seed cotton was designed for the Arbaminch Ginnery.

The project was originally designed for 10,000 ha to be irrigated by four pump station of which only two were constructed. A pilot farm of 75 ha was also established. Pump station no.1 was completed in October 1989 and has a nominal command area of 800ha. The area has now been formed since 1992/1993 and the farm has now been transferred to the North-Omo Agricultural Development Enterprise based in Arbaminch. This Enterprise includes a cotton ginnery, Bilate farm, Abaya farm and Sile farm, all of which are located in the vicinity of Arbaminch. The enterprise is a self-supporting and independent of the regional government and the ministry of state farm (Richard Wood roof and Associates, 1996).

2.8.2 Lower Omo-Gibe Basin Irrigation Potential sites

According to Omo-Gibe River Basin master Plan Final Report pre-feasibility Studies, in the lower Omo Gibe basin there are a highly potential sites suitable for irrigation development and the study have identified development proposal for irrigation projects listed in Table 2.6.

Table 2-6 Irrigation potential sites in the lower Omo Gibe basin OGRBIDMP (1996)

Irrigation site	Irrigation Potential(ha)	Pump station	Description
Omo Rate Farm stage 1	800	1	Selected Irrigation site
Omo Rate Farm stage 2	540	2	Selected Irrigation site
Omo Rate Farm stage 3	1560	2	Selected Irrigation site
Omo Rate Farm stage 4	5800	3 and 4	Selected Irrigation site
Dip'a Hayk	5880	-Pump	Selected Irrigation site
Nargi	2070	-Pump	Selected Irrigation site
Omo Rate west	4020	-Pump	Selected Irrigation site
Mursi	8,000	-Pump	Extension Irrigation site
Kibish	26,000	-Pump	Extension Irrigation site
Total	54,670		

However, recent studies during the field investigation of Gibe III impact assessment there was evidence only 150-200 ha in operation. Most are small farms growing high value crops like vegetables and fruits, particularly bananas; using either diesel pumps or windmills to extract water from the river. Generally the present level of irrigation development is really quite low. The damage caused by annual flooding, low river levels in the dry season (too low for pumping), and limited market development are probably some of the reasons, but another may simply be the traditional, nomadic, pastoralist way of life of the people.



Figure 2-5 Small scale pumped irrigation site at Lobet Dasenech Wereda



Figure 2-6 Recession cultivation site at Dasenech-Tobacco field

\

The whole of the eastern side borders the Rift Valley Lakes Basin. Gilgel gibe and Gojeb (as shown in Fig 3.1) rivers are major tributaries to the main river which drains the western high lands. (Omo-Gibe River Basin Integrated Development Master Plan Study”, Vol. VI, Water Resources Surveys and Inventories, Dec 1996, by Richard Woodroffe & Associates)

3.2 Climate and Rainfall Features

The climate of the study area is classified as tropical humid in the highlands that include areas surrounding Jimma and around the head waters of Gojeb River. For the rest, and greatest part, of the watershed the climate is classified as a tropical sub-humid, intermediate between the tropical humid and the hot arid climate characteristic of the southern most part of the floodplain toward Lake Turkana. Annual rainfall varies from 400 mm in the extreme south lowland to 1900 mm in the highland with the average being 1140 mm. The mean annual temperature in the basin varies from less than 17°C in the west highlands to over 29°C in the south lowlands (OMGRBIDMP, 1996). Fig 3.2 and 3.3 shows mean monthly values of temperatures and rainfall, recorded at Jima, Wolayita, Sekoru, Gojeb, Jinka and Agaro stations, referring to upper middle and lower part of the basin.

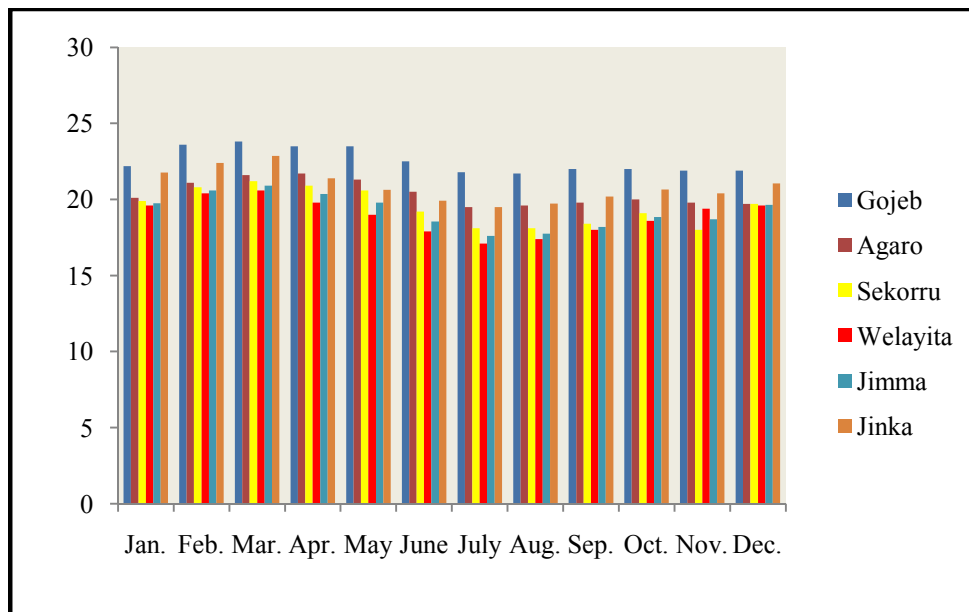


Figure 3-2 Mean monthly temperature in the basin

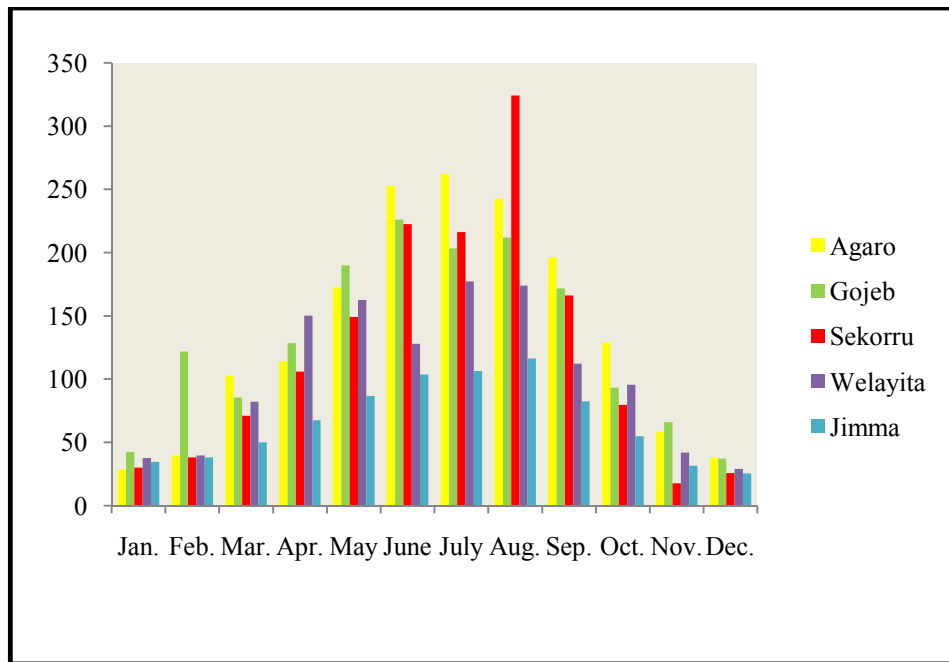


Figure 3-3 Mean monthly rainfall in the basin

3.3 Topography

The basin divides sharply and almost exactly into highlands in the northern half and lowlands in the southern half. This division is reflected in almost all other aspects of the basin. The northern highlands are deeply dissected and drained by the Gibe and Gojeb river systems merging to form the Omo in a deeply entrenched gorge. Steep slopes with dissected hills characterize the highlands while the lowlands are characterized by relatively gentle and undulating slopes. The highland areas have elevations as high as 3625 masl on Mount Ghuge while the lowland areas fall in the altitudes of up to 235 masl.

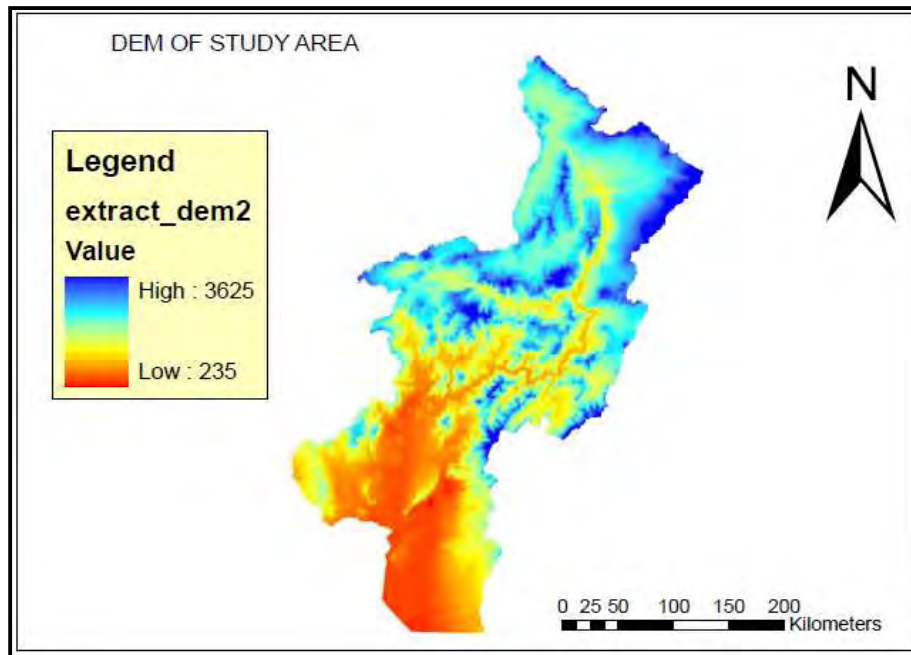


Figure 3-4 DEM of the study area

The head waters of the Great-Gibe River are at an elevation of about 2200 masl. Although there are some important tributaries from different directions, the general direction of flow of the Gibe River is southwards, towards the Omo River and then to Lake Turkana a fault feature, filled with alluvial and lacustrine sediments of recent origin associated with the Great Rift Valley. The Gibe River is known as the Omo River in its lower reaches, south-westwards from the confluence with the Gojeb River. This is the reason behind the name Omo-Gibe River Basin.

3.4 Hydrography and drainage subasins

The northern part of the catchment has a number of tributaries from the NE, the largest ones being the Walga and the Wabi river. These drain largely cultivated land, much of it with rather impeded drainage. This is an area where erosion processes are important. The Tunjo and Gilgel Gibe rivers are important tributaries, also draining mainly cultivated lands from the SW. These have a higher proportion of more permeable soils than the Walga and Wabi catchments. The cultivated land in the upper catchments is usually found on the uplands. In the valley bottom the land is mainly classified hydrologically as rangeland.

Going downstream another important tributary is found from the west, the Gojeb river. It drains uplands that have been less intensively used for agriculture than the area around Jima to the NE. The prevailing vegetation of the Gojeb headwaters is wooded shrubland. The Gibe river is known as the Omo River in its lower reaches, south-western from the confluence with the Gojeb River. Downstream the confluence with the Denchiya River, the Omo River changes its character in traversing the flood plain leading to Lake Turkana as a well-defined meandering river channel.

3.5 Land use

In a very broad term, most of the northern catchments of the Omo-Gibe Basin are under extensive cultivation with increased land pressure, meaning the expansion of cultivated areas in to increasingly marginal lands at the expense of wood lands. Deforested areas are now confined to areas too steep and inaccessible to farm. The flatter poorer drained bottom lands of the northern catchments are usually not cultivated but are used for dry season grazing and eucalyptus tree plantations. The main gorges of the basin are relatively unpopulated and support a cover of open wood-land and bush-land with grasses, the eastern part of the basin has some of the most densely populated and intensively farmed areas in the country. The south of the basin is more sparsely populated with a greater population of natural vegetation.

3.6 Lake Turkana

3.6.1 Geographical Location and physical description

Lake Turkana (formerly Lake Rudolf) is a closed basin lake stretching from 35⁰50' to 36⁰40' east and 2⁰27' to 4⁰40' north, in north western Kenya and it is the largest permanent desert lake in the world. It covers an area of 7,560 km² and is the largest water body wholly in Kenya. The regional climate in its basin is highly variable; thus the lake experiences highest water level fluctuations of all Kenyan lakes. The major river draining into Lake Turkana is the Omo which has its source in the Ethiopian highlands. It enters the lake from the north and contributes greater than 90% of the total water influx. Other inflowing rivers are the Turkwell and Kerio both of which are temporary, flooding only during sporadic rains. Generally catchment of the Lake is made up as follows:

Catchment	Area (km²)
Omo-Gibe Basin	79000
Kerio-Turkwell Rivers	39400
Ephemeral Streams	9900
Lake Surface	<u>7560</u>
	Total 135860

The Omo-Gibe Basin represents 58% of the total catchment area but contributes some 90% of total inflows to the Lake. The Kerio and Turkwell rivers, comprising 28% of the catchment, provide less than 10% of the inflow and the contribution of the ephemeral streams which make up 7.5% of the catchment is negligible. The Omo-Gibe flood peak reaches Lake Turkana between August and October each year. Low discharges from the Omo-Gibe from 1968-75 led to a fall of 1.5 m in the level of the Lake. The Lake is alkaline and contains high concentrations of sodium chloride and sodium bicarbonate, lead and iron. Its waters cannot support crop growth, neither are they suitable for human consumption (although they are used both for domestic purposes and watering livestock).

3.7 Existing Hydropower Schemes on the Omo-Gibe River Basin

Gilgel-Gibe cascaded hydropower (Gibe-I and Gibe II)

The Gilgel Gibe system is a purely hydroelectric scheme including two power plants located on the Gilgel Gibe and Omo rivers, about 250 km South-West of Addis Ababa and 80 km North East of Jimma. The Gilgel Gibe is a tributary of the Great Gibe river, known as the Omo river downstream of the bridge of the Highway from Addis Ababa to Jima. The first two stages of the Gibe cascade development include two power plants, namely the Gibe I and Gibe II. The first plant, Gibe I, is a conventional hydroelectric power plant with a capacity of 220 MW. Started in 1986 and completed in 2004 (after being interrupted in the early 90's) was the Ethiopia's largest power plant.



Figure 3-5 Photograph view of Gibe I dam and reservoir
It is possible to see intake tower and the spillway chute.

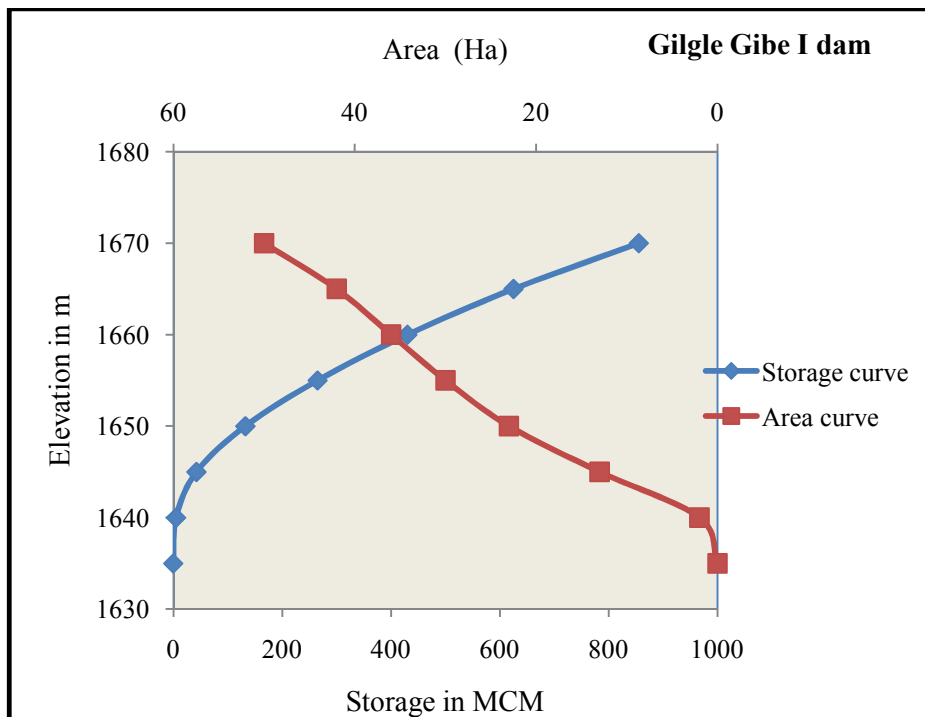


Figure 3-6 Elevation-Area- Storage curve of Gibe I reservoir

The downstream power plant Gibe II will convey the flow, regulated by the Gibe I dam, through a 26 km long hydraulic tunnel to the great gibe river about 150 km downstream of Gibe I dam. This second phase started in 2005 and is scheduled for operation in 2008 but due to complexity during tunnel boring and the sudden collapse in 2010 the plant was in operation since this year. The plant will produce about 420 MW.



Figure 3-7 Photograph view of Gibe II power house and penstocks

When operative the Gibe I and II hydropower system will provide totally about 640 MW, which would make considerable contribution to increase the existing national energy system. The first plant of the cascade regulates the Gilgel Gibe River with a reservoir of approximately 840 Mm³. The second plant uses the water discharged by the first one diverting the flows into a waterway that bypasses about 110 km of the two rivers, Gilgel Gibe and Omo. The intake is located on the Gilgel Gibe river about 2.5 km downstream of the Gibe I outlet. The waterway crosses the ridge between the Gilgel Gibe valley and the Omo valley by means of 26 km of tunnel and 1.2 km of penstocks.

The outdoor powerhouse is located along the Omo river right bank approximately 60 km d/s of the Addis Ababa to Jimma Highway Bridge on the Gibe River. The basic features of the two plants are summarized below:

a) Upstream plant:

- ✚ Reservoir, with a live storage of 657 million m³ and a dead storage of 182 million m³,
- ✚ Operating between elevation 1,653 and 1,671 m a.s.l., with an average inflow of 50 m³/s,
- ✚ Rock fill dam of volume of 2.5 million m³, with a 105,000 m² impervious bituminous facing, approximately 40 m high and 1,600 m long,
- ✚ Gated open chute spillway located on the left abutment and designed for a not routed discharge of 1,450 m³/s and verified for an exceptional routed flood of 2253 m³/s,
- ✚ Power intake for 101.5 m³/s; 5.5 m of diameter and approximately 9.0 km long concrete lined tunnel with terminal surge shaft; underground penstocks and manifold,
- ✚ Cavern powerhouse equipped with three Francis units of about 70 MW; 240 m of gross head.

b) Downstream Plant:

- ✚ Daily reservoir with a live storage for daily regulation, operating at elevation 1,431.5 m a.s.l., with an average yearly inflow of 50 m³/s,
- ✚ Concrete gravity weir 40 m high and 170 m long, incorporating an ungated spillway on the crest; upstream de-silting weir,
- ✚ Power intake tower for 101.5 m³/s on the right bank of the upstream reservoir; 6.3 m in diameter and 25.8 km long concrete lined tunnel with terminal surge shaft;
- ✚ Underground penstock for the first 100 m followed by two outdoor penstocks after bifurcation, final manifold,

- ✚ Outdoor powerhouse on the right bank of the Omo river, equipped with four 105 MW Pelton units.

Flow and operation:

The rated outflow of Gibe I is $101.5 \text{ m}^3/\text{sec}$ (3 units, $33.85 \text{ m}^3/\text{s}$ each). Continuous environmental flow of about $1.3 \text{ m}^3/\text{s}$ is released downstream of the Gibe I dam. This flow is not diverted by the Gibe II plant and spills downstream the weir together with the entire runoff of the residual catchment area between the two plants, which is about 79 km^2 , irrelevant if compared with catchment of Gibe I (4225 km^2). In order to avoid energy losses due to the spilling over of the weir in addition to the environmental release, the rated flow of the second plant is the same as the first one, i.e. $101.5 \text{ m}^3/\text{s}$ and the two plants in cascade operate in a synchronous manner according to a single operation rule. As a consequence the power output of each plant will be constantly in the ratio of the respectively net heads, apart the minor difference due to electromechanical equipment efficiency. It should be noted that, being the gross head over the two power houses, different, unequal turbines, both in type and number, were chosen. Nonetheless a synchronous operating rule should be followed.

Energy: According to the reservoir operation studies and the flow duration curve the installed capacity and energy production of the Gibe I plant is as follows:

- ✚ 220 MW Maximum power (considering three units operating at maximum discharge),
- ✚ 794 GWh/year Average Annual Energy produced,
- ✚ 622 GWh/year Firm Energy produced,

The Plant Factor for Gibe I results to be 0.46. As the two plants in cascade will operate in a synchronous manner, the plant factor value of the first stage can be assumed also for the second stage. With this assumption the following energy production results for Gibe II:

- ✚ 420 MW Maximum power,
- ✚ 1635 GWh/year Average Annual Energy produced, more than double of the energy produced by the Gibe I

Gibe III Hydropower project

Currently Gibe III hydroelectric is under construction and located in the middle reach of the Omo River around 450km from Addis Ababa to the south. The approximate geographic coordinates of the location of the dam axis is between 312,044E and 757,343N and 312,542E and 757,107N. The downstream area extends from the dam site down to Lake Turkana.

The Gibe III hydropower plant is the third plant of the Gibe cascade developing the hydroelectric potential of the Gibe-Omo River including Gibe IV and Gibe V projects, for hydropower and agricultural uses, currently being planned.

Gibe III Hydroelectric Project comprises a 230m high dam and will create a huge reservoir with a surface area of some 200km² and a total storage of some 11,750 million m³, the second largest in Africa. (EEPCO, 2009) .The Gibe III Hydropower Project is planned to generate 1870 MW of electricity. The cost of the Gibe III project is estimated at \$1.7 billion, for which foreign financing is currently being sought. The EEPCO predicts the export of 200MW to both Djibouti and Sudan, and 500 MW to Kenya.

Table 3-1 Gibe III hydropower project silent features (EEPCO, 2007)

hydrology	
Catchment area	34,150 km ²
Mean inflow	438.2 m ³ /s
10,000 years return peak flood	10,600 m ³ /s
Probable maximum flood	18660 m ³ /s
Dam	
Main Dam Type	Roller compacted concrete (RCC) dam
Height above river bed elevation	223 m
Crest elevation	896 m a.s.l
Crest length	580 m
Reservoir	
Total storage Volume at FSL	14700 Mm ³
Active storage	11,750 Mm ³

Minimum operating level	800 a.m.s.l
Max/Normal O.L. (max. ret. level)	892 m a.s.l
Extreme flood level in the reservoir	892.5 m a.s.l
Reservoir surface area at FSL	211 km ²
Spillway	
Type	gated (overflow)
Sill	873 m a.s.l.
Sill length	108m
Radial Gates (No, W x H)	9, 12x19 (#, m)
Design flood / Safety check flood	10600 / 18660 m ³ /sec
Power Generation	
Plant Load Factor (No, h/day, h/yy)	0.46, 11, 4010
Max. Net Head	211 m
Average Net head	189 m
Design flow	950 m ³ /sec
Installed power	1870 MW
Average energy production	6500 GWh/year
Firm energy production (95 %)	5400 GWh/year

Figure 3-8 shows the location of Gibe I, Gibe II and Gibe III power plants and other main cascade projects planned within the omo gibe river basin.

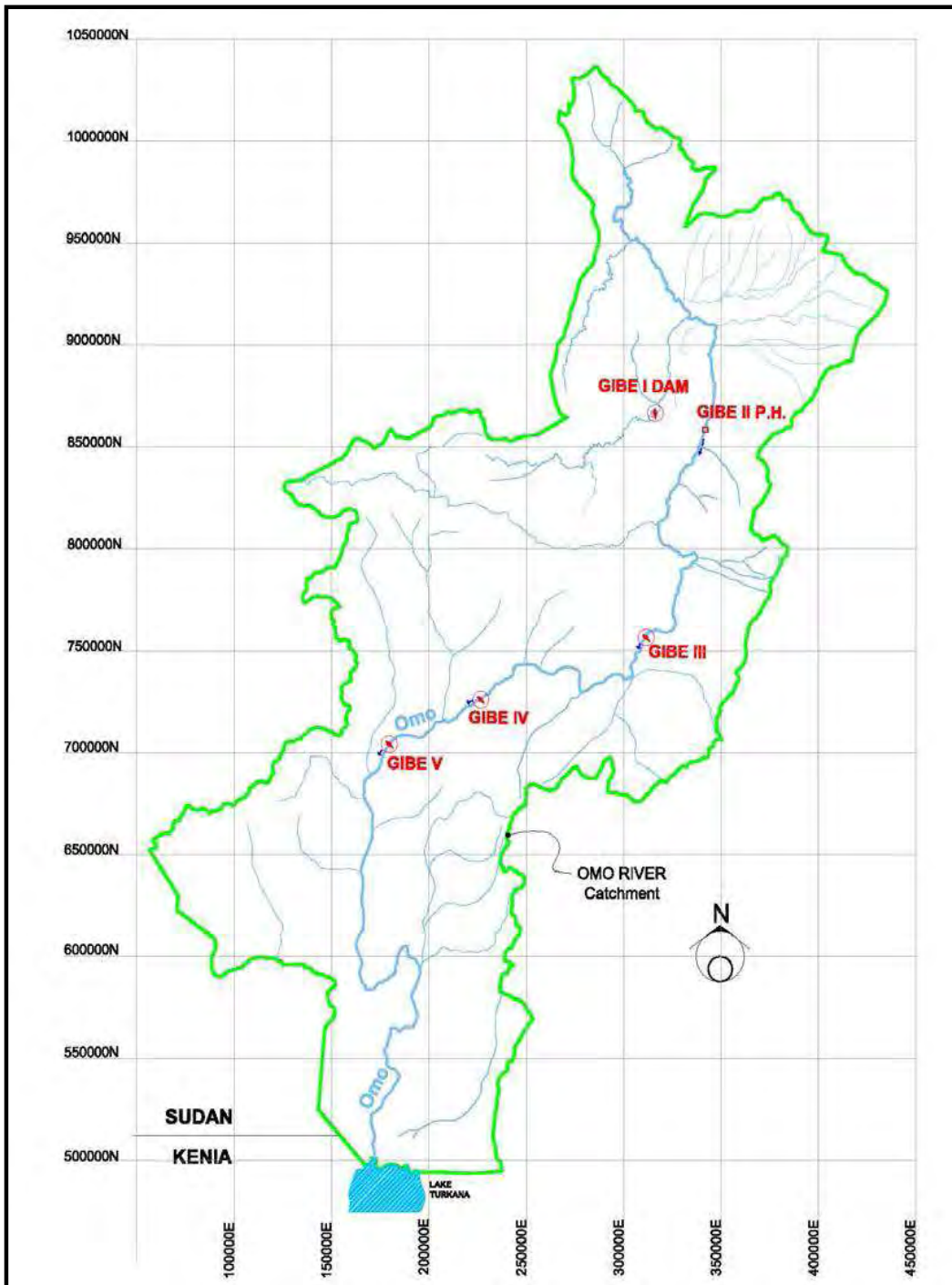


Figure 3-8 Location of Gibe I, II, III and other cascade projects planned in Omo Gibe basin

4.0 METHODOLOGY

4.1 General

To achieve the objective of the research, simulation of Omo Gibe river basin or before starting any river basin simulation, it is important to make a tough search of information about the principal simulation components.

1. Spatial configuration of the river basin system
2. River basin hydrology
3. Physical characteristics of reservoirs, spillways and outlet works, hydroelectric power plants, and other water control facilities
4. System operating rules
5. Water use requirements

HEC-ResSim model computes reservoir storage contents, evaporation, water supply withdrawals, hydroelectric energy generation, and river flows for specified system operating rules and input sequences of stream inflows and evaporation rates. Hence, different data were collected from review of previous studies as well as data from institutions such as Ministry of Water and Energy (MoWE), National Meteorological Agency (NMA), Ethiopian Electric Power Corporation (EEPCO) and information from the internet.

After collecting the necessary data for this research filling of missed data, flow transferring and evaporation loss analysis have been made. Thiessen polygon is drawn for the intervening catchment to determine the areal weightage of rainfall by using Arc GIS 9.2 and also to make the analysis of areal runoff. The unit hydrograph ordinate for upper part of omo basin was found in developing of Flood Warning and Forecasting System for Omo-Gibe River Basin (Kemal, 2007) and was employed in this study to generate runoff from the intervening catchment. Finally the HEC-ResSim model will be set up to simulate the recent condition within the catchment which will provide a “baseline” against which the existing and future scenarios can be compared.

Material Used

The materials used for this research are Arc view GIS tool to obtain hydrological and physical parameters and spatial information, SWAT software to delineate the basin and sub basin of the study area, HEC-ResSim model for basin simulation and Microsoft EXCEL 2007 to analyze HEC-ResSim outputs.

4.2 Data Collection and Analysis

4.2.1 General

Before undertaking and processing of any research data it is imperative to make a tough search for the data. Therefore, the primary assignment of the study was getting relevant information and data of the study area. This section identifies and discusses the types and source of data required for the study, and their analysis.

Before starting hydrological and metrological data analysis and simulation, it is important to check whether the data are homogenous, correct, sufficient and complete with no missing data. Because erroneous data resulting from lack of appropriate recording, shifting of station location and processing are serious because they lead to inconsistency and ambiguous results that may contradict to the actual situation.

4.3 Hydrological data

The ultimate aim of many computational techniques in engineering hydrology is the derivation of river discharge, and it might appear that once this is obtained the hydrologist work is done. However, whether they are gained indirectly from considerations of other hydrological variables or directly from river discharge measurement, the discharge data is only samples in time of the behavior of the river. The hydrologist or the engineer then must assess the worth of the data and their representativeness over the period for which the information is required, usually the expected life of water resources structure.

Gauging stations in Omo Gibe river basin are mainly maintained by the Hydrology Department of the Ministry of water and energy (MoWE) which processes and archives data. The longest record is that of the Abelti station on the Gibe River, starting in 1963. These stream flow data were used continuously by different consultants during the various studies conducted in the

basin. The MoWE has been continuously keep updating these data and most of the data at pertinent stations are reasonably well recorded. For this study, the hydrological data were made from the following source.

- ✚ Ministry of water and energy (MoWE), monthly flow data of 18 stations from 10 to 39 years have been collected.
- ✚ From technical reports of the Omo-Gibe river basin like Omo-Gibe river basin integrated development master plan study and hydropower design documents.

Fig 4.1 below shows spatial distribution of hydrometric stations in the basin, gauging stations are dense in the northern part of the basin. And on the other hand the south western parts of the basin have very low density.

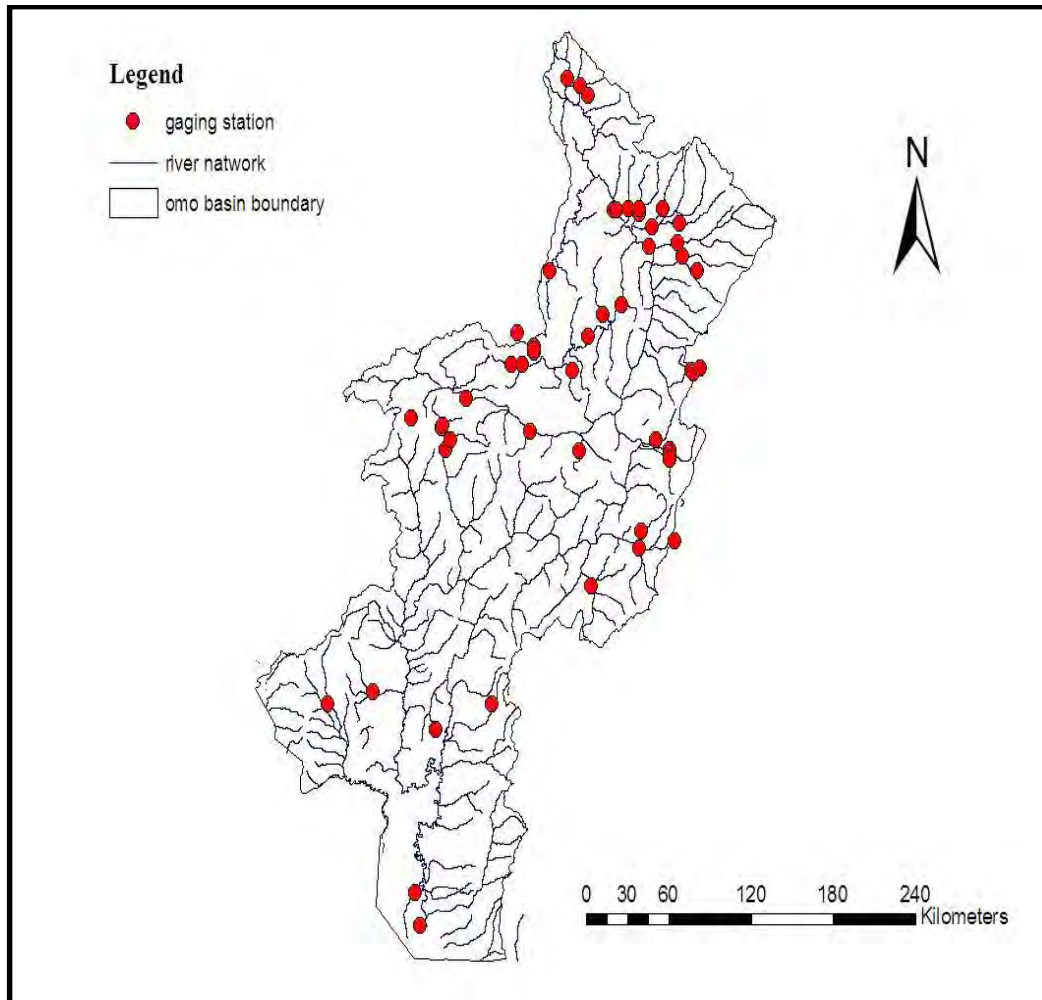


Figure 4-1 Stream flow gauging stations

Most of the time, long term data for the design and planning of water resource projects are not always available and also records of hydrological data are usually short and often have breaks in the records. For these reasons different techniques which can be appropriate for filling missing data and extending records, such as regression methods and area ratio, were used and presented in the following sections.

4.3.1 Hydrological data analysis

Filling of missed data

The quality, quantity and characteristics of hydrological parameters should be carefully assessed in order to make a sound decision on water resource allocation and utilization. In this study, filling of the missed data has been conducted by developing correlation between the station with missing data and any of the nearby station. When the correlation is done, geographic proximity (latitude and longitude) is considered and the missing data were filled by considering a good correlation. The following tables (Table 4-1 and 4-2.) illustrate these facts.

Table 4-1: Summary of selected Hydrometric stations

S.no	Station(site)	Reference	Sub – catchm.	Area (km ²)	X-Cor.	Y- Cor.	years of record	Missed data (%)
1	Nr. Tedel.	91027	Walga	457.5	337050.66	928826.4	1985-2006	42.80
2	Nr. Serbo	91032	G.gibe	526	288163.25	837228.89	1985-2006	29.17
3	Nr. Abelt.	91001	Gibe	15746	343590.65	910002.34	1985-2006	0.00
4	Nr. Wolki	91004	Wabe	1866	364528.81	912144.59	1985-2006	21.59
5	Nr. Areka	92010	Sokie	306	358650.7	788315.95	1985-2006	19.32
6	Nr. Areka	92009	Sokie	103	358656.84	790527.43	1985-2006	23.86
7	Nr. Tolie	91022	Warabesa	234	329354.96	932173.96	1985-2006	25.00
8	Nr. Gubre	91005	Gorombo	286	367810.29	904394.2	1985-2006	26.89
9	Nr. Asen.	91008	G.gibe	2966	299284.45	857090.12	1985-2006	7.58
10	Nr. Dimbra	91025	Sherma	47.5	170940.73	810215.04	1985-2006	4.55
11	Nr. Tedel.	91026	Walga	350	353580.09	932084.69	1985-2006	35.61
12	Nr. Endber	91007	Gorombo	109	378803.42	895516.97	1985-2006	4.55
14	Nr. Wolki.	91010	Walga	1792	345832.95	921053.07	1985-2006	25.38
15	Nr. SHEBE	91011	Gojeb	3577	210786.67	821033.23	1985-2006	10.61
16	Nr. Andra.	92004	Guma	231.2	196243.91	791238.74	1985-2006	1.89
17	Nr. Bong	92005	Guma	443.7	199592.89	796752.48	1985-2006	4.55
18	Nr. Danal	92013	Deme	266	337524.68	743039.95	1985-2006	30.3

Table 4-2 Correlated equations between stations for filling missing data

Missed River Station (Y)		Nearby River Station (X)		Correlation coefficient	Equation developed	Remark
River name	ID	River name	Station No.	(r)		
Gibe near Abelti	91001	G.gibe Nr.Assendabo	91008	0.86	$Y=3.645X^{1.031}$	Filled
Sokie	92009	Ajancho	92010	0.789	$Y=1.813X^{0.823}$	Filled
Guma	92004	Dincha	92005	0.74	$Y=1.033X^{1.078}$	Filled
Dincha	92005	Woshi	91025	0.74	$Y=3.526X^{0.626}$	Filled
Woshi	91025	Dincha	92005	0.74	$Y=0.268X^{1.184}$	Filled
Ajancho	92010	Sokie	92009	0.79	$Y=0.498X^{0.958}$	Filled
G.gibe Nr.Assendabo	91008	G.gibe near Abelti	91001	0.86	$Y=0.524X^{0.828}$	Filled
Gojeb near Shebe	91011	G.gibe Nr.Assendabo	91008	0.74	$Y=1.245X+11.71$	Filled
Gogeb Nr. Endeber	91007	Wabi	91004	0.86	$Y=0.060X^{0.887}$	Filled
Darge	91027	Megech	91005	0.71	$Y=0.515X+0.233$	Filled
Kulit	9026	Wabi	91004	0.75	$Y=0.227X^{0.759}$	Filled
Megecha	91005	Wabi	91004	0.92	$Y=0.161X^{0.876}$	Filled
Wabi	91006	Megech	91005	0.92	$Y=8.127X^{1.043}$	Filled
Karadus	93004	Omo river	Using rating curve	0.995	$Y=0.173h^{0.545}$	Extended
Deme	92011	Mazi	92013	0.5	$Y=0.33X+2.206$	Filled
Walga	91010	Wabi	91004	0.76	$Y=0.093X^{1.228}$	Filled
Warabesa	91022	Walga	91010	0.62	$Y=0.179X+2.074$	Filled
Gogora	92013	Deme	92008	0.5	$Y=0.571X+0.777$	Filled

4.4 Meteorology Data

There are several rainfall stations in operation, especially in the upper part of the basin, with quite long time series of observation. But only the stations show in fig 4-2 which is applicable to this study are collected and analyzed. Meteorological data analysis carried in this study are mainly based on rainfall data obtained from the National Meteorological Service Agency (NMA) and summary the selected rainfall stations is also presented in Table 4-3.

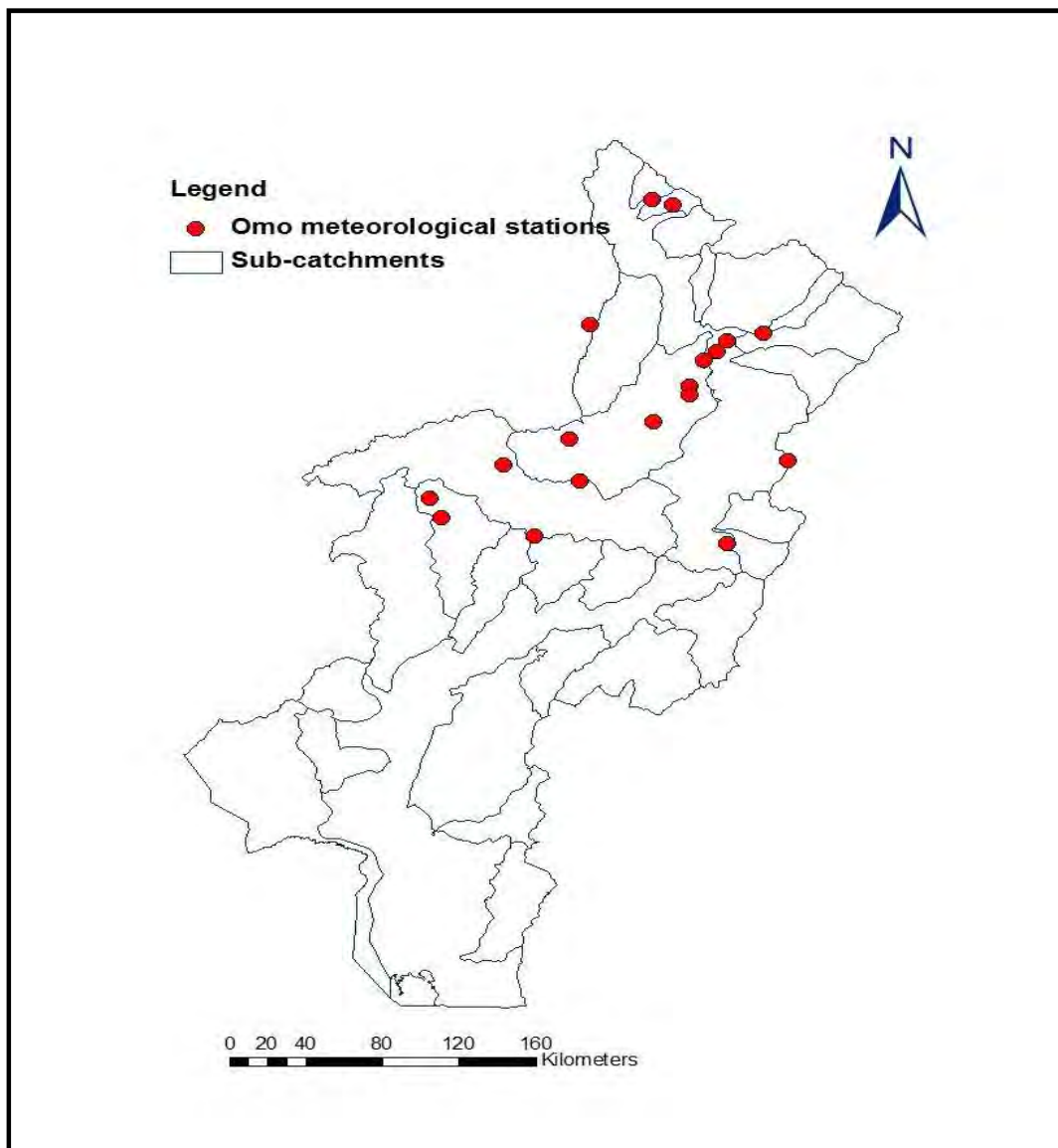


Figure 4-2 Metrological gauging stations

Missing data is common problem in hydrology. To perform hydrological analysis and simulation using data of long time series, filling in missing data is very vital. The missing data can be

completed by using meteorological and/or hydrologic stations located in the nearby area, provided that the stations are located in a hydrologically homogenous region. Hence, the study has applied all the necessary data treating methods and presented it in the next sections

Table 4-3: Summary of selected rainfall stations

S.no	Station Name	Latitude (Degree)	Longitude (Degree)	Elevation (m)	Years of Data used	Missed data (%)
1	Assendabo	7.77	37.23	2400	1985-2006	6.82
2	Atnago	8.32	36.93	1850	1985-2006	7.95
3	Ejaji	9	37.32	1900	1985-2006	4.17
4	Bonga	7.22	36.23	1650	1985-2006	7.2
5	Jimma	7.67	36.83	1725	1985-2006	5.3
6	Babu	7.12	36.67	1880	1985-2006	6.44
7	Wushwush	7.33	36.17	1950	1985-2006	4.17
8	Shebe	7.52	36.52	1635	1985-2006	11.74
9	Sekoru	7.92	37.4	2100	1985-2006	15.15
10	Abelti	8.17	37.53	2050	1985-2006	6.44
11	Saja School	7.97	37.4	2100	1985-2006	15.15
12	Hosanna	7.55	37.87	2200	1985-2006	4.55
13	Tibe	9.03	37.22	1680	1985-2006	4.17
14	Wolkite	8.27	37.75	1550	1985-2006	14.02
15	Bele	7.08	37.58	1200	1985-2006	2.27
16	Gibe Farm	8.23	37.58	1110	1985-2006	0.38
17	Kumbi	8.12	37.47	1980	1985-2006	9.85
18	Metesso	7.43	36.88	2270	1985-2006	14.77

4.4.1 Meteorology Data Analysis

Checking Homogeneity of stations

Homogeneity analysis is used to identify a change in the statistical properties of the time series. The causes can be either natural or man-made. These include alterations to land use and relocation of the observation station. Therefore in order to select the representative meteorological station for the analysis of areal rainfall estimation, checking homogeneity of group stations is essential, the homogeneity of the selected gauging stations monthly rainfall records were carried out by non dimensionalizing using equation:

$$P_i = \frac{\bar{P}_i}{\bar{P}} \dots\dots\dots 4.1$$

Where:-

P_i = Non dimensional Value of precipitation for the month i

\bar{P}_i = Over years averaged monthly precipitation for the station i

\bar{P} = the over years average yearly precipitation of the station

The selected stations are also plotted for comparison with each other; for illustration figures below show the result of homogeneity analysis and Appendix B also has figures plotted to check similarity of the other selected group stations. Same-mode and pattern of the stations are observed and hence group stations selected are homogenous.

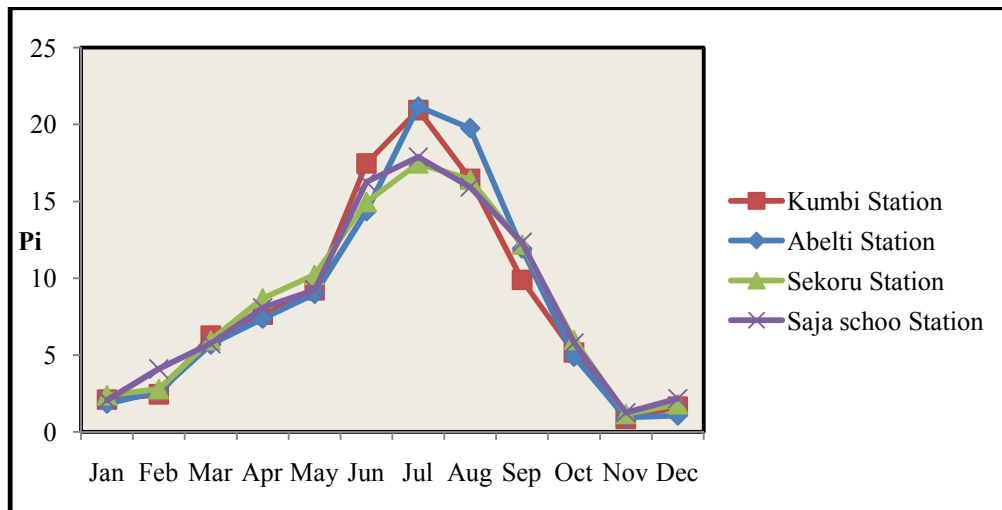


Figure 4-3 Homogeneity test for Kumbi, Abelti, and Sekoru and Saja school stations

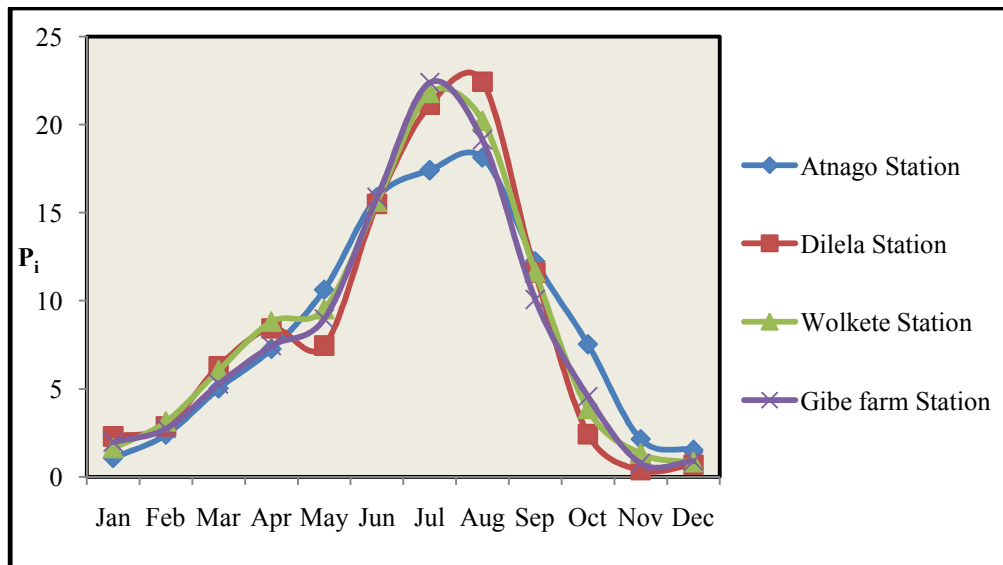


Figure 4-4 Homogeneity test for Atnago, Dilela, Wolkete, Gibe farm stations

Filling in rainfall data

Measured precipitation data are important to many problems in hydrologic analysis and design. Because of the cost associated with data collection, it is very important to have complete records at every station. Obviously, conditions sometimes prevent this. For gages that require periodic observation, the failure of the observer to make the necessary visit to the gage may result in missing data. Vandalism of recording gages is another problem that results in incomplete data records, and instrument failure because of mechanical or electrical malfunctioning can result in missing data. Any such causes of instrument failure reduce the length and information content of the precipitation record.

The two procedures for estimating daily totals rely on the data from any adjacent stations. The locations of the adjacent stations are such that they are close to and approximately evenly spaced around the site with the missing data. When the average annual precipitation at each of the adjacent stations differs from the average at the missing data station by less than 10%, the following formula can be used to estimate the missing monthly data.

$$P_x = \frac{(P_A + P_B + P_C + \dots + P_N)}{N} \dots \dots \dots 4.2$$

Where, P_x =Estimated daily precipitation at station x, P_A , P_B , P_C and P_N are daily precipitation depth at the adjacent stations A, B, C and N adjacent stations.

When the difference between the average annual rainfall at any of the adjacent stations and the missing data station is greater than 10% a normal ratio method is normally used and it is given by:

$$P_x = \frac{1}{n} \left[\left(\frac{N_x}{N_A} \right) + \left(\frac{N_x}{N_B} \right) + \left(\frac{N_x}{N_C} \right) + \dots + \left(\frac{N_x}{N_N} \right) \right] \dots\dots\dots 4.3$$

Where, P_x =Average annual precipitation at the missing data. N_i =Average annual precipitation at the adjacent site. After analyzing rainfall records of the selected stations it is found that the difference between the average annual precipitation (PPT) at any of the adjacent stations and the missing data stations is greater than 10%. Therefore to fill all the missed rainfall data normal ratio method is used.

Test for consistency of record

If the conditions relevant to the recording of a rain gauge station have undergone a significant change during the period of record, inconsistency would arise in the rainfall data of that station. The checking for inconsistency of the record is done by the double-mass curve technique. This technique is based on the principle that when each recorded data comes from the parent population, they are consistent. The double mass curve technique is used to adjust precipitation records to take account of non-representative factors such as change in location or exposure of rain gauge. The accumulated totals of the gauge in question are compared with the corresponding totals for a representative group of nearby gauge. If significant change in the regime of the curve is observed, it should be corrected.

$$P_x' = P_x * \frac{M'}{M} \dots\dots\dots 4.3$$

Where: P_x' = corrected precipitation at station x

P_x =original recorded precipitation at station x

M' =corrected slope of the double mass curve

M = original slope of the double mass curve

According to the double mass curves, all the stations were consistent. For illustration the double mass curves for some selected stations are presented below and for the others it is attached in Appendix C

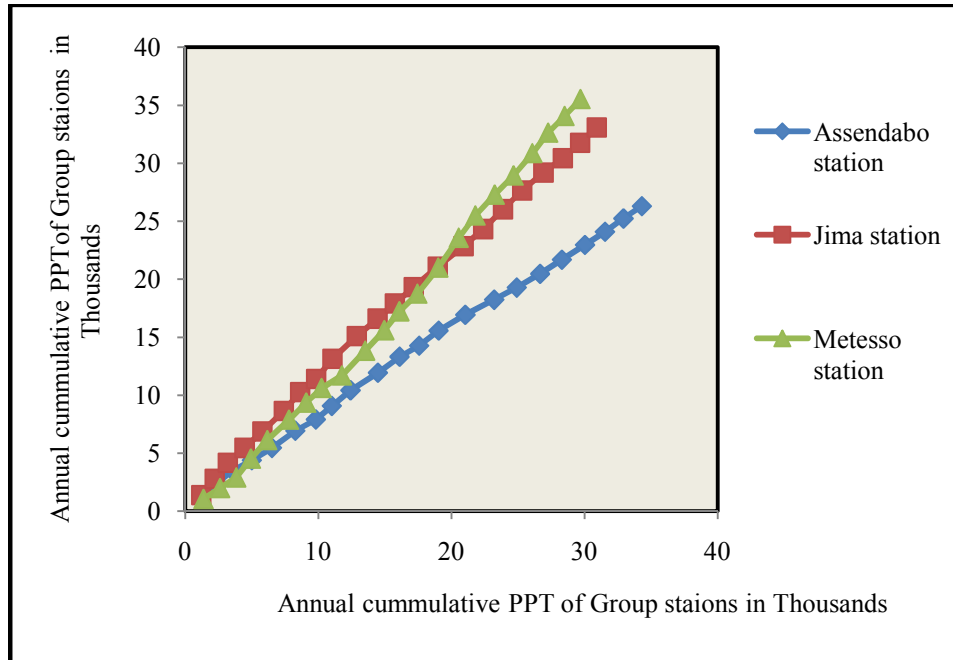


Figure 4-5 Consistency Test for Assendabo, Jima and Metesso stations

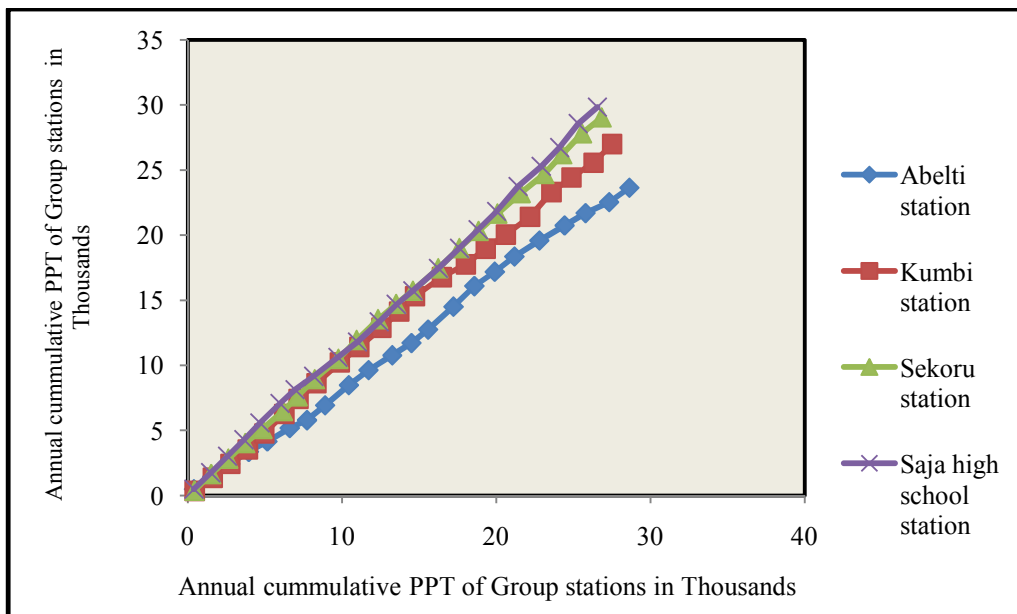


Figure 4-6 Consistency Test for Abelti Sekoru and Kumbi stations

Areal Rainfall Determination

In describing the measurement of precipitation, emphasis has been made on point sampling procedure. Rainfall over an area of interest has to be estimated from these point measurements. The areal rainfall is required for many hydrological studies, and it is most important to have the limits of the catchment carefully defined.

There are commonly three ways of deriving the areal precipitation over a catchment from rain gauge measurement. These methods are the Arithmetic mean, the Thiessen polygon and the Isohyetal method. However, the Thiessen polygon was used for this study for its sound theoretical basis and availability of computational tools. But the method is dependent on a good network of representative rain gauges and does not allow the hydrologist to consider factors, such as topography (McCuen, 1989).

To determine the mean areal rainfall, the rainfall amount of each station is multiplied by the area of its polygon and the sum of these products is divided by the total area of the catchment. If $P_1, P_2, P_3, \dots, P_n$ are the rainfall magnitudes recorded by the stations 1, 2, ..., n, respectively and if the areas of Thiessen Polygon $A_1, A_2, A_3, \dots, A_n$, are formed as representative of the respective stations then the average rainfall over the catchment P is given by:

$$P_{avg} = \frac{P_1 A_1 + P_2 A_2 + P_3 A_3 + \dots + P_n A_n}{A_1 + A_2 + A_3 + \dots + A_n} \dots \dots \dots 4.5$$

Where, $P_1, P_2, P_3, \dots, P_n$ = the point rainfall measurement of the i station, mm/d

$A_1, A_2, A_3, \dots, A_n$ = the area of the polygon, km^2

Accordingly this method was used to determine areal rainfall for intervening catchment between Abelti gauging station and Omo and Gojeb river confluence. Figure 4-7 shows the Thiessen polygon drawn for the selected rainfall stations.

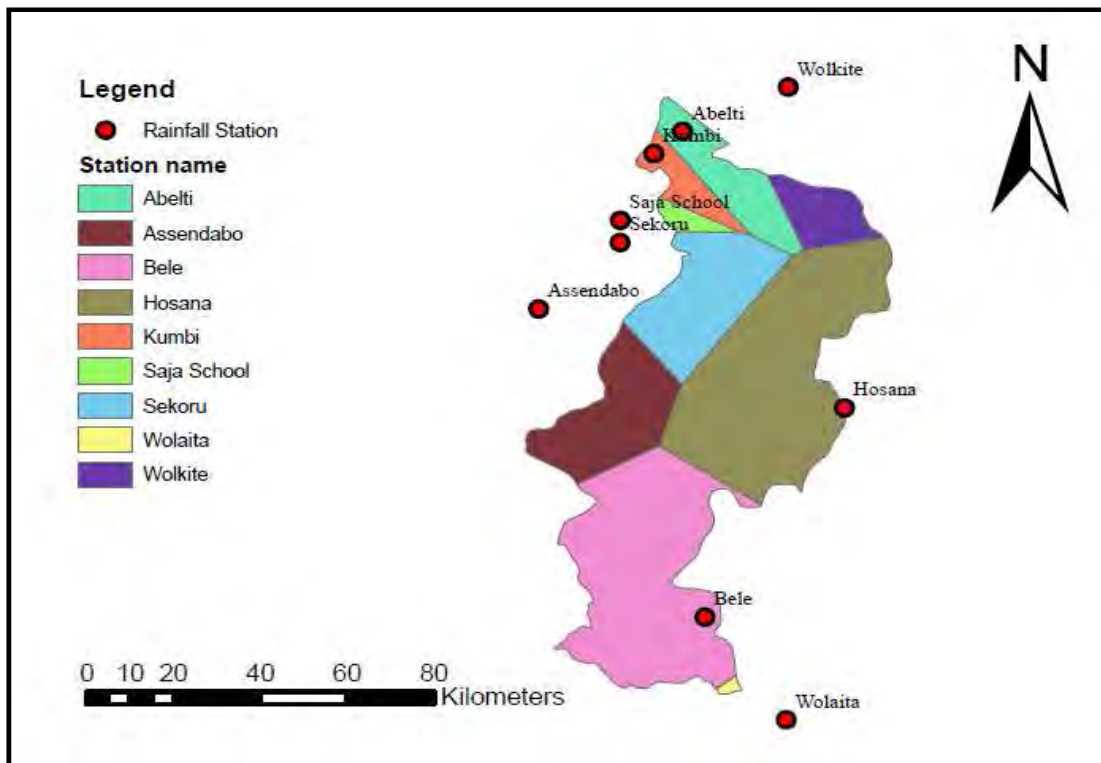


Figure 4-7 Thiessen polygon for the intervening basin

4.4.2 Runoff from the intervening (residual) catchment

Unfortunately no hydrometric station is located in the residual part of the basin between Abelti hydrometric station and the Gibe and Gojeb River at confluence. Therefore to determine the runoff resulted from this catchment this study uses the only available information and methods i.e. discrete convolution equation by multiplying and summing up of the rainfall and pulse response ordinate obtained from rainfall runoff model developed by Kemal (2007).

Table 4-4 Unit hydrograph ordinates developed for abelti sub- catchment, Kemal (2007)

Ordinate No.	Input No (H)	Ordinate No.	Input No (H)	Ordinate No.	Input No (H)	Ordinate No.	Input No (H)	Ordinate No.	Input No (H)
1	0.013	6	0.049	11	0.051	16	0.043	21	0.017
2	0.075	7	0.045	12	0.05	17	0.034	22	0.014
3	0.063	8	0.051	13	0.049	18	0.038		
4	0.043	9	0.052	14	0.047	19	0.028		
5	0.046	10	0.05	15	0.039	20	0.036		

The convolution equation that was used to determine the runoff from the residual basin is;

$$Q_n = \sum_{m=1}^{n \leq M} P_m U_{n-m+1} \dots\dots\dots 4.6$$

Where the notation $n \leq M$ as the upper limit of the summation shows that the terms are summed for $m= 1, 2, 3, \dots, n$ for $n \leq M$, but for $n > M$, the summation is limited to $m=1, 2, M$. For example, let there are $M=3$ pulses of input: P_1, P_2 and P_3 . For the first time interval ($n=1$), there is only one term in the convolution, that for $m=1$

$$Q_1 = P_1 U_{1-1+1} = P_1 U_1 \dots\dots\dots 4.7$$

For $n=2$, there are two terms in the convolution, corresponding to $m= 1, 2$:

$$Q_2 = P_2 U_1 + P_1 U_2 \dots\dots\dots 4.8$$

For $n=3$, there are three terms, corresponding to $m=1, 2$, and 3 :

$$Q_3 = P_3 U_1 + P_2 U_2 + P_1 U_3 \dots\dots\dots 4.9$$

Where:-

- Q=Runoff
- P=Effective rainfall of areal rainfall
- U=Ordinate of pulse response
- n =memory length of unit hydrograph
- m=number of effective rainfall

Runoff from the intervening residual basin is computed; the first areal rainfall in the basin is determined by Thiessen polygon method as shown in Fig4-7, and then from rainfall runoff model, the pulse response function is multiplied with areal rainfall and summed up. Following the above two principal ways to generate hydrological time series, stream flows are computed at all relevant Gibe and Omo rivers confluence. In addition long term monthly flow sequence for the residual catchment upstream of the Greater Gibe at Abelti i.e. downstream of the Gilgel Gibe at Assendabo and Walga stations is derived by subtraction.

4.5 Transfer of data to dam site and river confluence

4.5.1 Transfer of gauged data using area ratio method

Although gauging stations are available in a river basin, it is unusual for these gauges to be located precisely at rivers confluence and dam sites. The most recommended guideline to transfer stream flow data to the point of interest is to use area ratio methods described by eq.4.10. This method uses the drainage areas to interpolate flow values between or near gauged sites on the same stream. Flow values are transferred from a gauged site, either upstream or downstream to the ungauged site.

$$Q_{\text{site}} = Q_{\text{gauge}} * \left[\frac{DA_{\text{site}}}{DA_{\text{gauge}}} \right]^n \dots\dots\dots 4.10$$

Where DA_{site} = drainage area at site of interest

DA_{gauge} = drainage area of the gauge site

Q_{site} = discharge at site of interest (m³/s)

Q_{gauge} = discharge at gauge (m³/s)

n = a parameter typically varies between 0.6 and 1.2.

If the DA_{site} is within 20% of the DA_{gauge} ($0.8 \leq \left[\frac{DA_{\text{site}}}{DA_{\text{gauge}}} \right] \leq 1.2$), then n = 1 to be used. The estimated discharge at the site will then be within 10% of actual discharge. When DA_{site} is within 50% of the DA_{gauge} two station data are considered for data transferring. Relation can be developed to estimate a weighted average flow at a site lying between upstream and downstream gauges.

$$Q_{\text{site}} = \frac{(DA_{\text{gauge1}} - DA_{\text{gauge2}})Q_{\text{gauge1}} + (DA_{\text{site}} - DA_{\text{gauge2}})Q_{\text{gauge2}}}{(DA_{\text{gauge1}} - DA_{\text{gauge2}})} \dots\dots\dots 4.10$$

Where: - Gauge1 upstream gauging site and gauge2 downstream gauging site. These methods were applied to transfer all river discharge to the proposed dam sites and river confluence locations (mainly confluence to Omo and Gibe River)

The monthly records of stream flow for 22years of hydrologic period (1985-2006) were collected for, Ajancho, Gojeb, Great Gibe (at Abelti), Gilgel Gibe (at Assendabo), Megecha, Wabi, Weyobo, Walga, Warabesa, and Soke Rivers and employing the Area-Ratio method flow of these rivers is transferred to the Dam site, and Gibe and Omo River. Besides, all major tributary rivers at the confluence of Omo River located downstream of the basin and rainfall on the reservoirs were also prepared as inflow time series to the model.

Table 4-5 Mean Monthly inflow at dam sites

Dam site	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Avg
Gibe I	17.83	14.2	14.2	18.6	33.6	81.9	151	217.847	181.3	94.5	52.45	25	75.21
Gojeb	23.67	20.2	21.9	26.5	55.6	97.1	174	217.801	208.6	150	48.56	30	89.53
Gibe III	82.11	67.7	68.6	92.8	159	327	761	1527.19	1021	527	212.7	432	439.8
Halele	8.166	6.72	7.36	10.2	14.3	34.2	137	235.225	198.5	108	38.34	17	67.92

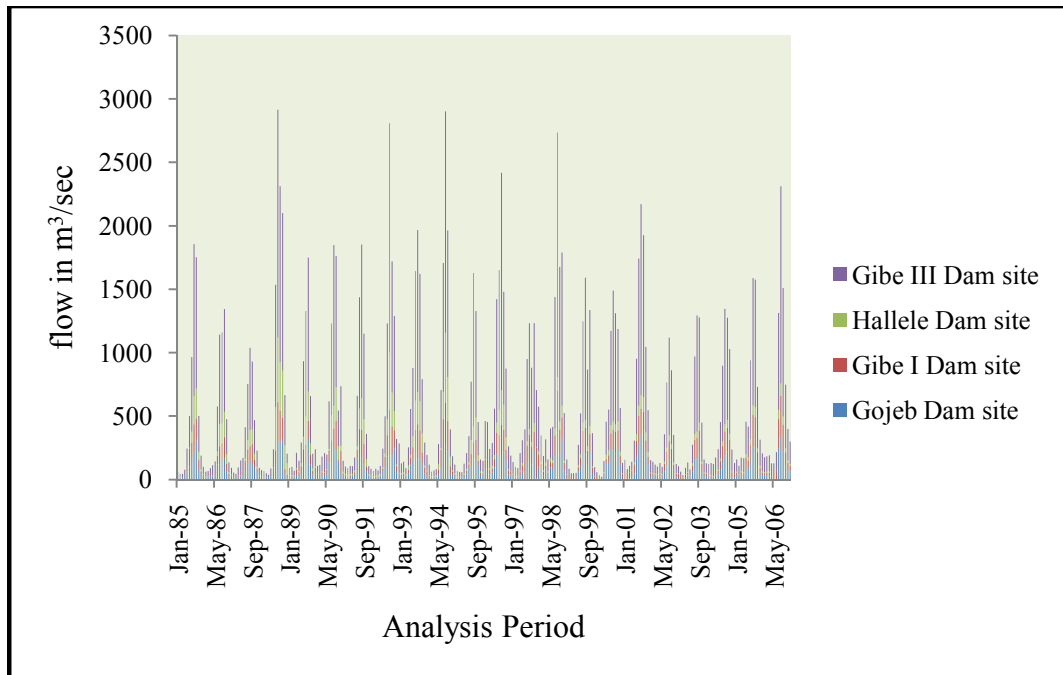


Figure 4-8 Inflow time series at dam sites

4.6 Meteo Climatic Data

4.6.1 Evaporation

The loss of water by evaporation must be considered from two main aspects. The first, evaporation from an open water surface E_o , is the direct transfer of water from lakes, reservoirs and rivers to the atmosphere. This can be relatively easily assessed if the water body has known capacity and does not leak. The second form of evaporation loss occurs from the transpiration from vegetation, ET_o . This is sometimes called Evapotranspiration, since loss by direct evaporation of intercepted precipitation and transpired water on plant surfaces is also included.

Evaporation can be estimated using different methods such as; Water balance, Energy balance, Aerodynamic, Penman and Pan evaporation methods being the most common (Chow,1988). Each method is limited due to difficulties in estimating required input parameters. Fortunately mean monthly evaporation data for each existing and proposed reservoirs were obtained from their respective study documents.

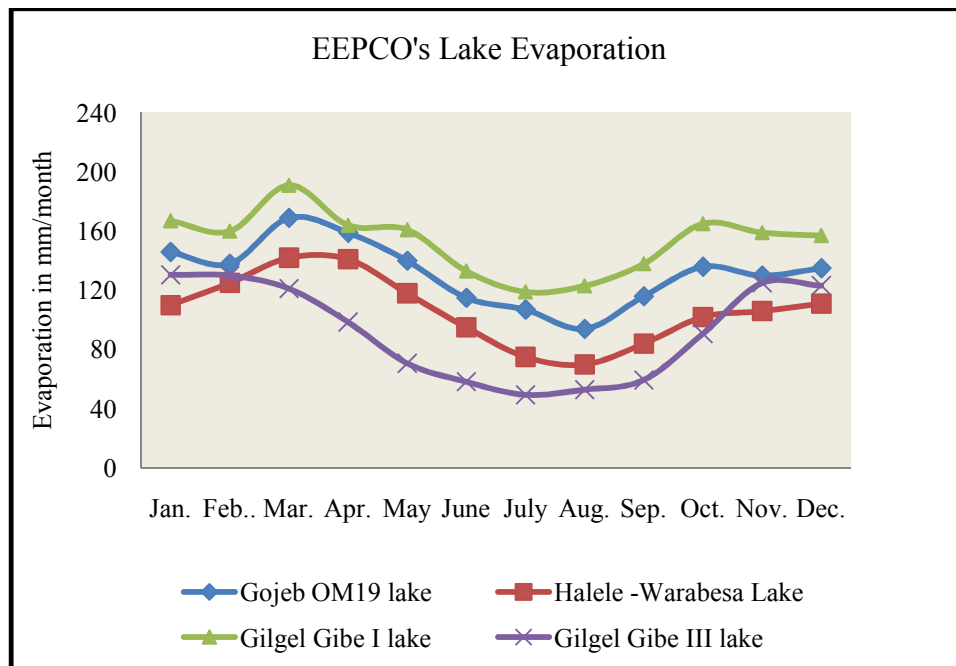


Figure 4-9 Lake evaporation from previous studies

4.7 Hydropower related data

4.7.1 Reservoir physical characteristics and Power plant data

Physical and operational reservoir data including reservoir pool definition (elevation-storage-area tables), outlet capacity curves, and hydropower plant data (turbine capacity and generation requirement, tail water level and installed capacities, efficiency, losses, etc), operational zones, minimum and maximum release requirements, etc for each project were taken from their respective feasibility and detail design document.

In the scope of long term system management the monthly demands regarding electricity generation for each proposed and existing power plant should be specified for simulation. Physical and operational parameters of the hydropower plants are presented on Appendix D table 2-1.

Table 4-6 Energy generation requirement in GWh for existing and proposed power plants

Hydropower	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Gilgel Gibe I	53	54	59	55	54	69	83	79	76	97	63	51
Gilgel Gibe I	116	107	118	115	117	118	124	150	235	192	132	109
Gilgel Gibe III	568	500	536	509	509	482	509	550	509	596	573	582
Halele Stage I	39	35	38	37	38	37	40	45	53	53	40	41
Halele Stage II	128	128	129	129	129	132	141	171	192	185	141	129
Gojeb OM19	31	28	31	30	29	32	50	70	84	65	36	31

4.8 Irrigation and Ecological Water demand data

4.8.1 Irrigated Agriculture water demand data

The quantity of water used in agriculture is a function of crop area, type of crop and climatic conditions. As per lower omo irrigation pre-feasibility study major crops proposed to grown are Cotton, Maize, and Groundnut Sesame and Banana. Water requirement of these crops were estimated using the Penman-Monteith approach based on climate and crop culture.

The quantity of water required at each demand is also adjusted using overall irrigation efficiencies of 45%. Water requirement calculation was done assuming no effective rainfall, see table below. (Richard Wood roof and Associates, 1996)

Table 4-7 Crop water requirement based on no effective rainfall (mm/day)

Crop	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Maize		2.3	4.2	5.4	3.5	0.8						
Sesame	2								2	3.8	4.5	4.5
Cotton	1.8	3.1	5.3	5.6	4	3.5						
Groundnut						0.7	2	2.8	4.3	3.6	0.7	
Banana	4	4.5	4.5	4.4	3.2	3.7	3	2.8	3.8	4	3.8	3.9
Irrigreq. mm/day	1.8	2.9	4.8	5.4	3.7	2.5	1	0.8	1.7	2.1	1.6	1.5
Irrig req. l/s/ha	0.2	0.3	0.6	0.6	0.4	0.3	0.01	0.1	0.2	0.2	0.2	0.2

According to lower omo irrigation master plan, irrigation development proposals are selected in two options or phases; the first option is diverting water to the main canal from the Omo River to priority sites (i. e. Omo rate farm stage 1, 2, 3 and 4, Omo rate west Dipa hayk and Nergi Irrigation site) with total command area of 20,670ha and the second phase (Irrigation Expansion), considering that the remaining proposed irrigation site to be connected in the network , (Mursi and Kibish) with total irrigable area of 34,600ha. The diversion requirement in both cases is computed based on no effective rainfall. In addition to this preliminary data, this study has also considered latest irrigation potential basin to be 10,100ha for small and 142,900ha for large scale irrigation schemes (EEPCO, 2009).

Experts familiar with this region have assessed the existing and potential small and large scale irrigation developments in the lower omo area as in Table 4.6 below and in this study it is used as Phase 3 irrigation proposal.

Table 4-8 Existing and potential irrigation schemes in lower omo region

Wereda	Small Scale Irrigation Schemes		Large Scale Irrigation Schemes	
	Existing	Potential	Existing	Potential
Dasenech	267	6,000	-	20,00
Selamago	-	1,000	-	34,000
Hamer	250	3,000	-	5,000
Nyangatom	150	100	-	83,900
Total	667	10,100	-	142,900

Source: (EEPCO, 2009)

Phase 1 development- This level of irrigation requirement consists of Omo rate farm stage 1, 2, 3 and 4, Omo rate west Dipa hayk and Nergi priority irrigation site with total command area of 20,670ha. This sub scenario requires 18.88 m³/s of water for entire system during the peak month, April.

Phase 2 development- The second phase (irrigation expansion), considering the rest proposed irrigation site to be connected in the network, (Mursi and Kibish) with total irrigable area of 34,600 ha. The system requires 31.06 m³/s of water during the peak month.

Phase 3 development- This is the last likelihood of irrigation development in the lower omo region, which consists of 142,900ha of land. The system requires 130.1 m³/s of water during the peak month.

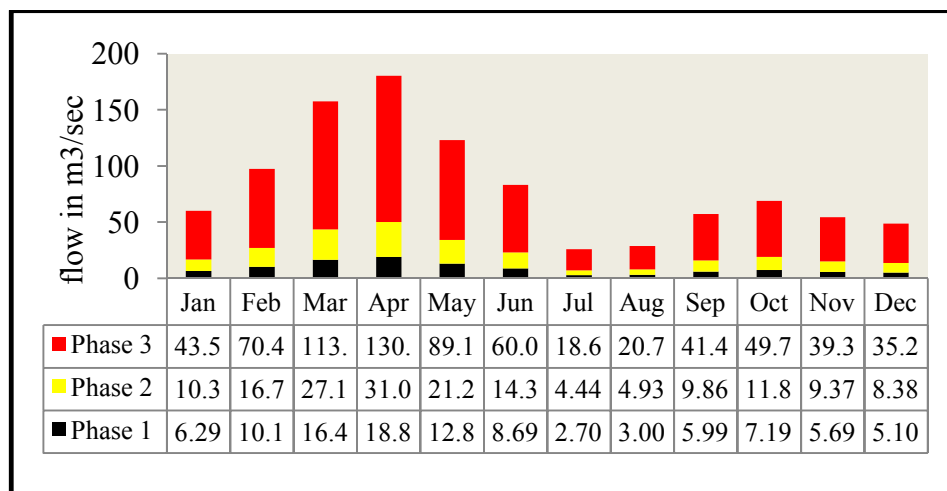


Figure 4-10 Total crop water requirements

4.8.1 Ecological required flow

Water storage reservoirs typically provide multiple benefits viz. hydropower, water supply (municipal, industrial and agricultural), flood control and recreational opportunities. On the other hand, well-known detrimental effects include impoundment of free-flowing river habitat, blockage of fish migration and reduced water quality in reservoirs and downstream river reaches. Less-obvious effects include the interruption of geomorphologic processes that maintain aquatic habitat diversity required to sustain healthy river ecosystems. Regarding the state of omo-gibe basin environment, different minimum environmental flow has been assumed since planning of each hydropower projects. Table 4.8 shows the required minimum monthly environment flow at each hydropower project sites

Table 4-9 Minimum environmental flow release from existing and planned dams in m³/sec

Hydropower	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Gilgel Gibe I and II	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Gilgel Gibe III	22	21.5	21.5	21.5	21.5	21.5	21.5	22	22	21.5	21.5	22
Halele Warabesa	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Gojeb OM19	9.8	9.2	8.9	9.3	13.2	23.1	22.4	22.4	23.1	22.4	22.6	13.1

For Halele Warabesa project as can be seen from the table, no flow is set, this is the fact that river stretch between the dam and the tailrace outlet is short and supports only very limited aquatic resources, maintaining a environmental flow during operation does not seem to be justified (EEPCO, 2000).

5.0 BUILDING HEC- ResSim FOR OMO GIBE BASIN

5.1 Overview

HEC-ResSim was developed by US Army Corps of Engineers on September 2003. This model was used in reservoir simulation for water resources allocation, flood control, river routing and etc., with different operation policy. The model has three main modules: Watershed Setup, Reservoir Network and Simulation. In this model one can make different management in reservoir system by defining scenarios in a time series data or configurations. Model input data are: reservoir properties (Volume-Area and Elevation Curve, Operation levels, Operation rules and etc), control and operation points, rivers routing parameters and time series input file. The highest capability of this model is defining of different operation rules in power plant generation, flood control conditions, creating scenarios for conditional operation, downstream control point, reservoir system balance (series and parallel) to imitate the hydrological condition and installing of different structures in dam body, comparison of output with observed data, defining of different operational level, different computational steps (15 min to a day), adjusting output and etc. (USACE- 2003)

5.2 HEC-ResSim Model Framework of Omo Gibe River Basin

5.2.1 Watershed Network Setup

The foundation of HEC ResSim model is the watershed which is created in the watershed setup module. Within this module, the stream alignment for main rivers like; Gibe, Omo, Gilgel gibe, Gojeb etc., and all existing, ongoing and planned hydropower projects, diversion canals proposed at lower omo for irrigation and computation points (e.g., location of interest) were defined. Geo-referenced map files were used as the background of the model schematic and for delineation of the stream alignment (the framework or skeleton upon which the model schematic going to be created). Map file includes rivers, streams, the existing and the proposed dam sites (projects), hydrological and metrological gage locations and a watershed boundary. These projects and computation points are created by using the appropriate drawing tools from the HEC-ResSim drawing toolbar. Computation points (modeling points) include reservoir inflow and outflow points, operational location and confluences. The watershed setup of omo gibe reservoir/river system is shown as in Figure 5.1

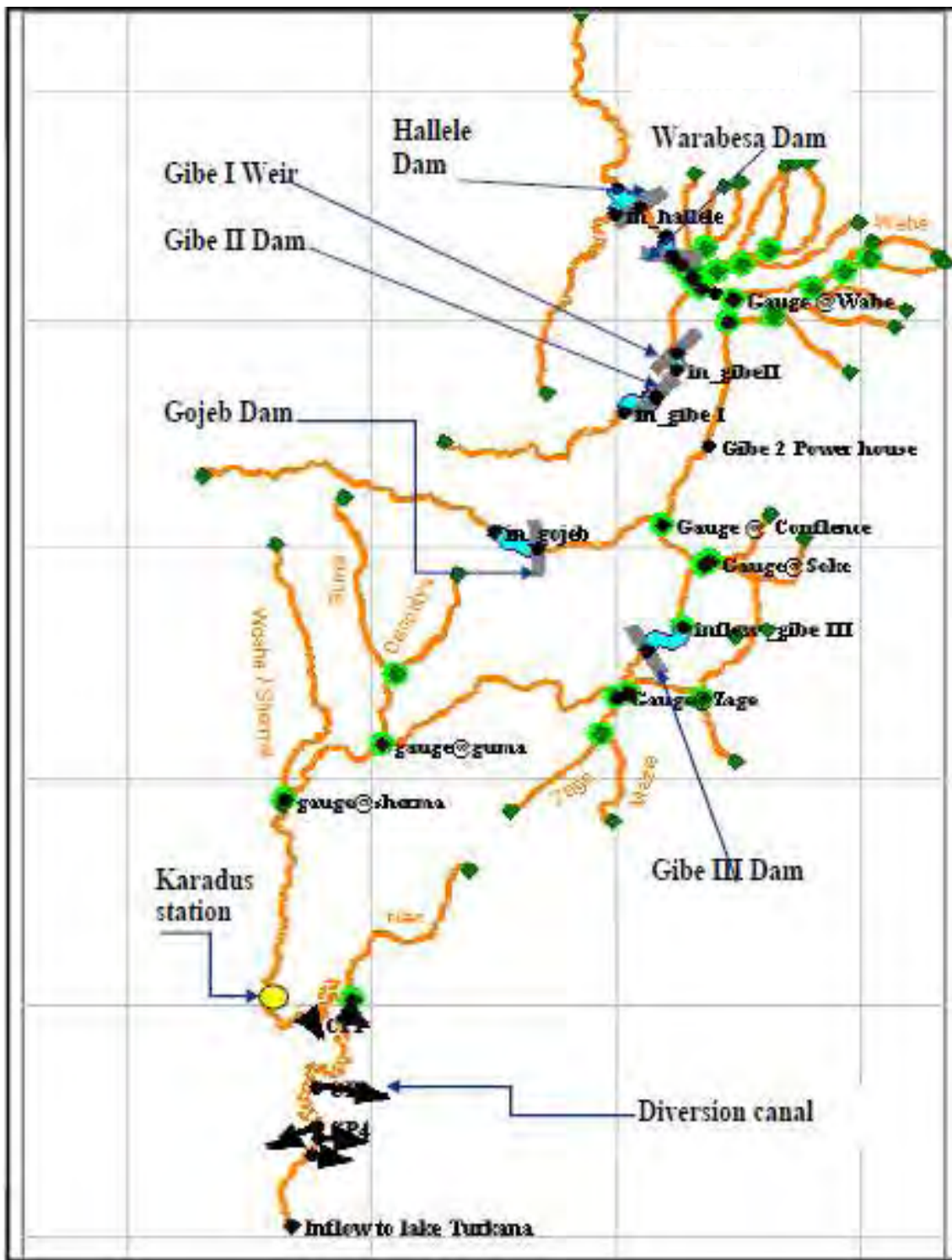


Figure 5-1 ResSim Watershed setup of Omo Gibe basin

5.2.2 Reservoir Network setup

In the Reservoir Network module, one will build the river system schematic, describe the physical and operational elements of the reservoir model, and develop the alternatives that to be analyzed. With stream alignment in place and configurations that were created in the watershed setup module, network of reservoirs and routing reaches have been created in this module. After this, making the network editable (HEC-ResSim meaning; locked) and saving five relevant reservoir networks (likelihood of water resource developments in omo gibe watershed) were created for water allocation modeling. The networks are named; RN-model test, RN-Scenario A, RN-Scenario B, RN-Scenario C and RN-Scenario D. All of these scenarios deal with projects studied at pre-feasibility, feasibility and detail design stage and an overview for each is given below:

RN- Test scenario (Reservoir network for testing the model)

Calibration and validation of water allocation models poses difficulties due to many factors including the complexity of system under study, lack of data and other drivers of water allocation in the system, which cannot be modeled. In this network (scenario) the HEC-ResSim model will be set up to use available flow data as input (i.e., it will not be used to simulate natural hydrological processes) and configured to simulate the recent condition within the catchment i.e. without intervention of human activities. This will provide a “baseline” against which the existing and future scenarios can be compared. Accordingly simulation in this scenario will be used to validate the flow accumulated from sub-basins situated upstream of the main hydrometric station located at Karadus station.

RN-Scenario A (Reservoir network for scenario A)

To achieve the targets of the EEPSCO (Ethiopian Electric Power Corporation) forecast of 250-300 MW increase in the energy demand between 1997 and 2002, the only significant addition at the time proposed was the realization of new power plants in omo gibe basin. The first two stages of the Gibe cascade development include two power plants, namely the Gibe I and Gibe II. The first plant, Gibe I or simply Gilgel Gibe HPP, is a conventional hydroelectric power plant with a capacity of 210 MW and in operation since 2004.

The aim of this scenario is explicitly to show the current water using systems of the basin and also to analyze output and operational characteristics of each power plant when operating synchronously. During this system simulation tandem rule of HEC-ResSim will be applied at the operation zones of Gilgel gibe I reservoir. The scenario has also used the estimated minimum release from each power reservoirs for environmental requirements and moreover flood routing effect due to Gibe I Dam will be processed in the conservative assumption of complete filling of the reservoir.

RN-Scenario B (Reservoir network for scenario B)

The main objective of this network (idem, scenario) setup is to evaluate the effects of upstream development measures; Gibe I, Gibe II and Gibe III hydropower schemes on downstream irrigation and other effects foreseen . In particular; the focus is to assess different phases of irrigation development against operation of new reservoirs, Gibe III reservoir. In this scenario a total of two possible command areas 55,270 and 142, 900ha will be analyzed in a phase wise (as sub scenarios) with three hydropower plants in operation having an annual energy requirement of 794,1635 and 6421GWh/year for Gibe I, II and III respectively. At this stage of the study again, tandem and implicit operation rules of HEC-ResSim will be also employed for Gibe I and II cascade reservoirs. The scenario will then be used to show the new hydrologic regime (change flow) downstream of the Gibe III dam, availability of water for lower omo irrigation projects and hydrologic change of the Omo River. This scenario also includes the minimum release from each power reservoirs for environmental requirements.

RN-Scenario C (Reservoir network for scenario C)

This scenario will be used to assess likely development impact of power reservoir called Gojeb OM19 and will be introduced to RNF-Scenario B which is configured as above. Gojeb OM19 dam's catchment contributes about 15% the total watershed area of Gibe III dam site and its flow regulation will be simulated making in operation with all Gibe I, II and III power plant and reservoirs. The change in reservoir level, inflow series, power plant capability and operational characteristics of Gibe III reservoir and power plant will be thoroughly identified in this scenario. Reservoir and Power plant operation of Gojeb OM19 project will be simulated and the average values simulated characteristics will be compared with the previous studies by EEPCO.

RN-Scenario D (Reservoir network for scenario D)

All effects considered in scenario setup discussed previously will also be evaluated in this scenario but the important issue to be analyzed in this scenario is effect of changes in upstream basin or Scenario B i.e. the likely development impact of Both Gojeb OM19 and Halele Warabesa Stage I and II hydropower development on downstream Gibe III reservoir which is now under construction. The Halele and Warabesa project is cascade scheme comprising two medium sized dams in series and two powerhouses, an average of 1687 GWh per year could be generated with a total installed capacity of 435 MW.

The construction and operation will potentially regulate runoff from Abelti and Gojeb catchment which contributes about 50% of the watershed area at Gibe III dam site. Hence, it will be important to analyze the model output and examining the relative hydrologic changes that could be seen in the upper part of the basin, at Abelti gauge station. Here again lower omo irrigation development during Phase 3 has been considered and tandem operation rule of HEC-ResSim has been employed for Halele and Warabesa cascade reservoirs.

The scenario will be used to examine the hydrological change of inflow at Abelti station, inflow to Gibe III reservoir, Omo River and change in water level and power production at Gibe III pool and power plant. In addition reservoir and power plant operation of Halele Warabesa Stage I and II will be simulated and the average simulated values will be compared with the previous studies by EEPKO. Accordingly this scenario setup and simulation will give preliminary insight to the effects of development of all the proposed cascaded power plants in the basin. Table 5.1 summarizes projects considered under each scenario.

Table 5-1 Summary of the likely development scenarios in omo gibe basin

Scenarios	Hydropower	Irrigation considered
Scenario T	No intervention	No intervention
Scenario A	Gilgel Gibe I and II	All potential sites
Scenario B	Gilgel Gibe I,II and III	All potential sites
Scenario C	Scenario B+ Gojeb OM19	All potential sites
Scenario D	Scenario C+ Halele Warabesa	All potential sites

5.2.3 HEC-ResSim model elements

Modeling element in HEC-ResSim that makes up each of the reservoir network or scenarios includes reservoirs, river reaches, junctions, diversions and reservoir systems. Each of these elements consists of one or more sub elements. The following section will describe the network component and modeling of each element type in the last reservoir network or scenarios D beginning with the simplest element, the junction and working up to the most complex part the reservoir.

Junctions:

The initial phase of modeling concerns the tracing of the connected flow elements of the Omo and gibe watercourses. Junction and reach elements were first used for this purpose. The junction element serves four functions 1) they link model elements together; 2) they are the means by which flow (head or incremental) enters the network 3) they combine flow-the outflow of a junction is the sum of the inflow to the junction ,and 4) when provided with an optional rating curves ,they calculate stage using the computed outflow. Modeling of junction includes placement of inflow segments gathering the water drained from different watershed nourishing Gojeb, Gibe, Omo etc., rivers. Major watershed inflow points selected for discussion are:

- ✚ Abelti inflow: It receives the water drained by the watersheds Gilgel gibe, Warabesa Walga Tunjo Amara, Fato and Alenga; determines the quantity of water entering Gibe I, Gibe II, Gibe III, Halele and Warabesa dams.
- ✚ Gojeb inflow: This point receives inflow from Gojeb watershed and determines the quantity of water which enters Gojeb OM19, Gibe III dam and Gibe River.
- ✚ Wabe and Megecha inflows; gathers water drained from their respective catchments
- ✚ Weyobo, Soke, Deme, Zege Guma and Sherma inflows; gathers the water drained from their respective catchment to Omo river

All the necessary flow series for each of these points were fed into HEC-ResSim using the HEC-DSS program as a means of data transfer. As HEC-ResSim operates on a time step no longer

than one day the average monthly inflow for the time period of Jan 1985 through Dec 2007 were transformed to average daily flows.

To do so the average daily inflows (cms) for each day in a month was set equal to the average monthly inflow (cms) for that month and data manipulation for each inflow point has been done using the HEC DSS program .

Reaches:

Routing reaches represent the natural streams in the system, and the lag and attenuation of flow in a HEC-ResSim can be computed by one of a variety of available standard hydrologic routing methods, such as Muskingum, Modified Puls, Coefficient, or Muskingum-Cunge. In this study, only two of the available methods were used; Null (direct translation no lag or attenuation), and Muskingum. Null routing was used for very short reaches that have no appreciable impact on the flow that can be represented in a one day time step.

Estimating Muskingum K and X

The routing parameters K and x are related to flow and channel characteristics, K being interpreted as the travel time of the flood wave from upstream to downstream end of the channel reach. In a gauged situation, the Muskingum K and X parameters can be calculated from observed inflow and outflow hydrographs. However, estimating Muskingum parameter for this large watershed with observed data would be difficult and time consuming. K and X can be estimated from channel characteristics. For example, USACE 1994 proposes estimating K as follows:

- 1) Estimate the flood wave velocity, V_w , using Seddon’s law, as:

$$V_w = \frac{1}{B} \frac{dQ}{dy} \dots\dots\dots 5.1$$

Where B = top width of the water surface, and dQ/dy = slope of the discharge rating curve at a representative channel cross section. As an alternative, HEC 1994 suggests estimating the flood wave velocity as 1.33-1.67 times the average velocity, which may be estimated with Manning's equation and representative cross section geometric information.

2) Estimate K as: $K = \frac{L}{V_w}$ 5.2

Estimating the Muskingum x parameter in an ungauged situation can be very difficult. X varies between 0.0 and 0.5, with 0.0 providing the maximum amount of hydrograph attenuation and 0.5 no attenuation. Experience has shown that for channels with mild slopes and flows that go out of bank, x will be closer to 0.0. For steeper streams, with well defined channels that do not have flows going out of bank, x will be closer to 0.5, (HEC-1994). A general rule of thumb is that K can be estimated by the travel time through the reach and a value of 0.2 can be used for x, (McCuen, 1989). K can also be approximated using the (Kirpich's, 1940) formula for time of concentration

$T_c = 0.0078L^{0.77} * S^{0.385}$ 5.3

Where:

T_c = Time of concentration (minutes)

L = length of Channel/ditch from head water to the outlet (ft)

S = Average watersheds slope (ft/ft)

Selection of the number of sub reaches: In channel routing, the travel time through the river reach is often greater than the computation interval. When this occurs, the channel must be broken down into smaller routing steps to simulate the floodwave movement and changes in hydrograph shape.

Muskingum equation also has a constraint related to the relationship between the parameter K and the computation interval t. Ideally, the two should be equal, but t should not be less than 2KX to avoid negative coefficients and instabilities in the routing procedure. A long routing reach should be subdivided into sub reaches so that the travel time through each sub reach is approximately equal to the routing interval t. That is:

No of sub reaches = $\frac{K}{\Delta t}$ 5.4

Where, Δt = computation interval;

K = the travel time of the flood wave

The maximum amount of attenuation will occur when the channel routing computation is done in one step. As the number of routing steps increases, the amount of attenuation decreases. Adopting appropriate methods and principles discussed as above values of x and K is estimated for reaches created in each scenario.

Diversion Elements:

A diversion is a more complex element. It represents a “withdrawal” of water from the natural stream. The quantity of the withdrawal can be specified as a constant amount or as a function of some parameter such as time or flow. Some or all of the diverted water can be routed and returned by a diversion or it can be removed from the system entirely. In the current study five diversion canals with monthly varying diversion requirement were used to divert water into the proposed irrigation sites and all are located in the lower reaches of the omo river .

Reservoirs:

The reservoir is the most complex element in HEC-ResSim. The physical data of a reservoir are represented by a pool and one or more dams. Both the pool and the dam are complex sub elements of the reservoir. The pool contains the reservoir’s elevation-storage-area relationship and can optionally include evaporation and seepage losses. The dam represents both an uncontrolled outlet and an outlet group top of dam elevation and length specifies minimum parameters for an uncontrolled spillway and dam may contain one or more controlled or uncontrolled outlets. Controlled outlets can be used to represent any outlet, such as a gate or valve, capable of regulating flow. An advanced outlet type is power plant which is a controlled outlet with additional features to represent their special purposes. The power plant adds the ability to compute energy production to the standard controlled outlet. By combining all elements discussed so far reservoirs, reaches, junctions, and diversions, a HEC-ResSim model of Omo Gibe basin has been built for specific water resource scenarios Fig 5.2 below shows ResSim network developed for the last scenario or RN-Scenario D

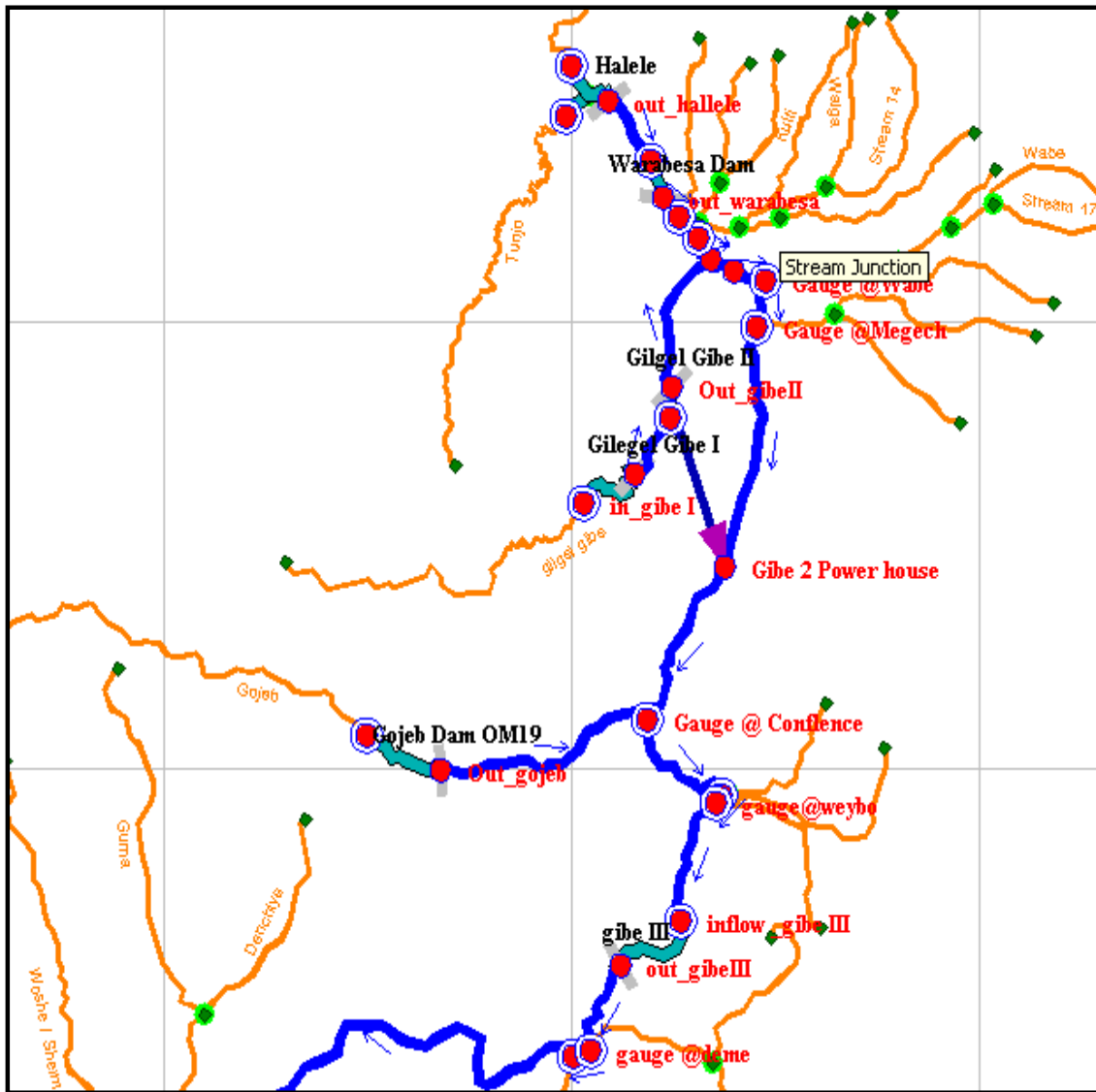


Figure 5-2 Reservoir System Network for scenario D

Following the geographic placement of the HEC-ResSim elements including main stream segments, inflow points, dams with their connections to the main river stream as well as irrigation canals, the next step of the HEC-ResSim set-up is the definition of the technical parameters defining for each dam. The geometric property of pools, capability of hydropower plants if appropriate and the definition of the various management constraints regarding, the electric power production, and the regime of released flow. As an illustration how HEC-ResSim dam parameters have been set, the detailed process followed for Gibe III dam is presented.

5.2.4 Operational parameters

A – Definition of pool parameters

Physical reservoir data includes: reservoir pool elevation-storage - area definition, dam elevation and length, For the Gibe III reservoir, the height of the bottom duct is 780 m. This defines the lowest elevation from which it is possible to release water. Below this level the storage capacity of the reservoir is considered to be equal to zero since the stored water cannot be used. When the upper operation level is reached at 896m, the volume of the stored water is 15984 BCM and the area covered with water is 229 km².

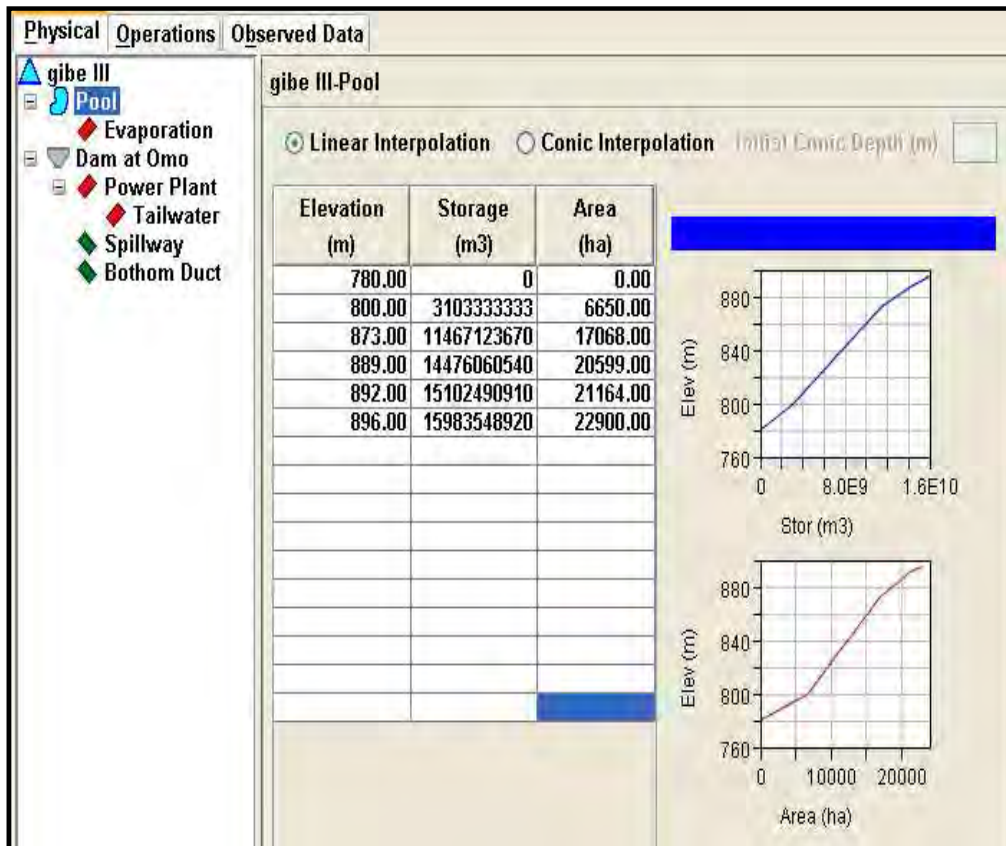


Figure 5-3 Storage capacity and surface area at different elevation for Gibe III reservoir

B – Parameters of the hydro technical equipment

The next group of parameters which needs to be defined concerns the various hydro technical equipments, namely: the flood spillway, the plant intake and the bottom duct.

The flood spillway

Elevation versus capacity relation with 9 gates opening for Gibe III dam has been taken from EEPKO, RCC- Dam Alternative design report 2006

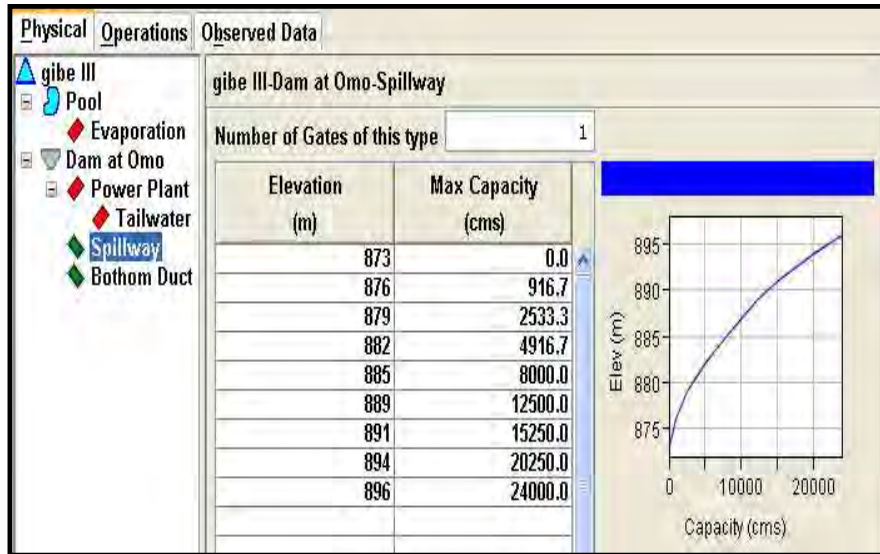


Figure 5-4 Spillway maximum outflow capacity for Gibe III dam

The bottom duct

Permanent ecological outlet or the bottom duct properties of need also to be defined. A maximum flow capacity of 23.5m³/s has been designed for Gibe III dam. The flow decreases linearly with lake elevation down to the opening hole of the duct which is situated at 780.

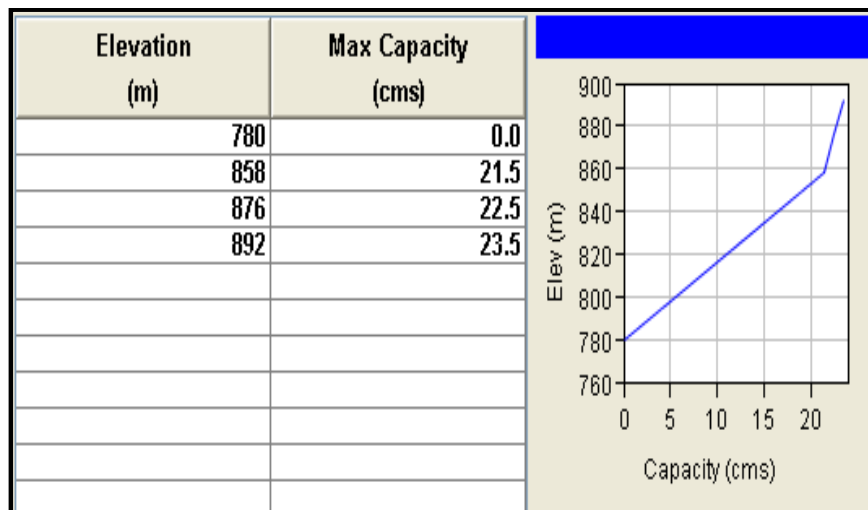
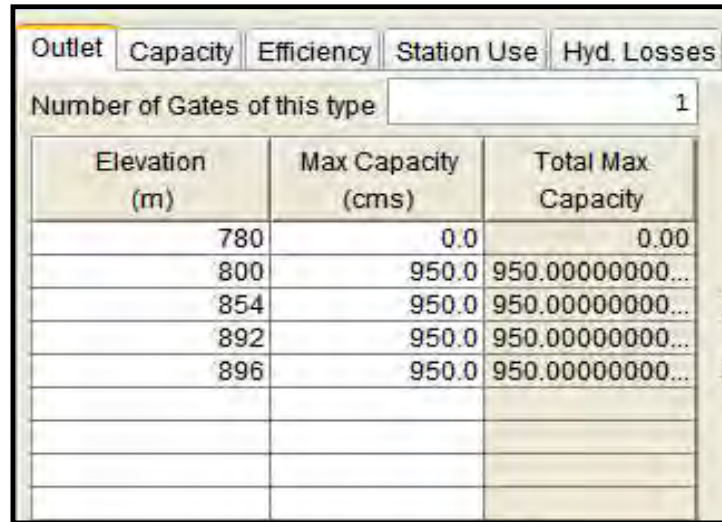


Figure 5-5 Bottom duct capacity for Gibe III dam

The plant intake

The plant intake setting is concerned with the relation between the elevation of the water in the lake and the flow intensity in the pipe reaches the turbines. Gibe III intake is in operation as soon as the water level reaches 780m. Engineering detail in RCC- Dam Alternative design report 2006 of EEPKO has shown the maximum flow in the pipe is 950m³/s.



Outlet	Capacity	Efficiency	Station Use	Hyd. Losses
Number of Gates of this type				1
Elevation (m)	Max Capacity (cms)	Total Max Capacity		
780	0.0	0.00		
800	950.0	950.00000000...		
854	950.0	950.00000000...		
892	950.0	950.00000000...		
896	950.0	950.00000000...		

Figure 5-6 Gibe III plant intake maximum capacity

C – The power plant parameters

In HEC-ResSim, the power plant module is used in order to define the electric power generated by the turbines. The total installed capacity of the Gibe III plant is 1800 MW, station Use 0, total head loss 5.5m, overall efficiency 92% and the average tail water elevation used is 681m a.s.l.

D - Operational parameters

The formulation and assessment of basin-wide development scenarios requires information on the likely operation of hydropower reservoirs. This information should consist of monthly maximum and minimum limits to the reservoir elevation. However, this information is not available for some of proposed projects considered for in this study. Accordingly during simulation of each scenario computed guide curve for a hydropower reservoir will be identified.

In HEC-ResSim, the dam operation is defined by three typical operation modes, also called “zones”, which are called respectively: Flood control, Conservation and Inactive. These “zones” of operation are based on specific reservoir elevations and contain a set of rules that describe the goals and constraints that should be followed when the reservoir's pool elevation is within a particular zone. For each mode of operation, the rules are ordered by priority. Accordingly total storage zone of Gibe III reservoir has been divided in to five zones, the Dam crest (max flood control), flood control, conservation, minimum operation zone and dead storage zone and has been set at 896,894,892, 854 and 800 a.m.s.l respectively.

The conservation zone is the preferred zone for normal reservoir operations. The HEC-ResSim model is configured to make release such that the level of the reservoir tries to stay within the conservation zone. In the conservation zone all releases are based on the objective of meeting energy, irrigation and environmental requirements. Since the primary purpose of Gibe III reservoir is to generate hydropower, normal flood operation focuses on conserving water in the pool (not spilling) and therefore the guide curve is set at the top of the spillway gate i.e. at 892 a.m.s.l.

6.0 RESULTS AND DISCUSSION

6.1 Simulation in HEC-ResSim

The purpose of the Simulation module is to separate output analysis from the model development process. Once the reservoir model is complete and the alternatives have been defined, the simulation module is designed to facilitate the analysis phase of reservoir/river modeling used to configure the simulation. During the creation of the simulation model it was a must to specify a simulation time window, a computation interval, and the alternatives to be analyzed. The time windows for present case were starting, lock back, and end time of the simulation. The general simulation procedures followed in this study includes;

1. Preparation of the time series data and store the data set in to the HEC Data Storage System, (i. e in the HEC-DSS).
2. In the watershed module of HEC-ResSim, configure all water resource projects proposed and existing ones, using appropriate drawing tools for; streams, reservoirs, diversion outlet, Computational points
3. Making the reservoir network module locked (editable) draw reaches, diverted outlet and then make editing and saving the network to develop four likely reservoir network or water resource development projects for omo gibe watershed.
4. For each the reservoir network module, fix the reservoir elevation for the Inactive, conservation and the flood storage. Add additional zones (if necessary) and parameters for controlled outlet, uncontrolled outlet, and power plant. Add also the require data for diverted outlet and reaches.
5. At the operation window of reservoir network module, add the operational rules at each zone of reservoir and assign the required information.
6. Create an alternative and retrieve the input time-series data from HEC-DSS and fix at the required nodes or junctions found in each network scenario. Finally bring and run all alternatives in the simulation window, and evaluate and compare each system.

Simulation Assumptions

The simulation made a number of assumptions to simplify the complexity of the actual Operation system and river basin simulations. Some of the basic assumptions must be made:

1. Seepage through the reservoir and the body of the dam is assumed to be zero.
2. Seepage and evaporation through the reaches are negligible and assumed to be zero
3. Only free water surface evaporation losses were assumed.

6.2 Scenario modeling and graphic outputs

6.2.1 Simulation for testing the model

There are two general approaches for assessing the calibration quality; namely subjective and objective. Subjective assessment is based on a visual comparison of the simulation results with the observed data. In contrast, objective approaches are based on developing some quantitative measures of the quality of fit. The graphical evaluation includes comparison of the simulated and observed hydrograph, and comparison of the simulated and observed stream flow time series. As can be seen in Fig 6.1 and 6.2, good overall agreement of the shape of the hydrograph and time series is observed.

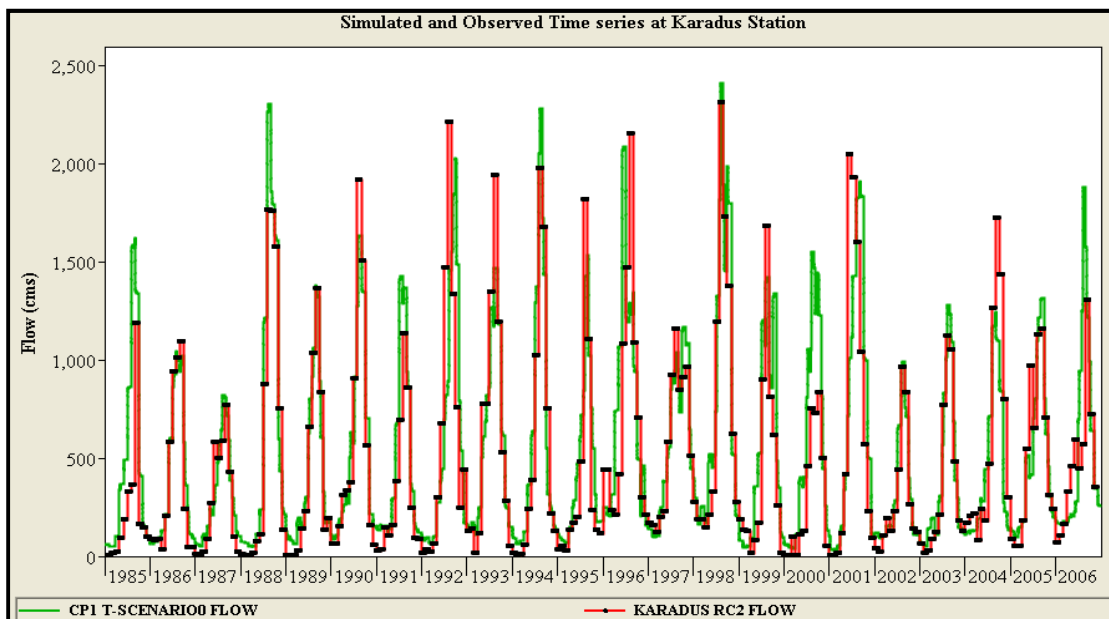


Figure 6-1 Comparison between measured and simulated time series at Karadus

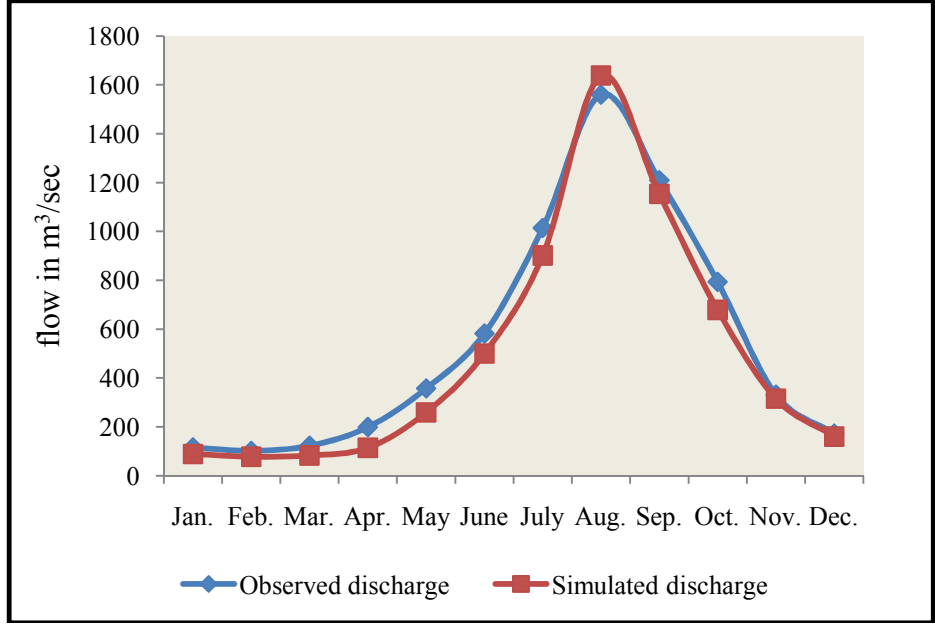


Figure 6-2 Comparison of measured and simulated hydrograph at Karadus

The numerical performance measures include the overall water balance error (i.e. the difference between the average simulated and observed runoff), and a measure of the overall shape of the hydrograph base on objective functions.

To evaluate the result of the model simulated with respect to discharge derived from a rating curve at lower Omo basin or with Karadus hydrometric station, the most widely used objective function in model calibration, the Nash-Sutcliffe (1970) efficiency criterion is used.

$$EFF = 1 - \frac{\sum_{i=1}^N (Q_{obs_i} - Q_{sim_i})^2}{\sum_{i=1}^N (Q_{obs_i} - Q_{bar})^2} \dots\dots\dots 6.1$$

Where; Q_{bar} is the observed mean monthly flow over the whole period. An efficiency criterion of 1 means that observed and simulated values are in perfect agreement whereas a negative criterion means that the simulation gives worse results than replacing simulated values with the observed mean monthly flow. Consequently the Nash-Sutcliffe coefficient computed at the Karadus station is 0.782 hence the model ability and efficiency is acceptable.

6.2.2 Simulation in Scenario A

Gilgel Gibe I and II Cascaded Reservoir operation

In the systems of this type, cascaded, the operation of particular power plant cannot be analyzed separately from the remaining power plant in the system (i.e. in the cascade). Operation of these reservoirs has been driven by an operating rule called Tandem rule which seek to produce continuous power in each day without having the reservoir drop below minimum operating level (MOL) and seek to minimize spillage in any day. Fig 6-3 below shows the reservoir system network developed in the model for scenario A.



Figure 6-3 Reservoir System Network for Scenario A

Figure 6.4 and 6.5 shows the standard HEC-ResSim reservoir plot for Gibe I and Gibe II, the upper plot region shows the computed reservoir pool elevation, guide curve and operating zone. The lower region shows the computed pool inflow and outflow.

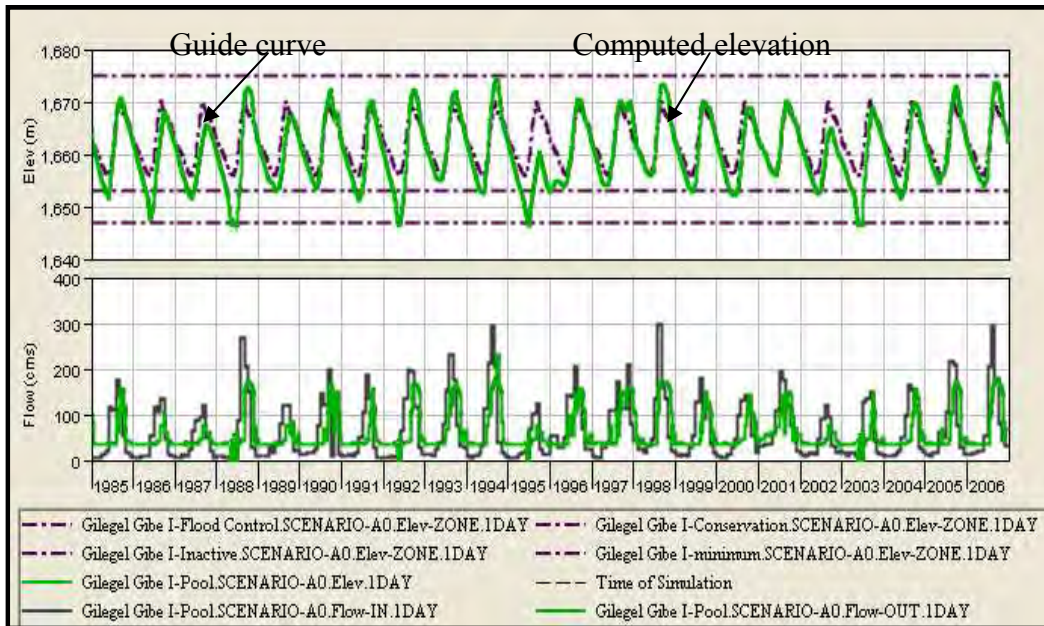


Figure 6-4 Simulated Gibe I Pool, level, Inflow and outflow at scenario A

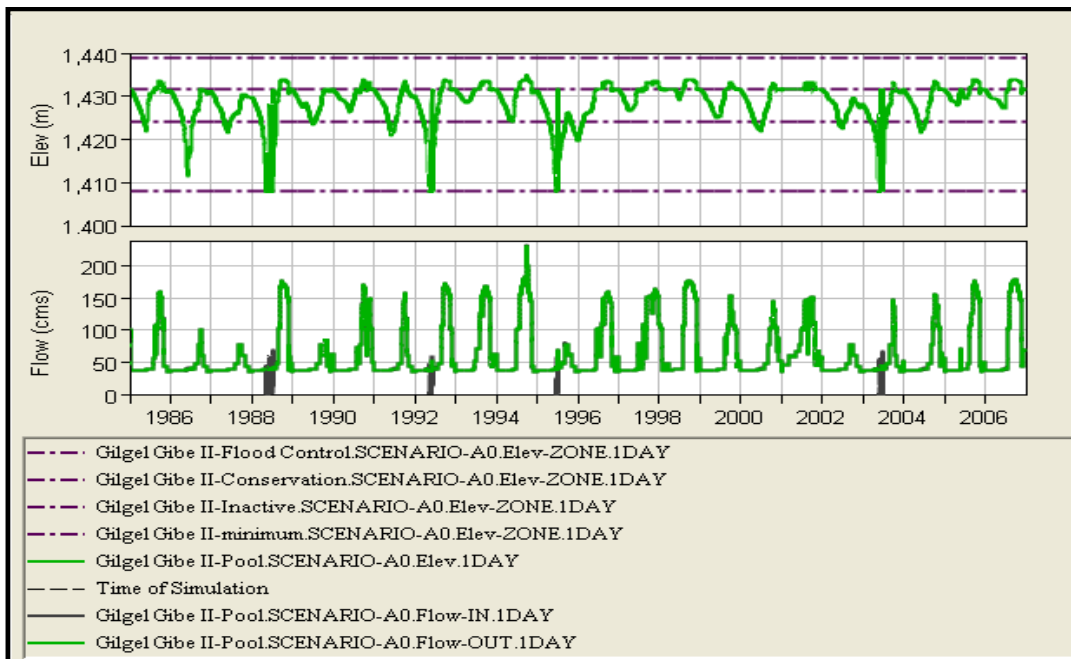


Figure 6-5 Simulated Gibe II pool level, inflow and outflow at scenario A

The maximum, minimum and average water level simulated for Gibe I pool are 1670, 1647 and 1660 a.m.s.l respectively, and 1435.1,1408 and 1428.1 a.m.s.l for Gibe II hence the result of tandem rule has shown good storage distribution among reservoirs in the entire simulation period. The water levels of each reservoir have also been observed almost in the same operational zone during the analysis period. Fig 6-6 below shows guide curve or monthly water level fluctuation simulated using the HEC-ResSim model for Gibe II pool.

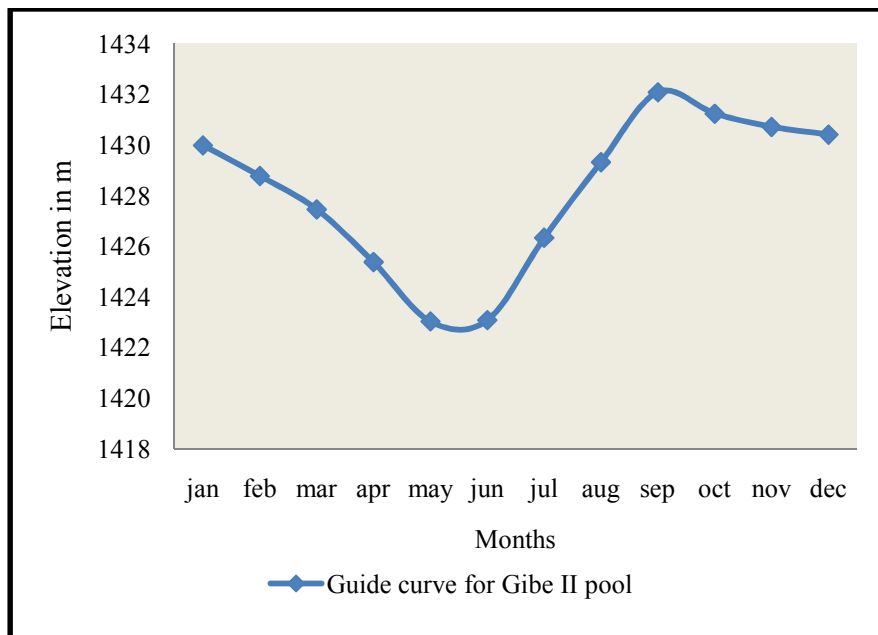


Figure 6-6 Guide curve for Gibe II pool

Gilgel Gibe I and II Power plant operation

The two plants are in cascade and ResSim was configured for tandem operation simulation with monthly requirement of the power plant. Energy generation and plant characteristics during the simulation period for both power plants are shown in Fig 6-6 and 6-7 the average annual energy production using HEC-ResSim was 784 GW/year for Gibe I and 1911 GW/year for Gibe II. In the current study (tandem operation) the performance of Gibe II power plant has been observed to produce an additional 286GW/year above its requirement which is 1635GW/year (EPCO, 2004). However the average annual energy simulated in Gibe I power plant is nearly same with the current production 794 GW/year.

As mentioned in the previous chapter irrigation activities in lower omo is quite minimal hence from the model run, total discharge in scenario A has estimated the annual volume of water at Karadus without any irrigation activities to be 18.9BCM with mean inflow of 596.8 m³/sec. Fig 6.7 through 6.10 show power plant operations, energy and turbined flow duration curves for both power plant.

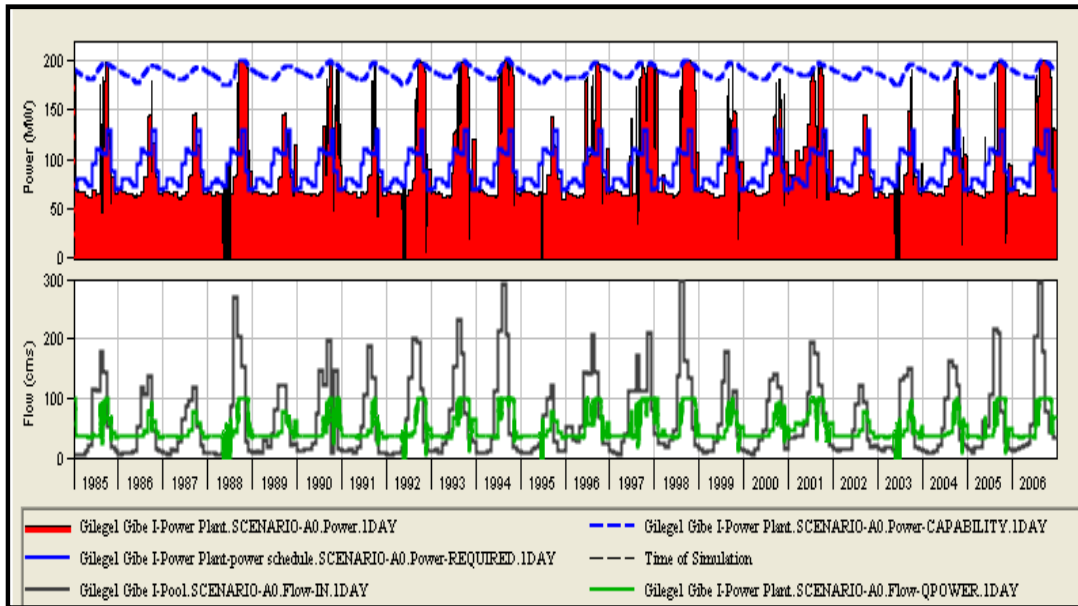


Figure 6-7 Simulated Gibe I power plant operation at scenario A

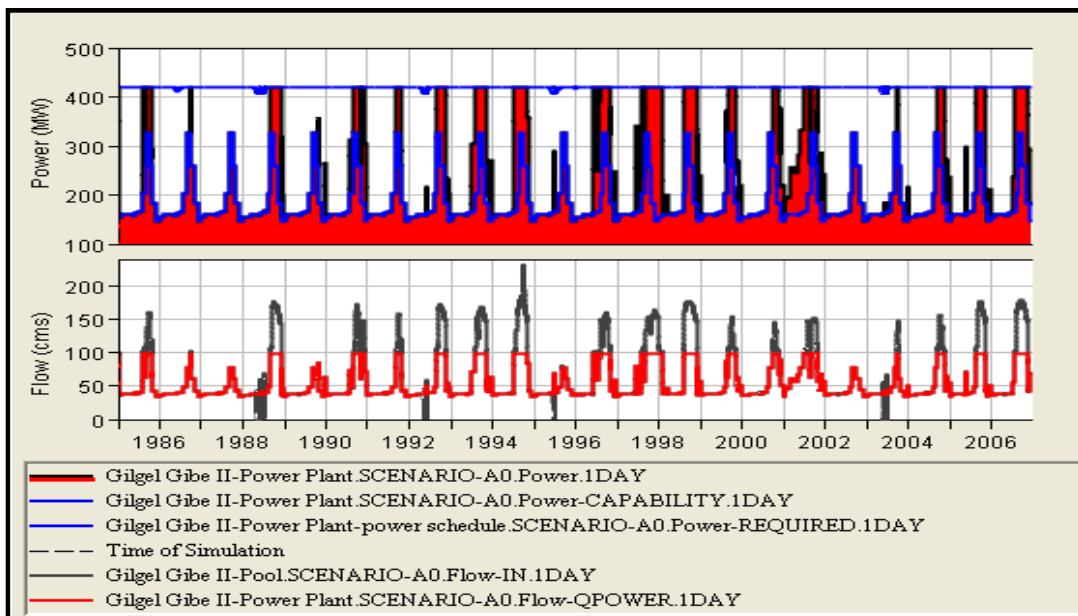


Figure 6-8 Simulated Gibe II power plant operation at scenario A

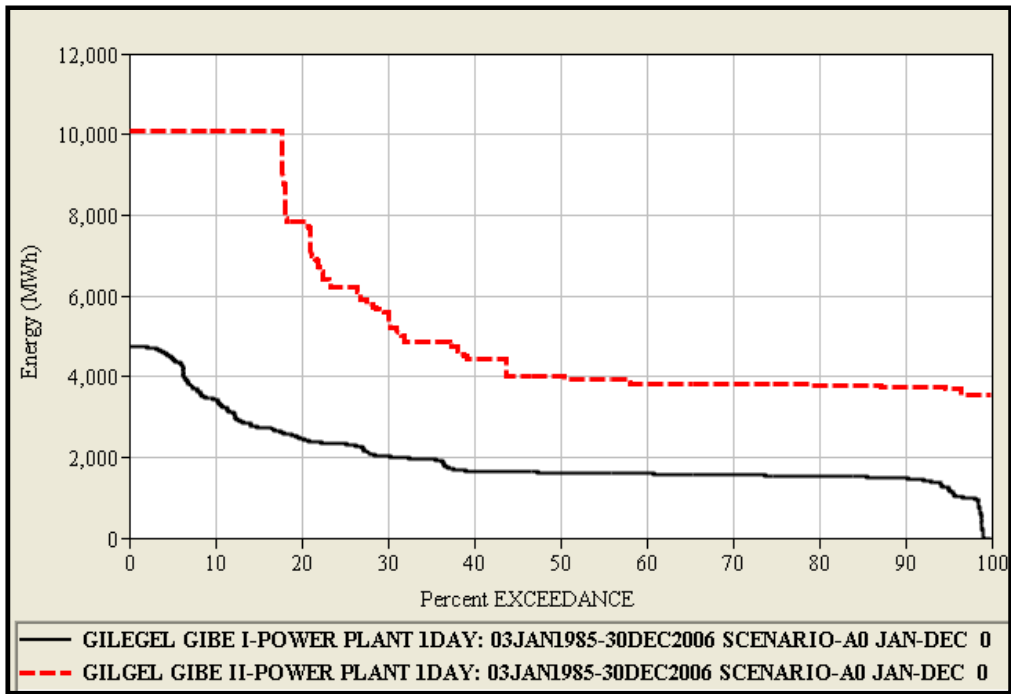


Figure 6-9 Global energy duration curve for Gibe I and II power plant at scenario A

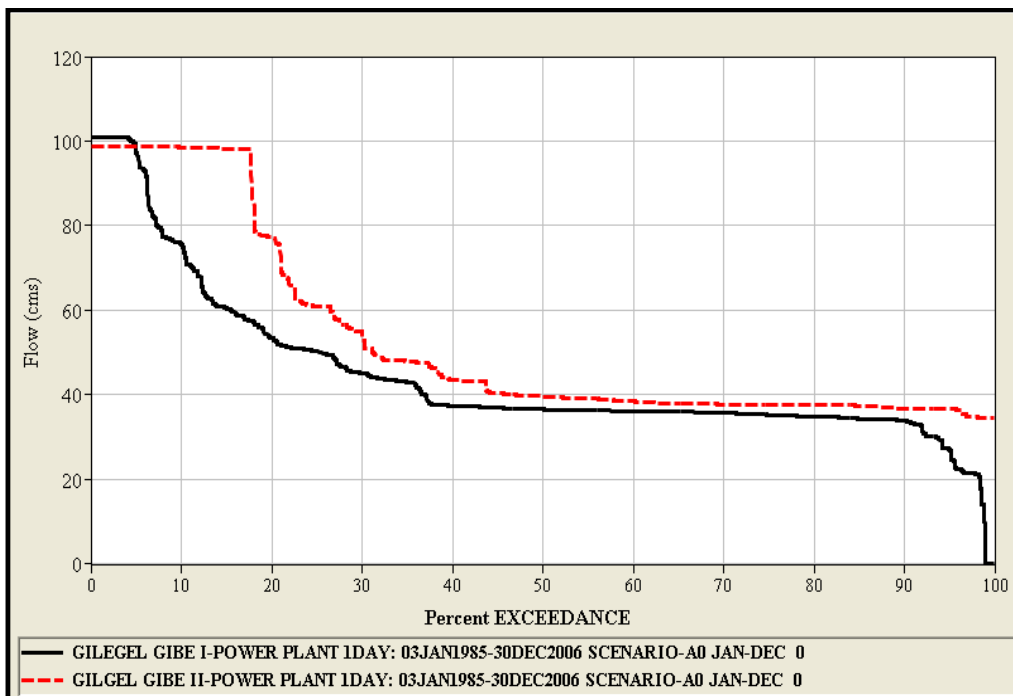


Figure 6-10 Global turbined flow duration curve at Gibe I and II tail race at scenario A

6.2.3 Simulation in Scenario B

Gilgel Gibe III reservoir and power plant operation

One of the immediate benefits of constructing the Gibe-3 dam will be the ability to avoid severe drought periods and to control the large flooding downstream which cause the loss of lives, both human and animal, as well as damage to property and infrastructure. Its operation will also allow controlling the downstream peak floods, occurring in August/September, including the sudden and critical ones of wet years (increased in peak because of the deforestation of the basin) which often causes critical events as in year 2006. Therefore in order to analyze effects due to Gibe III reservoir it is necessary to discuss here the basic operational output simulated in HEC-ResSim, Reservoir and its power plant Operation. Fig 6-11 below shows the reservoir system network developed in the model for scenario B.



Figure 6-11 Reservoir System Network for Scenario B

The results of this scenario simulation are illustrated in through the tables and standard plot of HEC- ResSim for reservoir and power plant operation including: Reservoir levels sequence, pool duration curves, and power and energy duration curves.

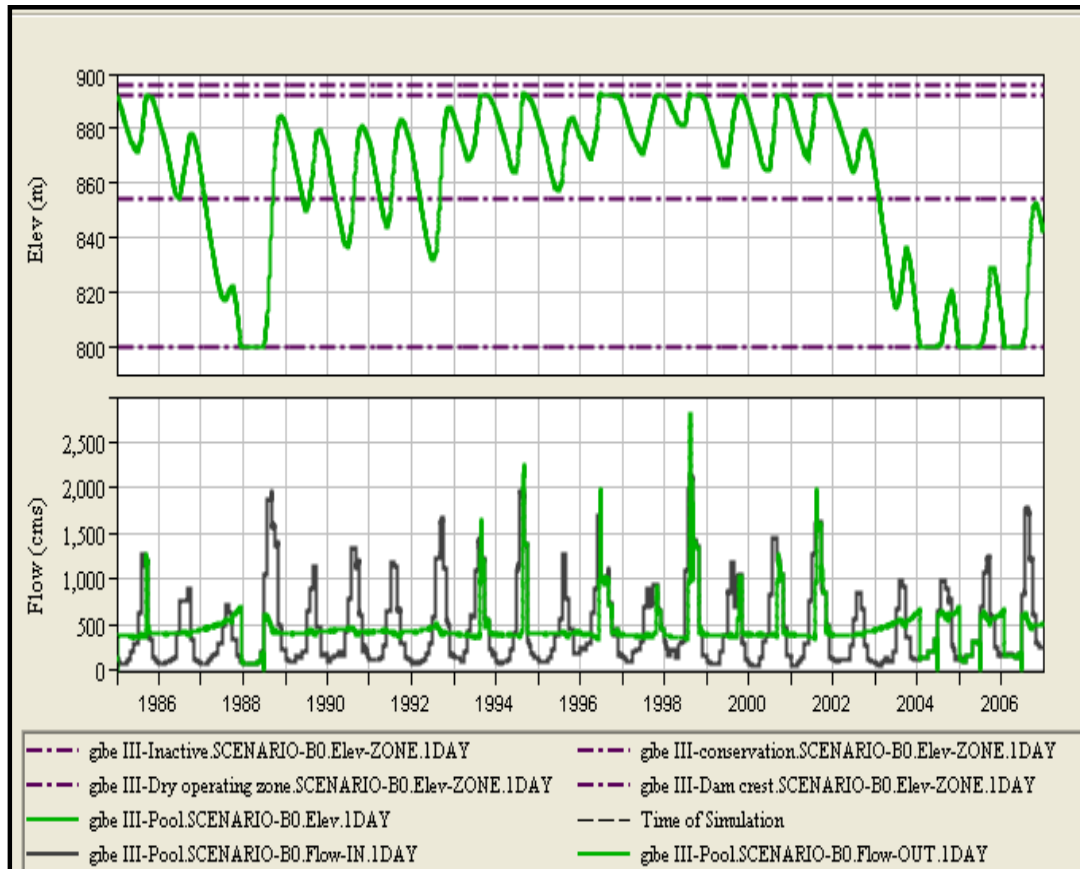


Figure 6-12 Simulated pool level, inflow and outflow for Gibe III reservoir during scenario B

Based on 22 years historic inflow the study has identified guide curves shown in the next page and from Fig 6-13 the maximum, mean and average operation levels of the reservoir can be identified. Over the period simulation the maximum, minimum and average water level for Gibe III pool are 888.30, 806.00 and 863.30 a.m.s.l respectively,

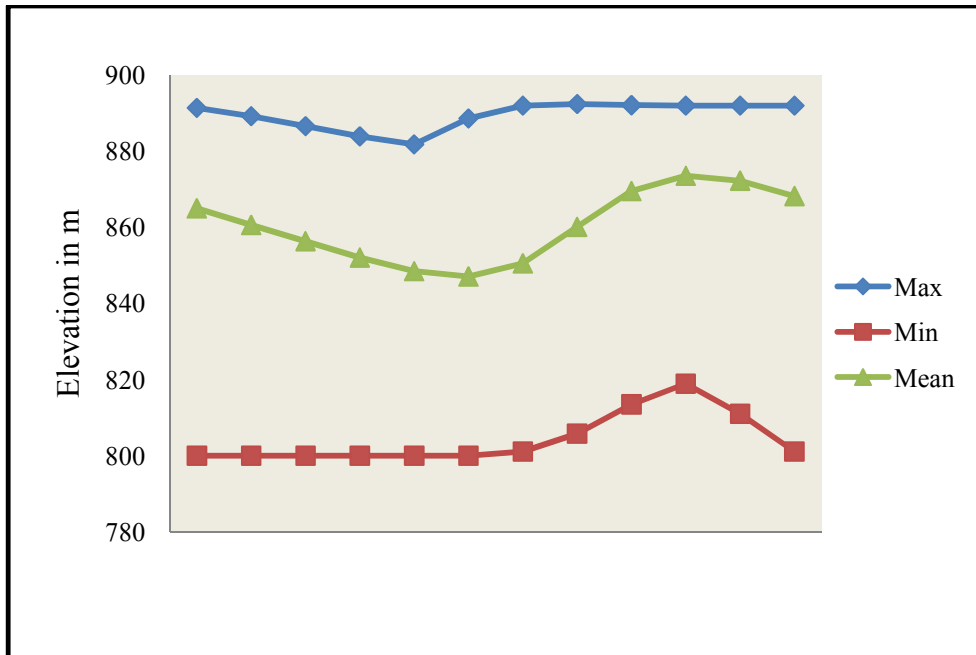


Figure 6-13 Year Max-Min- Mean pool level (simulated Guide curves) at scenario B

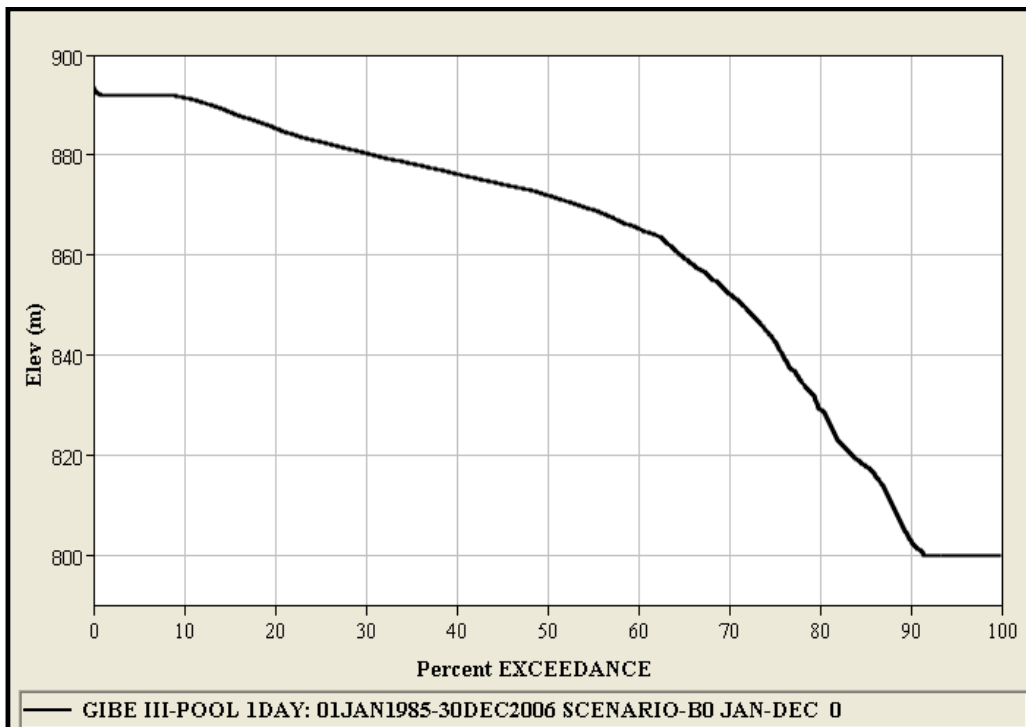


Figure 6-14 Global pool duration curve for Gibe III reservoir at scenario B

From the figure 6.13 the water level reached minimum between two timeframes May and Jun and maximum of in August to September., as can be shown in pool duration curve only 50% of the time the water level in the reservoir is above 860 m a.s.l which the mean operating level of the reservoir .In this scenario about 90 % of the time the power intake is in operation between 800 and 896 a.m.s.l. Simulation run for this scenario also reveals that on average 14.5 BCM of water enter in to the reservoir per year.

Power and Energy generation

ResSim simulation of Gibe III power plant produced an average annual energy of 6,486GWh/year and average power of 758.94MW. And with 90% exceedance the firm energy and power generated are 5885.62GWh/year, 679.25MW respectively. The average energy obtained in this scenario is close with the study made by EEPCO studied using sequential stream flow routing (SSR) method developed on Microsoft Excel program. And the firm energy obtained in this scenario is also close to firm energy obtained at 90% reliability (percent of the time the energy is secured) by EEPCO. Moreover water level simulated in HEC-ResSim has shown a similar trend with EEPCO and all result simulated in this scenario has good agreement as compared with SCENARIO 6 of Reservoir Operation studied by EEPCO. A standard HEC-ResSim plot for power plant operation including capability, generated and required energy, and power and energy duration curves are presented; Figs 6.15 through 6-18. In addition table 6.1 and 6.2 shows the simulated average, maximum and minimum power plant and reservoir parameters.

Table 6-1 Simulated Gibe III power plant parameters in HEC-ResSim

Parameter Simulated	SCENARIO-B		
	Average	Max	Min
Generation Efficiency	0.95	0.95	0.95
Power Head (m)	180.8	213.9	120.5
Energy Generated (MWh) per time step	17772.48	43200	0
Power Generated (MW)	758.98	1800	0
Plant Factor	0.42	1	0
Flow Power (cms)	434.3	916.2	0

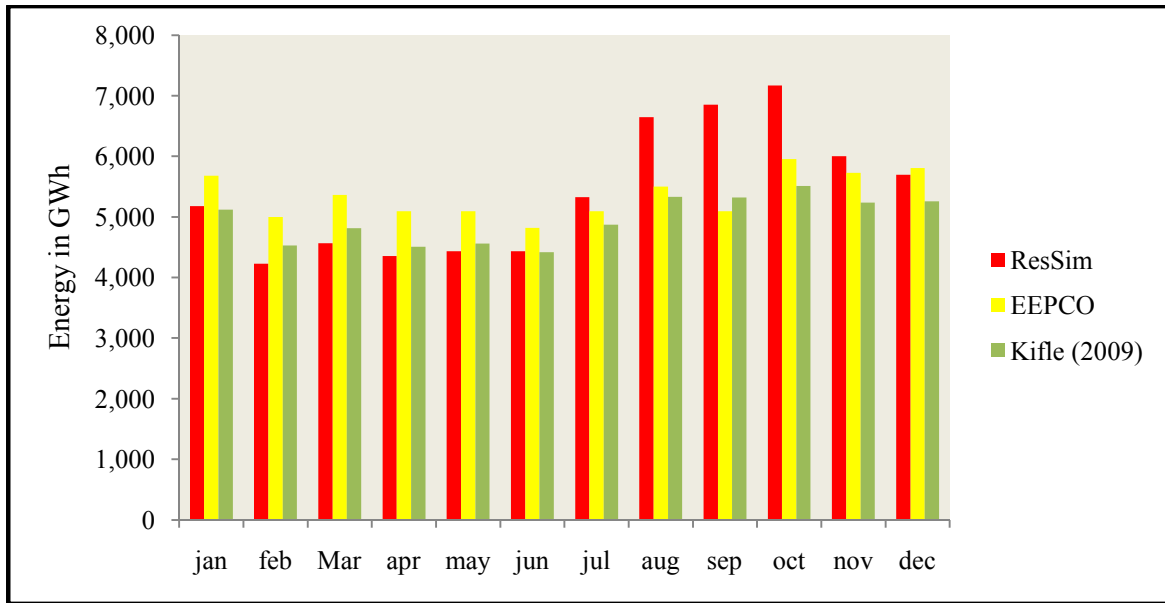


Figure 6-15 Energy generated using HEC-ResSim and EEPCO and Kifle (2009) studies

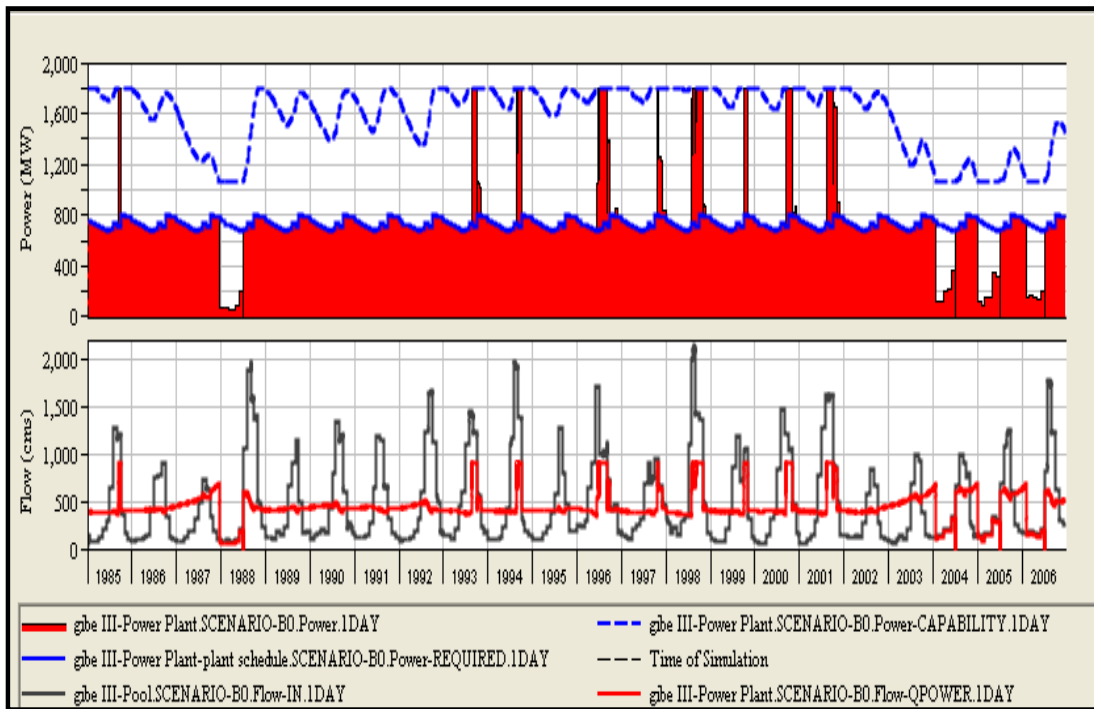


Figure 6-16 Simulated Gibe III power plant operation during scenario

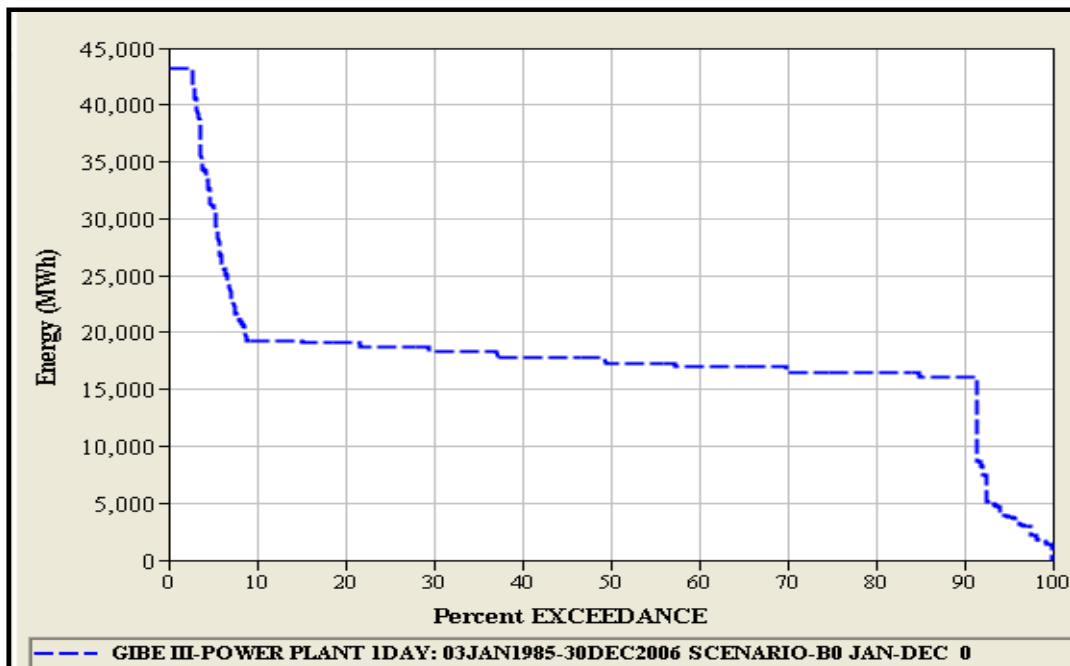


Figure 6-17 Global energy duration curve at Gibe III power plant during scenario B

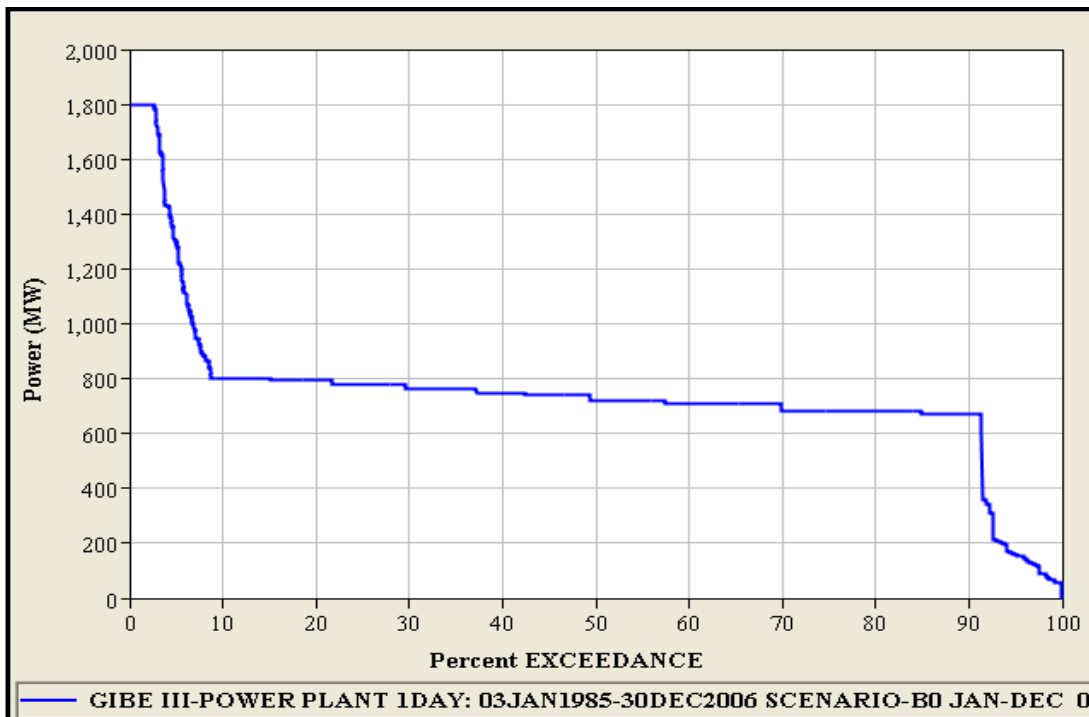


Figure 6-18 Global power duration curve at Gibe III power plant during scenario B

Table 6-2 Gibe III power plant and reservoir characteristics between years 1985-2006

PARAMETER	Jan	Feb.	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Energy in GWh	Max	568.20	500.00	536.40	509.10	509.10	798.33	1035.14	1297.12	1230.04	1220.13	918.34	661.59
	Min	50.68	48.65	41.95	41.28	66.43	141.22	492.68	550.00	509.10	595.50	572.70	272.77
	Mean	517.56	422.94	456.32	435.54	443.14	443.44	532.61	664.50	685.32	717.14	600.17	569.39
Power in MW	Max	767.13	744.05	720.97	707.08	684.27	1089.21	1402.33	1743.49	1708.39	1639.96	1275.53	889.23
	Min	68.12	69.90	56.38	57.34	89.29	196.14	662.20	739.25	707.08	800.40	795.42	366.62
	Mean	699.16	625.55	613.34	604.91	595.61	615.00	716.35	891.36	951.85	963.89	833.58	766.45
Q-power m3/sec	Max	647.80	466.80	475.90	490.70	501.90	556.80	708.60	879.90	863.40	828.80	648.20	645.90
	Min	60.70	62.30	50.20	51.10	79.60	174.80	363.00	392.80	362.80	407.40	404.10	319.60
	Mean	400.02	352.96	356.73	362.83	369.13	387.31	459.88	531.25	532.93	534.38	472.69	443.31
Pool level	Max	891.40	889.20	886.60	883.90	881.80	888.60	892.00	892.40	892.10	892.00	892.00	892.00
	Min	800.00	800.00	800.00	800.00	800.00	800.00	801.10	805.80	813.50	818.90	811.00	801.10
	Mean	865.00	860.62	856.36	852.08	848.50	847.09	850.54	860.11	869.53	873.55	872.25	868.21

Impacts of Gilgel Gibe III dam in the Lower Omo region

Influence during Operation

As discussed previously greater than 90% of Turkana Lake is the contribution from the Omo-Gibe river system with mean inflow of $596.6\text{m}^3/\text{s}$ or 18.9BCM per annum at Karadus. Therefore, the predominant influence of the Gibe III project will be to smooth monthly distribution of contributions from this catchment. There will also be a slight reduction in the total annual contribution as a result of evaporation losses from the Gibe III Lake. These effects are illustrated, for the average year, on Table 6.3. The modified flows downstream of Gibe III dam will have two components; discharge from the power station tailrace and discharge from the dam spillway. The first will be relatively constant, as the power station will be operated to deliver firm energy with a reliability factor greater than 90%. Spillage from the reservoir, however, will take place only during the wet season and these flows will be intermittent and variable. For the purposes of this illustration, monthly year average discharge simulated from the power plant is assumed. From simulation it will be observed that dry season monthly average flows at the dam site are increased by up to 326% (in February) at Gibe III dam site and wet season flows reduced by up to 63, % (in August). Fig 6-19 below shows effects at the dam site.

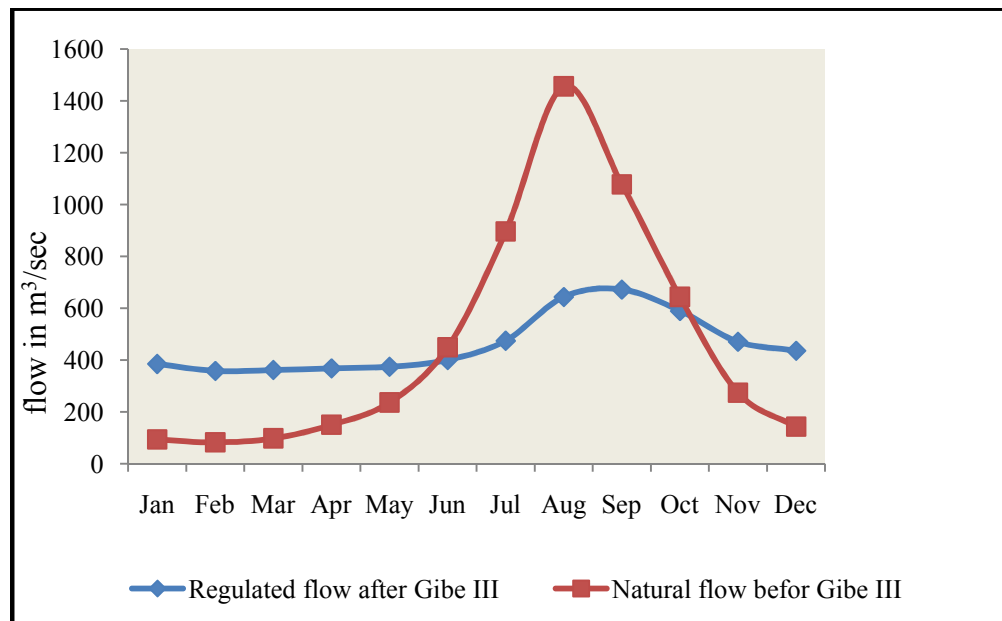


Figure 6-19 Flow hydrograph before and after gibe III downstream of the dam

Long term effects over the period of simulation also shown that operation Gibe III power plant would increase the dry season contribution of the basin to Lake Turkana (an average increase of 130% or increase by 4.033BCM in mean monthly inflows from November to June at Karadus) and decrease in flood season contribution (an average decrease of 25% or decrease by 4.3BCM in mean monthly inflows from July to October at Karadus). But the mean annual flow out from Omo-Gibe river basin at Karadus will be decrease by 1.14% and the annual volume of water will be decrease by 1.45% or 273MCM and it will be 18.6BCM. Fig 6-20, 21 and Table 6.3 below illustrate the above results.

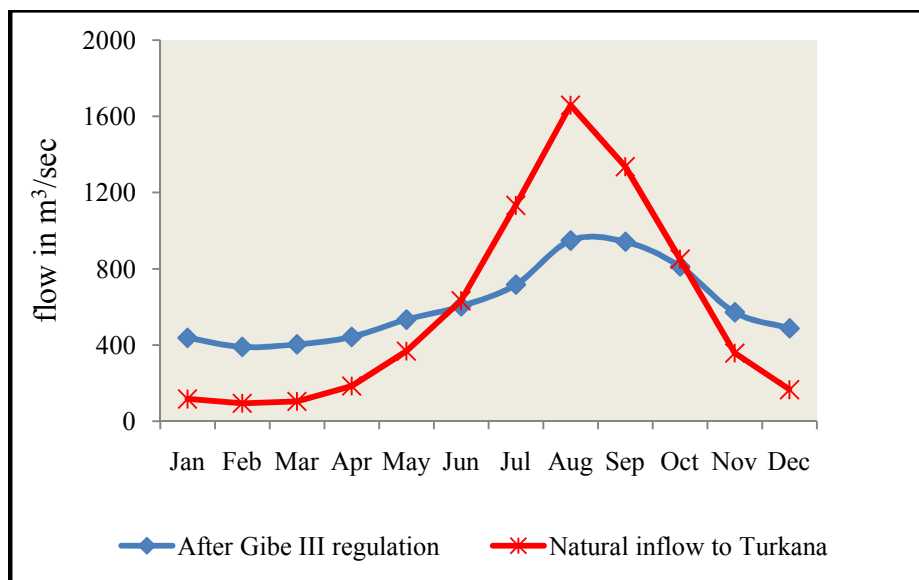


Figure 6-20 Inflow hydrograph at Karadus before and after scenario B

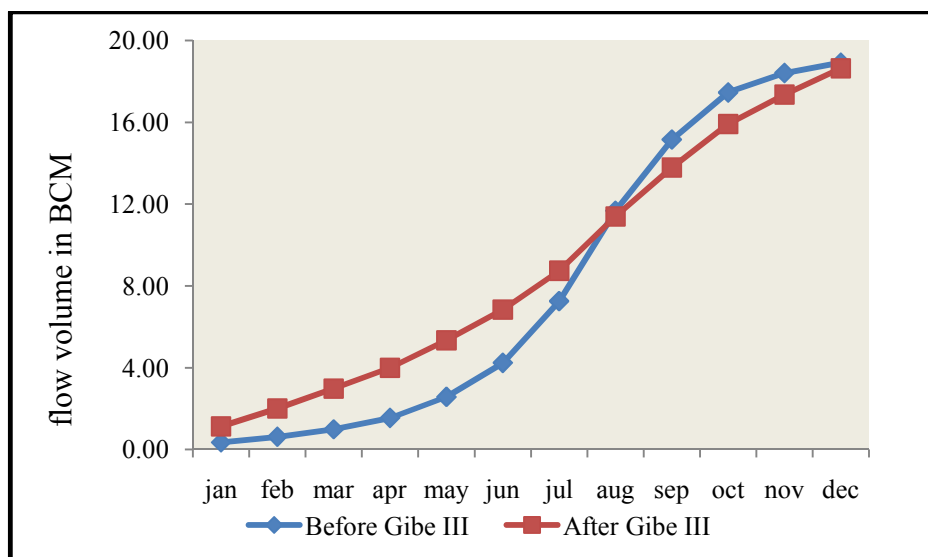


Figure 6-21 Cumulative volume at Karadus before and after scenario B

Table 6-3 Natural and regulated flow at Karadus and Gibe III dam site

Months	Natural flow in cms at Gibe III site	Modified flow in cms out Gibe dam	% age change	Natural flow in cms at Karadus	Modified inflow in cms to Karadus	% age change
Jan	94.11	400.02	+325.06	129.16	422.16	+226.84
Feb	82.92	352.96	+325.67	113.46	363.93	+220.75
Mar	98.46	356.73	+262.29	136.13	360.69	+164.96
Apr	150.61	362.83	+140.91	215.32	393.39	+82.70
May	236.82	369.13	+55.87	383.49	499.81	+30.33
Jun	449.70	387.31	-13.87	642.49	580.73	-9.61
Jul	896.25	459.88	-48.69	1126.76	710.25	-36.97
Aug	1456.26	531.25	-63.52	1651.92	990.01	-40.07
Sep	1078.25	532.93	-50.57	1342.61	925.53	-31.06
Oct	644.02	534.38	-17.02	859.69	793.13	-7.74
Nov	274.48	472.69	+72.21	367.17	557.10	+51.73
Dec	143.36	443.31	+209.23	189.74	479.60	+152.77
Mean	467.10	433.62	-7.17	596.49	589.69	-1.14

Water availability in lower Omo Irrigation sites

In a river basin, development and management of one part of the basin affects the land and water in other parts of the basin. As described in the previous chapter, in this study the aim is also to evaluate the potential of surface water resources of the Omo River for different future levels of irrigation development and impacts on the total volume of water leaving basin. Assuming the agricultural demand per area and hydrological condition is unchanged into the future; the water demand of the future extension of the irrigation network has been computed using a coefficient proportion equal to the ratio between the existing irrigated area and its future extension. Accordingly the three different phases of irrigation development discussed in the previous section (with total command area of 20,670ha, 34,600 ha and 142,900ha for the phase 1, 2 and 3 respectively) were simulated as a sub scenario and the results of simulation is discussed below.

HEC-ResSim model in scenario B was configured to operate to meet these three future scenarios, and to the extent possible, release all flows through Gibe III power plant. In operation zones, hydropower production was designated a higher priority than irrigation since it provides the highest economic returns. During power prioritized simulation of each scenario monthly totals irrigation demand has been set for downstream control rule of HEC-ResSim.

The analysis of this scenarios revealed that the outermost lower omo irrigated agriculture would affect insignificantly the power production. Simulation under the Phase 3 irrigation scenario has shown the average power production from Gibe III to be 758.74 MW which is by 0.0247% less as compared to the previous result. However even improvements of 0.1% in efficiency corresponds to great values for the hydropower industry. The result is almost same with simulation including other irrigation scenarios, phase 1 and phase 2. The main reason for this is effect of operation rule (in HEC-ResSim) assigned for lower omo irrigation area, i.e. downstream control rule. In the HEC-ResSim operation tab of Gibe III the downstream control rule can only be assigned to the reservoir (pool), not a specific outlet, this is because only the reservoir can account for all release from Gibe III outlets that could influence the flow at the intended point.

Even after the regulation of the upper catchment, the total inflow below Karadus has 19% runoff contribution from the lower residual basin. Therefore the final release will be determined based on the influence of routing and cumulative local flows at the downstream control point. Considering only the power release for illustration; relatively a high firm flow (200m³/sec with 95% exceedance), from Gibe III power plant at the tail race is much enough to allocate simultaneously the diversion requirements, even during, Phase03.

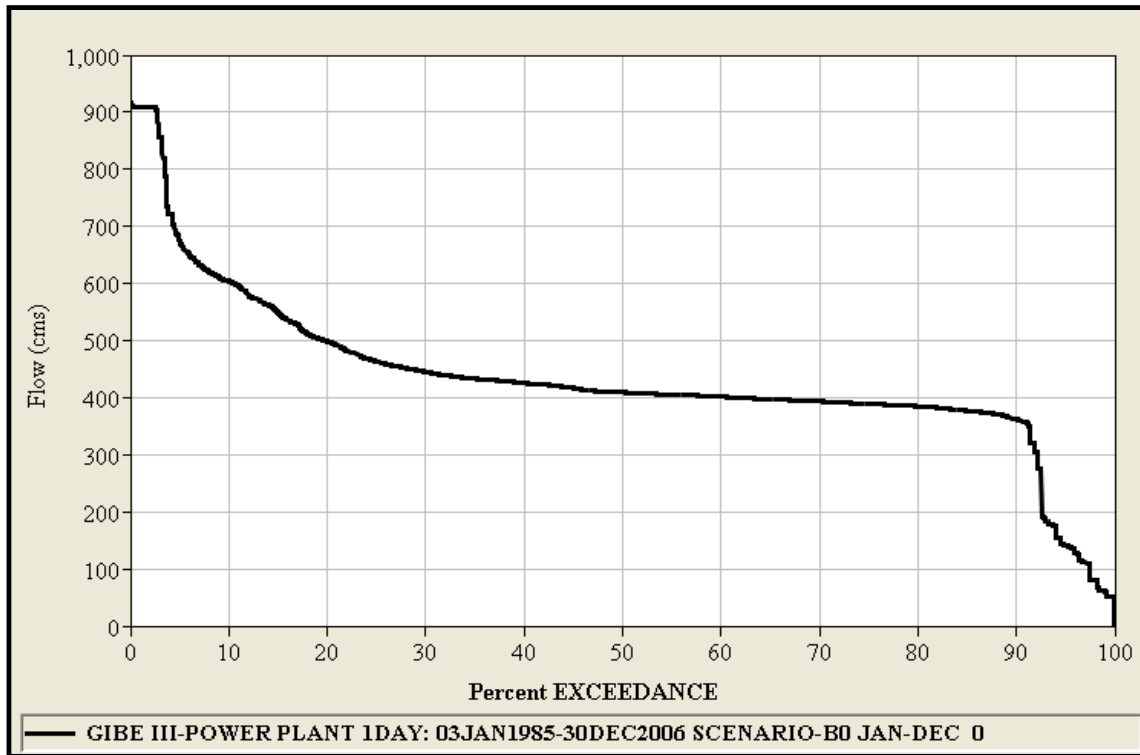


Figure 6-22 Global turbined flow duration curve at Gibe III tail race at scenario B

In the simulation period, the minimum downstream inflows at different diversion nodes are observed to be greater than the minimum requirements or diversion outflow with an acceptable reliability. Hence this analysis confirms the regulation (or power release) of Omo River would also increase availability of water for lower Omo irrigation projects. Fig 6-23 illustrates the available regulated flow after gibe III and the required diversions during phase 3 irrigation development.

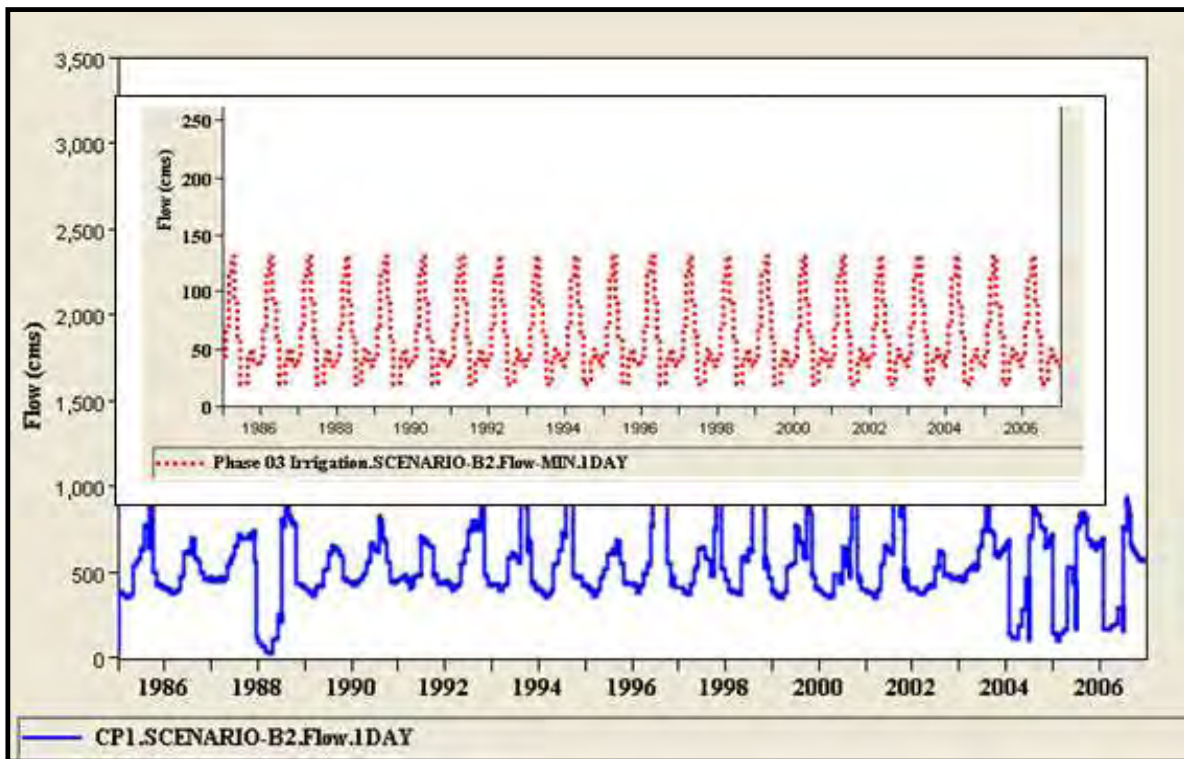


Figure 6-23 Comparison of regulated flow with maximum diversion requirement at scenario B

At present, irrigation infrastructure is frequently damaged by floods and the land is often inundated for weeks at a time. Farmers and private companies in the sector are not investing in permanent pumping stations. Because of this, most irrigation is limited to low capacity portable pumps. Consequently, the construction of Gibe III dam will ensure adequate water levels and a regulated flow at all times of the year, this will encourage investment in irrigation to produce food, fodder and cash crops. And, annually about 1.87BCM volume of water will be diverted into phase 03 irrigation sites, 714MCM of water into phase 02 irrigation site and 270 MCM of water into phase 01 irrigation site. Therefore the volume of water in Omo River below these proposed irrigation sites will be reduced by 10.01% during phase 03 irrigation development, 3.83 % during phase 02 irrigation developments and 1.45 during phase 01 irrigation development. These results are also illustrated graphically in figure 6-24 and 6-25.

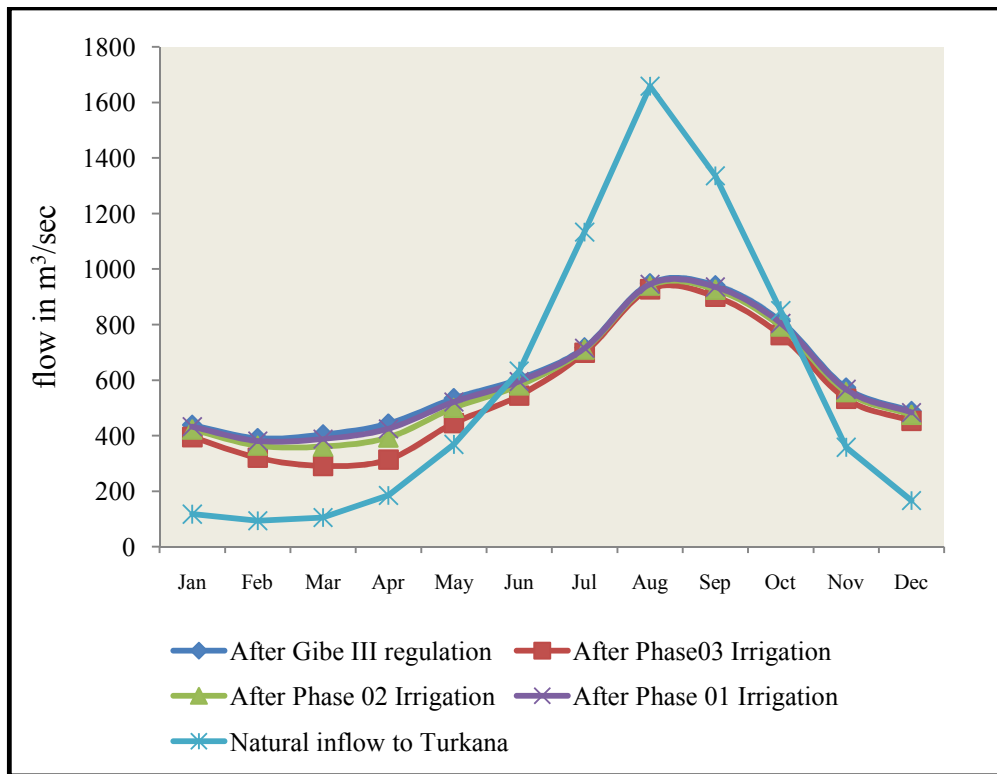


Figure 6-24 Hydrographs of the Omo river before and after scenario B below Karadus

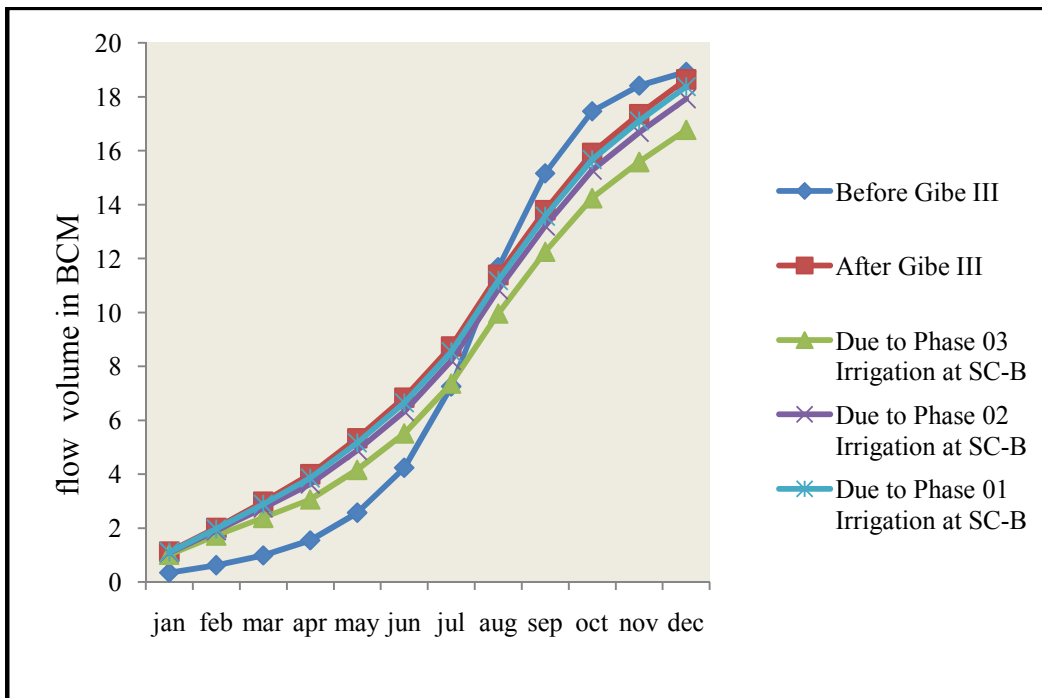


Figure 6-25 Cumulative flow volume of the Omo river before and after scenario B

6.2.3 Simulation in Scenario C

One of the likely future development scenarios in omo gibe basin is the Gojeb OM19 hydropower which is located upstream of Gibe III dam and as said before this dam catchment contributes about 15% of the total watershed area of Gibe III dam site. Consequently its construction and operation would result in alteration of the natural flow regime downstream of the dam. The inflow to gibe III reservoir would be affected and little depends on the outflow from Gojeb reservoir. Fig 6-26 below shows the reservoir system network developed in the model for scenario C.



Figure 6-26 Reservoir System Network for Scenario B

The effects in this scenario are simulated employing basic principle of reservoir operation. Implicit operation simulation in HEC-ResSim has shown that the net system storage in all

reservoirs is kept proportionally distributed and about 18% Gibe III dam inflow is the contribution from Gojeb dam site.

Generally results obtained are summarized below and standard graphic output of HEC-ResSim and other important figures are also presented from Fig 6-27 to Fig6-32

- ✚ The total net area that can be irrigated by Omo River with acceptable failure levels amounts to 142,900 ha.
- ✚ The total installed hydropower and energy production in the basin amounts to 2568MW and 9506 GWh per year, respectively. The increase rate is 6.4% from the previous scenario
- ✚ The average power factor of Gibe III power plant is improved to 0.42 to 0.46
- ✚ Due to the upstream regulation firm energy production from Gibe III power plant is improved by 1.85 % to 5996.22GWh per year with same reliability and the average annual energy is also increased to 6839 GWh per year by 5.45%.
- ✚ And energy production of Gojeb OM 19 amounts to 591GWh per year which is similar and greater than EEPCO studied 516GWh per year.
- ✚ Power production operating level of Gibe III reservoir is simulated about 90% of the time between 856 and 896 a.m.s.l and 95% of the time level is between 842 and 896 a.m.s.l but the average operating level observed to increase to 878.2 a.m.s.l

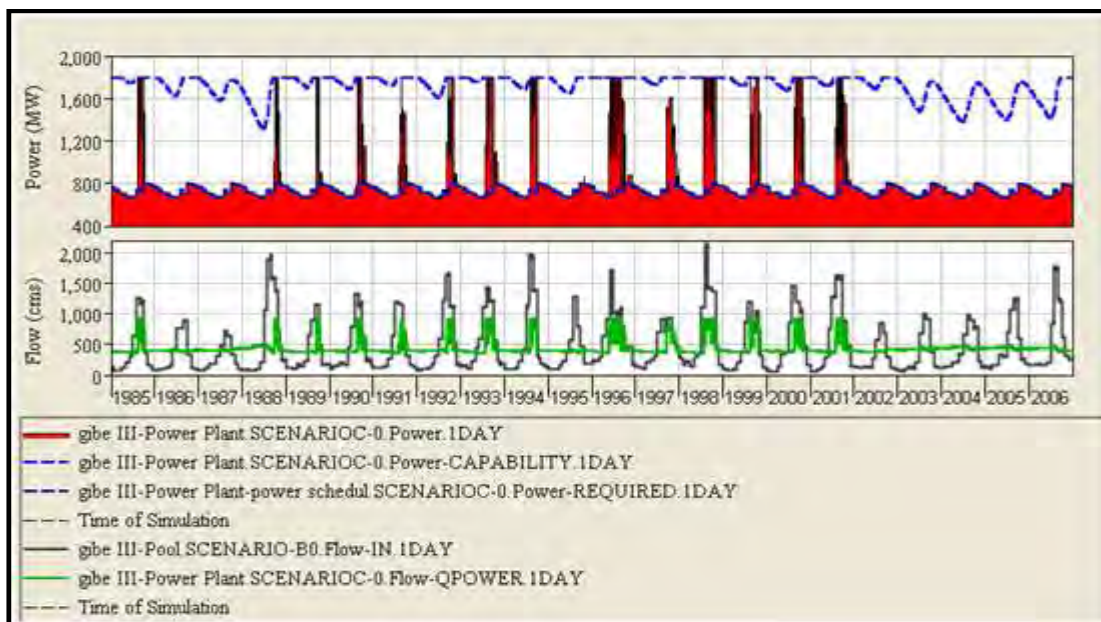


Figure 6-27 Simulated Gibe III power plant operation at scenario C

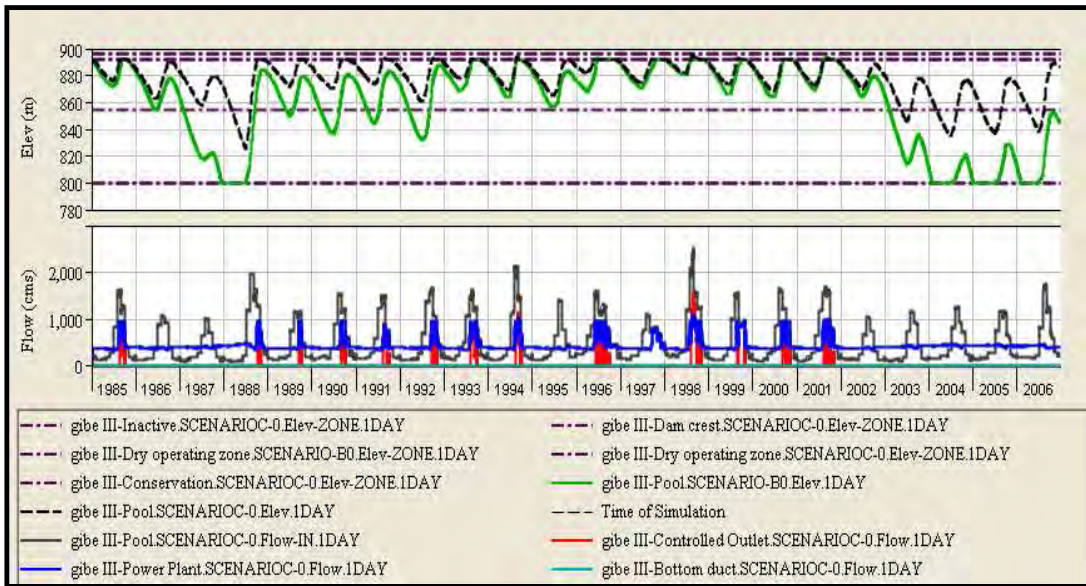


Figure 6-28 Pool level, inflow and outflow for Gibe III reservoir at Scenario B and C

In this scenario also the study has identified modified guide curves and from Fig 6-29 the maximum, minimum and average operation levels of the reservoir can be identified. ResSim outputs for the maximum, minimum and average water level of Gibe III pool in this scenario are 888.30, 857.40 and 878.20 a.m.s.l respectively,

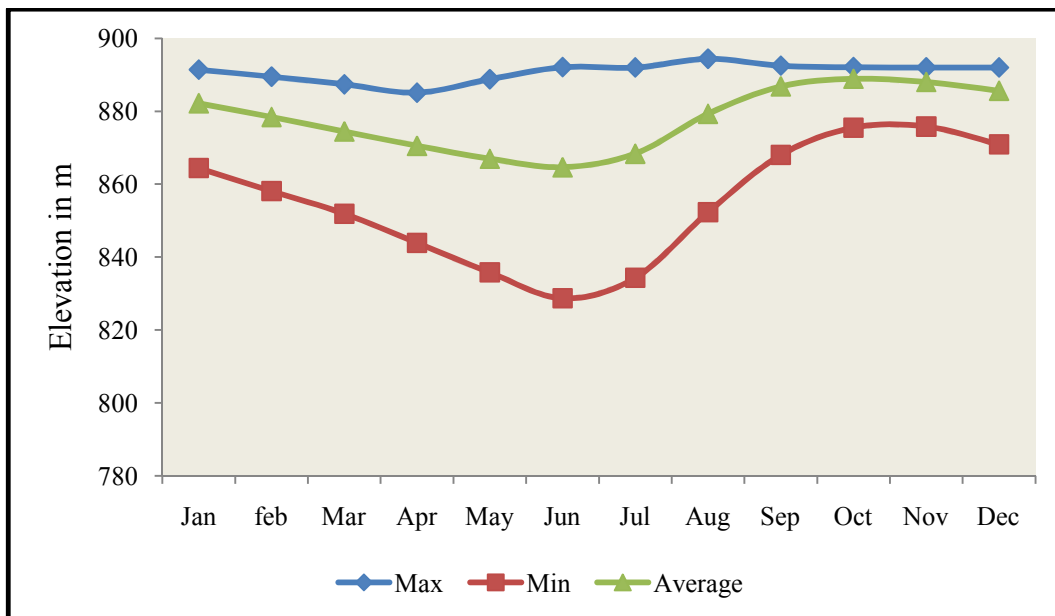


Figure 6-29 Max-Min-Mean water level (Guide curves) at scenario C

In this scenario also the effect of regulation is investigated upstream of the Gibe III reservoir and Omo river below Karadus, and the simulation result is summarised as follow ;

- ✚ The inflow hydrograph at Gibe III dam site will be smoothed with low discharge increased by 40% in February and high discharge decreased by 11% in August. This is illustrated in Fig 6-30
- ✚ Average increases of 137% or 4.1BCM in mean monthly inflows from November to June at Karadus would be observed and decrease in flood season contribution; an average decrease of 27.95% or 4.8BCM in mean monthly inflows from July to October. Fig 6-31 and 30 illustrates these results.
- ✚ The volume of Omo River at without any irrigation in this scenario is 18.3BCM and 16.4BCM after Phase 3 irrigation, 17.6BCM after Phase 2 irrigation and 18.0BCM after Phase 3 irrigation developments.

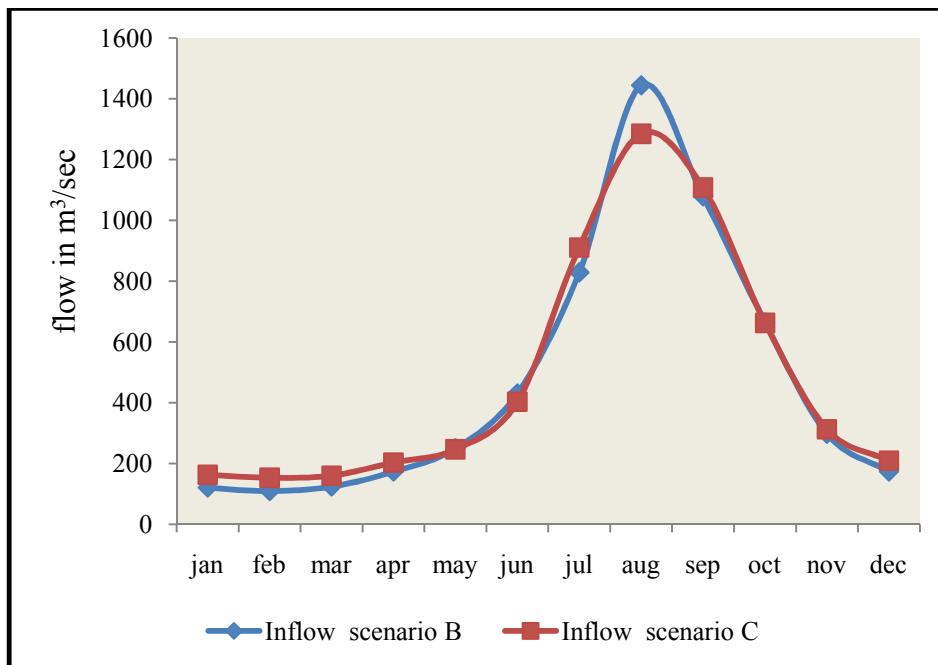


Figure 6-30 Inflow hydrograph at Gibe III dam site for scenario B and C

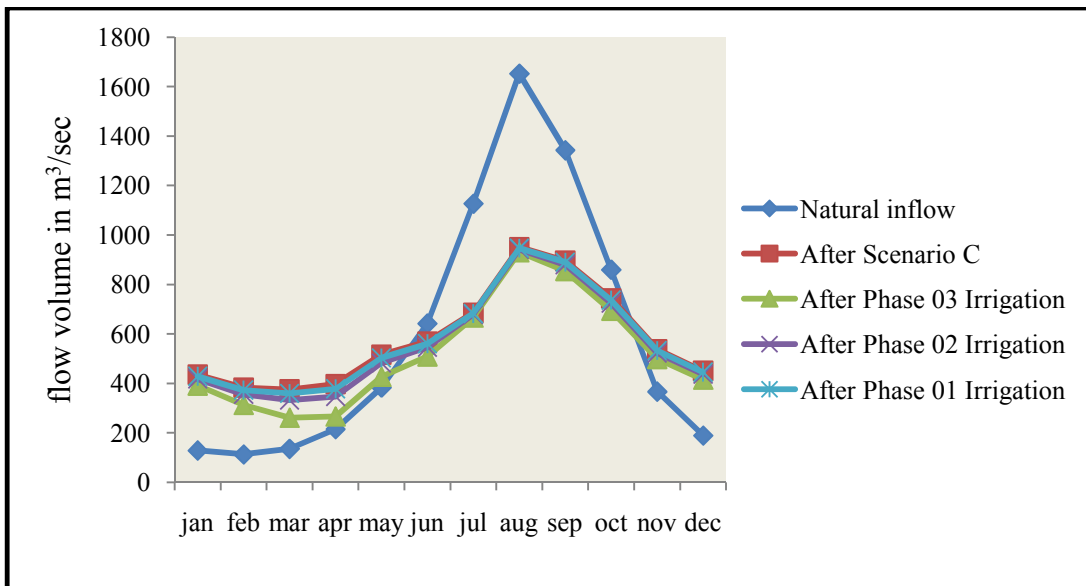


Figure 6-31 Hydrograph of the Omo river before and after scenario C below Karadus

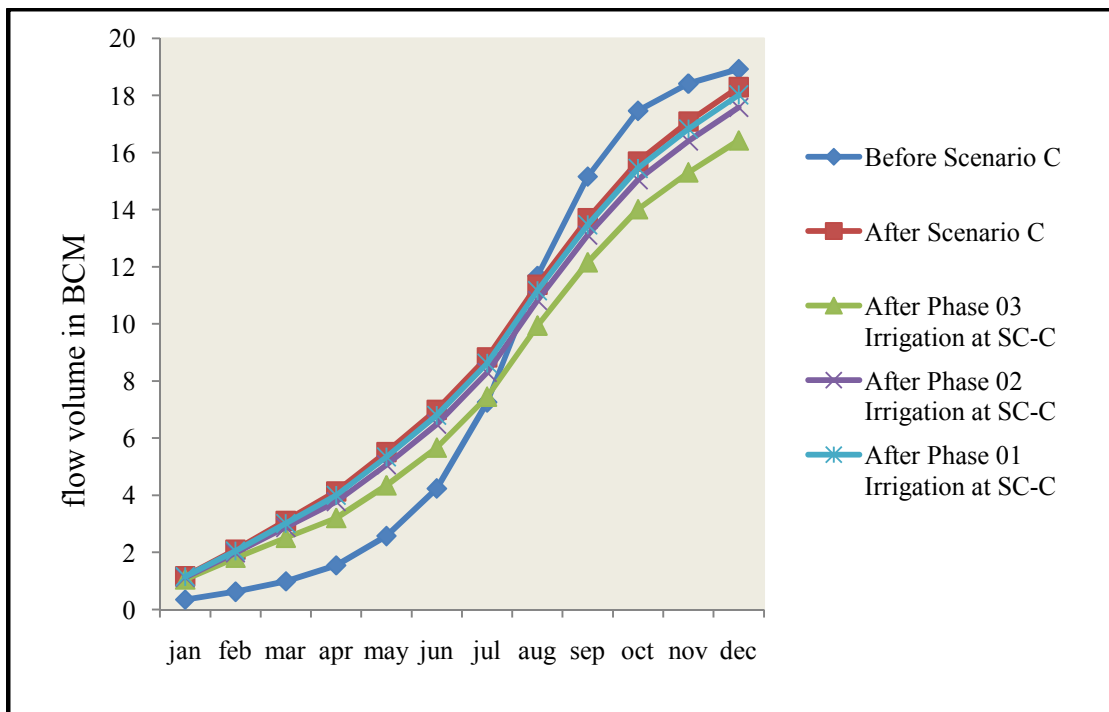


Figure 6-32 Cumulative flow volume of Omo river before and after scenario C

6.2.4 Simulation in Scenario D

HEC- ResSim simulation of this scenario involves intervention of Halele –Warabesa stage I and II cascade hydropower on great Gibe River just upstream from the confluence of Gilgel gibe and great gibe river. With all upstream dam intervention, simulation has shown that about 34 % Gibe III dam inflow is regulated and affected by the outflow from these power plants. The results of simulation can be summarized as follow;

- ✚ Complete development of the proposed power plant leads the basin to have a total installed hydropower and energy production of 3000MW and 11,667 GWh per year
- ✚ Due to upstream regulation firm energy production from Gibe III power plant is nearly same increase by 2.75 % to 6023GWh per year with same reliability and the average annual energy is also increased to 7587 GWh per year by 15.66%. And the average power factor of Gibe III power plant is improved to 0.42 to 0.484
- ✚ The average annual energy production from Halele Warabesa stage I and II amounts to 351, 1615 GWh per year respectively which is close to the required energy.
- ✚ The power intake operating level is simulated about 90% of the time between 858 and 896 a.m.s.l and the average operating level observed to increase to 884 a.m.s.l

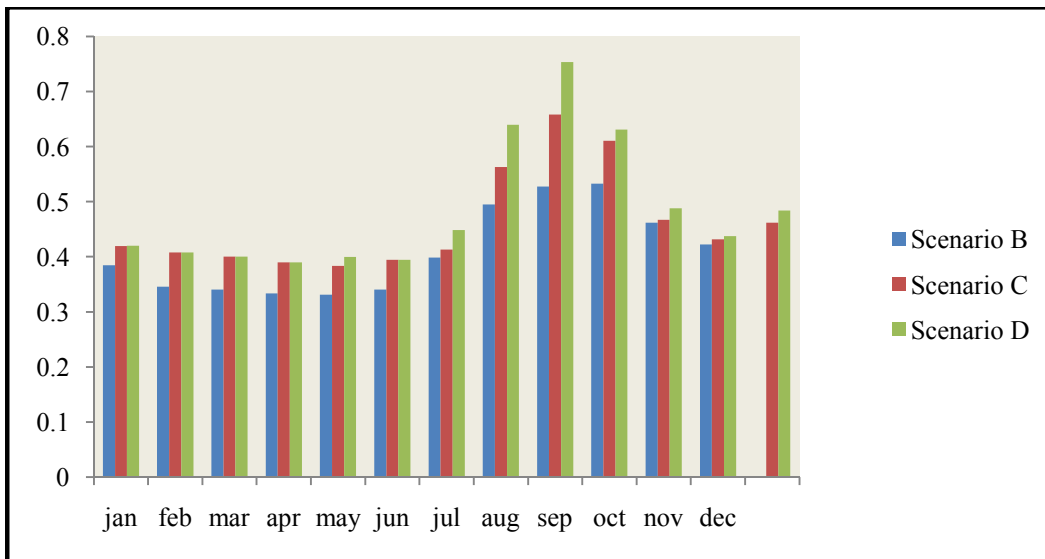


Figure 6-33 Monthly plant factor for Gibe III power plant simulated for each scenario

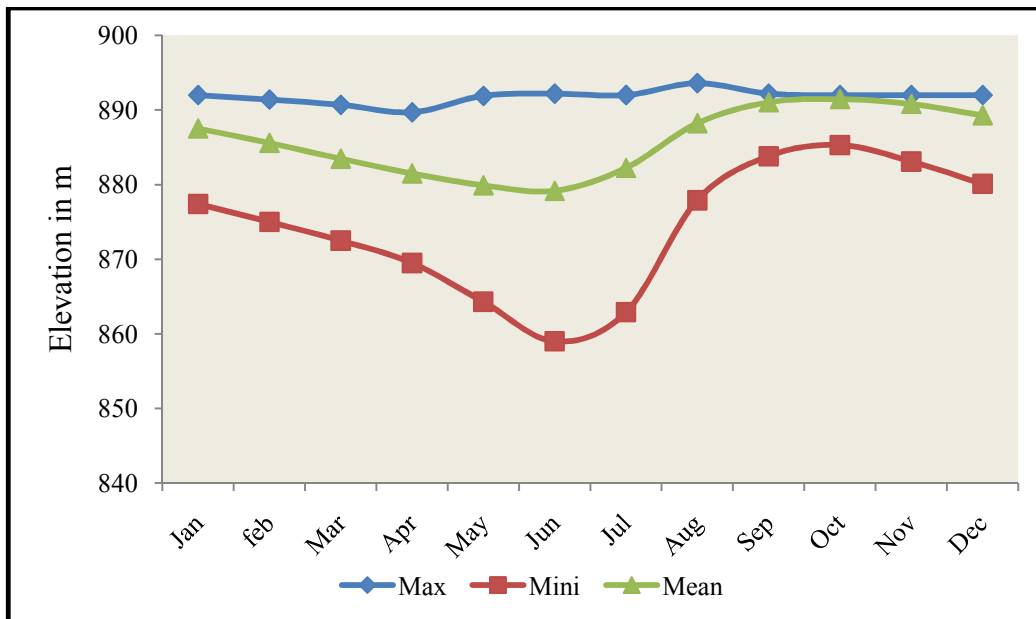


Figure 6-34 Max-Min- Mean pool level (Guide curves) for Gibe III reservoir at scenario D

- ✚ An average increase of 148% or 4.4BCM in mean monthly inflows from November to June and decrease in flood season contribution; an average decrease of 32% or 5.4 BCM in mean monthly inflows from July to October. See Fig 6 -35 through Fig 6-37.
- ✚ Stream flow hydrograph at Abelti hydrometric station is now smoothed with low discharge increased by 14.63% in April and high discharge decreased by 14% in August. This is illustrated by graph below Fig 6-38 and 39
- ✚ Again inflow hydrograph at inflow point to Gibe III is smoothed well with low discharge increased by 120% in February and high discharge decreased by 14% in August. This is illustrated in Fig 6-40

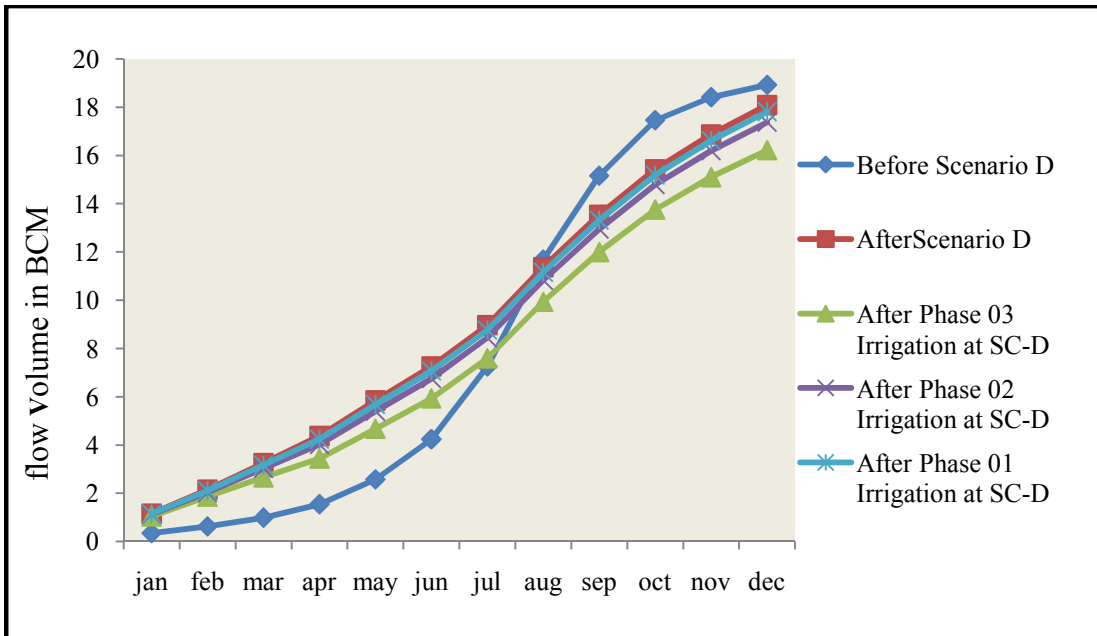


Figure 6-35 Cumulative flow volume of Omo river before and after scenario D

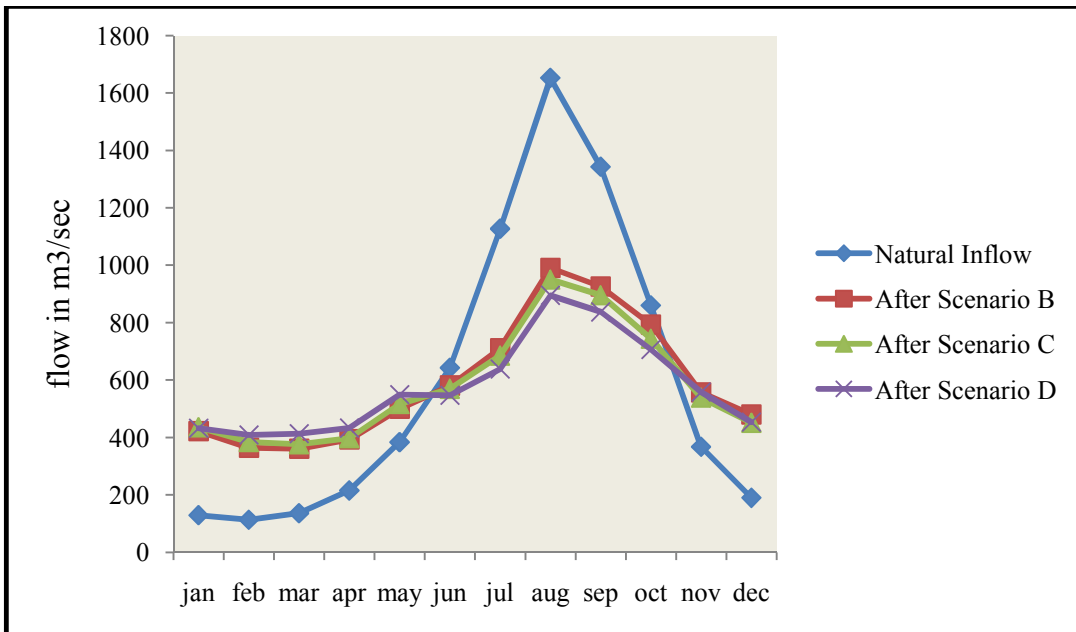


Figure 6-36 Hydrographs before and after HP developments at Karadus

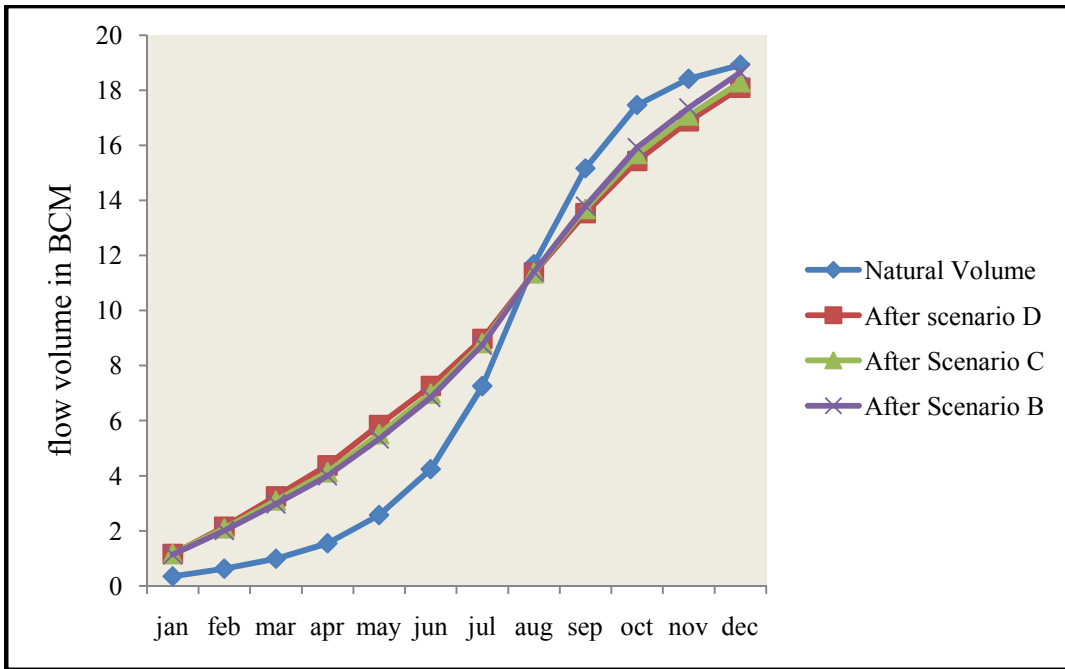


Figure 6-37 Cumulative flow volume Omo river before and after HP developments

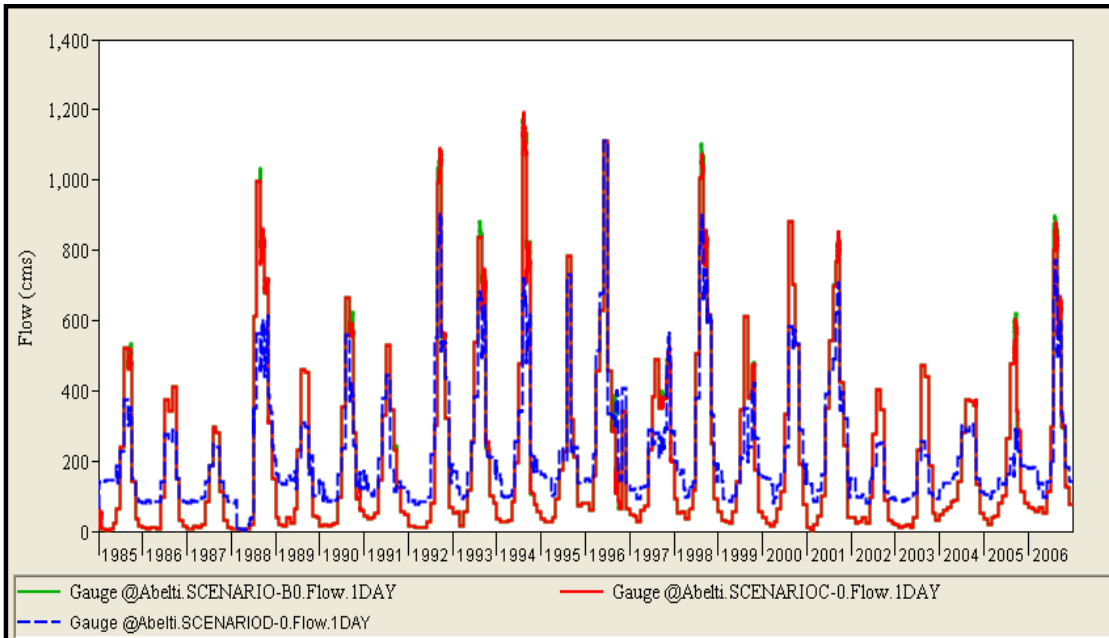


Figure 6-38 Time series at abelti station before and after scenario D

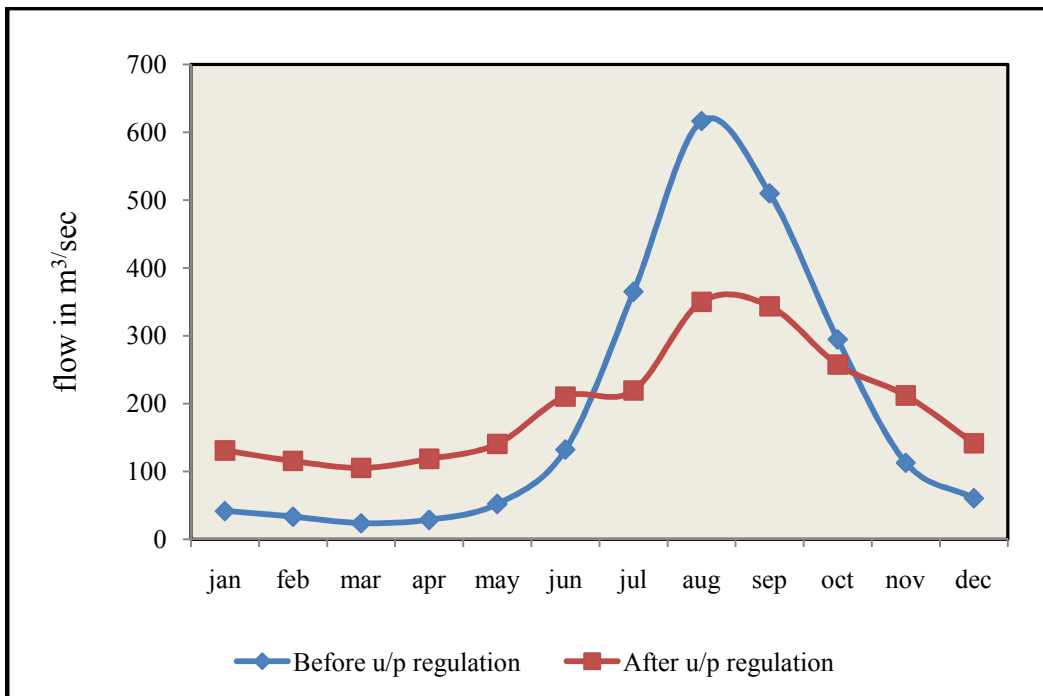


Figure 6-39 Hydrograph at abelti before and after senario D

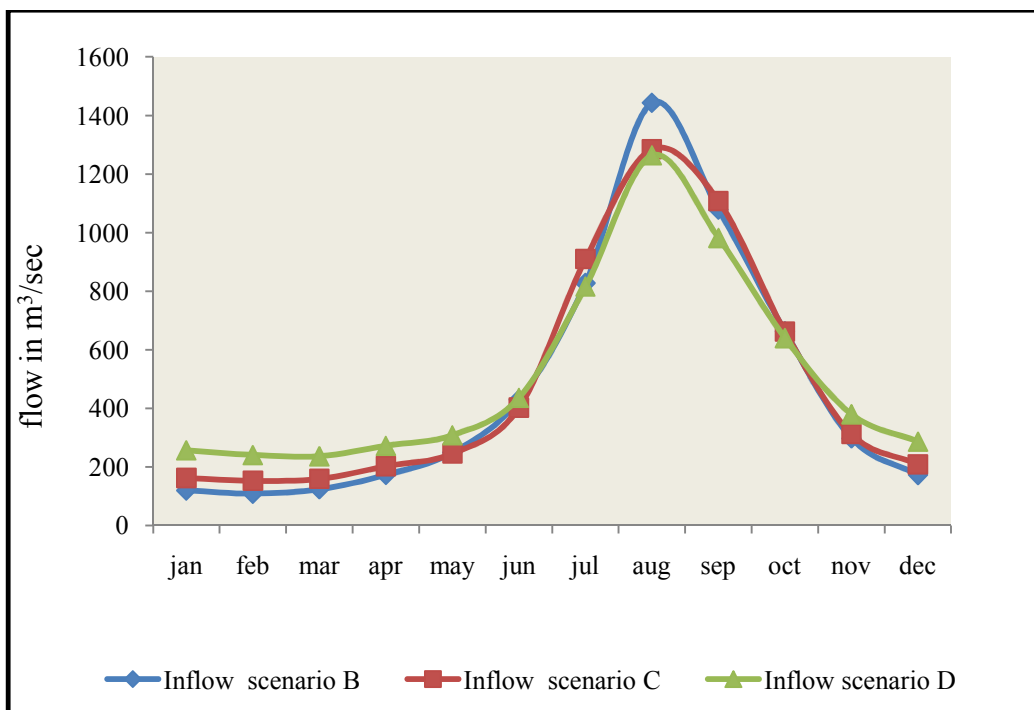


Figure 6-40 Inflow at Gibe III dam site at Scenario B, C and D

7.0 SUMMARY, CONCLUSION AND RECOMMENDATION

7.1 Summary and conclusion

The work conducted in this study is to test the HEC-ResSim ability to simulate the impact of water resource development on basin hydrology. The general objective of the study was to simulate water use and operations of existing, planned and ongoing water resource projects on Omo Gibe river basin (Gilgel Gibe I, II, III, Halele, Warabesa , Gojeb OM19 hydropower projects and a total of 142,000ha irrigated agriculture located in lower omo region) using HEC-ResSim model.

HEC-ResSim model was first set up to simulate gauged flow routing without taking into account effects of development and using this set up hydrological time series comparison against flow data available at the basin outlet, i.e., Karadus hydrometric station, has been done. A good agreement was observed between simulated (routed) and the measured flow at Karadus station, and the Nash-Sutcliffe efficiency criterion obtained for the catchment was 0.782. Following this, the model was reconfigured mainly to simulate four different water resource scenarios named; Scenario A, Scenario B, Scenario C and Scenario D. All of this scenarios deal with existing water infrastructures and projects studied at pre-feasibility, feasibility and detail design stage .the result obtained during simulation are summarized as follows;

The two existing power reservoir are in cascade and ResSim was configured for tandem operation with monthly requirement of the power plant. The average annual energy production using HEC-ResSim was 794GWh/year for Gibe I and 1911 GWh/year for Gibe II. In the current study (tandem operation) the performance of Gibe II power plant was observed to produce an additional 286GWh/year above its requirement (i.e.1635GWh/year).However the average annual energy simulated in Gibe I power plant is nearly same with the current production (i.e.783.2 GWh/year). In addition good storage distribution was examined among reservoirs in the entire simulation period. Simulation run also estimated the annual volume of Omo River at Karadus without any irrigation activities to be 18.9BCM with mean inflow of 596.8m³/sec

The hydrologic impact of the massive dam, Gibe III, was simulated and a long term effects over the period of simulation shown that operation of Gibe III power plant would increase the dry season contribution of the Omo-Gibe river system to the Turkana Lake and decrease in flood season contribution. An average increase of 130% in mean monthly inflows from November to June and decrease of 25% in mean monthly inflows from July to October at Karadus. But the mean annual contribution of the Omo-Gibe to the Lake of will be decrease by 1.14%.

The study also attempted to simulate the Gibe III power plant operational characteristics in the HEC-ResSim model and from which the impact of future water resource development upstream and downstream of the dam was analyzed. Simulation of Gibe III power plant under the current basin condition produced an average annual energy of 6,488GWh/year and power of 758.94MW. The firm energy and power that can be guaranteed 90% of the time are 5885GWh/year, 679.725MW respectively. The average energy obtained is close with EEPCO studied which is 6340GWh/year. The firm energy obtained is also similar and greater than with the energy obtained during reservoir operation studied made by EEPCO (5780 GWh/year).

Table 7-1 Annual average energy ,firm energy and power of Gibe III power plant

Studies	Energy		Power
	AVERAGE	FIRM (90 %)	FIRM (90 %)
	GWh/year	GWh/year	MW
Current study	6486.00	5885.62	679.25
EEPCO(2008)	6340.00	5780.00	1440.00
Kifle (2009)		5410.10	420.00

As per Table 7.1 above current ResSim simulation Gibe III power plant shows almost the same result with the study made by EEPCO. But Melkamu (2009) study has variation on the firm power and energy, and this is the fact that the maximum power pool (or conservation level) for Gibe III reservoir he set was at 873m (sill of the gated spillway). Since the primary purpose of Gibe III reservoir is to generate hydropower, normal flood operation focuses on conserving water in the pool (not spilling).Hence, in the current study it was at 896m.

Gibe III power plant was also configured to operate to meet three likely future irrigation scenarios, (20,670ha of phase 1, and 54,600ha of phase 2 and 142,900ha of phase 3). The analysis of these scenarios revealed that the outermost lower omo irrigated agriculture would affect insignificantly the power production. Simulation under the extreme scenario has shown the average power

production from Gibe III to be 758.74 MW which is 0.025% less as compared to the previous result. Hence the analysis confirms the regulation of Omo River would also increase availability of water for lower omo irrigation projects and will encourage investment in irrigated agriculture. Annually about 1.87BCM volume of water will be diverted into phase 03 irrigation site, 714MCM of water into phase 02 irrigation sites and 270 MCM of water into phase 01 irrigation site.

The likely future development scenarios in Omo Gibe basin are the Gojeb, Halele –Warabesa stage I and II cascade hydropower projects on great Gibe and Gojeb river which are located upstream of Gibe III dam. However, their construction and operation would alter the natural flow regime downstream of the dam. With all upstream dam intervention simulation has shown that about 34 % Gibe III dam inflow will be regulated and affected by the outflow from these power plants. Accordingly the inflow to Gibe III reservoir is affected but little depends on the outflow from Gojeb and Halele I/II plants. Hence due to upstream regulation firm energy production from Gibe III power plant was increased by 2.75 % to 6023GWh per year with 90% reliability and the average annual energy is also increased to 7587GWh per year by 15.66%. Power factor of Gibe III power plant was improved to 0.42 to 0.484. The power intake operating level is simulated about 90% of the time to be between 858 and 896 a.m.s.l and the average operating level observed to increase to 884 a.m.s.l. Moreover annually flow volume of the Omo river after scenario B, C, and D will be 18.60, 18.28, and 18.08BCM without irrigation and 16.2BCM if all the proposed hydropower and irrigation projects are realized, hence 14.15% reduction in volume.

Based on the current and previous studies on water use and operation simulation it can be concluded that HEC-ResSim is a useful tool for assessment of water resource development in Omo Gibe Basin. Moreover there are only few studies that deal with water resource assessment and impact of development at the scale undertaken in the current study. This seems to be a critical step as water management will have to be achieved at this scale. Therefore, HEC-ResSim could be a useful planning and management tool, and not only for Omo Gibe river basin, but also for different basins of country.

7.2 Recommendation

This study has recommended the following important activities to be included in future studies and shall be carried out in the catchment for better management of the basin water.

1. The work conducted in this thesis was by employing HEC-ResSim 3.1 which still does not have ability to simulate the rainfall runoff process in the catchment, as a result outputs for reservoir and power plant simulation was dependent on the discharge inflow into the reservoirs. Hence, it is recommendable to use a stochastically generated time series of rainfall and stream flow instead of the 22 years of historic hydrological data, and maintain the preservation of rivers of the basin.
2. When individual hydropower reservoirs deliver energy and capacity into a common power system, operating the projects as system can often produce more energy or firm energy than the sum of individual projects operating independently. Therefore further study shall be made considering system operation of the existing and planned power reservoirs.
3. Nowadays the sign of climate change and its impact is revealing on different natural and manmade systems, in one or other ways. Accordingly, the study recommends including further refinement of scenarios with impacts of climate change.
4. This study has not considered seepage from all proposed and existing pools; therefore, quantification and simulation of seepage from the reservoir can alter result obtained from HEC-ResSim and mode of operation of a reservoir. Therefore, the study recommends including this parameter in future studies.
5. Implementation of hydrological gauges that can measure the inflows to the reservoirs is recommended and also at least one discharge measure station for the residual basin or reaches between Abelti station and Gibe III dam site. This will show how the river behaves in that reach for further study and practical application. Moreover at downstream of the basin, lower reaches, there were no gauged data except level data to compare the simulated flow. Hence, it is also recommended to setup a stream gauging station on the lower reaches of Omo River so that better validation and calibration of the HEC-ResSim or any applicable model can be made.

REFERENCES

- Awulachew, S. B.; Yilma, A. D.; Loulseged, M.; Loiskandl, W., Ayana, M.; Alamirew, T., 2007, International Water Management Institute: Water Resources and Irrigation Development in Ethiopia 78p, (Working Paper 123), Colombo, Sri Lanka*
- Chow V. T., 1988, Maidment, and L Mays, Applied Hydrology, McGraw-Hill, New York.*
- EEPCO, 2004, Gilgel Gibe II HPP Project: Level 1 Design (Complete Basic Design), Studio Pietrangeli, Salini Costruttori*
- EEPCO, 2007, Gilgel Gibe III HPP Project: RCC- Dam Alternative 3 Power House on the Left River Bank, Studio Pietrangeli, Salini Costruttori*
- EEPCO, 2004, Feasibility Study of Halele – Warabesa Stage II Hydropower Project, Draft Final Report, Lahmeyer International*
- EEPCO, 2006, Gilgel Gibe III HPP, Basic Design: 200 HYD R SP 001 A Hydrological report vol.I, Studio Pietrangeli, Salini Costruttori*
- EEPCO, 2006, Gilgel Gibe III HPP: Basic Design Report, Reservoir operation and Energy production studies, Studio Pietrangeli, Salini Costruttori*
- EEPCO, 2007, Gilgel Gibe III HPP: Level 1 Design, RCC DAM - Alternative 3 Powerhouse on the left river bank, Studio Pietrangeli, Salini Costruttori*
- Hydrologic-Engineering Center, Feb2007, Delaware River Basin Flood Analysis Model: Reservoir Operations and Stream Flow Routing Component U.S. Army Corps of Engineers, Report PR-73, Davis, Calif.*
- Hydrologic-Engineering Center, 2007, HEC-ResSim, Reservoir System Simulation, User's Manual Version 3.0:U.S. Army corps of Engineers, Report CPD-82, Davis, Calif.*
- Hydrologic-Engineering Center, Dec2010, Water Balance and Regulation Alternative Analysis for Kajakai Reservoir using HEC-ResSim, Phase I and II Final Report PR-63, U.S. Army Corps of Engineers, Davis, Calif.*
- Hydrologic Engineering Center, 1998, HEC-5, Simulation of Flood Control and Conservation System, User's Manual, Report CPD-5, U.S. Army Corps of Engineers, Davis, Calif.*
- Hydrologic Engineering Center, 2006b, HEC-DSSVue, HEC Data Storage System Visual Utility Engine, User's Manual, Report CPD-79, U.S. Army Corps of Engineers, Davis, Calif.*

- Jose Alonso Jaimes**, 2009 *Management of Reservoirs in an Operational Forecasting Environment, the Case of the Alberche Basin in Spain*, Msc Thesis, UNESCO-IHE Institute for Water Education, Delft, the Netherlands
- Kemal Abdella**, 2007, *Developing Of Flood Warning and Forecasting System for Omo-Gibe Basin, Ethiopia*, M.Sc. Thesis, Arba Minch University, Ethiopia
- Kifle Melkamu**, 2009, *Evaluation and Multi-Purpose Analysis of Gibe III Hydropower reservoir to Include Downstream Irrigation Development*, M.Sc. Thesis, Arba Minch University, Ethiopia
- Linsley, R.K, and Paulhus, L.H**, 1983, *Hydrology for Engineers*, McGraw-Hill
- Labadie, J.**, 2004, *Optimal Operation of Multi reservoir Systems: State-of-the-Art Review.*" *Journal of Water Resources Planning and Management* 130(2): 93-111.
- McCartney, M.P.**, 2007, *Decision support systems for large dam planning and operation in Africa*, International Water Management Institute, 47p. (IWMI Working Paper 119), Sri Lanka, Colombo
- Maidment, D.R.**, 1993, *Hand Book of Hydrology*. McGraw-Hill, New York
- Ministry of Water Resources**, 1998, *Gojeb Medium Hydropower Project: Main Report, Draft Design Report*, Howard Humphreys & Partners, Coyne et Bellier, Rust Kennedy and Donkin
- McKinney, D.C**, 2005, *International Survey of Decision Support Systems for Integrated Water Management*, Bucharest, Romania
- Subramanya, K.**, 1998, *Engineering Hydrology*, Tata McGraw-Hill 2nd Edition
- Salini and Mid-day**, 2009, *Gibe III Environmental and Social Impact Assessment*, Addis Ababa, Ethiopia
- Simonovic, S.** 1996a, *Decision Support Systems for Sustainable Management of Water Resources: 1. General Principles*", *Water International* Vol 21 No 4
- The World Bank**, 2006, *World Bank Water Resources Assistance Strategy for Ethiopia*, Washington, DC
- The United Nation World Water Development Report**, 2003, *Water for People, Water for Life*, Accessed on line: :< <http://www.unesco.org/wwap/wwdr>>
- Richard Woodroffe & Associates**, 1996, *Omo-Gibe River Basin Integrated Development Master Plan Study Final Report, Vol. VI Water resources Surveys and Inventories*, Ministry of Water Resources, Addis Ababa
- Richard H. McCuen**, 1989, *Hydrologic Analysis and Design*, United States of America

Ralph A. Wurbs, April 2005, *Comparative Evaluation of Generalized River/Reservoir System Models*, Civil Engineering Department Texas A&M University

U.S. Army corps of Engineers, 2007, accessed online HEC-ResSim

:< <http://www.hec.usace.army.mil/software/hec-ressim/hecressim-hecressim.htm>>

U.S. Army Corps of Engineers, 1994, EM 1110-2-1417, *Stream flow and Reservoir Routing*, Chapter9, Washington, D.C.

Vedula, S. and Mujumdar, P.P., 2006. *Water Resources Systems Modeling Techniques and Analysis*

World Energy Council, 2010, *Survey of Energy Resources 2010*, London UK

Yeh, W.W.G., 1985, *Reservoir Management and operation models: A State of The Art Review*.
Water resource Research 21(12):1797-1818

APPENDIX

APPENDIX-A Measured and Generated Stream Flow Data

APPENDIX-B Graphs Plotted to Test Homogeneity of the Stations

APPENDIX-C Graphs Plotted To Check Consistency of the Stations

APPENDIX-D Physical and Power plant characteristics of hydropower dams

APPENDIX-E Standard Graphic Output of HEC-ResSim Model

APPENDIX-A Measured and Generated Stream Flow Data

Table A-1 Mean monthly flow at Abelti hydrometric station [m³/s]

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1985	7.92	4.86	2.91	4.81	20.51	62.81	238.65	519.84	461.63	139.23	35.70	14.83
1986	8.20	6.79	8.38	8.81	7.50	97.13	375.24	350.23	409.88	151.09	30.02	14.31
1987	7.27	5.81	12.38	11.76	20.18	82.71	186.19	297.85	278.54	111.14	32.73	11.73
1988	6.67	6.29	4.52	2.17	4.62	19.94	589.27	993.06	758.43	675.91	308.05	29.71
1989	24.40	16.77	12.21	36.58	20.47	62.43	227.51	459.83	453.48	145.30	41.85	35.68
1990	12.86	15.48	15.17	16.81	19.94	95.03	355.67	663.91	567.07	22.25	389.89	37.10
1991	24.02	20.11	28.80	17.53	41.26	141.50	279.77	477.62	353.96	81.32	12.76	9.10
1992	12.06	16.14	8.63	8.94	25.87	80.42	298.42	960.99	568.56	309.24	79.72	167.55
1993	28.02	33.27	13.63	54.31	117.20	257.56	530.14	839.57	624.50	204.16	92.27	81.64
1994	53.82	11.96	16.41	19.00	82.82	292.71	476.05	1071.05	696.32	110.46	44.40	22.31
1995	12.16	11.43	9.33	31.23	45.82	60.18	186.12	782.41	465.90	74.74	30.80	23.81
1996	167.55	167.55	74.19	63.80	157.58	455.68	629.41	1113.24	456.52	284.88	103.45	63.72
1997	47.25	41.81	25.25	59.52	73.46	230.78	383.93	489.15	350.38	376.84	402.75	198.79
1998	92.46	52.89	55.23	34.47	64.72	117.89	505.73	1004.54	745.09	586.34	248.07	92.69
1999	54.72	30.81	27.91	22.42	54.27	139.42	346.51	611.44	377.14	471.19	173.36	55.02
2000	39.07	22.20	14.90	25.42	63.11	114.48	296.21	524.82	477.63	315.91	149.34	43.33
2001	92.44	27.63	31.15	29.26	67.59	258.81	554.80	723.61	588.80	327.03	140.51	61.12
2002	38.36	22.70	28.09	38.17	20.74	94.63	276.61	401.19	343.88	87.66	32.15	24.49
2003	16.50	9.76	13.02	17.54	8.61	37.84	233.03	473.98	440.55	184.89	52.13	29.10
2004	45.38	61.16	67.89	82.39	89.11	141.89	282.31	373.63	368.53	356.88	131.66	52.28
2005	35.85	18.56	40.39	43.30	78.11	99.25	262.04	475.01	488.05	286.10	110.54	78.37
2006	65.53	62.60	56.53	66.04	49.38	110.72	295.11	798.81	555.01	292.65	126.81	76.73

Table A-2 Mean monthly flow at Gojeb OM 19 dam site [m³/s]

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1985	15.62	12.34	13.08	21.19	64.96	103.65	156.70	224.91	306.25	81.99	41.55	21.89
1986	13.79	14.83	19.16	24.84	33.59	119.42	118.71	152.13	168.84	61.86	25.20	20.82
1987	13.02	11.72	18.25	21.01	33.67	64.88	126.75	143.76	130.46	89.06	59.43	25.92
1988	21.54	18.09	14.14	10.75	27.90	69.17	122.25	307.92	304.47	301.57	43.39	22.09

1989	19.21	17.73	16.70	39.54	36.22	53.32	137.19	126.19	311.97	117.18	39.86	60.15
1990	29.00	26.05	38.15	36.47	45.34	135.36	134.07	256.50	231.66	140.91	46.43	30.01
1991	21.49	18.18	18.76	26.61	37.17	165.86	267.59	175.12	117.25	63.34	29.00	24.40
1992	16.71	18.99	16.16	25.34	67.67	97.29	183.41	187.54	189.41	245.65	66.71	33.87
1993	26.72	27.11	22.55	49.10	117.78	154.48	210.12	168.48	178.32	118.12	50.65	24.83
1994	18.24	13.23	14.29	16.19	38.61	97.55	231.50	280.26	220.16	52.41	37.69	27.46
1995	17.35	14.18	14.12	20.46	46.48	88.43	115.88	168.71	161.74	110.92	36.78	38.89
1996	85.51	85.51	39.57	55.94	96.40	199.70	183.08	192.85	218.04	144.77	40.40	30.90
1997	26.06	17.14	20.04	31.68	63.31	6.69	132.76	152.25	121.46	239.55	8.67	94.73
1998	68.16	33.88	79.37	33.17	98.86	73.86	186.52	369.74	204.11	323.49	64.70	9.01
1999	1.52	0.49	0.36	4.37	64.47	103.30	227.53	199.36	111.50	218.76	43.81	4.28
2000	0.41	0.29	0.21	35.85	122.91	133.32	237.12	229.77	203.77	241.87	118.53	20.34
2001	4.48	1.62	8.52	21.60	50.01	176.90	274.30	352.89	386.58	213.06	122.18	20.37
2002	26.90	28.55	19.47	24.73	21.57	64.35	108.44	156.47	122.57	75.23	22.60	18.55
2003	7.38	4.46	20.47	32.52	19.58	63.82	156.18	165.23	205.18	64.35	26.28	26.44
2004	21.05	19.68	14.76	15.58	40.84	81.41	138.03	188.95	221.10	163.67	17.35	15.89
2005	34.68	26.61	36.77	33.98	93.53	82.38	144.51	259.33	252.37	114.49	54.36	36.01
2006	31.93	34.81	35.84	1.00	1.35	1.78	243.71	333.26	220.91	114.74	72.69	61.42

Table A-3 Mean monthly flow from Wabi river in [m³/s]

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1985	1.10	1.05	0.97	2.32	9.22	17.69	79.46	254.23	63.04	9.32	3.64	10.23
1986	9.77	12.23	18.08	25.91	28.86	51.02	78.52	73.76	79.35	13.04	4.35	3.16
1987	2.52	2.38	11.69	45.46	21.63	32.95	40.92	83.37	25.88	6.96	2.24	1.45
1988	1.54	1.95	1.50	1.31	1.68	15.34	127.18	217.15	120.24	73.19	7.36	3.93
1989	1.63	1.78	1.50	9.04	1.73	10.17	108.62	114.03	84.67	31.21	8.32	3.51
1990	1.81	10.28	25.87	49.88	14.85	51.09	107.55	140.97	74.52	28.92	5.29	2.42
1991	1.51	1.69	2.14	0.99	2.58	6.67	140.70	345.65	78.63	8.32	2.67	1.79
1992	1.76	5.21	3.71	9.69	10.32	46.65	114.95	381.10	91.69	26.57	9.02	5.26
1993	2.58	4.14	1.35	9.07	34.31	26.61	112.25	105.88	68.66	27.85	5.87	2.44
1994	1.31	0.92	2.83	2.94	4.75	7.04	121.45	152.69	77.79	11.47	3.62	2.16
1995	1.45	1.66	1.32	6.47	2.54	10.09	65.89	95.89	54.84	6.67	2.50	1.68

1996	2.85	1.27	9.80	18.90	28.22	116.95	124.27	195.60	44.94	16.71	5.96	2.65
1997	2.50	1.42	2.07	11.79	2.82	4.87	36.55	64.81	15.12	17.94	6.72	2.31
1998	3.31	2.06	5.32	4.16	8.07	15.88	143.27	208.46	90.89	71.73	9.48	4.59
1999	2.17	1.27	2.19	1.63	4.23	16.85	74.46	146.41	32.45	59.19	7.50	2.76
2000	1.51	1.04	0.81	1.76	3.00	5.26	79.39	114.19	53.71	22.83	5.49	3.17
2001	1.60	1.29	2.89	2.04	10.95	36.92	118.26	145.78	59.37	9.04	3.25	1.86
2002	4.28	1.45	2.39	1.89	2.37	13.73	45.03	86.69	27.81	4.77	1.84	1.50
2003	1.30	1.03	1.46	4.47	2.28	6.15	97.79	119.57	37.91	9.08	4.08	1.72
2004	1.83	1.28	2.00	22.81	4.77	16.97	77.90	176.14	68.61	30.40	7.63	4.76
2005	3.99	3.13	5.82	6.19	10.34	9.61	89.48	86.06	92.67	16.96	8.07	5.89
2006	4.50	4.17	10.56	17.41	21.84	15.57	66.49	154.73	76.70	17.47	5.20	3.36

Table A-4 Mean monthly flow from Megech river [m³/s]

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1985	1.25	1.18	1.11	2.42	9.37	9.75	31.05	78.58	48.40	9.51	2.59	1.61
1986	0.77	1.06	1.78	5.29	8.17	26.57	60.95	53.22	57.18	10.05	2.39	1.41
1987	0.90	0.90	6.48	26.25	8.62	30.85	23.19	48.09	31.36	6.33	1.90	1.10
1988	0.91	1.33	1.13	1.09	1.94	3.77	52.07	99.69	53.80	41.97	6.22	2.33
1989	1.37	1.43	1.72	13.30	4.84	7.26	47.92	59.87	39.41	13.58	3.37	2.55
1990	1.34	6.44	14.96	26.35	8.24	26.77	56.53	72.75	40.18	16.71	3.50	1.71
1991	1.11	1.23	1.71	0.76	1.70	3.89	56.62	117.53	38.60	5.49	1.95	1.33
1992	1.24	3.25	2.39	4.97	5.18	20.27	46.31	158.66	48.73	15.45	5.71	3.48
1993	1.84	2.66	0.92	5.62	19.63	19.17	58.92	69.38	37.89	16.31	4.17	1.87
1994	1.11	0.72	1.76	1.86	2.69	5.48	60.77	81.36	37.44	10.97	2.42	1.60
1995	1.19	1.66	1.52	5.93	3.25	2.94	33.27	68.02	57.94	6.88	2.84	2.06
1996	2.44	0.99	7.89	11.76	27.82	80.21	57.88	100.88	26.46	9.95	2.68	1.73
1997	1.69	0.86	1.25	12.11	2.64	2.48	21.42	46.17	15.49	10.88	7.22	2.24
1998	3.09	1.47	2.42	2.84	7.34	10.12	86.92	120.15	59.39	46.25	6.15	2.88
1999	2.26	1.75	1.54	1.21	2.72	9.84	37.59	59.50	21.23	29.30	5.54	2.30
2000	1.86	1.27	1.13	1.22	1.73	2.15	12.02	47.39	35.88	21.43	5.86	2.84
2001	2.04	1.51	2.22	2.13	15.92	35.19	69.75	90.58	37.24	9.72	3.51	2.27
2002	2.63	1.69	2.66	1.94	2.92	11.25	28.96	42.83	21.21	4.26	1.68	1.45
2003	1.26	1.03	1.27	3.07	2.05	4.19	42.31	63.74	36.28	14.60	2.64	1.73
2004	1.55	1.17	1.07	7.32	3.24	5.34	25.14	71.71	31.68	22.37	4.67	2.94
2005	2.79	2.26	3.89	4.11	6.45	6.05	47.63	43.61	36.80	7.99	3.08	1.92
2006	1.40	0.84	3.15	15.18	11.13	9.44	36.14	79.35	41.27	10.49	3.44	2.31

Table A-5 Mean monthly flow from Weyobo river [m³/s]

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1985	1.85	1.89	2.28	3.69	2.43	2.52	3.40	2.03	1.93	1.86	1.83	1.78
1986	1.80	1.81	1.84	3.06	2.43	2.34	3.56	2.14	1.91	1.84	1.88	1.82
1987	1.82	2.95	2.25	2.25	2.66	1.91	2.33	3.01	2.23	1.86	1.84	1.93
1988	1.86	1.86	2.65	2.41	2.01	4.95	7.06	3.37	2.82	1.82	1.78	0.53
1989	0.69	0.49	0.96	0.73	1.15	3.78	5.27	8.45	5.16	1.59	1.00	0.55
1990	0.88	0.80	1.18	0.98	0.79	3.65	4.03	5.17	2.56	0.93	0.56	0.45
1991	0.50	0.75	0.51	0.97	0.92	2.77	3.61	6.71	2.45	0.75	0.65	0.50
1992	0.80	0.57	1.27	0.97	0.91	1.94	6.64	10.35	9.22	2.18	0.89	0.63
1993	1.15	0.47	0.91	5.54	4.12	3.24	5.43	4.98	2.05	0.91	0.53	0.43
1994	0.39	0.51	1.02	2.92	2.91	7.93	10.38	6.01	2.16	0.83	0.58	0.45
1995	0.40	0.61	0.88	1.23	0.97	2.25	3.95	7.61	3.88	1.01	0.58	0.54
1996	0.40	0.87	1.56	4.38	10.98	8.75	8.21	12.16	6.06	1.48	0.82	0.56
1997	0.45	0.42	2.47	3.27	1.34	2.48	3.53	2.88	9.43	7.70	3.23	1.66
1998	0.69	1.32	1.44	3.70	4.19	10.22	19.66	8.56	10.67	4.19	1.34	0.77
1999	0.56	0.57	0.79	1.68	1.17	3.22	6.43	5.60	16.51	3.00	0.86	0.57
2000	0.46	0.39	2.66	8.78	3.50	5.04	3.02	3.86	4.20	1.91	0.82	0.49
2001	0.43	0.54	1.00	1.14	0.80	4.24	13.56	9.83	6.79	1.67	0.77	0.55
2002	0.47	0.76	1.02	0.70	1.24	1.10	1.77	2.37	2.03	0.65	0.57	0.47
2003	0.43	0.53	0.51	0.52	1.44	5.01	5.83	3.00	1.95	1.95	1.98	2.03
2004	1.96	1.96	2.06	2.12	1.36	0.97	4.11	2.52	3.76	1.13	0.63	0.52
2005	0.49	0.75	0.65	9.73	1.62	1.59	7.85	8.35	2.31	2.26	1.68	1.40
2006	1.45	1.40	1.40	5.19	1.88	2.20	12.37	5.32	3.29	1.90	2.23	2.31

Table A-6 Mean monthly flow from Soke river [m³/s]

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1985	0.79	0.79	0.94	3.03	12.36	3.88	4.44	10.29	6.77	3.05	2.03	1.41
1986	1.09	1.08	1.60	1.11	1.71	3.58	11.41	11.45	11.73	6.05	2.17	1.50
1987	1.11	1.02	1.05	1.06	3.20	2.55	2.17	6.19	4.49	6.38	1.94	1.23
1988	0.94	1.11	0.83	1.13	0.95	2.08	8.89	23.06	1.40	1.40	5.17	2.18
1989	1.78	16.67	1.08	1.60	1.28	2.25	5.10	5.60	11.05	6.63	3.11	2.89
1990	1.51	2.13	2.31	2.44	1.79	1.83	2.90	6.24	5.49	3.76	1.96	1.27
1991	1.11	1.62	1.27	1.10	1.12	1.11	4.40	8.71	23.58	7.55	2.31	1.46
1992	1.36	1.91	1.30	3.23	2.11	2.35	21.08	24.00	34.99	26.60	8.20	2.56

1993	1.84	2.03	1.17	1.44	9.52	6.17	6.05	9.81	6.12	4.39	2.28	1.39
1994	1.04	0.91	1.36	1.41	10.12	6.06	11.28	14.18	12.23	4.21	1.94	1.23
1995	0.87	0.86	1.47	1.93	2.77	1.82	3.67	9.82	15.51	6.44	2.91	1.73
1996	0.78	1.41	2.00	5.02	9.22	14.59	11.80	14.14	26.17	9.56	5.03	8.52
1997	2.23	1.51	1.30	2.10	3.36	2.77	5.19	6.39	25.19	17.14	13.18	2.89
1998	4.09	4.40	2.37	2.24	8.20	6.99	12.86	25.83	15.72	15.04	10.89	2.77
1999	1.96	1.49	1.46	1.40	1.49	1.75	3.07	5.66	6.68	14.99	4.74	3.46
2000	1.40	0.99	0.72	1.48	1.88	1.48	2.96	5.11	6.01	7.14	3.53	2.30
2001	1.76	0.94	1.02	1.64	2.36	2.01	7.79	14.27	11.17	9.60	4.44	1.98
2002	1.48	1.24	1.38	1.19	1.58	2.25	2.90	5.73	9.96	3.70	1.80	2.15
2003	1.31	1.11	1.72	1.91	0.80	3.03	3.46	8.95	10.70	1.40	1.40	1.61
2004	1.91	1.51	1.51	2.09	2.49	1.22	4.24	6.73	7.08	13.46	3.25	1.68
2005	1.39	1.16	1.39	3.95	14.10	6.85	8.88	8.18	7.83	1.68	2.26	1.68
2006	1.40	1.45	1.40	1.40	8.13	3.90	4.31	17.03	9.86	6.47	2.94	1.87

Table A-7 Mean monthly flow from Deme river [m³/s]

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1985	2.49	2.49	2.90	7.71	24.70	9.46	10.58	21.24	4.67	3.43	2.57	2.19
1986	1.61	1.88	1.93	2.32	17.15	9.46	8.39	23.10	5.96	3.21	2.35	2.80
1987	2.10	2.07	15.78	7.25	14.92	12.23	3.13	8.31	16.51	6.35	2.54	1.99
1988	2.41	2.89	1.97	12.56	7.55	4.48	42.85	59.87	21.33	15.03	2.65	1.32
1989	1.87	1.89	1.93	6.61	7.96	6.78	6.49	7.60	13.85	24.49	2.79	5.35
1990	2.12	4.38	6.75	4.14	3.58	2.49	6.79	12.05	7.29	2.61	0.89	0.57
1991	1.07	1.14	2.60	1.20	6.58	7.06	11.98	6.95	20.51	1.32	0.45	0.43
1992	0.34	0.64	0.68	11.08	22.24	16.83	34.16	69.86	40.77	17.25	6.26	4.21
1993	11.28	10.61	5.08	9.01	34.17	19.39	6.44	13.72	3.68	3.71	1.38	0.37
1994	1.98	1.99	2.23	4.46	9.51	4.57	50.09	50.09	26.83	15.13	16.38	8.85
1995	5.42	3.61	1.52	11.07	11.32	19.77	37.64	18.53	17.00	4.82	2.70	1.23
1996	1.59	1.16	17.02	17.77	15.04	54.70	23.54	51.97	51.01	8.19	7.34	5.81
1997	4.38	4.04	3.80	21.48	11.27	7.71	17.81	10.05	3.99	36.48	69.57	7.34
1998	7.26	6.08	5.12	6.30	9.50	26.18	21.14	22.22	7.81	25.50	4.88	3.54
1999	3.24	3.48	5.62	15.61	6.97	14.81	17.49	18.53	9.75	15.07	5.73	4.21
2000	3.09	2.66	2.68	8.26	48.17	15.06	26.18	35.44	10.11	9.91	6.04	2.81
2001	1.85	1.73	3.46	5.98	26.60	12.40	20.89	16.85	16.27	12.96	2.79	2.59
2002	1.98	1.07	4.72	4.70	6.43	1.58	4.39	12.59	6.95	3.42	1.87	6.54

2003	3.73	1.55	6.06	43.38	5.68	7.88	23.00	51.32	16.40	3.60	3.60	4.05
2004	4.64	3.83	3.83	4.97	5.71	3.11	14.29	11.33	10.23	9.39	6.72	4.46
2005	3.79	4.12	8.67	24.76	56.00	8.14	26.48	20.09	64.52	12.87	9.61	2.79
2006	2.99	4.00	9.35	27.44	10.65	10.91	14.67	49.71	17.47	15.69	10.86	8.13

Table A-8 Mean monthly flow from Zege river [m³/s]

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1985	10.28	10.28	10.64	14.69	29.03	16.17	17.12	26.11	12.13	11.08	10.36	10.04
1986	9.54	9.77	9.82	10.15	22.66	16.17	15.26	27.69	13.21	10.90	10.17	10.55
1987	9.96	9.94	21.51	5.81	14.40	1.48	0.79	3.44	5.48	19.42	10.38	10.14
1988	11.08	10.36	10.39	2.28	7.52	2.29	39.94	50.06	22.47	35.61	1.50	0.05
1989	0.03	0.20	0.26	12.26	6.84	10.89	20.30	8.50	22.99	27.03	1.79	2.75
1990	1.80	11.75	15.02	20.52	20.39	4.72	4.08	20.82	10.60	6.33	0.32	0.14
1991	0.05	0.08	1.06	9.40	15.65	3.18	14.66	4.98	39.38	1.84	1.44	0.03
1992	1.01	0.36	0.31	1.45	26.79	16.57	44.82	33.91	79.64	85.99	4.20	0.77
1993	1.57	24.42	7.29	12.33	31.99	53.49	10.94	6.15	8.26	13.00	14.37	3.41
1994	0.63	0.15	0.00	33.83	86.68	31.13	42.65	147.58	35.91	32.85	18.49	1.86
1995	12.76	11.24	5.88	21.79	35.34	14.80	14.36	18.54	80.11	43.80	5.85	0.60
1996	1.08	0.68	17.60	49.17	52.63	129.80	49.33	76.30	96.36	13.97	3.73	10.05
1997	9.92	10.01	10.01	9.18	42.31	8.33	41.02	27.35	15.66	63.37	159.42	64.12
1998	11.25	3.51	11.91	8.80	36.67	10.49	57.18	41.62	16.40	69.23	26.81	1.57
1999	0.82	0.42	0.03	2.51	4.09	3.74	34.14	35.41	30.86	61.14	33.71	6.75
2000	0.85	10.51	10.73	3.08	54.84	13.07	33.26	44.36	27.12	46.58	15.88	1.31
2001	0.67	9.85	2.90	48.33	94.71	49.48	13.19	56.29	64.29	42.95	20.88	3.44
2002	1.79	0.73	8.64	21.11	37.50	6.70	6.07	19.94	14.51	16.37	2.58	5.63
2003	4.93	3.93	62.58	28.07	24.05	18.35	12.99	97.71	14.92	10.07	11.22	11.60
2004	12.11	11.42	11.42	7.89	18.64	15.41	3.16	9.27	60.93	11.30	3.98	5.10
2005	0.50	10.57	0.35	2.94	76.00	44.36	17.07	17.23	1.83	24.57	21.49	11.34
2006	12.27	13.64	10.18	27.59	16.75	7.54	7.97	22.43	22.04	20.91	12.38	8.42

Table A-9 Mean monthly flow from Gumma river [m³/s]

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1985	4.70	4.08	4.59	17.62	66.01	99.80	127.09	164.22	127.56	63.83	19.42	12.76
1986	7.46	6.43	11.05	24.62	32.02	105.61	119.57	105.51	92.36	40.83	17.33	15.03
1987	8.38	4.74	6.47	12.69	48.95	66.38	61.32	83.33	87.32	32.11	25.97	25.74
1988	10.14	5.27	4.21	5.35	12.93	40.16	84.05	189.04	153.35	152.72	22.08	14.87
1989	7.70	7.02	7.94	41.33	20.88	57.47	89.74	104.42	105.52	73.33	20.64	9.81
1990	5.94	6.48	22.51	36.09	64.82	116.68	90.28	143.05	134.96	67.42	21.07	23.13
1991	49.72	77.78	67.65	9.48	8.55	18.15	117.03	136.02	137.71	49.76	15.44	19.40
1992	29.44	32.93	12.42	11.52	55.40	87.39	79.56	114.52	126.60	189.41	39.74	12.37
1993	13.74	18.72	17.97	41.96	92.95	121.19	107.96	83.52	104.50	88.35	25.73	13.95
1994	16.85	7.58	14.08	11.56	60.89	132.20	137.17	134.79	100.44	25.72	23.28	14.59
1995	9.86	8.72	4.29	12.93	28.50	56.34	83.75	117.72	130.73	46.64	13.05	13.13
1996	18.68	10.12	23.33	46.82	97.83	136.70	105.18	122.19	138.48	75.72	17.34	12.05
1997	13.33	7.16	18.62	57.35	93.76	173.68	143.31	100.33	77.97	140.42	150.80	10.98
1998	47.98	28.19	32.44	38.55	143.26	144.00	144.39	269.86	125.72	205.73	28.94	63.56
1999	8.61	2.91	7.58	18.32	34.08	51.58	82.98	67.21	56.76	92.10	19.79	10.27
2000	4.92	4.38	6.02	9.59	23.77	23.97	89.24	40.04	45.99	104.98	17.71	8.92
2001	5.72	5.83	6.82	11.48	58.02	127.14	104.29	120.80	149.80	79.22	23.28	8.91
2002	20.22	13.82	16.85	27.04	24.12	31.83	77.02	76.60	58.79	31.06	22.86	22.85
2003	18.40	15.07	14.50	27.61	23.42	93.84	104.83	129.49	132.80	38.59	20.68	18.33
2004	16.64	13.55	12.71	23.30	59.50	73.11	49.80	136.08	129.82	81.41	27.17	25.39
2005	17.97	13.90	19.72	27.29	80.35	73.93	81.03	118.74	140.63	59.18	48.88	37.52
2006	26.32	21.19	25.95	30.18	61.95	97.18	135.51	138.90	79.02	54.99	42.72	38.91

Table A-10 Mean monthly flow from sherma river [m³/s]

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1985	5.49	2.04	1.27	8.41	88.66	106.69	109.08	167.92	159.04	40.19	10.63	5.76
1986	2.25	3.68	5.45	9.99	33.55	101.89	68.36	123.78	92.88	31.63	9.44	7.75
1987	2.16	0.87	1.43	4.20	11.86	25.18	64.98	62.41	65.44	56.88	43.55	9.02
1988	6.49	3.42	1.92	1.12	27.02	35.02	47.25	193.63	197.91	161.32	13.68	7.61
1989	3.49	3.13	2.60	6.66	18.12	54.53	79.41	99.02	117.47	67.59	22.01	11.74
1990	9.40	5.14	22.61	42.08	59.72	122.27	81.64	182.16	163.40	80.83	18.92	8.52
1991	4.22	2.11	6.18	14.83	47.86	55.88	140.74	127.58	99.90	31.47	12.14	8.87
1992	3.42	3.23	1.68	5.51	29.02	69.64	112.65	79.18	132.47	197.05	41.17	20.57
1993	15.51	11.73	24.72	29.11	80.25	73.53	99.29	80.33	49.58	46.40	13.17	5.37
1994	2.25	0.76	0.92	5.04	38.88	99.71	114.76	115.91	111.13	25.41	26.77	11.71
1995	2.51	0.68	0.65	6.62	33.66	57.43	70.77	57.46	96.41	56.73	14.67	16.73
1996	12.83	4.38	11.12	43.04	54.17	127.30	71.87	87.89	111.78	70.77	15.01	5.93
1997	11.61	4.14	3.93	19.02	42.55	104.58	69.09	53.91	34.39	127.52	244.35	8.69
1998	21.49	9.80	19.18	9.42	84.08	59.64	57.56	144.65	74.50	282.32	78.29	18.30

1999	2.26	0.40	1.85	15.78	145.26	126.21	255.36	171.91	142.48	251.48	34.53	4.91
2000	2.69	1.28	1.01	1.23	10.00	20.07	117.01	36.87	40.74	116.45	22.86	6.76
2001	1.95	1.55	1.34	3.45	26.15	123.58	125.47	136.75	147.54	85.55	12.95	12.70
2002	7.03	4.74	5.63	18.12	13.49	17.60	56.55	104.85	38.87	26.15	12.76	11.17
2003	6.59	4.41	4.65	11.34	8.03	31.18	66.94	76.93	91.52	23.54	7.62	8.89
2004	5.11	5.61	3.73	5.41	30.19	59.57	45.62	95.10	84.00	63.89	11.49	10.44
2005	6.97	4.39	5.00	6.17	33.75	36.13	46.27	48.64	99.56	39.75	14.86	6.24
2006	3.48	3.35	3.82	5.16	8.79	10.35	11.53	107.32	78.06	43.74	29.22	25.17

Table A-11 Mean monthly flow from sherma river [m³/s]

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1985	1.81	1.89	2.66	44.78	41.92	21.97	23.40	13.22	6.37	5.03	4.33	2.34
1986	0.56	0.43	2.06	9.38	17.45	22.88	13.51	8.44	10.48	8.34	6.10	10.71
1987	5.34	4.82	5.28	6.96	17.86	15.78	7.26	6.46	6.30	9.80	8.50	7.03
1988	6.39	5.56	5.07	8.50	11.34	9.19	40.07	27.62	18.59	24.45	10.84	8.07
1989	6.83	8.67	8.16	17.15	14.48	12.51	26.09	13.29	22.03	24.76	9.74	14.48
1990	11.67	11.50	17.35	21.39	13.66	8.65	8.03	12.10	8.18	9.62	8.02	6.38
1991	5.99	5.91	5.29	8.10	11.51	8.73	12.00	22.34	14.09	19.76	8.95	7.97
1992	9.29	10.01	6.28	7.46	19.15	12.76	8.48	7.30	6.96	19.02	9.05	8.15
1993	5.13	5.16	6.96	9.11	20.37	12.53	17.05	22.73	9.04	9.81	15.85	8.72
1994	6.17	5.44	6.34	13.69	17.80	9.85	13.78	8.60	13.78	14.52	8.23	6.66
1995	7.71	5.70	7.00	14.24	11.42	31.36	21.76	14.79	16.19	7.58	6.17	5.68
1996	7.71	5.70	7.00	14.24	11.42	31.36	21.76	14.79	16.19	7.58	6.17	5.68
1997	5.18	4.67	4.76	12.25	13.56	6.58	22.78	11.12	6.61	14.49	21.25	12.91
1998	16.45	10.65	6.90	13.69	13.37	11.47	15.34	26.17	8.33	15.66	10.18	5.21
1999	4.64	3.95	5.43	7.56	7.45	5.14	8.31	6.74	6.21	11.88	5.87	3.45
2000	2.64	2.28	2.47	3.48	5.87	4.39	7.17	17.16	7.06	21.76	7.18	4.03
2001	3.40	3.05	4.77	11.92	14.99	11.93	5.76	10.60	10.41	13.50	8.31	3.61
2002	3.53	2.49	3.87	5.11	8.72	1.93	1.59	2.73	1.47	2.97	1.91	3.95
2003	3.70	1.59	1.91	3.50	8.97	5.02	3.19	19.49	13.85	14.42	14.99	17.37
2004	16.82	18.66	14.69	13.68	3.54	3.43	2.36	3.70	3.46	3.50	3.55	3.03
2005	2.28	1.73	3.01	4.16	11.40	4.51	3.86	4.75	7.54	3.97	2.99	1.59
2006	1.40	1.48	2.31	8.76	8.34	5.17	3.10	6.27	3.22	5.32	5.48	4.61

Table A-12 Mean monthly flow from Gilgel gibe at river Assendabo hydrometric station [m³/s]

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1985	2.55	1.66	1.24	5.57	12.83	73.96	69.81	108.10	90.13	36.79	12.67	5.97
1986	2.10	2.56	4.07	3.56	4.35	34.18	74.13	67.82	85.90	32.94	10.23	6.99
1987	3.24	0.51	7.39	5.47	15.95	41.43	57.13	61.31	76.38	35.47	15.15	4.03
1988	3.86	4.28	1.64	1.44	3.42	10.71	56.06	155.48	121.66	94.75	20.49	7.34
1989	4.83	4.98	3.50	21.12	11.39	27.30	52.12	76.33	77.67	41.57	14.92	17.09
1990	8.14	6.42	9.60	8.88	16.27	48.58	90.96	75.87	120.02	5.77	92.54	9.47

1991	6.22	5.23	7.41	4.58	10.50	34.66	67.09	112.65	84.26	20.26	3.37	2.43
1992	0.63	1.45	3.12	3.21	10.70	42.22	85.17	186.76	118.13	74.54	19.88	7.71
1993	7.22	8.52	4.56	14.32	27.07	51.94	94.43	138.18	108.15	49.44	22.90	20.06
1994	5.82	3.16	4.30	4.95	21.37	70.09	126.42	167.50	124.17	27.26	11.27	5.79
1995	3.21	3.03	2.49	8.02	11.62	15.14	45.20	64.82	78.15	18.67	7.91	6.16
1996	36.39	36.39	18.54	16.36	34.58	88.24	86.99	123.00	89.59	45.84	17.13	16.34
1997	6.50	3.21	2.40	17.08	26.16	70.07	69.82	104.23	71.64	71.19	125.28	53.42
1998	28.42	16.10	16.27	11.70	20.59	30.14	84.70	171.24	99.16	84.52	34.15	14.90
1999	10.07	5.87	7.30	6.05	16.58	35.55	79.59	108.69	59.56	72.57	26.01	11.01
2000	6.36	3.83	2.38	7.27	19.90	29.80	62.93	82.78	87.82	75.47	36.51	11.01
2001	22.94	23.58	24.68	23.97	36.55	67.65	117.56	106.54	77.50	49.86	29.78	15.36
2002	9.78	5.88	7.23	9.74	7.13	29.69	57.77	76.41	61.24	21.91	12.23	12.61
2003	10.64	5.28	9.01	10.01	5.74	24.30	80.97	85.15	94.59	30.78	12.74	9.90
2004	6.46	4.95	4.12	6.70	13.44	32.60	65.19	99.09	95.64	77.73	20.45	13.21
2005	9.16	4.84	10.28	8.79	40.68	34.71	67.98	129.46	125.73	51.90	19.70	9.88
2006	7.69	9.23	9.79	12.12	14.40	35.93	121.09	169.05	108.89	52.03	29.52	23.48

Table A-13 Mean monthly flow from Walga river [m³/s]

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1985	1.04	0.93	0.77	1.51	4.39	8.02	57.56	108.08	30.97	9.59	2.33	1.43
1986	1.09	1.17	1.36	2.94	3.20	18.16	55.78	53.33	44.39	8.30	2.63	1.43
1987	1.10	0.94	3.13	3.74	4.42	14.98	27.11	67.93	38.90	4.47	1.52	1.53
1988	0.76	1.17	1.92	1.87	1.63	4.84	65.46	126.16	85.92	29.53	4.57	1.52
1989	1.29	1.17	1.28	4.69	2.91	5.58	46.42	69.69	46.98	10.29	2.43	1.74
1990	1.15	1.84	3.04	4.61	2.12	6.16	29.61	68.34	30.89	10.22	1.68	0.77
1991	0.75	0.49	0.93	0.38	0.53	2.97	28.22	48.94	13.24	2.93	1.42	1.54
1992	1.38	2.37	1.23	2.77	3.14	8.37	37.97	141.30	77.64	19.58	2.97	1.53
1993	2.43	6.07	11.40	10.07	7.42	30.71	90.30	124.26	96.12	23.82	4.70	3.31
1994	1.85	1.38	1.34	1.39	1.24	4.14	51.30	90.15	40.23	5.72	67.89	35.98
1995	0.81	0.66	0.59	2.85	1.70	2.90	17.15	69.67	35.71	5.56	1.24	1.45
1996	1.38	0.37	2.99	4.93	8.17	49.52	84.74	110.79	43.45	11.90	3.22	1.54
1997	1.55	0.91	0.93	2.62	2.14	7.38	31.27	34.58	14.21	5.54	2.88	1.47
1998	1.35	1.02	1.81	1.43	3.62	13.97	73.61	144.64	73.33	45.79	11.50	3.47
1999	2.77	2.03	1.77	1.75	2.70	6.92	35.37	87.26	36.95	41.78	7.60	4.62
2000	1.04	0.68	0.39	0.61	2.16	3.01	24.73	44.05	30.70	19.76	3.06	1.57
2001	1.17	0.87	1.44	1.18	5.71	16.93	52.88	66.77	25.29	4.13	1.69	1.44
2002	0.96	0.41	1.13	0.93	1.19	6.09	25.21	37.99	16.98	2.07	0.70	0.54
2003	0.46	0.72	0.44	1.33	1.10	3.15	76.21	104.20	39.17	5.27	0.81	0.58
2004	0.93	0.86	1.02	2.84	0.99	5.24	24.31	47.94	25.20	11.02	1.43	1.51
2005	1.83	1.51	2.51	2.64	4.20	3.92	42.00	68.81	50.50	10.50	3.54	1.52
2006	1.76	1.65	2.89	5.08	5.38	6.19	27.22	68.16	31.72	6.92	2.28	1.59

Table A-14 Mean monthly flow from Warabesa river [m³/s]

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1985	5.59	6.96	7.87	9.02	10.45	16.78	26.23	30.32	32.38	18.73	8.89	6.48
1986	4.30	4.55	4.94	4.13	4.93	16.17	27.50	25.45	25.16	15.70	9.68	7.61
1987	4.65	3.33	4.98	4.95	5.78	17.19	21.32	25.96	26.54	17.91	7.43	4.54
1988	3.07	3.11	1.01	0.03	0.17	4.87	22.28	34.41	36.88	31.93	2.17	0.95
1989	0.48	0.50	0.46	1.08	0.50	2.25	9.48	14.94	15.10	12.93	1.42	0.90
1990	0.40	0.49	0.23	0.23	0.71	3.62	6.26	17.38	17.09	6.27	1.14	0.64
1991	0.50	0.37	0.50	0.32	0.37	1.43	6.75	9.58	3.65	2.35	0.81	0.64
1992	0.57	0.62	0.32	0.31	0.96	2.60	9.86	20.44	10.85	10.43	1.77	0.96
1993	0.49	0.50	0.38	1.43	2.98	11.01	11.42	25.99	15.29	9.52	2.42	1.09
1994	0.78	0.54	0.24	0.08	0.15	0.95	7.09	13.83	18.76	2.73	1.40	0.62
1995	0.56	0.72	0.20	0.22	0.25	0.58	3.80	17.84	11.66	3.08	0.81	0.43
1996	0.39	0.17	0.58	0.55	3.35	17.97	16.88	19.52	18.88	5.80	1.62	0.94
1997	0.73	0.42	0.44	0.70	0.71	4.88	9.17	8.24	5.74	4.35	3.98	2.25
1998	1.45	1.08	1.16	0.72	1.01	1.93	10.99	23.40	13.01	11.26	4.06	2.96
1999	2.18	1.72	1.56	1.44	1.69	3.15	8.26	11.55	12.41	14.22	3.72	3.84
2000	1.72	1.51	1.29	1.65	2.33	4.33	9.59	15.60	16.84	10.05	4.08	3.62
2001	1.90	1.63	1.90	1.85	4.13	5.93	13.31	16.16	7.77	4.02	3.72	2.65
2002	3.61	3.60	3.63	3.61	3.62	4.38	8.41	10.89	7.02	3.84	3.66	3.65
2003	3.64	3.63	3.63	8.18	6.96	9.45	19.16	34.81	23.13	13.24	9.26	3.66
2004	7.80	3.66	3.67	3.65	3.65	4.41	8.16	12.52	8.13	5.13	3.62	8.46
2005	3.76	3.72	3.84	3.86	4.09	4.05	11.75	19.13	14.32	5.62	3.98	3.62
2006	3.78	3.76	3.81	3.73	3.88	4.41	8.39	17.11	9.31	4.53	3.81	3.73

Table A-15 Mean monthly flow from Denchiya river (catchment) [m³/s]

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1985	4.70	4.08	4.59	17.62	66.01	99.80	127.09	164.22	127.56	63.83	19.42	12.76
1986	7.46	6.43	11.05	24.62	32.02	105.61	119.57	105.51	92.36	40.83	17.33	15.03
1987	8.38	4.74	6.47	12.69	48.95	66.38	61.32	83.33	87.32	32.11	25.97	25.74
1988	10.14	5.27	4.21	5.35	12.93	40.16	84.05	189.04	153.35	152.72	22.08	14.87
1989	7.70	7.02	7.94	41.33	20.88	57.47	89.74	104.42	105.52	73.33	20.64	9.81
1990	5.94	6.48	22.51	36.09	64.82	116.68	90.28	143.05	134.96	67.42	21.07	23.13
1991	49.72	77.78	67.65	9.48	8.55	18.15	117.03	136.02	137.71	49.76	15.44	19.40
1992	29.44	32.93	12.42	11.52	55.40	87.39	79.56	114.52	126.60	189.41	39.74	12.37
1993	13.74	18.72	17.97	41.96	92.95	121.19	107.96	83.52	104.50	88.35	25.73	13.95
1994	16.85	7.58	14.08	11.56	60.89	132.20	137.17	134.79	100.44	25.72	23.28	14.59
1995	9.86	8.72	4.29	12.93	28.50	56.34	83.75	117.72	130.73	46.64	13.05	13.13
1996	18.68	10.12	23.33	46.82	97.83	136.70	105.18	122.19	138.48	75.72	17.34	12.05
1997	13.33	7.16	18.62	57.35	93.76	173.68	143.31	100.33	77.97	140.42	150.80	10.98
1998	47.98	28.19	32.44	38.55	143.26	144.00	144.39	269.86	125.72	205.73	28.94	63.56

1999	8.61	2.91	7.58	18.32	34.08	51.58	82.98	67.21	56.76	92.10	19.79	10.27
2000	4.92	4.38	6.02	9.59	23.77	23.97	89.24	40.04	45.99	104.98	17.71	8.92
2001	5.72	5.83	6.82	11.48	58.02	127.14	104.29	120.80	149.80	79.22	23.28	8.91
2002	20.22	13.82	16.85	27.04	24.12	31.83	77.02	76.60	58.79	31.06	22.86	22.85
2003	18.40	15.07	14.50	27.61	23.42	93.84	104.83	129.49	132.80	38.59	20.68	18.33
2004	16.64	13.55	12.71	23.30	59.50	73.11	49.80	136.08	129.82	81.41	27.17	25.39
2005	17.97	13.90	19.72	27.29	80.35	73.93	81.03	118.74	140.63	59.18	48.88	37.52
2006	26.32	21.19	25.95	30.18	61.95	97.18	135.51	138.90	79.02	54.99	42.72	38.91

Table A-16 Mean monthly flow from Deme and Gogora river [m³/s]

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1985	2.49	2.49	2.90	7.71	24.70	9.46	10.58	21.24	4.67	3.43	2.57	2.19
1986	1.61	1.88	1.93	2.32	17.15	9.46	8.39	23.10	5.96	3.21	2.35	2.80
1987	2.10	2.07	15.78	7.25	14.92	12.23	3.13	8.31	16.51	6.35	2.54	1.99
1988	2.41	2.89	1.97	12.56	7.55	4.48	42.85	59.87	21.33	15.03	2.65	1.32
1989	1.87	1.89	1.93	6.61	7.96	6.78	6.49	7.60	13.85	24.49	2.79	5.35
1990	2.12	4.38	6.75	4.14	3.58	2.49	6.79	12.05	7.29	2.61	0.89	0.57
1991	1.07	1.14	2.60	1.20	6.58	7.06	11.98	6.95	20.51	1.32	0.45	0.43
1992	0.34	0.64	0.68	11.08	22.24	16.83	34.16	69.86	40.77	17.25	6.26	4.21
1993	11.28	10.61	5.08	9.01	34.17	19.39	6.44	13.72	3.68	3.71	1.38	0.37
1994	1.98	1.99	2.23	4.46	9.51	4.57	50.09	131.10	26.83	15.13	16.38	8.85
1995	5.42	3.61	1.52	11.07	11.32	19.77	37.64	18.53	17.00	4.82	2.70	1.23
1996	1.59	1.16	17.02	17.77	15.04	54.70	23.54	51.97	51.01	8.19	7.34	5.81
1997	4.38	4.04	3.80	21.48	11.27	7.71	17.81	10.05	3.99	36.48	69.57	7.34
1998	7.26	6.08	5.12	6.30	9.50	26.18	21.14	22.22	7.81	25.50	4.88	3.54
1999	3.24	3.48	5.62	15.61	6.97	14.81	17.49	18.53	9.75	15.07	5.73	4.21
2000	3.09	2.66	2.68	8.26	48.17	15.06	26.18	35.44	10.11	9.91	6.04	2.81
2001	1.85	1.73	3.46	5.98	26.60	12.40	20.89	16.85	16.27	12.96	2.79	2.59
2002	1.98	1.07	4.72	4.70	6.43	1.58	4.39	12.59	6.95	3.42	1.87	6.54
2003	3.73	1.55	6.06	43.38	5.68	7.88	23.00	51.32	16.40	3.60	3.60	4.05
2004	4.64	3.83	3.83	4.97	5.71	3.11	14.29	11.33	10.23	9.39	6.72	4.46
2005	3.79	4.12	8.67	24.76	56.00	8.14	26.48	20.09	64.52	12.87	9.61	2.79
2006	2.99	4.00	9.35	27.44	10.65	10.91	14.67	49.71	17.47	15.69	10.86	8.13

Table A-17 Mean monthly rainfall at Gibe I reservoir [m³/s]

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1985	0.19	0.73	1.05	2.76	3.53	1.65	4.49	3.07	1.49	0.81	0.27	0.09
1986	0.04	1.39	1.81	1.37	2.57	3.83	3.55	4.15	2.01	0.65	0.06	0.52
1987	0.42	1.58	2.37	0.75	3.82	3.99	2.79	3.19	1.05	1.43	0.00	0.17
1988	0.51	1.41	0.67	1.37	1.29	3.91	4.28	4.42	4.84	1.51	0.00	0.00
1989	0.48	1.49	1.95	1.94	2.25	2.08	3.77	4.47	1.45	2.07	0.09	1.33
1990	0.39	1.71	1.80	2.24	1.22	4.00	3.70	4.23	2.08	0.17	0.50	0.48

1991	0.01	1.03	1.69	0.48	2.90	2.02	3.73	3.89	2.26	0.95	0.15	1.08
1992	0.38	0.56	1.89	1.04	3.50	4.01	2.41	6.58	2.02	1.25	0.41	0.24
1993	0.63	1.86	1.60	3.76	2.52	4.41	3.40	2.61	2.16	2.74	0.27	0.00
1994	0.22	0.11	1.45	3.05	2.16	4.90	3.63	5.77	2.52	0.13	0.26	0.55
1995	0.18	0.66	1.06	1.88	1.87	2.12	4.09	2.19	1.46	0.16	0.18	2.22
1996	0.74	1.03	3.13	3.77	2.73	3.96	3.67	3.84	2.73	0.17	0.52	0.00
1997	0.73	0.00	0.56	2.92	2.63	3.85	4.53	3.88	2.07	4.75	2.79	0.21
1998	1.04	1.13	1.15	1.59	2.48	4.13	4.17	3.80	3.24	2.88	0.51	0.00
1999	0.45	0.00	0.99	1.35	3.22	4.31	5.64	2.76	1.45	1.97	0.04	0.01
2000	0.00	0.00	0.11	2.28	2.17	3.00	2.85	2.75	3.00	1.65	0.66	0.06
2001	0.59	0.42	1.97	3.09	4.62	4.98	3.75	4.49	1.73	2.31	0.16	0.11
2002	0.71	0.36	2.37	1.41	2.11	3.09	3.23	3.02	1.65	0.16	0.10	1.97
2003	0.52	1.74	3.99	1.68	0.68	0.00	3.88	2.76	0.37	0.57	0.37	0.59
2004	0.86	0.15	1.38	2.25	1.31	4.12	0.00	5.09	2.42	0.99	0.54	0.75
2005	0.57	0.04	1.86	3.17	3.53	1.90	3.34	2.58	3.37	0.56	0.26	0.00
2006	0.14	0.00	3.36	2.20	2.27	4.04	5.47	3.49	1.32	2.28	0.71	0.47

Table A-18 Mean monthly rainfall at Gibe III reservoir [m³/s]

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1985	2.39	2.39	5.09	16.91	15.19	3.93	4.58	8.33	3.46	0.84	1.40	0.57
1986	0.06	0.32	1.47	1.67	2.92	2.51	2.84	2.78	1.20	0.00	2.78	6.03
1987	1.84	5.81	8.89	11.12	29.15	8.89	2.04	12.16	8.99	11.81	1.73	1.33
1988	1.41	4.50	2.95	7.11	6.88	6.86	22.26	16.78	13.15	8.06	0.18	0.80
1989	6.21	3.95	6.51	7.94	10.66	6.14	8.10	12.01	8.85	6.71	7.95	15.49
1990	2.39	2.39	5.09	16.91	15.19	3.93	4.58	8.33	3.46	0.84	1.40	0.57
1991	2.43	7.11	10.18	10.32	14.46	9.59	12.61	9.12	4.93	2.22	0.79	3.90
1992	1.87	5.90	4.03	11.97	8.36	11.42	11.13	17.66	9.37	9.37	6.48	2.32
1993	7.33	4.80	1.55	21.50	31.53	7.46	16.69	10.60	5.21	6.22	0.17	0.65
1994	0.00	1.46	8.68	7.75	14.19	6.74	22.64	16.70	3.92	0.91	2.97	0.65
1995	0.06	4.28	4.24	18.32	6.96	12.34	14.70	7.26	8.78	3.44	3.57	1.15
1996	3.92	1.98	8.06	13.12	18.33	23.71	15.99	17.82	14.64	2.27	2.32	0.04
1997	2.11	0.00	2.06	18.77	14.13	9.63	0.00	10.76	3.21	22.06	19.40	2.94
1998	4.42	7.26	4.30	9.38	13.47	14.41	17.10	13.81	5.60	14.71	1.09	0.32
1999	2.02	0.05	3.59	8.95	8.77	8.67	12.58	9.85	5.24	12.37	1.08	0.74
2000	0.20	0.00	2.44	11.95	17.71	15.59	9.78	17.60	13.35	13.23	4.71	0.89
2001	1.50	0.91	8.46	7.07	23.27	12.90	18.39	19.87	8.92	10.56	3.45	3.33
2002	3.77	0.43	9.60	7.70	13.65	6.61	7.13	17.74	4.27	4.62	0.16	7.59
2003	7.84	1.77	4.88	10.34	5.25	14.71	15.61	20.69	2.85	4.92	3.17	6.77
2004	4.36	4.14	3.23	21.88	8.35	8.14	14.59	12.55	5.01	7.33	3.09	2.18
2005	0.65	2.42	14.72	16.42	25.46	8.54	19.04	10.60	11.93	8.45	8.94	0.39
2006	0.35	1.97	9.89	17.50	11.23	8.01	10.77	20.37	4.89	10.51	2.96	9.52

Table A-19 Mean monthly rainfall at Gojeb OM19 reservoir [m³/s]

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1985	0.23	0.15	0.97	2.50	0.00	2.96	2.00	2.71	1.61	0.92	0.32	0.18
1986	0.04	0.69	1.18	0.90	1.05	2.47	1.79	2.47	2.07	1.08	0.09	0.73
1987	2.41	1.64	0.96	0.70	2.67	2.06	1.31	2.20	1.52	1.80	0.12	0.33
1988	0.91	1.08	0.46	1.29	1.07	1.82	2.95	4.04	3.85	1.80	0.01	0.02
1989	0.49	0.96	1.14	1.80	1.70	1.49	2.41	2.24	1.57	1.01	0.15	1.68
1990	0.12	1.19	1.60	1.38	1.90	3.00	2.33	1.82	2.78	0.35	1.25	0.28
1991	0.69	1.21	3.54	1.61	1.52	2.20	2.85	2.59	1.62	0.46	0.23	0.77
1992	0.78	1.89	0.89	2.51	3.33	3.30	3.56	3.54	3.01	2.43	0.14	0.51
1993	0.84	0.82	0.86	3.33	0.00	3.15	4.66	2.98	3.29	2.31	0.28	0.03
1994	0.27	0.14	1.25	1.56	2.56	2.56	2.98	2.14	1.36	0.23	0.10	0.19
1995	0.02	0.56	0.07	3.01	1.56	1.98	3.24	2.55	2.24	0.28	0.09	0.76
1996	0.72	0.77	2.72	1.99	0.76	2.10	3.02	1.82	1.53	0.70	1.67	0.90
1997	1.00	0.04	0.91	0.96	2.68	2.42	2.43	3.35	1.49	3.93	2.50	0.45
1998	0.73	0.46	0.73	1.06	0.61	0.93	2.23	1.37	1.00	1.25	0.54	0.00
1999	0.12	0.02	0.76	1.05	1.44	0.00	3.94	2.60	1.00	1.71	0.00	0.09
2000	0.33	0.06	0.35	2.30	1.93	1.71	1.90	2.58	0.99	1.83	0.55	0.28
2001	0.22	0.35	1.59	1.67	2.03	2.44	3.89	2.89	1.08	1.15	0.12	0.14
2002	0.39	0.33	1.26	1.35	1.31	2.59	2.65	2.30	1.24	1.12	0.17	1.42
2003	0.94	0.39	2.11	1.37	0.68	2.43	2.26	2.81	1.89	0.22	0.85	0.23
2004	0.51	0.16	0.58	1.36	0.89	2.11	1.51	2.79	2.03	1.14	0.67	0.31
2005	0.28	0.02	1.37	1.50	1.39	1.69	1.68	2.26	1.45	0.38	0.06	0.00
2006	0.03	0.00	1.38	1.05	1.23	1.65	2.29	2.58	1.14	1.03	0.30	0.11

Table A-20 Mean monthly rainfall at Halele reservoir [m³/s]

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1985	1.31	0.50	4.15	14.67	21.52	23.38	26.71	18.29	11.97	4.74	3.53	3.71
1986	0.00	4.13	3.33	9.66	16.68	20.57	48.65	20.46	24.71	5.95	0.62	0.33
1987	0.42	8.03	9.42	9.36	12.21	32.69	26.11	28.13	18.10	9.87	3.69	4.45
1988	1.70	14.06	1.88	1.91	24.67	30.82	32.68	48.41	30.79	33.60	0.19	0.42
1989	0.42	5.63	9.27	18.98	18.63	26.52	28.42	37.55	23.07	6.46	3.22	12.16
1990	1.12	6.44	14.56	13.18	20.04	30.44	21.87	41.60	19.90	5.21	2.14	1.46
1991	5.62	8.18	7.18	2.82	8.48	35.36	35.22	27.02	18.38	4.78	0.59	2.05
1992	5.62	11.76	12.50	16.81	8.48	16.77	27.33	20.58	9.73	17.26	10.32	1.88
1993	1.81	10.89	14.18	21.13	19.01	31.18	13.08	16.08	25.18	10.00	0.00	0.00
1994	0.03	0.42	7.51	7.30	25.28	26.01	33.70	48.88	21.29	0.18	0.00	0.00
1995	0.00	1.13	11.81	29.53	13.26	12.12	33.34	31.12	10.88	1.39	0.15	3.63
1996	8.15	0.21	20.78	11.50	29.33	36.61	30.80	27.99	21.79	6.85	2.67	2.28
1997	3.03	0.02	2.89	24.65	35.92	27.68	26.34	35.15	25.89	25.35	21.64	1.57
1998	0.30	3.27	8.62	0.00	21.26	26.32	39.73	36.71	21.69	26.76	3.26	0.00
1999	2.32	0.15	5.96	9.37	14.97	17.30	34.28	34.08	19.33	26.91	0.00	0.00

2000	0.00	0.00	3.33	10.64	16.60	23.26	21.25	27.43	28.58	0.00	13.82	5.63
2001	0.41	1.12	13.05	8.53	28.15	43.03	28.99	21.78	29.16	26.09	0.38	0.47
2002	2.29	1.89	11.54	6.84	14.99	27.72	20.99	34.66	0.00	4.94	0.84	8.94
2003	1.80	2.41	6.26	11.54	2.47	18.21	25.31	23.23	10.38	5.56	2.13	0.08
2004	2.23	2.47	2.35	7.52	14.23	32.55	32.23	25.63	20.65	10.18	3.39	4.11
2005	0.22	0.05	6.20	9.68	13.37	25.30	22.57	31.09	19.95	13.29	5.71	0.00
2006	0.86	5.99	9.39	11.53	14.24	24.23	35.65	35.83	21.60	21.04	0.97	3.43

Table A-21 Mean monthly rainfall at Warabesa reservoir [m³/s]

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1985	0.06	0.03	0.03	0.26	0.58	0.48	1.35	1.11	0.26	0.12	0.01	0.05
1986	0.00	0.16	0.22	0.44	0.41	0.89	0.76	0.41	0.88	0.14	0.00	0.01
1987	0.17	0.12	0.42	0.24	0.90	0.52	0.79	0.69	0.28	0.09	0.04	0.02
1988	0.11	0.27	0.07	0.08	0.22	0.61	1.78	0.88	0.75	0.32	0.00	0.00
1989	0.07	0.12	0.42	0.50	0.21	0.60	1.22	1.18	0.34	0.29	0.00	0.13
1990	0.00	0.41	0.25	0.20	0.16	0.60	1.08	1.32	0.35	0.04	0.02	0.01
1991	0.07	0.38	0.23	0.13	0.39	0.61	1.01	1.38	0.28	0.02	0.00	0.09
1992	0.22	0.28	0.32	0.36	0.27	0.91	0.77	1.68	0.38	0.46	0.16	0.06
1993	0.05	0.26	0.18	1.01	0.50	0.90	0.75	0.92	0.51	0.49	0.01	0.00
1994	0.00	0.00	0.40	0.34	0.40	0.62	1.43	0.99	0.59	0.01	0.03	0.00
1995	0.00	0.11	0.02	0.46	0.26	0.79	0.75	0.73	0.25	0.02	0.00	0.09
1996	0.29	0.06	0.39	0.44	0.92	1.16	1.21	1.22	0.18	0.06	0.08	0.01
1997	0.27	0.00	0.14	0.63	0.53	0.80	0.63	0.66	0.49	0.71	0.11	0.01
1998	0.10	0.10	0.79	0.18	0.73	0.97	1.64	1.04	0.66	0.55	0.00	0.00
1999	0.08	0.00	0.34	0.22	0.64	0.81	1.09	1.07	0.40	0.59	0.01	0.01
2000	0.00	0.00	0.02	0.41	0.41	0.32	0.82	0.64	0.40	0.05	0.09	0.02
2001	0.09	0.04	0.24	0.35	0.43	1.14	1.21	0.61	0.78	0.09	0.07	0.00
2002	0.22	0.01	0.17	0.14	0.24	0.84	0.86	0.34	0.25	0.05	0.00	0.19
2003	0.06	0.18	0.13	0.54	0.05	0.84	1.08	0.88	0.45	0.01	0.08	0.14
2004	0.07	0.07	0.08	0.35	0.13	0.84	0.94	0.72	0.73	0.24	0.05	0.08
2005	0.10	0.00	0.39	0.24	0.43	0.81	1.20	0.98	0.54	0.24	0.03	0.00
2006	0.02	0.32	0.27	0.30	0.61	0.57	1.11	0.59	0.80	0.20	0.02	0.02

Table A-22 Extended flow at Karadus hydrometric station from level data [m³/s]

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1985	82.17	1.57	14.31	22.95	89.78	186.05	325.09	362.52	386.75	159.48	144.38	97.63
1986	82.80	79.64	83.21	30.74	203.20	578.16	940.05	1009.51	1095.70	241.30	45.20	41.93
1987	5.92	2.13	18.92	85.79	267.61	579.54	500.42	584.84	768.92	429.98	95.91	20.61
1988	9.41	4.79	2.40	12.35	74.78	109.07	873.01	3763.79	1762.57	1577.81	754.17	130.95
1989	1.10	1.21	1.08	27.80	137.95	225.82	660.14	1036.86	1362.25	835.16	131.56	190.63
1990	64.00	63.52	152.34	310.07	333.69	376.70	905.90	1919.98	1505.63	561.08	158.58	53.06
1991	26.95	32.27	142.69	103.68	156.82	381.26	690.84	1133.83	856.96	246.51	93.02	84.82
1992	15.54	33.36	22.95	63.18	298.77	673.55	1468.57	2216.09	1337.45	756.83	242.94	439.59
1993	127.18	138.94	14.98	112.73	772.42	776.73	1348.68	1940.48	1191.58	528.85	280.25	49.07
1994	14.73	3.20	6.99	56.77	238.19	387.12	1022.04	1977.32	1678.32	751.30	212.49	126.23
1995	30.47	47.38	23.90	134.37	167.04	199.18	481.16	1816.25	1107.59	231.78	133.40	117.76
1996	439.59	439.59	230.56	207.29	417.26	1084.71	1473.69	2556.98	1086.58	702.29	296.05	207.10
1997	170.24	158.04	120.97	197.70	228.91	581.15	924.06	1159.65	848.94	908.19	966.19	509.53
1998	271.46	182.85	188.09	141.62	209.35	328.39	1196.76	2313.61	1732.70	1377.26	619.86	271.97
1999	186.95	133.42	126.93	14.73	79.96	170.42	901.49	1683.28	811.46	616.02	258.09	15.63
2000	3.78	0.11	97.81	3.60	110.04	128.13	459.59	753.16	726.86	836.85	498.94	52.51
2001	3.75	0.38	15.95	114.89	414.14	2051.68	2879.42	1600.92	1040.66	571.52	228.98	88.55
2002	36.75	18.58	104.94	194.40	129.23	228.85	440.39	965.44	834.39	260.71	136.43	119.27
2003	62.63	12.04	24.87	86.76	123.76	212.23	767.04	1125.68	1050.83	478.40	181.17	129.60
2004	166.05	201.37	216.43	79.26	238.47	180.19	470.60	1266.31	1726.15	1433.14	798.51	299.73
2005	87.17	52.88	49.43	180.19	543.83	972.45	651.14	1127.99	1157.19	705.02	311.94	239.91
2006	69.24	103.96	160.73	328.79	455.36	594.12	447.94	566.74	1307.12	719.69	348.36	236.23

Table A-23 Estimated runoff for the residual basin (Abelti- Gojeb-Gibe confluence) [m³/s]

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1985	1.29	1.40	3.96	10.78	7.70	11.27	11.49	12.92	6.11	4.58	2.33	1.59
1986	0.34	5.84	6.39	7.33	10.65	14.08	11.32	10.43	6.86	3.50	0.63	3.41
1987	3.68	5.51	7.08	5.83	13.98	9.95	8.10	13.40	8.67	6.10	0.53	1.21
1988	2.65	5.69	2.52	5.83	6.28	10.79	14.20	16.40	11.99	8.62	0.56	0.70
1989	2.40	4.53	6.51	7.44	5.27	9.31	11.50	12.32	8.39	5.56	1.47	7.70
1990	2.40	4.53	6.51	7.44	5.27	9.31	11.50	12.32	8.39	5.56	1.47	7.70
1991	2.00	4.67	8.13	6.38	9.87	10.84	13.73	13.17	5.83	3.66	1.39	3.20
1992	3.59	5.43	5.64	9.47	11.32	13.57	13.29	16.91	9.75	9.23	2.81	1.93
1993	2.94	5.12	4.59	14.01	9.65	12.32	15.72	13.23	9.52	8.82	1.45	0.18
1994	0.66	1.07	5.27	8.13	10.40	10.93	11.69	11.39	5.55	3.45	3.26	2.07
1995	0.93	2.42	3.68	12.78	7.82	8.22	13.26	10.94	5.85	2.79	0.83	4.06
1996	4.56	2.12	10.84	11.39	10.39	13.03	13.71	9.88	7.56	3.30	4.79	1.79
1997	3.72	0.18	4.12	10.20	9.95	11.49	9.60	13.26	12.70	18.61	10.99	2.53
1998	3.25	3.13	4.35	7.99	7.65	10.42	13.38	11.73	10.65	9.55	1.85	0.07
1999	0.74	0.05	3.33	5.99	8.14	9.21	13.71	10.24	9.40	10.43	0.42	0.50

2000	0.46	0.85	2.12	9.59	9.99	9.34	9.06	10.60	10.05	8.76	2.30	1.40
2001	0.82	2.31	6.43	7.30	10.85	11.36	16.99	13.83	7.35	6.33	0.93	1.07
2002	3.60	1.48	7.00	6.05	6.27	11.04	11.16	11.97	5.96	2.68	0.48	7.17
2003	3.57	2.77	6.89	8.79	4.00	10.94	12.36	13.11	5.83	1.75	2.76	1.94
2004	3.92	0.97	3.34	9.85	6.32	9.68	8.28	12.86	7.24	5.09	2.83	1.46
2005	1.73	0.58	7.30	7.46	10.74	9.28	10.76	10.52	7.19	3.18	2.44	0.12
2006	0.95	1.34	6.59	6.54	5.70	8.70	10.60	10.88	7.06	5.24	1.90	1.20

APPENDIX-B Graphs Plotted to Test Homogeneity of the Stations

Figure B-1 Homogeneity test for Tibe, Ejaji and Gedo metrological stations

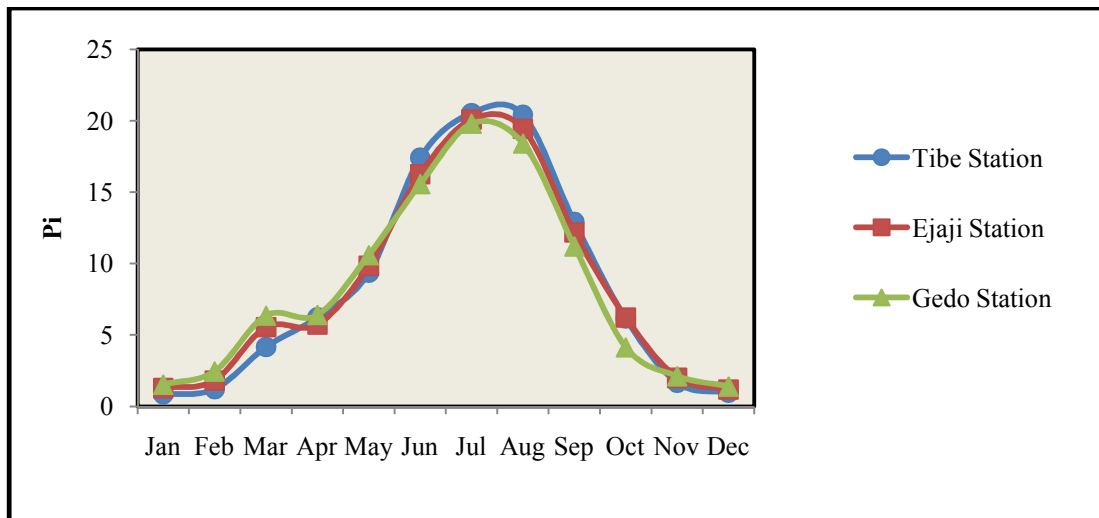


Figure B-2 Homogeneity test for Atnago, Dilela, Welkite, Gibe farm and Tikure encheni metrological stations

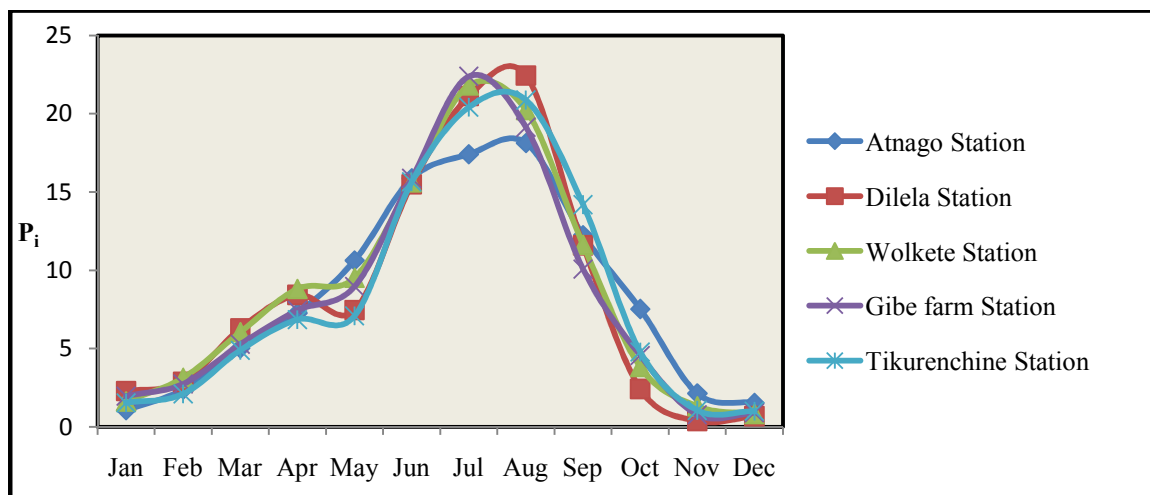


Figure B-3 Homogeneity test for Kumbi, Abelti, Sekoru and Saja school metrological stations

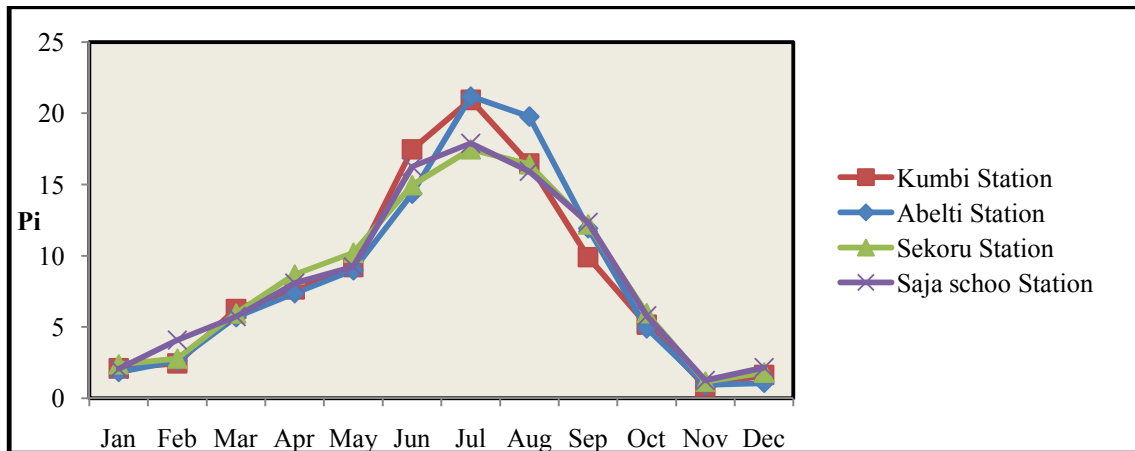


Figure B-4 Homogeneity test for Assendabo, jima, metesso and Babu metrological stations

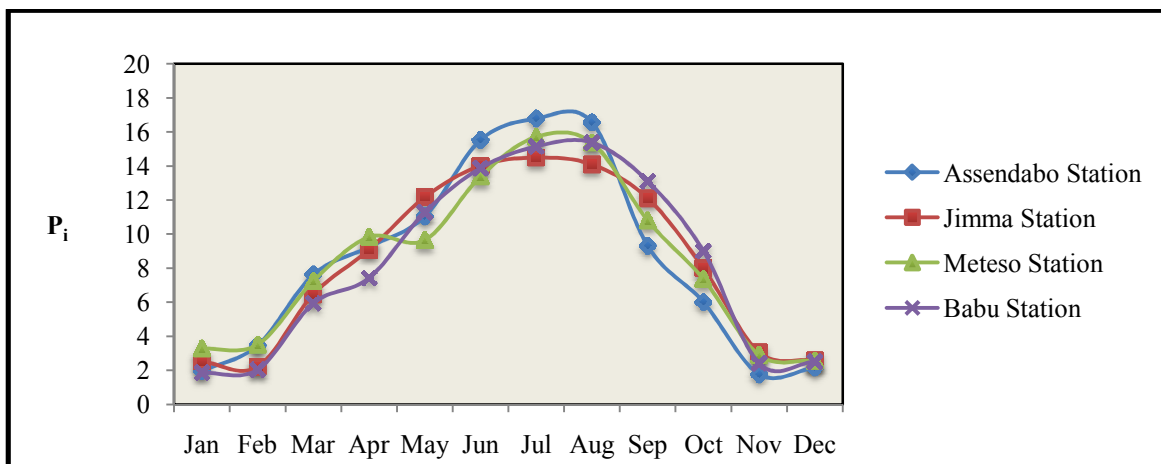


Figure B-5 Homogeneity test for Tibe, Ejaji and Gedo metrological stations

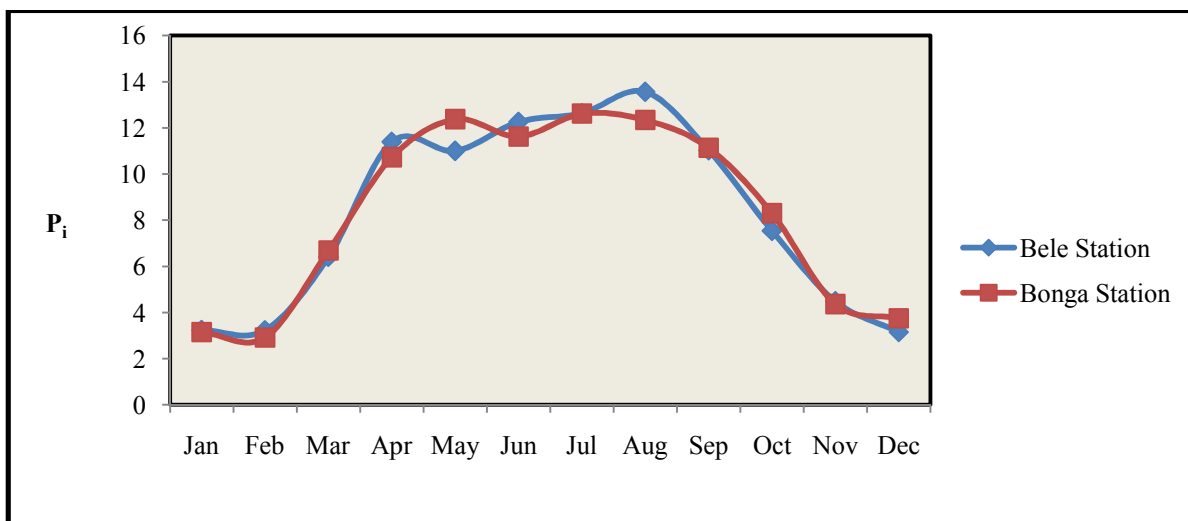


Figure B-6 Homogeneity test for Tibe, Ejaji and Gedo metrological stations

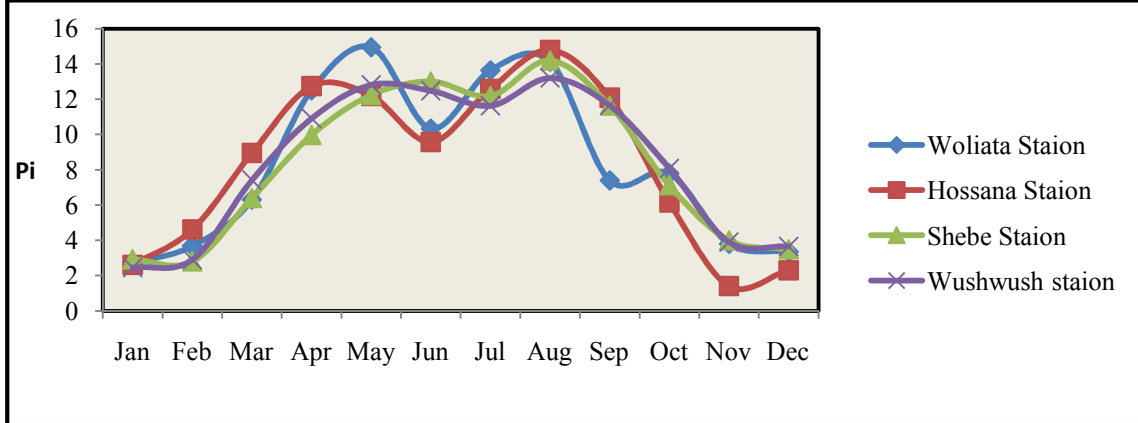
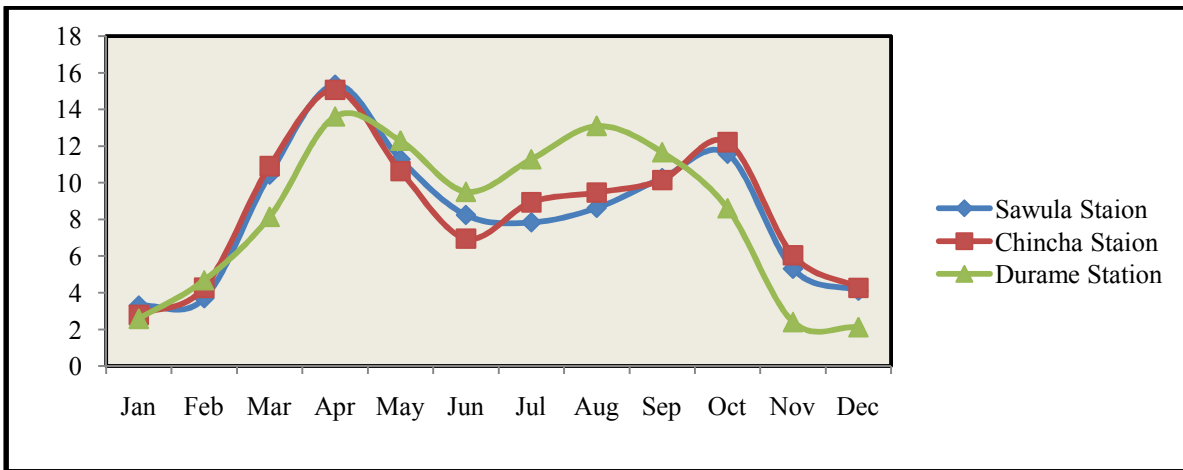


Figure B-7 Homogeneity test for Sawula, Chinchá and Durame meteorological stations



APPENDIX-C Graphs Plotted To Check Consistency of the Stations

Figure C-1 Consistency Test for Atnago, Dilela, Welkite and Gibe farm metrological stations

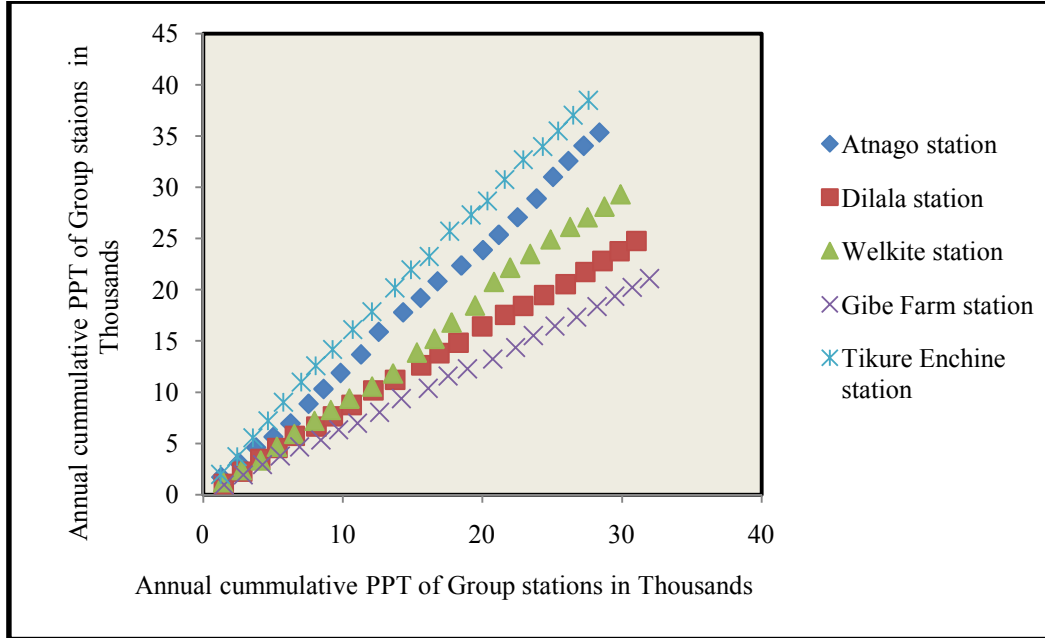


Figure C-2 Consistency Test for Abelti and Kumbi metrological stations

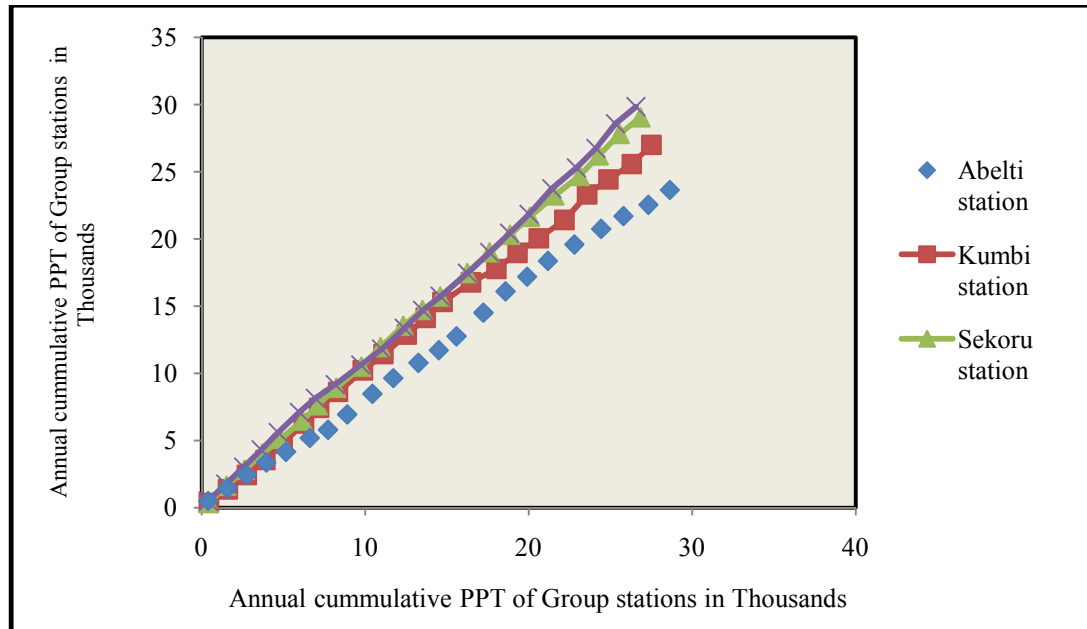


Figure C-3 Consistency Test for Assendabo, Jima and metesso metrological stations

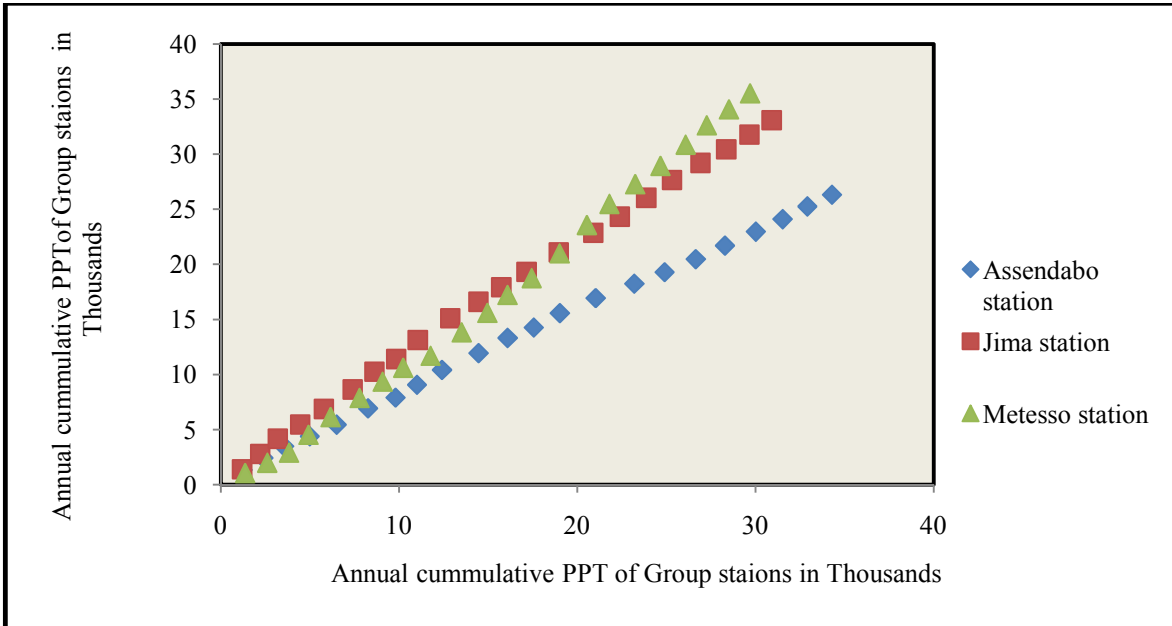
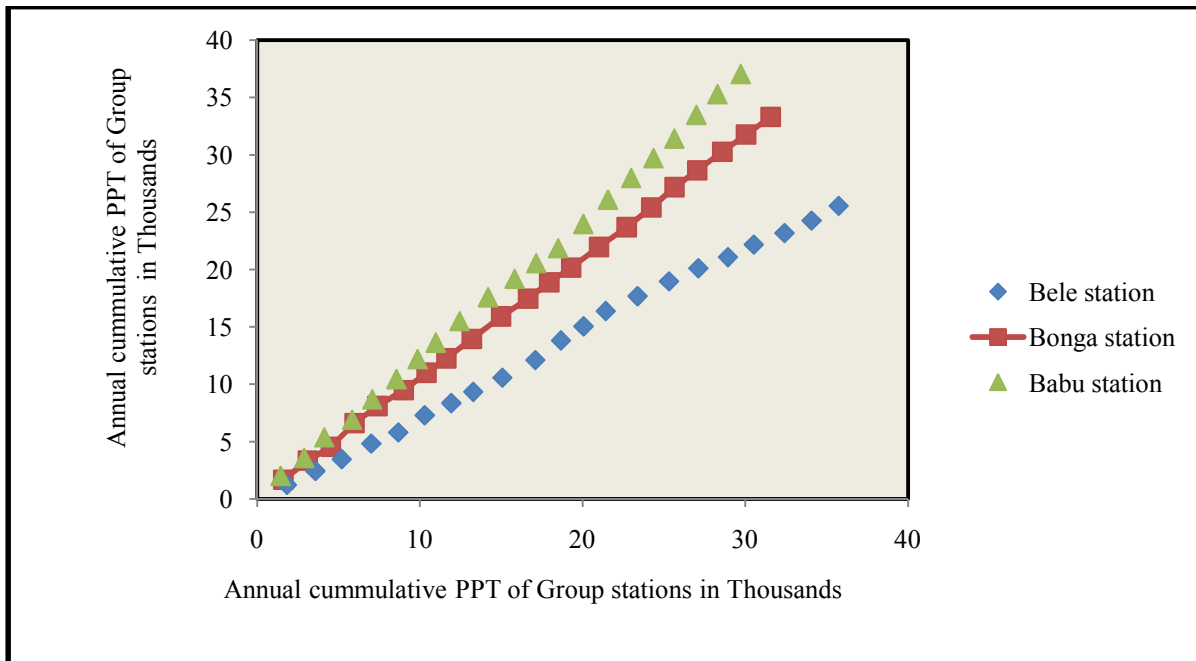


Figure C-4 Consistency Test for Bele, Bonga and Babu metrological stations



APPENDIX-D Physical and Power plant characteristics of hydropower dams

Figure D-1 Elevation-Storage curve for Gilgel Gibe I reservoir

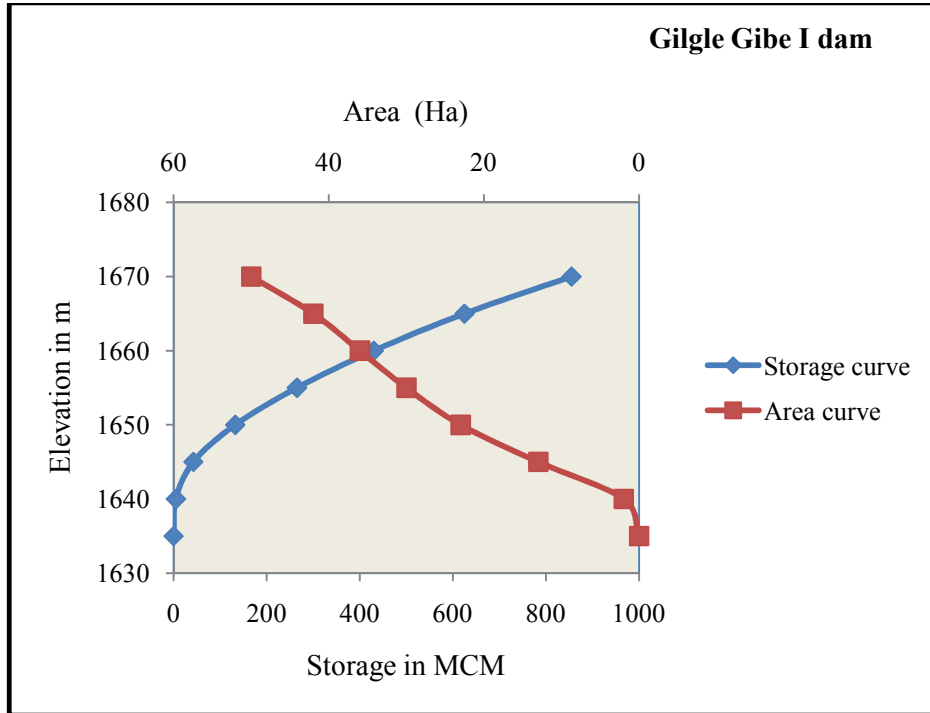


Figure D-2 Elevation-Storage curve for Gilgel Gibe II reservoir

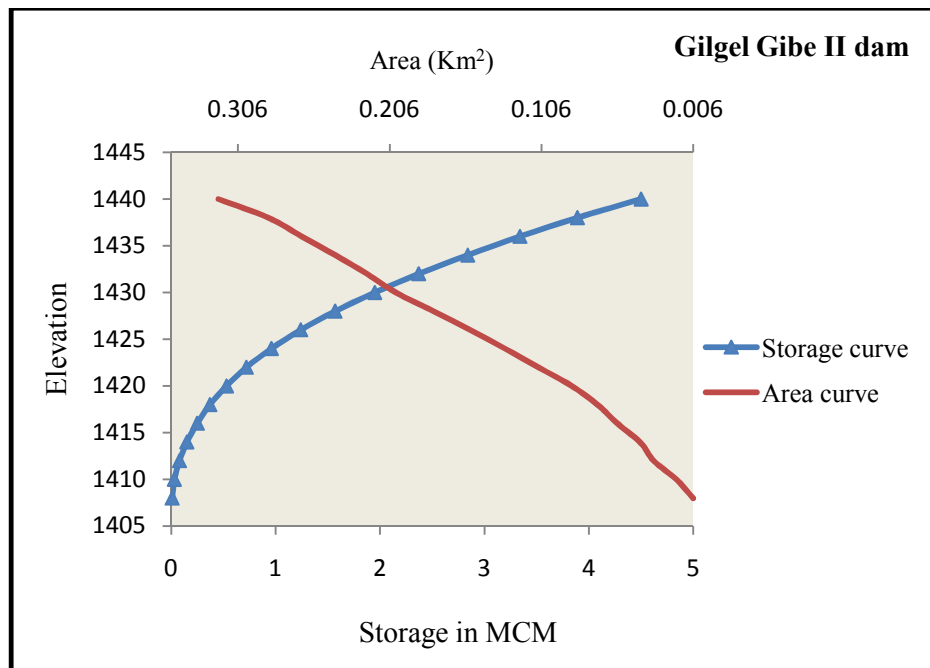


Figure D-3 Elevation-Storage curve for Gilgel Gibe III reservoir

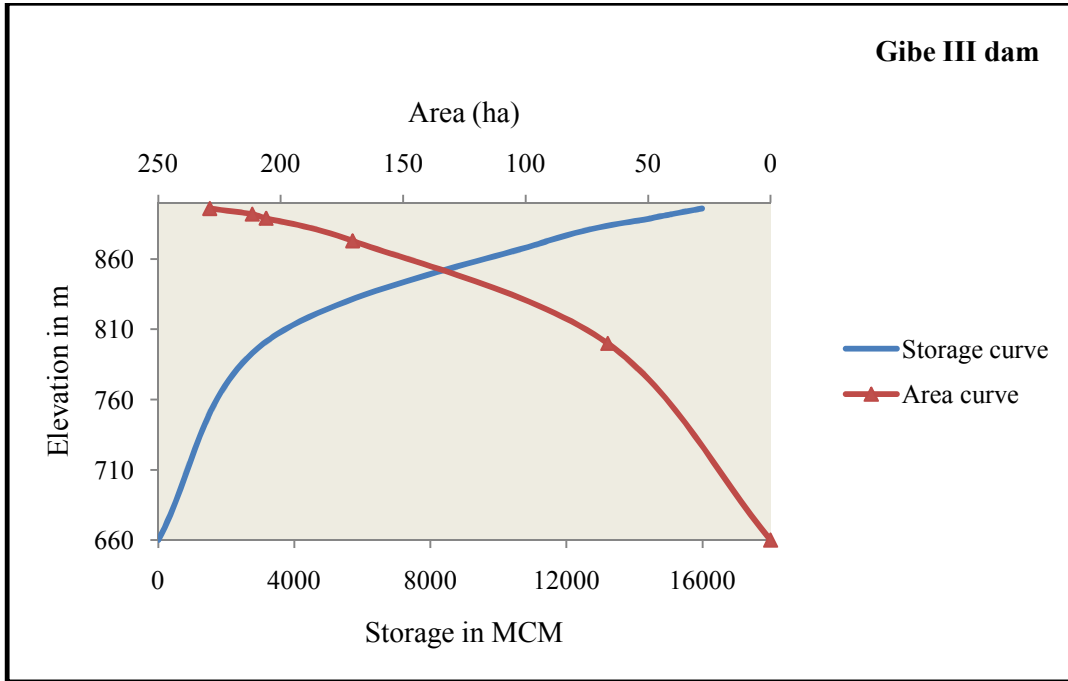


Figure D-4 Elevation-Storage curve for Gojeb OM19 reservoir

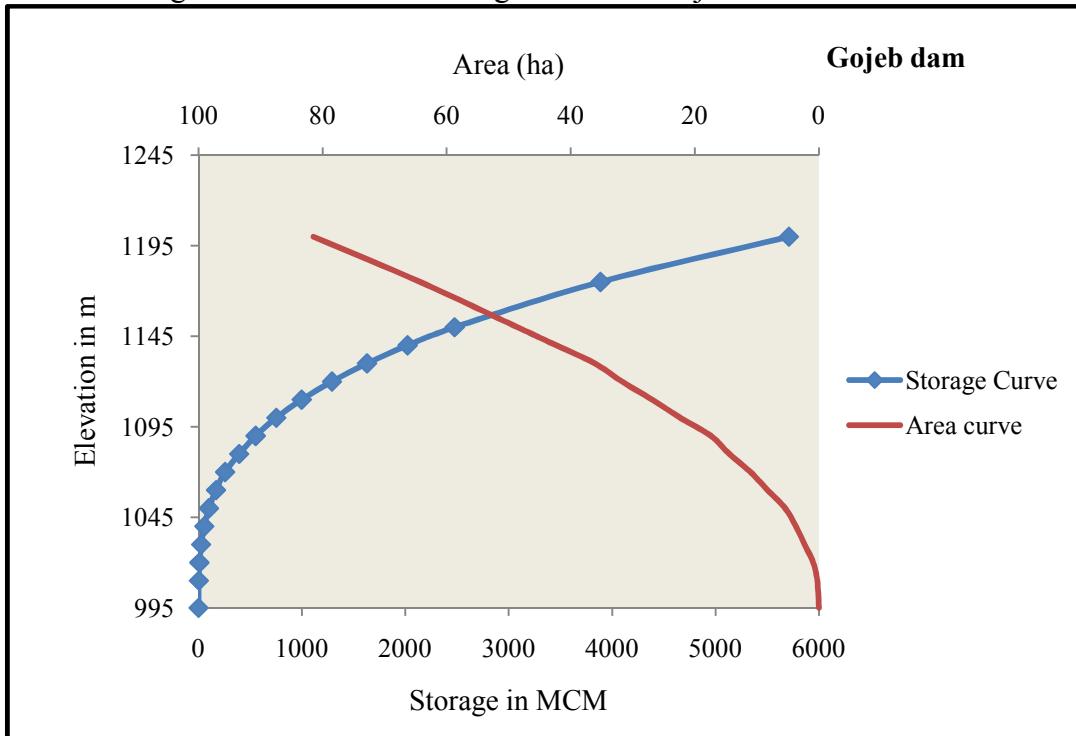


Figure D-5 Elevation-Storage curve for Halele reservoir

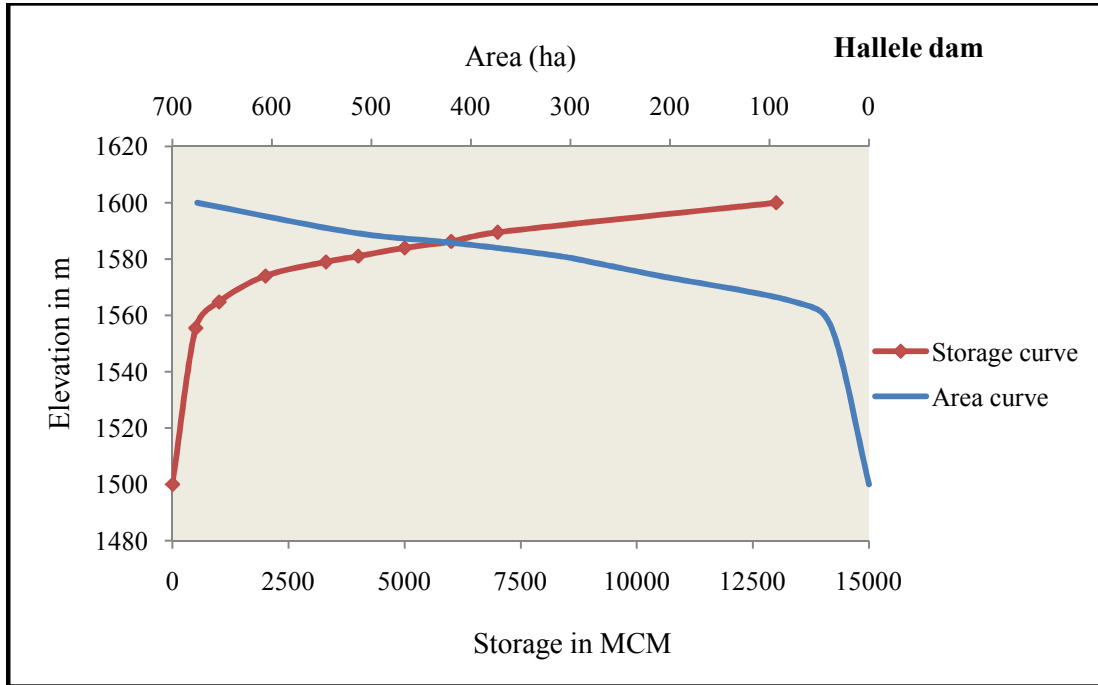


Figure D-6 Elevation-Storage curve for Warabesa reservoir

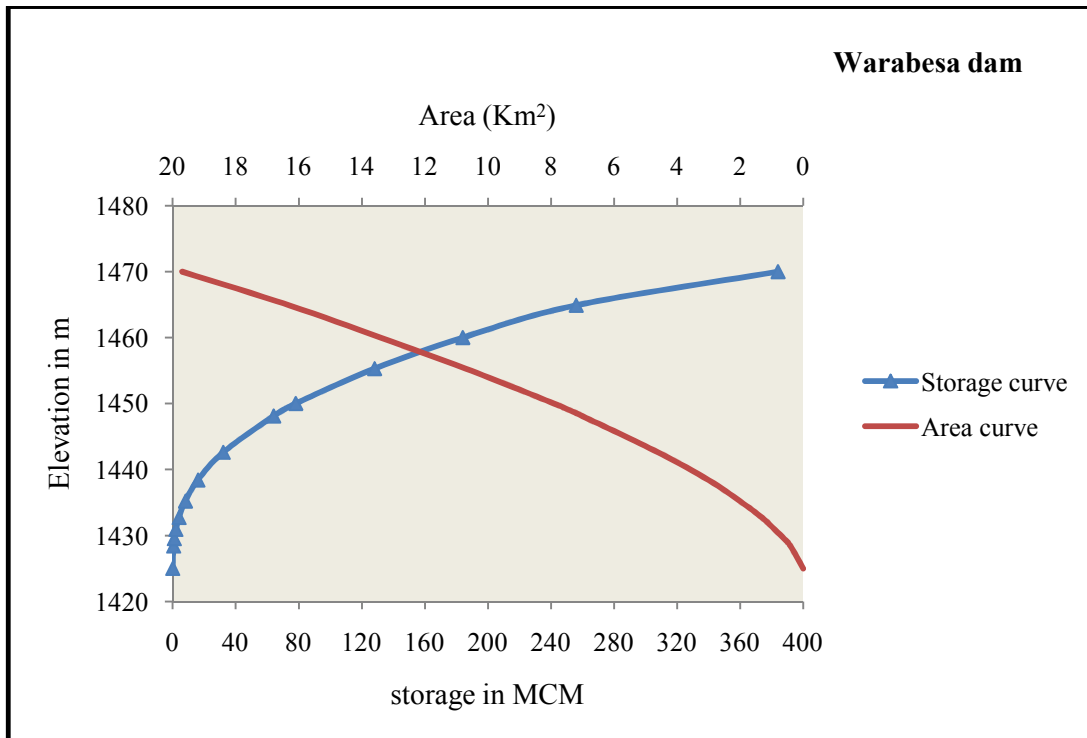
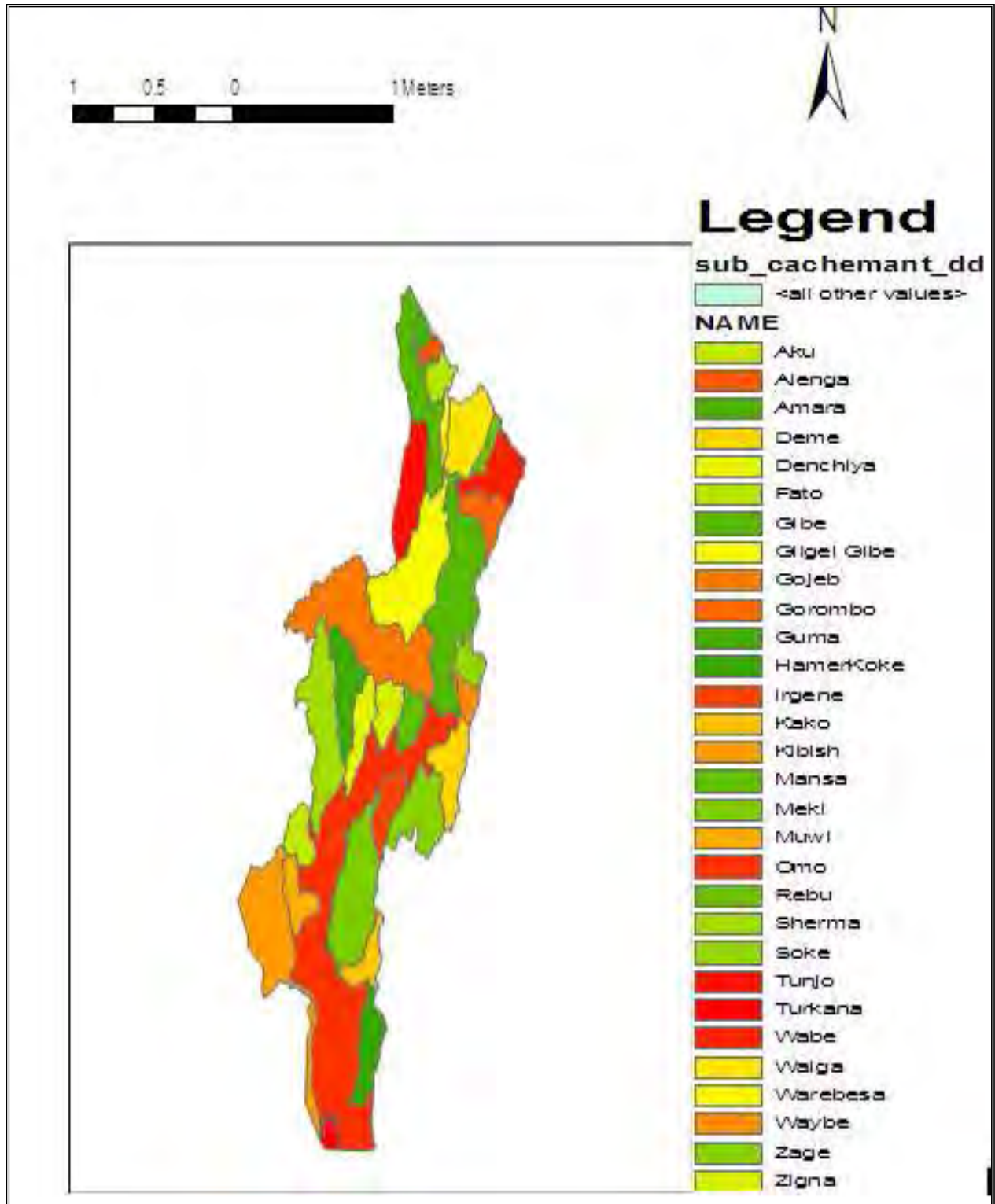


Figure D-8 Drainage subbasins of Omo-Gibe River basin



Dam characteristics

Dam Name	Crest Level(m)	Crest length(m)	Max Fl.con level(m)	Full sup. level(m)	Min Op. level(m)	Dead Level (m)
Gilgel Gibe I	1675.00	1704.00	1675.00	1670.00	1653.00	1647.00
Gilgel Gibe II	1439.00	166.00	1437.10	1431.50	1424.00	1408.00
Gilgel Gibe III	896.00	601.00	894.00	892.00	800.00	780.00
Halele	1585.00	580.00	1582.00	1579.00	1553.00	1500.00
Warabesa	1464.50	500.00	1463.50	1460.00	1450.00	1433.00
Gojob OM19	1116.00	300.00	1113.63	1109.00	1068.00	995.00

Power plant characteristics

Dam Name	Max intake capacity(m ³ /s)	Efficiency%	Tail race level	Annual average energy requirement GWh/y	Head loss (m)	Install capacity MW
Gilgel Gibe I	102.00	90.00	1439.00	794.00	16.6.0	210.00
Gilgel Gibe II	102.00	92.00	930.00	1635.00	35.50	420.00
Gilgel Gibe III	950.00	93.00	674.00	6400.00	5.50	1800.00
Halele	124.00	95.00	1481.00	494.00	6.20	96.00
Warabesa	128.00	87.00	1140.00	1732.00	8.00	326.00
Gojob OM19	160.00	90.00	997.00	516.00	5.02	134.00

Spillway characteristics

Dam Name	Spillway type	Sill level	PMF capacity	PMF level	Crest length	No of gates
Gilgel Gibe I	Gated	1665.00		1675.00		4
Gilgel Gibe II	Free overflow	1431.50		1437.10	77.00	-
Gilgel Gibe III	Gated	873.00		894.00		9
Halele	Free overflow	1579.00		1582.00	70.00	-
Warabesa	Free overflow	1460.00		1463.50	90.00	-
Gojob OM19	Free overflow	1109.00		1113.63	80.00	-

APPENDIX-E Standard Graphic Output Graph from HEC-ResSim Model

Figure E-1 Gibe III power plant operation simulated at scenario D

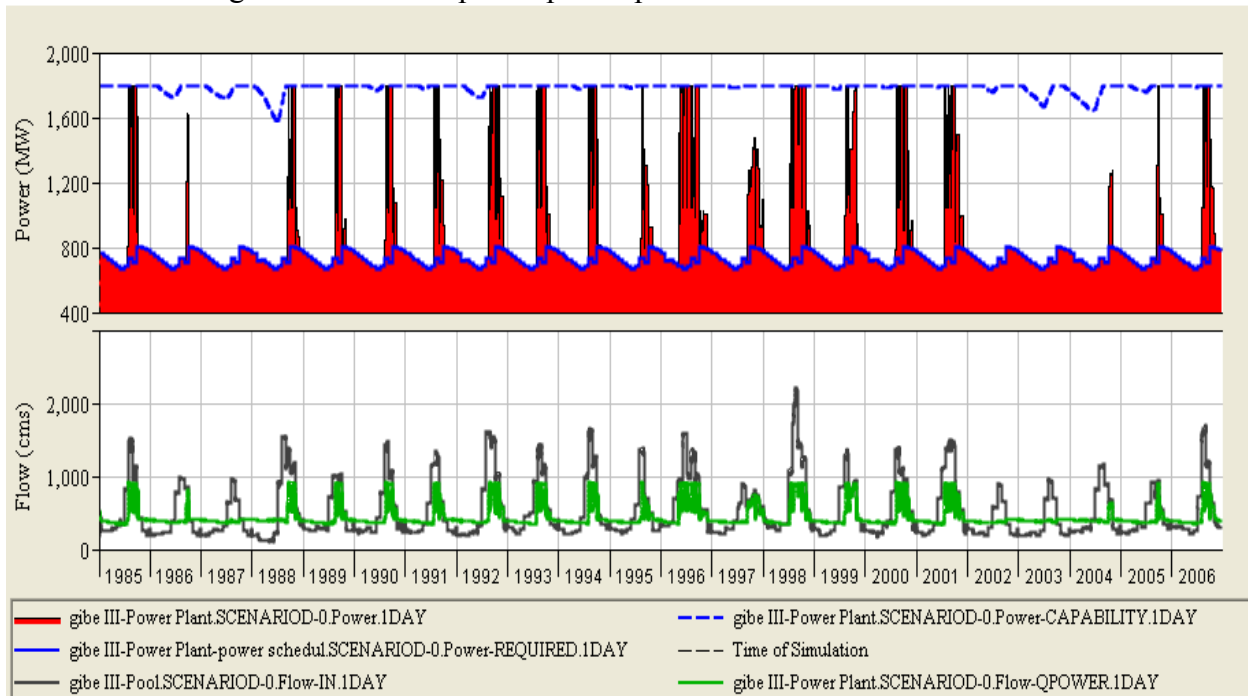


Figure E-2 Reservoir operation simulated for Halele reservoir at scenario D

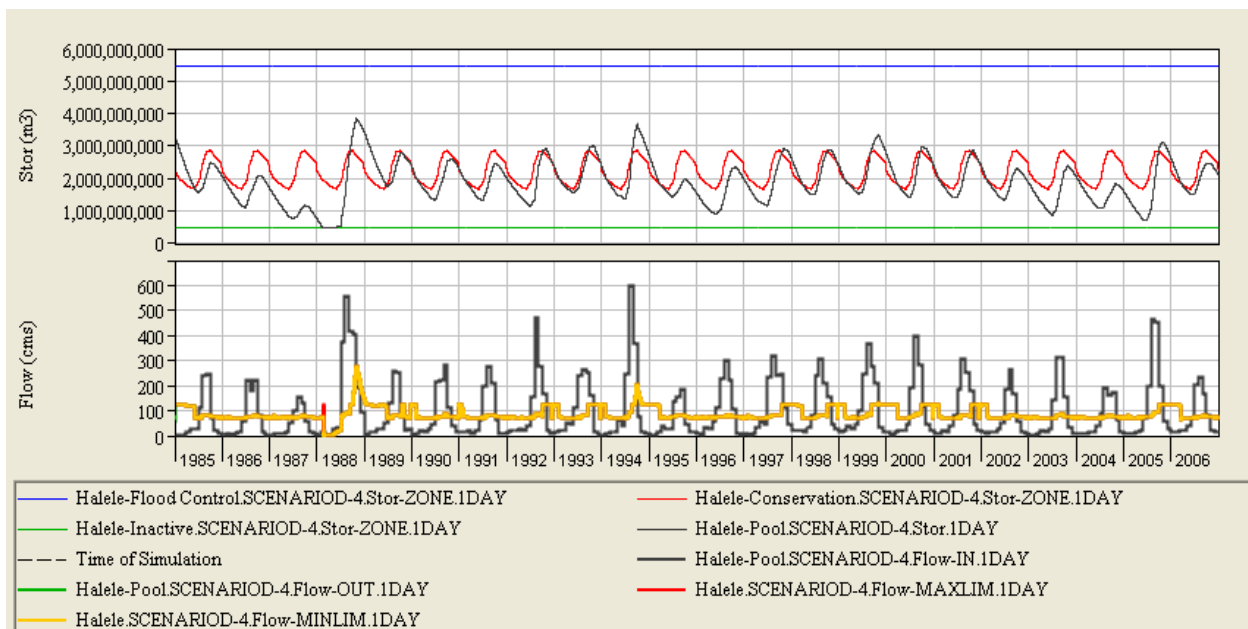


Figure E-3 Halele power plant operation simulated at scenario D

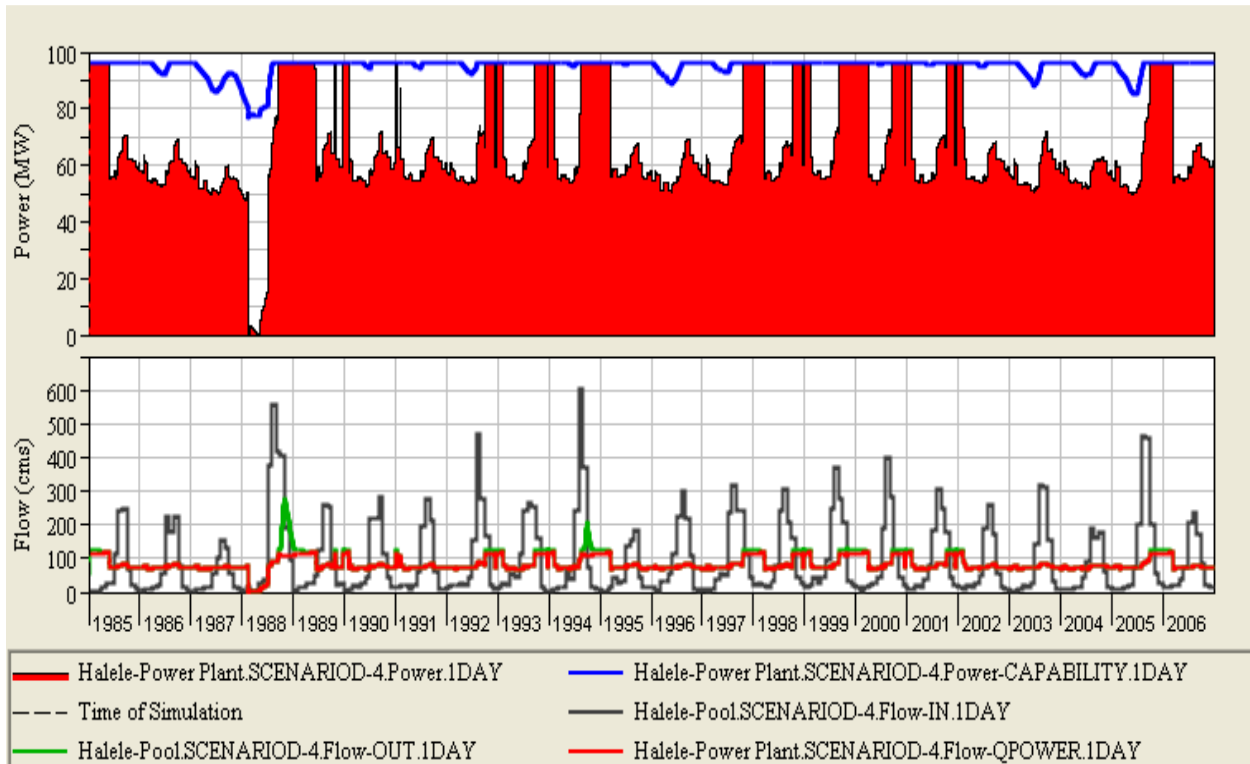


Figure E-4 Reservoir operation simulated for Warabesa reservoir at scenario D

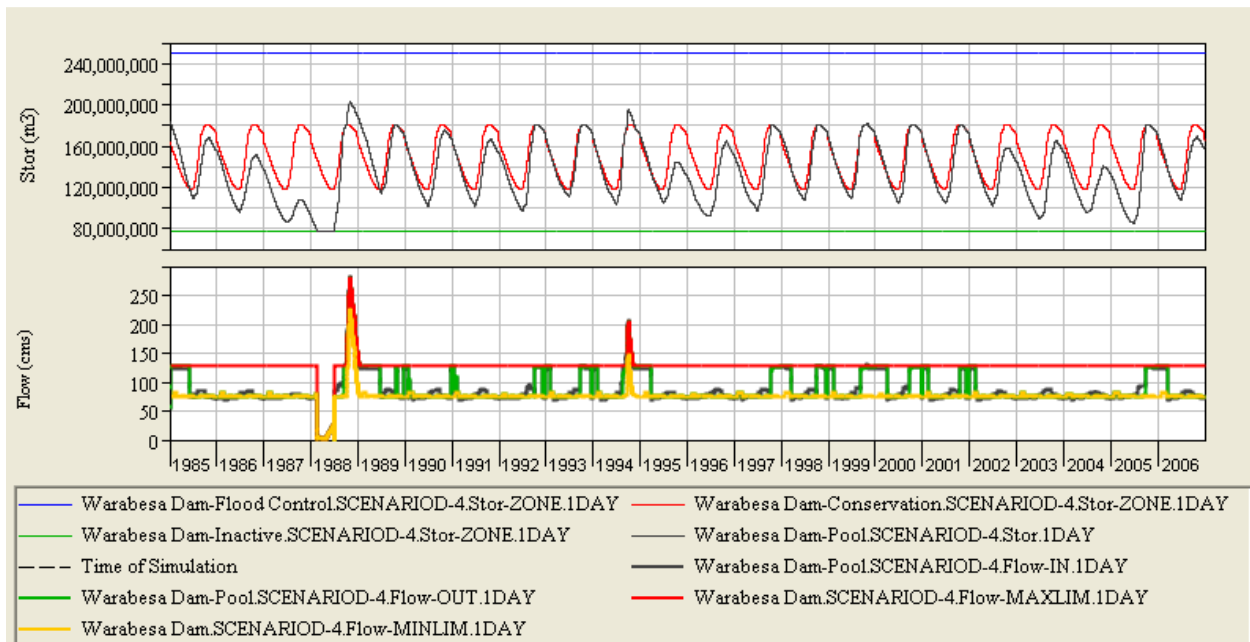


Figure E-5 Warabesa power plant operation simulated at scenario D

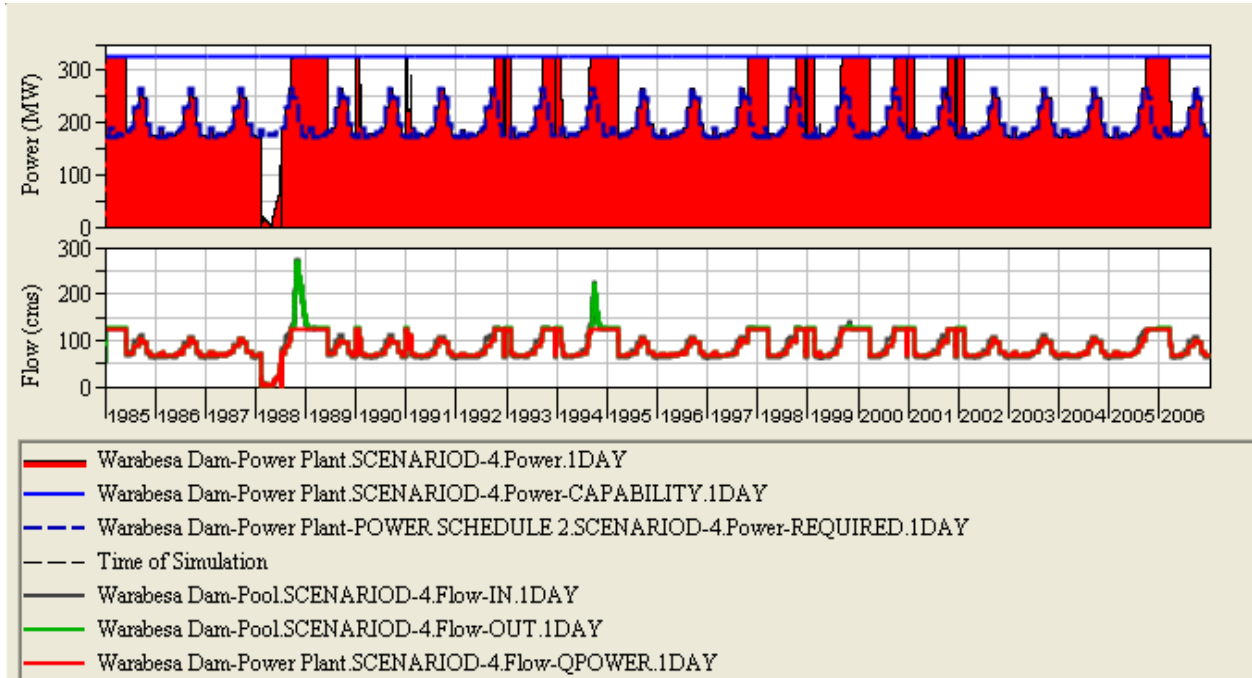


Figure E-6 Reservoir operation simulated for Gojeb reservoir at scenario D

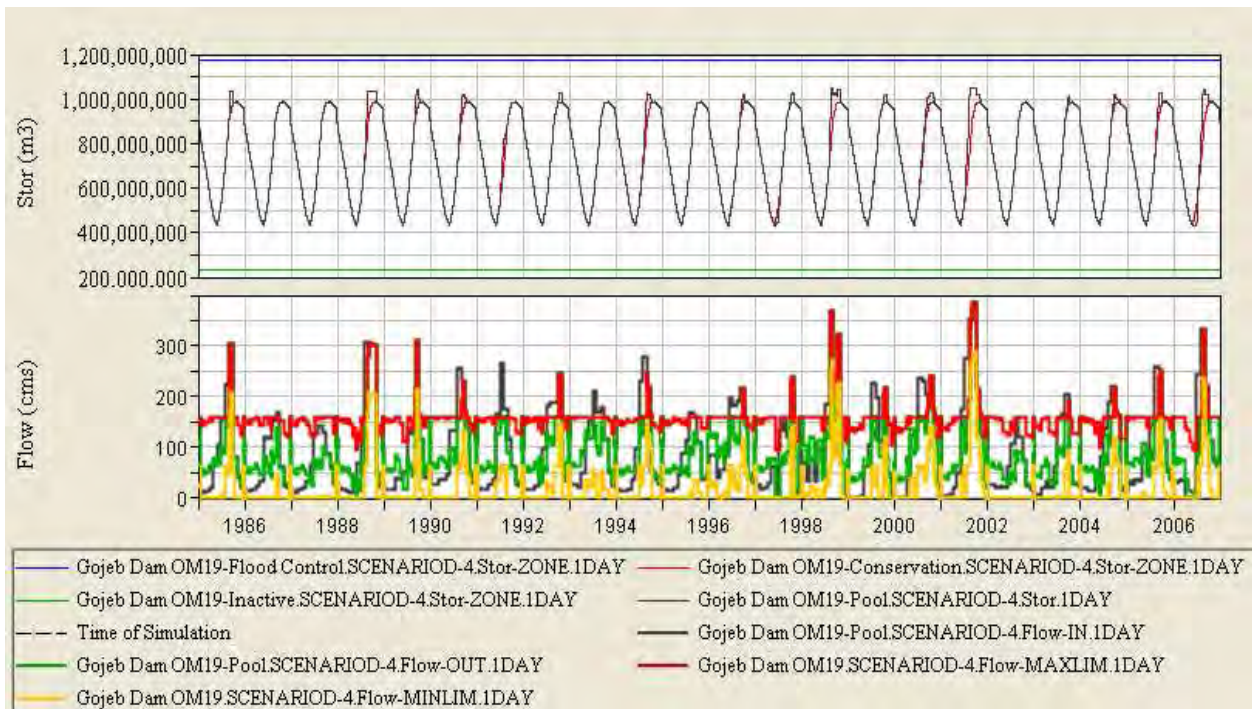


Figure E-7 Gojeb power plant operation simulated at scenario D

