Addis Ababa University

Addis Ababa Institute of Technology

Civil and Environmental Engineering Department

Optimal Reservoir operations on water resource projects at Wabi Shebelle river basin

A thesis submitted and presented to the school of graduate studies of Addis Ababa University in partial fulfillment of the degree of Masters of Science in Civil Engineering (Major Hydraulics Engineering)

By

Amir Abdulhamid

Advisor

Dr.Ing. Dereje Hailu

Addis Ababa University

Ethiopia

October, 2017

Declaration and copy right

I, Amir Abdulhamid Kiyar, 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

____

Date

Acknowledgement

I would like to express my sincere gratitude to my major advisor, Dr.Ing. Dereje Hailu for his close friendship, professional assistance, genuine and valuable criticism all the way from the outset to the completion of the study.

I would like to thank all staffs in the Ministry of Water, Irrigation and Energy especially to those staffs in the Departments of Hydrology and GIS, National Metrological Agency and Ethiopian Electric Power Corporation, for providing me with related materials.

I am very grateful to the School of Civil & Environmental Engineering, Institute of Technology, Addis Ababa University, for facilitating my work. I would like to thank all of Hydraulics Engineering department staffs who gave me the post-graduate courses.

I must extend special thanks to all my families and relatives, for there consistence support, concern and encouragement throughout my studies. Especially My mother has a very special role in motivating me to do this thesis.

Last but not least, my sincere thanks are also to all my friends and colleagues who directly or indirectly contributed for the success of both my course and thesis work.

Abstract

Wabi Shebelle River Basin is one of the twelve river basins in Ethiopia with catchment area of 202,697 Km2 and covering parts of the regions Oromia, Harari, Somali and a small area at the source of the Wabe River in SNNPE. Wabi Shebelle river basin has an estimated potential irrigable land of 237,905 and hydropower potential of 5,440 GWh/year is expected to contribute about 3.48% of the total estimated potential of the country.

In this study, HEC-ResSim (Hydrologic Engineering Center-Reservoir System Simulation) model was used to simulate reservoirs operation to optimize water for hydropower energy production, flood management as well as environmental flows. To control the model, two scenarios were simulated via scenario one (Baseline Scenario) and scenario two (future development scenario) based the project implementation period to incorporate the parameters that may influence flow requirements at a reservoir include hydrology conditions and simultaneous operation by other reservoirs in a system.

The model was attempted to represent the physical behavior of reservoirs in the basin with its hydrologic routing to represent the lag and attenuation of flows through the main and tributaries of the river. Hence, the model results suggest that the new reservoir operation rule selected, and its reservoir and power guide curves established for modeling of the dams and reservoirs operation enhances average energy production of the plant by 13% and also the study evaluate the effect of Erer and Gololcha irrigation project on Gode, results reveal that the new operation system will decrease water availability in the dry season by 4.07 and decrease flooding in the wet season by 9.5%. Overall the study has determined the new reservoir operation system will evenly allocate and release the available water in real time during day-to-day and emergency operations throughout the year.

Table of Content

List of Figure

List of Table

Abbreviations

DEM	Digital elevation Model
DSS	Decision Support Systems
EEPCO	Ethiopian Electric Power Corporation
ETO	Potential Evapotranspiration
FSL	Full supply level
GIS	Geographic Information System
HEC-ResSim	Hydrologic Engineering Center Reservoir Simulation
HEC-DSS	Hydrologic Engineering Center Data Storage Service
HEC ResPRM	Hydrologic Engineering Center Prescriptive reservoir model
MoWIE	Ministry of water, irrigation and energy
Max	Maximum
Min	Minimum
MOL	Minimum operating Level
masl	Meter above sea level
NMA	National meteorological Agency
SOP	Standard Operating Policy
WCD	World Commission on Dams

Units

ha	Hectare
km	Kilometer
Km2	kilometer square
l/s	Liter per second
mm	millimeter
Mm3	million cubic meters
MW	Mega watt
MWh	Mega watt hour
GWh	Giga Water hour

1. INTRODUCTION

1.1. Background

Access to water is fundamental to human survival, health and productivity. So it is necessary to ensure the sustainability of people's access to water, and to the environment which is dependent upon it. As pressures and demands on this limited resource increase, the need to find new and innovative approaches to providing it becomes more apparent. Water Resource Management (WRM) has emerged as a means to move away from a traditional sub-sector approach to water provision, to a more holistic or integrated approach to water management.

Dams were constructed to impound water at the upstream of the structure and provide water for irrigated agriculture, to generate hydropower, domestic water supply, commercial or industrial use, and help control floods (WCD, 2000). Most of the dams are single-purpose dams, but there are now a growing number of multipurpose dams. According to the most recent publication of the World Register of Dams, for the single purpose dams, 48 % are for irrigation, 17% for hydropower (production of electricity), 13% for water supply, 10% for flood control, 5% for recreation and less than 1% for navigation and fish farming.

Ethiopia has twelve major river basins. Its riparian systems, combined with its eleven major lakes, make Ethiopia the 'water tower' of Northeast Africa. However, only small numbers of them are developed to achieve the national economic and social development goals. 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, 2007) and showing that water resources have yet made little contribution towards the development of irrigated agriculture.

Dams and reservoirs are vital sources for sustainable development of integrated water resources projects. Reservoirs are one of the major storages of surface water and optimally operating single or multi reservoir network forms an integral part in water resources management. By altering the spatial and temporal distribution of runoff, reservoirs serve many purposes, such as flood control, hydropower generation, navigation, recreation, etc. (Chen, 2011). Reservoir operation is a complex problem that involves many decision variables, multiple objectives as well as considerable risk and uncertainty (Oliveira and Loucks, 1997). Nonetheless, they have also adversely affecting flow regime, affecting access to water and existing rights of riparian, significant impacts on the livelihoods and the ecosystem, and sedimentation. Some of the researchers pointed out that dams constructed for water resource projects have considerable impacts on the downstream river ecosystem (e.g. Collier, 1996, McCully, 2001, Willis and Griggs, 2003, McCartney, 2007). Hence, to minimize the adverse effects of dams, the World Commission on Dams (WCD) suggested the consideration of all stakeholders in the planning and management of water resources stored in a reservoir for an equitable distribution of the benefits to be gained from large dams (WCD, 2000).

One way of improving after management is increasing the efficiency of utilization of dam reservoirs. Even small improvement in reservoir operation can lead to large benefits. But there is no universal solution for reservoir operation problems (Bosona and Gebresenbet, 2010). Reservoirs is must operate to attain multiple purpose functions of the regions where they are deployed. Their operation requires decision how to distribute water storage and release. Reservoir operators must simultaneously satisfy the requirements for various needs, including all its purpose and the safety and structural integrity of the dam itself. Each of these needs imposes constraints on the storage and release of water from the reservoir, and the needs and constraints often come into conflict with one another (Klipsch and Evans, 2007). System operations take into account the inflow, the demands and the storage balance of the system for all reservoirs. Nonetheless, the real problem of reservoir operation is setting a schedule of reservoir releases that fulfill the purpose of a reservoir, meets operating constraints, and is physically possible is not a straightforward task, to best attain a specified objective or goal.

A number of models exist for modeling and simulation of the stream flows in the river system. 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.

The HEC-ResSim introduced by U.S. Army Corps of Engineers in 2013 is used to simulate the reservoir system of this study. The tool used was HEC-ResSim (Hydrologic Engineering Center –Reservoir System Simulation) model software.

Generally, this research helps to develop new reservoir operation guide curve for the Melka Wakena hydropower plant system and also on Erer-Gololcha irrigation project to meet yearly energy demand and to improve the water availability and flooding at Gode irrigation project.

1.2. Statement of the problem: -

Ethiopia is endowed with abundant water resources distributed in many parts of the country, which can be appropriately utilized to enhance socio-economic development of its people. Due to underdevelopment of this resource among others, the people of Ethiopia have been exposed to major problems such as impacts of drought and flood, shortage of clean water supply and inadequate energy supply (Tsegazeab, 2014).

Like many river basins in Ethiopia, water resources in the Wabi Shebelle 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. The recent history of Wabe Shebelle is marked by frequent destructive flash flood. The shebelle is said to have flooded every other year prior to 1960s that decade had only two devastating flood the hidigsayley in 1965 and the soogudud in 1966.in the 1970s the most devastating flood was kabahay of 1978, in 1996 flood devastated three woredas in Ethiopia. on October 1999, the river unexpectedly flooded in the middle of the night destroying home and crops in 14 kebeles out of 117 in kelafo woreda, as well as 29 of the 46 kebeles in neighboring mustahil woreda.

Most of the reservoirs in our country have a lack of predetermined, up-to-date and real time reservoir operation policy that will benefit all users in the basin. It is not unusual to observe that most of the reservoirs are unable to meet the desired purpose due to lack of optimum operation policies (Daniel, 2011).

The development of new water infrastructures in the basin and integrated management of water resources are required for sustainable socio-economic development of the area. Consequently, the operation of the existing single purpose reservoir of Melka Wakena will be influenced by the new water resources development to be introduced in the basin. (Bosona, 2010).

The basin water resource is under pressure by increasing population, new infrastructure and new large scale irrigation projects development. Therefore, determination of optimal reservoir operation is mandatory at the planning and real time operation in order to attain the objective of the power plants and irrigation projects to sustainable water allocation and conflict management.

The volume of discharge in Wabi Shebelle river basin is subjected to high fluctuation, sporadic flash of flood as a result of torrential tropical rains in summer and dry channels for some rivers and streams in dry season. Consequently, the complexities involved in water allocation and use of Wabi Shebelle river basin and any river basin in the world require optimal allocation and utilization to achieve sustainable, efficient, and equitable.

1.3. Significance of the study:

Development of new water infrastructures on a main river and tributaries in the Wabi Shebelle river need integrated water resources management. Therefore, when any new dam will be required to construct, the interaction among the existing should be considered for maximizing the benefit and minimizing the adverse effect of the system operation through interrelation or networking dams and reservoirs (Bergkamp, 2000). This complex task can be accomplished with the help of computer-based hydraulic modeling. So, this study plays a significant role in such a way that it simulates the reservoir system operations using HEC-ResSim for good and optimum operation of the reservoir water management in Wabi Shebelle river basin.

Moreover, in Ethiopia, evaluation and modification of the planning and management of reservoirs were given a little attention on how to dam and reservoir operation might be modified to mitigate, to the extent possible, the change watershed characteristics due to the rapid development of new dams. This study will endeavor to address this issue. The result of the study will provide tangible tools for the possible redesign of the operation and management of dams and reservoirs for an equitable distribution of water to different stakeholders in the basin and also contribute to resolve debates on the pro-and-con of future developed water infrastructure in the basin. At the very end, the study results may bridge the information gap that presently still exists on the Wabi Shebelle River Basin, so that concerned bodies and policy makers will get additional information to strengthen their decision.

1.4. Objective of the study:

1.4.1. General Objectives:

The General Objectives of this study is to model water use and operations of existing and planned water resource development projects at Wabi Shebelle river basin using HEC-ResSim (Hydrologic Engineering Center –Reservoir System Simulation) model.

1.4.2. Specific Objectives:

- Using HEC-ResSim model to set up reservoirs simulation model for Melka Wakena hydro power plant and Erer-Gololcha Irrigation Project.
- To evaluate the effects of the selected reservoir operating alternatives on either preventing flooding or avoiding low-flow at locations downstream of the Melka Wakena Reservoir.
- To evaluate effects of Erer-Gololcha Irrigation project on Gode irrigation project.

1.5 Structure of the Thesis

The thesis has been organized to have seven chapters including the introductory section. General Over views of each chapter are discussed as follows

Chapter 1 comprises the introduction part, problem statement and objectives of the study.

Chapter 2 is the literature review and discusses 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, it 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 Wabe Shebelle river basin including the location, rainfall characteristics, land use and topography. The chapter also discusses about the location, physical and operational characteristics of the existing hydropower plants and reservoirs

Chapter 4 describes methodology used 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 developed for Wabe Shebelle river basin and the number of alternatives used for the analysis to get the optimal power and/or energy from the system.

Chapter 6 describes result obtain in simulation

Chapter 7 conclusion and recommendation are given and Finally References and Appendices are attached.

2. LITERATURES REVIEW

2.1 Hydropower and irrigation schemes development in the Shebelle Basin

Irrigation along the Shebelle River began in the 1960s and was associated with the development of Gode town. At this time, Alemaya College of Agriculture set up a research center with the main objective of assessing the agro-climatic suitability for large-scale irrigated crop farming. This led to the engagement of private farmers in irrigation farming in the 60s and early 70s, which was then scaled up during the Derg and under the current government. Meanwhile, there were numerous ownership changes associated with the scheme starting with private farmers in the 60s, settled pastoralists as of mid-70s, settled highland farmers in the 1980s, and part of it being owned by the State Farms from mid-1980s onwards. However, the scheme was running at a loss in the 70s and 80s because of the use of diesel pumps and the isolation of the area from major market centers. After the downfall of the Derg, the state farm was transferred to the SRS, which in turn distributed the farm land to returnee claimants, and poor pastoral and agro-pastoral groups on the basis of promoting food self-sufficiency in the region **(**livestock, crop and rural development bureau, 2013).

Currently, irrigated agricultural production is taking place along the Shebelle bank all the way down to Ferfer (near the border with Somalia), mainly with pumps and to a lesser extent through flood recession or gravity. Despite this activity, the Region's history is punctuated by food insecurity due to factors such as climatic variability and the poor performance of the agricultural sector. Cognizant of this problem, the SRS has been implementing the Agricultural Development Led Industrialization (ADLI) strategy. The current five-year GTP Plan and /or SPM of the government gives recognition and focus to commercialization as the next step of agricultural development. It envisages diversification and specialization of crop and livestock production by farmers, and use of agricultural cooperatives and private investors to maximize the intensification of resource use to improve technical and production efficiency. For agriculture, the target commodities include rice, cotton, sesame, banana and forage crops which are viewed as potential export crops to be scaled-up through commercial production in woredas along the Shebelle river **(**livestock, crop and rural development bureau, 2013).

2.2 Decision Making Technologies in Water Resource Management

The competition for available water resources in much of the developing world is growing rapidly due to ever-increasing and conflicting demands from agriculture, industry, urban water supply and energy production. The demand is fueled by factors such as population growth, urbanization, dietary changes and increasing consumption accompanying economic growth and industrialization. Climatic changes are expected to further increase the stress on water resources in many regions.

The traditional fragmented approach is no longer viable and a more holistic and coordinated approach to water management is essential. River basin management engages 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, protection and enhancement of fish, wildlife, and other environmental resources are important considerations in managing reservoir/river systems.

Nevertheless, the multi-interdepend objective and constraints of river basin systems has made it difficult to satisfy 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. Thus the need to manage these complex integrated interests in a river basin or Reservoir system has led to 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.

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 a solution 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 (Simonovic, 1996).

2.3 Reservoir operation

Since the 1960s water resources management policy and practice have shifted to a greater reliance on improving water use efficiency. Water research teams in many countries have conclusively demonstrated the value of adopting the modern tool of operations research or systems analysis for assisting in the development, operation, planning and management of the water resources project. However, these tools can only assist; they cannot replace the water resource decision making process. Furthermore, some studies indicate a gap between theories of water resources models and the application of these models in the real world. There are many analysis techniques and computer models available in the real world for developing quantitative information for use in evaluating storage capacities, water allocation, and release policies.

Reservoir operation is the method used to allocate water stored in the reservoir among different upstream and downstream users. It is an important element in water resources planning and management. Reservoir operation consists of several control variables that defines the operation strategies for guiding a sequence of releases to meet a large number of demands from stakeholders with different objectives, such as flood control, hydropower generation and allocation of water to different users. A major difficulty in the operation of reservoirs is the often conflicting and unequal objectives that require optimal operation rule and strong decision.

2.3.1 Reservoir 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 are usually expressed in as water surface elevation or storage volume versus time of the year. Although the term rule curve denotes various other types of storage volume designations as well, the top of conservation pool is a common form of rule curve designation. The top of conservation pool may be varied seasonally, particularly in regions with distinct flood seasons.

The simulation analysis essentially requires an operation policy. Generally, operation policies are represented as rule curves. A rule curve is a graphical representation specifying ideal storage or empty space to be maintained in a reservoir during different times of the year. Here the implicit assumption is that a reservoir can best satisfy its purposes if the storage levels or empty spaces as specified by the rule curve are maintained in the reservoir at the specified time. The amount of water to be released from the reservoir will depend upon the inflows to the reservoir. The rule curves are generally derived through operation studies using historic flows or generated flows where a long term historic-record is not available.

The top of conservation pool may be varied seasonally, particularly in regions with distinct flood seasons. The seasonal rule curve illustrated by Figure 2.1 reflects a location where summer months are characterized by high water demands, low stream flows, and a low probability of floods.

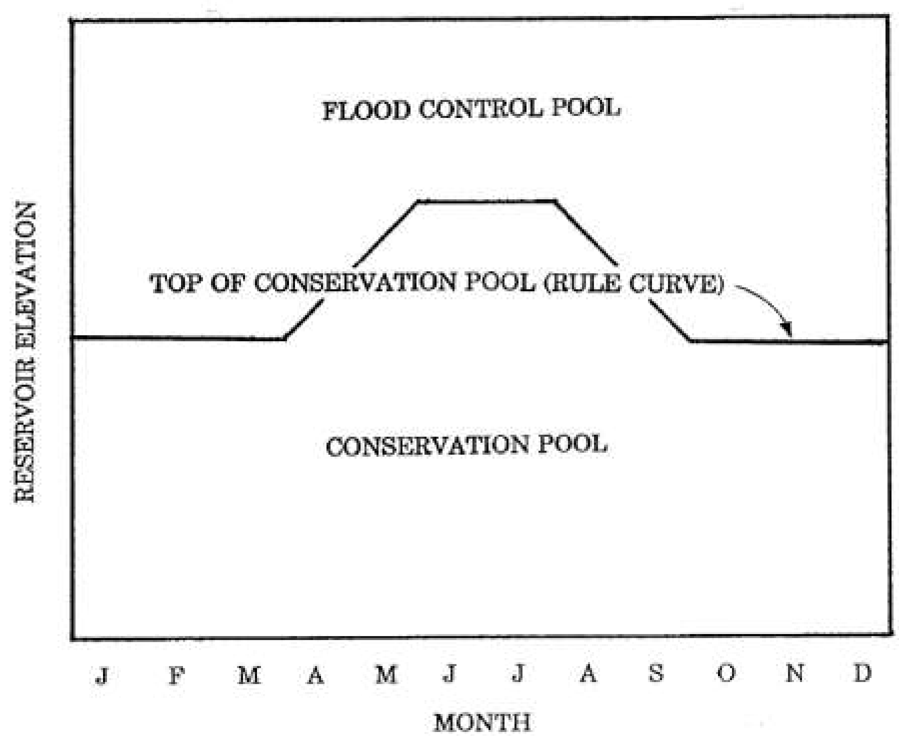


Figure 2.1: Seasonal Top of Conservation pool (Mulu Sewinet, 2009)

2.3.1.1 Standard Operation Policy

The Standard Operating Policy (SOP) is the optimal operating policy with an objective to minimize the total deficit over the time horizon. Standard Operating Policy (SOP) (Stedinger, 1984) is the policy that releases only the target releases in each period, if possible. If sufficient water is not available to meet the target, the reservoir empties. If copious water is available, the reservoir will fill and then spill any excess water. Mathematically this rule can be expressed as,

$$R_t = S_{t-1}+Q_t \qquad \text{if } S_{t-1}+Q_t \leq D_t$$

$$R_t = D_t \qquad \text{if } D_t \leq S_{t-1}+Q_t \leq C$$

$$R_t = S_{t-1}+Q_t - C \qquad \text{if } S_{t-1}+Q_t - D_t \geq C$$

Where Rt = Release at any time t; St-1 = Storage in the reservoir at time (t-1); Qt = Inflow in to the reservoir at time t; Dt = Demand in time t; C = Capacity of the reservoir.

2.3.1.2 Hedging Rule

An operating rule that places more penalties on large deficits than small ones is called Hedging Rule (Maass, 1962). According to Bower (1962) the term hedging as "the complexity of how much water to be withheld from the immediate release made, and retaining that water in storage for future use". If the reservoir system manager tries to meet the demand fully during early months of the critical period, he may incur severe deficits on later periods. In order to prevent severe deficit in the later period, the irrigation manager can tolerate some deficit during release periods. If a reservoir has been designed for a lower safe yield than the yield it is currently being used to provide, rationing could become a common experience. At the time of rationing, it is to be determined that the quantities or some values that should be used to trigger rationing to prevent larger deficit in the later period. The development of realistic rule for reducing demand and therefore draft from the reservoir is based on the answers to the following questions:

1) At what time and at what level of storage does the rationing begin?
2) How much demand and therefore the draft are to be reduced during each time period?

2.4 Effect of Reservoir Operation on Flooding at Downstream of Dams

A flood is an overflow of water that submerges land which is usually dry. The European Union (EU) Floods Directive defines a flood as a covering by water from land not normally covered by water. There are different reasons for the causes of flooding at the downstream of dams. Normally flooding occurs as an overflow of water from water bodies, such as a river or artificial reservoirs due to a strong storm at the upstream catchment. In this case water overtops or breaks dams and resulting water escaping its usual boundaries at the downstream. The other reason for the cause of flooding without the presence of dam is owing to an accumulation of rainwater on saturated ground in an aerial flood.

2.4.1 Regulation Rules for Flood Control Storage Capacity

Flood control regulation plans are developed to address the particular conditions associated with each individual reservoir and multiple-reservoir system. Peculiarities and exceptions to standard operating procedures occur at various projects. However, the regulation rules for most reservoirs follow the same general strategy.

Release decisions depend upon whether or not the flood control storage capacity is exceeded. A specified set of rules, based on downstream flow rates, are followed as long as sufficient storage capacity is available to handle the flood without having to deal with the water surface rising above the top of flood control pool. Operation is switched over to an alternative approach, based on reservoir inflows and storage levels, during extreme flood conditions when the anticipated inflows are expected to deplete the controlled storage capacity remaining in the reservoir. The reservoir release rates necessitated by the flood control storage capacity being exceeded will, in most cases, contribute to downstream flooding. The objective is to assure that reservoir releases do not contribute to downstream discharges rising above allowable levels as long as the storage capacity is not exceeded. However, for extreme flood events which would exceed the storage capacity, moderately high release rates beginning before the flood control pool is full may be preferable to waiting until a full flood control pool necessitates even higher release rates.

2.4.2 Regulation Based on Downstream Flow Rates

Assuming the flood control storage capacity is not exceeded, flood control operations are based on target allowable flow rates and stages at selected index locations or control points. The allowable flow rates are typically related to bank full stream capacities, stages at which significant damages occur, environmental considerations, and/or constraints such as inundation of road crossings or other facilities. Stream gaging stations are located at the control points. Releases are made to empty the flood control pool as quickly as possible without exceeding the allowable flow rates at each downstream control point. When a flood occurs, the spillway and outlet works gates are closed. The gates remain closed until a determination is made that the flood has crested and flows are below the target levels specified for each of the control points. The gates are then operated to empty the flood control pool as quickly as possible without exceeding the allowable flows at the control points. Normally, no flood control releases are made if the reservoir level is at or below the top of conservation pool. However, in some cases, if flood forecasts indicate that the inflow volume will exceed the available conservation storage, flood control releases from the conservation storage may be made if downstream conditions permit. The idea is to release some water before the stream rises downstream, if practical, for a forecasted flood. For many reservoirs, the allowable flow rate associated with a given control point is constant regardless of the reservoir surface elevation.

Most reservoirs are operated based on maintaining flow rates at several control points located various distances below the dam. The most downstream control points may be several hundred miles below the dam. Lateral inflows from uncontrolled watershed areas below the dam increase with distance downstream. Thus, the impact of the reservoir on flood flows decreases with distance downstream. Operating to downstream control points requires stream flow forecasts.

2.5 Irrigation Scheduling

Good irrigation management is required for efficient and profitable use of water for irrigating agricultural crops. Irrigation scheduling is dependent on design, maintenance and operation of irrigation system and availability of water. A major part of any irrigation management program is the decision-making process for determining irrigation dates and/or how much water should be applied to the field for each irrigation turn. This decision-making process is referred to as irrigation scheduling. Efficient scheduling of irrigation maximizes the production and prevents under and/or over watering of the crop.

2.5.1 Water balance and Crop management

The management of water resources in irrigation is a fundamental aspect for their sustainability. The current situation of irrigation throughout the world is characterized by a decrease in available water resources, especially in arid and semiarid zones. This trend, which will probably become more aggravated in the future, is due to the reduction in available water (competition for different users, environmental conditions, global change etc.) and is also caused by progressive deterioration of water quality (various sources of pollution). Since water prices are progressively increasing, it is necessary to analyze the factors that affect water uses in order to improve water management for sustainable agriculture. Worldwide, irrigated agriculture is responsible for more than 80% of water consumption in arid and semiarid zones. Thus, the improvement of water management in agriculture should deal with different aspects in a coordinated and integrated way. Among these aspects, Raman (1992) developed an expert system for drought management.

2.6 Reservoir System Analysis Models

2.6.1 Optimization

Optimization refers to a mathematical formulation in which an 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. 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.

Optimization models are more efficient to find an optimum decision for system operation meeting all system constraints while maximizing or minimizing some objective. However, simulation models are effective tools for evaluating water resource systems and provide the response of the system for certain inputs.

2.6.1.1 Linear programming

The most important optimization techniques used in reservoir operation are linear and dynamic programming. Linear programming is an operation research technique that has been widely used in water resource planning and management. Its popularity is due to the following considerations. Linear programming is applicable to a wide variety of problems; efficient solution algorithms and computer software packages are available for applying the solution algorithm. Various generalized optimization programs are commercially available for solving linear equation with constraints.

2.6.1.2 Dynamic programming

Dynamic programming, developed by Bellman (1957) for dealing with sequential decision processes, is not restricted by any requirement of linearity, convexity, or even continuity. Nevertheless, it is restricted to specific forms of the objective function. Mays and Tung (1992), which describe the fundamentals of dynamic programming for the perspective of water Resources planning and management. Unlike linear programming, for which many general-purpose software packages are available, the availability of general dynamic programming codes is limited. Most Dynamic programming computer programs have been developed for specific applications. Dynamic programming is not a precisely structured algorithm like linear programming, but rather a general approach to solving optimization problems. Dynamic programming involves decomposing a complex problem into a series of simple sub-problems which are solved sequentially, while transmitting essential information from one stage of the computations to the next using state concepts. Several dynamic programming models have been developed in the field of reservoir operation.

2.6.2 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 (Yeh, 1985). Simulation models still remain the primary tool for reservoir operation studies. It is an abstraction of reality and replicates the physical behavior of the system under a given set of conditions. Simulation models are used to evaluate the consequences of a set of decisions (what-if analysis) over a hydrologic period of interest.

Simulation is the process of experimenting with a simulation model to analyze the performance of the system under varying conditions. 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. Hence, the simulation model enables the analysis to test the alternatives scenarios (e.g. different operation rules) and examines the consequence before actually implementing them. 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:

$$S_t = S_{t-1} + I_t - R_t - L \quad \text{.........} \quad 3.1$$

Where:

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

I_t is the e 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.

2.7 Combined Simulation-Optimization Model

The simulation model may not directly find the best operation policy. The simulation model has to be operated with different combinations of operating decision variables and the policy that appears to perform best has to be selected. However, when there are several decision variables, this kind of selection process could be extremely time consuming, even on fast computers. Therefore, it can be realized that a more efficient procedure is needed for systematically finding the ‘best’ of at least the ‘near best’ operating policy among the many possible alternative combinations. By combining simulation and optimization, there is greater likelihood of finding optimal policy without having to consider all possible combinations of alternatives. Most of the times, the optimization problems in water resources management do not oblige the mathematician by changing into analytically solvable type. The search algorithms provide a mechanism to systematize and automate the series of iterative executions of the simulation model required to find a near optimum decision policy

2.8 Review of Reservoir Simulation Modeling

The most advantage of using simulation modeling is, replicates the physical behavior of a system on a computer and it reflects the actual mechanism of the nature. The fundamental characteristics of the different components of simulation models are characterized by a mathematical or an algebraic description. Simulation models are distinct from mathematical programming techniques in which they provide the response of the system to specify inputs under given conditions or constraints. Hence, simulation models enable a decision maker to test discrete alternative scenarios (e.g., in this case reservoir operating rules) and evaluate the feasibility before actually implementing them.

Simulation models remain the primary tool for river basin planning and management studies in practice. Simulation models have been routinely applied for operation of reservoir projects. Some of the most common applicable reservoir application models are briefly described hereunder.

WEAP: Water Evaluation and Planning Model is developed and distributed by Stockholm Environmental Institute Boston Center at the TELUS Institute located in Boston, Massachusetts. It is a simulation model developed to evaluate planning and management issues associated with water resource development.

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.

MIKE BASIN: runs within and is an extension to ArcView which is a geographical information system (GIS) software product available from ESRI (Environ mental System Research Institute). The model simulates multipurpose, multi-reservoir systems based on a network formulation of nodes and branches.

HEC-5: Simulation of flood control and conservation systems software developed by the hydrologic Engineering center of US army corps of Engineering. It is designed to perform a sequential reservoir operation based on a specified project demand and constraints. The simulation is performed with the specified flow data in the time interval for simulation. The simulation software determines the reservoir release at each time steps and the resulting downstream flows.

HEC-ResPRM: The Hydrologic Engineering Center (HEC) of the U.S. Army Corps of Engineers has developed a new reservoir Optimization model, HEC ResPRM is reservoir system operation optimization software package developed to assist planers operators and managers with reservoir operation planning and decision making. HEC ResPRM uses network flow optimization to suggest an idea of the best outcome that can be expected for the system based on any particular prioritization of the system objectives and given in flow time series.

Optimization is the approach to solving problems that seek the best solution by maximizing (or minimizing) a set of goal a form of an objective function specified constraint. Reservoir operation takes into account a number of goals from different interest (flood control water supply power generation recreation, etc.).

HEC ResPRM allows users to pose reservoir system as a network flow problem. Users create a network schematic or their watersheds reservoir and stream reaches. They then enter hydrological data and penalty functions for each reservoirs and reach, representing the cost/benefit of each interest interms of penalty and flow / storage. HEC ResPRM then uses network flow solves to find an optimal solution. Users can view optimization result in graphical and tabulate format directly with in the graphical user interface.

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 is a generalized reservoir simulation program that has been developed to provide watershed managers an effective tool for real-time decision support and use in planning studies. 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. The generalized nature of HEC-ResSim, its flexible scheme for describing reservoir operations, and its powerful new features, such as outlet prioritization, scripted state variables, and conditional logic, make it applicable for modeling almost any single- or multi-purpose reservoir system. Thus, as a result of unique features mentioned it is primarily selected for this study.

2.9 The Reservoir operation simulation model (HEC-ResSim)

Large man-made reservoirs are constructed and operated for multiple purposes. Reservoir operators must simultaneously meet requirements for many needs, including flood control, power generation, recreational use of the reservoir pool, environmental quality downstream of the reservoir, and the safety and structural integrity of the dam itself. Each of these needs imposes constraints on the storage and release of water from the reservoir, and the needs and constraints often conflict with one another. Setting a schedule of reservoir releases that fulfills the purpose of a reservoir, meets operating constraints, and is physically possible is not a simple task, and engineers have created reservoir simulation models to help develop those release schedules.

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. Designed to simulate reservoir operations for flood management as well as flow augmentation, HEC-ResSim represents a significant advancement in the decision support tools available to water managers.

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. The reservoirs designated to meet the flow requirements may have multiple and/or conflicted constraints on their operation. HEC-

ResSim describes these flow requirements and constraints for the operating zones of a reservoir using a separate set of prioritized rules for each zone. 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. The graphical user interface makes HEC-ResSim easy to use and the customizable plotting and reporting tools facilitate output analysis.

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.

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. It is utilized to simulate reservoir operations including all characteristics of a reservoir and channel routing downstream. Additionally, it is in line with ArcGIS shape files, which can serve as a background layer and facilitate the better representation of the physical system. The program consists of three modules and they are the watershed setup/or watershed configuration, the reservoir network and the simulation scenario module.

Watershed Setup

Represents the watershed development which is the model configuration of the schematic elements. These elements include streams, projects (i.e. reservoir, levees), gauge locations, impact areas, time-series locations and hydrologic and hydraulic data for that specific area. Schematic elements allow the representation of watershed, reservoir network and simulation data usually in a geo-referenced content that interacts with associated data.

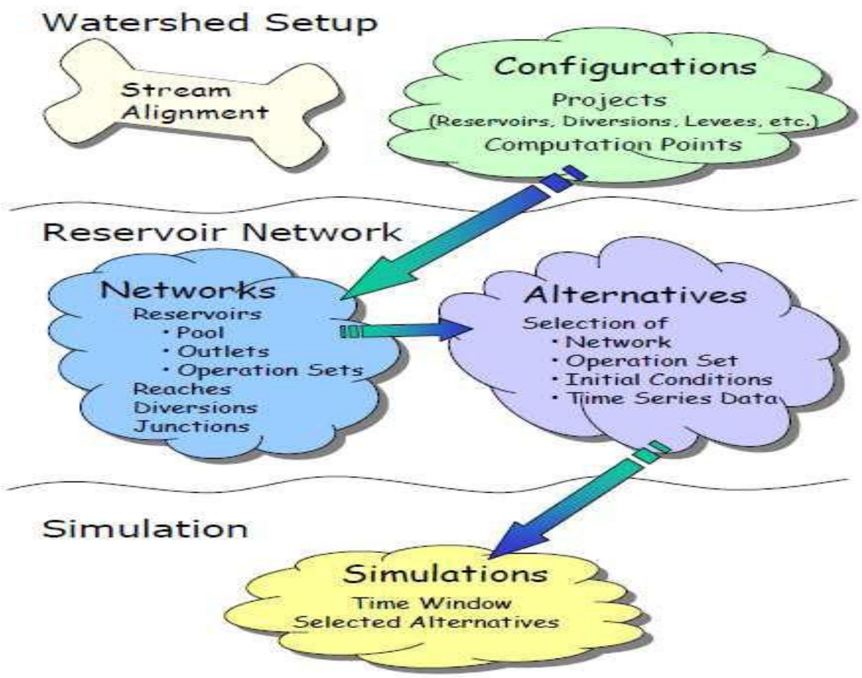


Figure 2.2: ResSim module concepts (HEC-2003)

Reservoir network

Represents a collection of watershed elements connected by routing reaches. The network includes reservoirs, reaches and junctions needed for the model and is where all the physical and operational data are entered and stored in the model. This module allows the model to describe 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.

Simulation Module

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 is used to configure the simulation. The computations are performed and results are viewed within the Simulation module (Hydrologic Engineering Center, 2013).

2.9.1. Reservoir Operation Rule in HEC-ResSim

Reservoir operational management needs a set of operational rules that applies a certain procedure that best meet a set of objectives. For this purpose, reservoir operation rules should be utilized to establish a guideline for responding to the questions how the reservoir storage releases during the operation time.

Reservoir in HEC-ResSim must have a target elevation. A reservoir's target elevation, presented 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 guidelines for determining release from reservoir are based on the current reservoir pool level. When the reservoir's pool elevation is above the guide curve in flood control, the reservoir always 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. Additional goal and constraint are applied to temple such the rigid operational rule 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, 2007). In each reservoir it must to determine how much water to release at each time step of simulation.to make this possible it must to describe operation plan this plan is known as operation set.

Operation set consist three basic Features: Zone is operational sub division of Reservoir pool, Rule is the goal and constraint up on the release and Guide curve is identified by selecting one of your operational zones to represent the target elevation of the reservoir.

HEC-ResSim establishes three set of zones with in operation set:

Flood control pool refers to zone serves for flood control purposes. It is located between the maximum reservoir level and the normal reservoir level. This storage space should be as much as possible empty to make the reservoir kept safe during extreme flooding, and also to avoid downstream damage.

Conservation pool is defined as the storage zone between the flood control pool and the inactive pool, and the storage space set aside for the purpose of water stored for hydropower, environmental releases and other activities.

Inactive pool is sometimes called dead storage zone.is represent the lowest operational elevation of a reservoir, and by the default of the model, water releases cannot be permissible below this elevation.

A few reservoir operating rules are found in HEC-ResSim which is applied for the reservoir pool includes:

- Release Function
- Downstream Control Function
- Tandem Operation
- Induced Surcharge
- Flow Rate of Change Limit
- Elevation Rate of Change Limit
- Script

2.9.1.1 Downstream Control Function Rule in HEC-ResSim

Downstream Control Function is the method in HEC-ResSim reservoir simulation model that used to analyses the reservoir operation in the system (Where two or more parallel reservoirs are operated to have balance storage while controlling a common downstream requirement) and the storage distribution among the reservoirs.

For every decision interval an end-of-data, storage is first estimated for each reservoir based on the sum of the beginning of date storage and daily 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, 2013).

Operational system storage in HEC-ResSim

There are for two types of operational system storage in HEC-ResSim. The implicit system storage balances (default) and explicit system storage balances (user defined).

Implicit system storage balance

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.

Explicit system storage balance

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, 2013).

The process of determining desired storages is repeated every decision interval in order to assign the priority for release to the reservoir that is furthest above the desired storage. A release decision made for a particular time period may not necessarily achieve the desired balance. The reservoirs are considered in balance when both reservoirs have reached their Guide Curves or are operating at the desired storage levels along their balance line curves as prescribed in the explicit storage balance scheme.

2.9.1.2 Hydropower Reservoir Operation Rules

Hydropower reservoir operation rules stipulate the minimum releases required from a reservoir's power plant (or from the power plants in a reservoir system) to meet a power generation requirement of the power plant and the schedule set for it. In HEC, the desired release depends on a plant's generation capacity, the hydraulic head, and the required energy. Most of the time, in the various hydropower rules, the generation requirement can be expressed as a relationship between the storage, season, and sometimes can be directly specified as an external time series. In HEC-ResSim, there are four discrete hydropower rule types available to establish a rule that describes a hydropower requirement. These rules include Schedule, Time Series, Power Guide Curve and System Schedule. The differences among these rules are based on the input data, specification or defining of the hydropower requirement. For this study Hydropower schedule operation rules are used.

The Hydropower schedule operation rules allows defining a regular monthly or user specified seasonally varying hydropower requirements. In reservoir network, there are various options on this rule editor that permit to define each month's power generation requirement, the type of requirement (megawatt-hour or plant factor), and the hours of the day and days of the week during which the plant can Generate.

2.9.3 Studies using Hec-ResSim Models

Due to its feature of flexibility and ability to simulate complex one or more projects having multipurpose function, Hec-ResSim has been widely used since the release of the program. Reservoir operation simulation studies done on different basin of Ethiopia and other countries using ResSim model has been referred for the preparation of this study. These papers include, Reservoirs Water Balance Analysis, Joint Operation and Optimal Operation Rules Curve for

System Performance (A Case Study Of Proposed Reservoirs on the Main Blue Nile River, Ethiopia), (Genet, 2008), Water Use and Operation Analysis of Water Resource Systems in Omo Gibe River Basin (Daniel, 2011), Application of Reservoir Simulation and Flow Routing Models to the Operation of Multi-Reservoir System In terms of Flood Controlling and Hydropower's Regulation (Madani, 2013), Tandem Reservoir Operation off Cascade Hydropower Plants Case of Genalle - Dawa River Basin(Tesgazab Dejene, 2014) and Modeling of Cascade Dams and Reservoirs Operation for Optimal Water Use: Application to Omo Gibe River Basin(Teshome Seyoum,2015)

2.10 Previous Study in the Basin

2.10.1 BCEOM-EDF-ORSTOM-1974

The BCEOM carried out feasibility level study for Melka Wakena and Kuldash Dam projects. The consultant suggested, in their studies Melka Wakena for Hydropower development and Kuldash Dam for regulated flows for the development of Irrigation in the lower valley of Gode, Kalefo and Mustahil areas. A brief reference was made in their studies that power can be generated from Kuldash Dam but detailed studies were not carried out. As the study is at feasibility level, this project i.e. Kuldash Dam is included in the present study.

2.10.2 WAPCOS (I) Ltd.

In their report of "Water Resources Development Master Plan for Ethiopia," suggested sixteen new sites for construction of 100m high Dams for Hydropower development in the Wabi Shebelle basin. These sites are labeled as WS1-WS16 (Refer Map/Lsection) and are included for initial evaluation. WAPCOS (I) Ltd. in their desk study did not propose power development from Kuldash Dam site.

Wabi Shebelle River Basin, Integrated Development Master Plan Project Reconnaissance Phase (Dams and Hydropower). The Ministry of Water Resources in their study did not specify any new Dam site on the main Wabi Shebelle River but suggested new sites on some of the major tributaries.

All the above-mentioned sites including the additional identified sites namely WS17, WS18 GL1, GL2, DK1 and WY1 during Phase-1 reconnaissance studies are included in the initial evaluation. These sites are marked on the enclosed Fig.1. WAPCOS in their studies limited the height of these Dams to 100m only. But now with the availability of additional Topographical, Hydrological, Geological as well as Geotechnical data the features of the Dam and appurtenant works have been finalized. Area capacity curves for each site have been plotted to finalize the capacities of the reservoirs. But the height of the Dam is still limited to around 100m, as the geology of the Dam sites does not permit to have Dams more than this height.

In the background of these studies overall potential of the basin has been studied and all available documents have been assessed. Projects comprising reasonably good storage reservoirs are included for detailed analyses to include costs from which two projects will ultimately be short-listed for pre-feasibility studies in the present phase.

2.10.3 BECOM-ORSTOM, 1971

The Wabi Shebelle Survey carried in 1969-71 by a French company (BECOM-ORSTOM) had identified 14 large and medium scale irrigation potential sites with a total of 112,000ha under this study. The study concentrates on the main Wabi Shebelle River course in Lower Valley. In this study a total of 269,000 ha of suitable land for irrigation development was studied along left and right banks of Wabi Shebelle River within the stretch Imi up to Mustahil. But due to the shortage of water only 112,000 ha of land was considered in the planning which is highly suitable with respect to the soil class.

2.10.4 MOWR, 1998.

The Ministry of Water Resources carried out the reconnaissance study of the Wabi Shebelle basin in 1998. Reconnaissance survey was also carried out to review and evaluate the previous studies, existing irrigation schemes and to identify additional irrigation potential in the basin. In the study various additional irrigation potentials are identified and some of them, identified by BCEOM and WAPCOS are included in the report with additional area at the same site. Accordingly, twenty-six large-scale sites with a potential of 1,079,730ha of land are indicated in the report. Out of which WAPCOS identified 204,200 ha and 112,000 ha were identified by BECOM. Finally, the area identified by the MoWR is 764,730 ha of irrigation potential. The study however, does not provide detailed information of the identified sites.

2.10.5 BOSONA, 2004.

The study carried on modeling Melka Wakena hydropower plant system to improve its reservoir operation. One way of improving water management is increasing the efficiency of utilization of dam reservoirs. Even small improvement in reservoir operation can lead to large benefits. But there is no universal solution for reservoir operation problems. Hence, it is necessary to study the system and determine optimal reservoir operation guides for each scheme. The tool used was Powersim Simulation software. Mean monthly data of reservoir inflow, evaporation rate, recorded energy production; recorded discharge (turbine flow) and recorded reservoir elevation were used as time series input data. Different variables and relationships between variables were defined along with the constraints. After developing and calibrating the model successfully, detailed simulation analysis was carried out by controlling reservoir releases for energy production, taking into consideration; increasing yearly energy production and improving the uniformity of monthly energy production. The results of the simulation analyses indicated that the yearly energy production was increased by 5.67% while evaporation loss was reduced by 38.33%. But this power plant still produces below its design capacity by 12.21%. The uniformity of monthly energy production from this plant was also improved. The new reservoir operation guide curve has been developed for the optimum energy production from this plant.

2.10.6 KINDIE, 2016.

The study carried on Surface Water Potential and Demands of Wabi Shebelle Basin. Water is vital for many aspects of economic and social development, e.g., for energy production, agriculture, domestic and industrial water supply, and it is a critical component of the global environment. The output of this study is to assist planners and managers to make decision on water resource availability in a catchment and also is to assess and forecast water demand in the basin. The soil and water assessment tool (SWAT) and water evaluation and planning system (WEAP) were used for the prediction of surface water potential and demands of Wabi shebelle River basin respectively. In the study quantify the surface water resources within the basin and assessing the demands in the basin using rainfall-run-off and water resource modeling.

3. DESCRIPTION OF THE STUDY AREA

3.1 Location of Wabe Shebelle Basin

The study area is found in south eastern Ethiopia covering a large part of the country‘s land mass. Ethiopia has 12 river basins. The total mean annual flow from all the 12 river basins is estimated to be 122 BMC (MOWIE 1999). The Wabe Shebelle river basin is one of the twelve major river basins in Ethiopia which is situated in the South Eastern part of the country, is a trans boundary river basin shared Between Ethiopia and Somalia. The Basin is situated between $4^0$45'N to $9^0$45'N latitude and 38°45'E to 45°30'E longitude. Wabe Shebelle river basin has an area of 202,697 Km2, covering parts of the regions Oromia, Harari, Somali and a small area at the source of the Wabe River in SNNPE. This river basin has a lowest elevation of 184 m. and a highest elevation of 4182 m. It springs from the Bale mountain ranges of the Galama and the Ahmar about 4216 m above mean sea level and drains into Indian Ocean crossing Somalia. The basin covers about 19% of the area of the country.

The Basin is limited to the West by the Ganale Basin, to the North-West by the Rift Valley depression, to the North by the awash basin and to the East by a desert region stretching down to Aden bay.

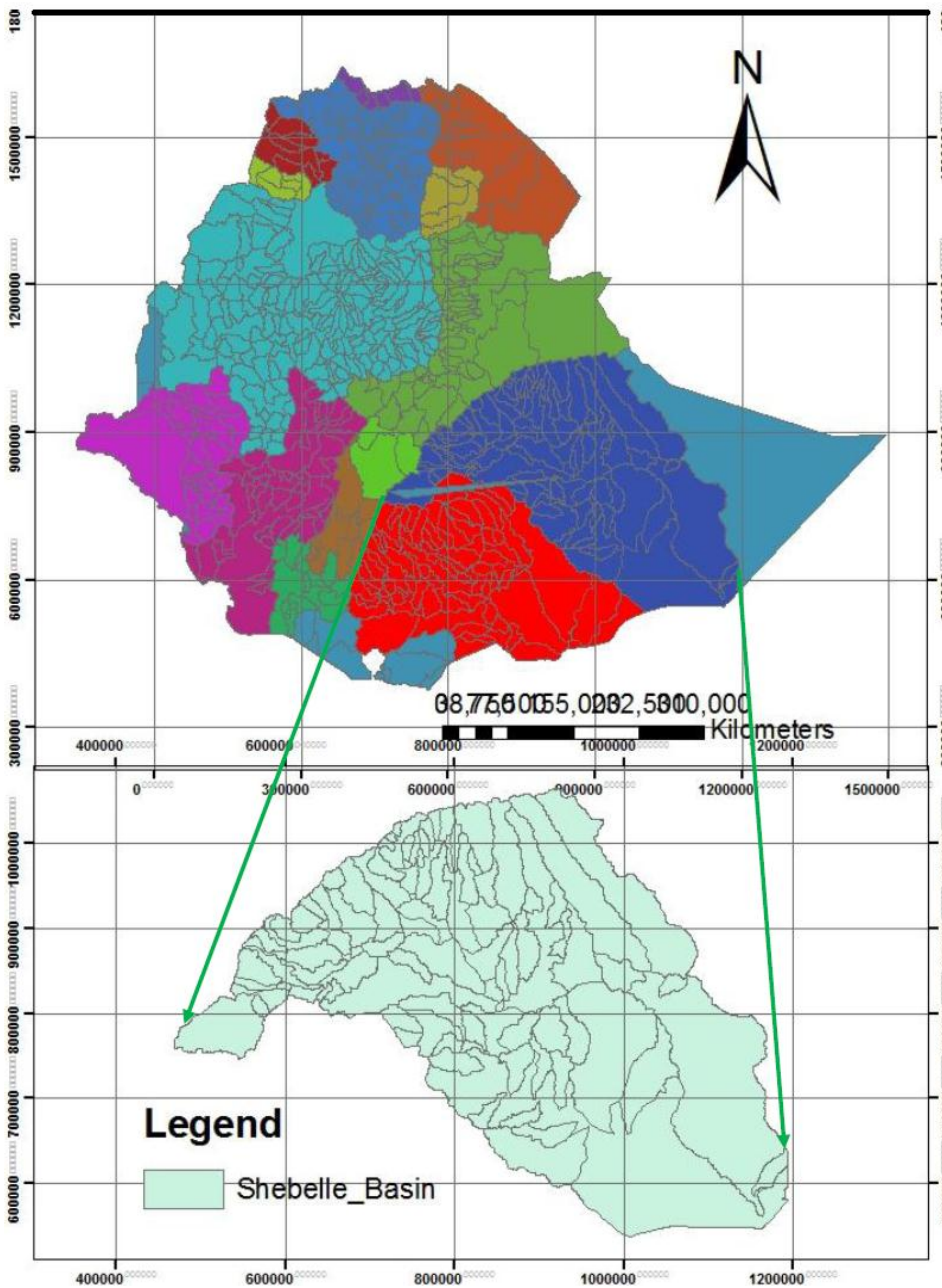


Figure 3.1: Location map of the watershed

3.1.1 Location and Description of the Wabe-Melkawakena watershed.

The Wabe –Melka Wakena sub-basin is located in the West of the Wabe Shebelle river basin extending from the Babay Elika and Bory Elika high lands in the waste to the Melka Wakena hydroelectric power generation dam site in the North with an area of 4126.25 km^2 or 412625 ha. Administratively the sub basin is located in West Arsi zone in Oromiya regional state. the area making up about 9.2 % in West Arsi zone and about 7.1 % in arsi zone. The Wester Arsi zone comprises 6 woredas of which Kofele, Dodola, Gedeb Assasa and Adaba Make up the most part (85.7%) and Kore & Kokosa have small areas (7.2 %) within the sub basin. the Arsi zone comprises only one woreda (Limuna bilbilu woreda) with small areas (7.2 %). A total of 105 kebeles are incorporated within the sub basin of which 94 kebeles are fully and 11 kebeles are partly found in the sub watershed.

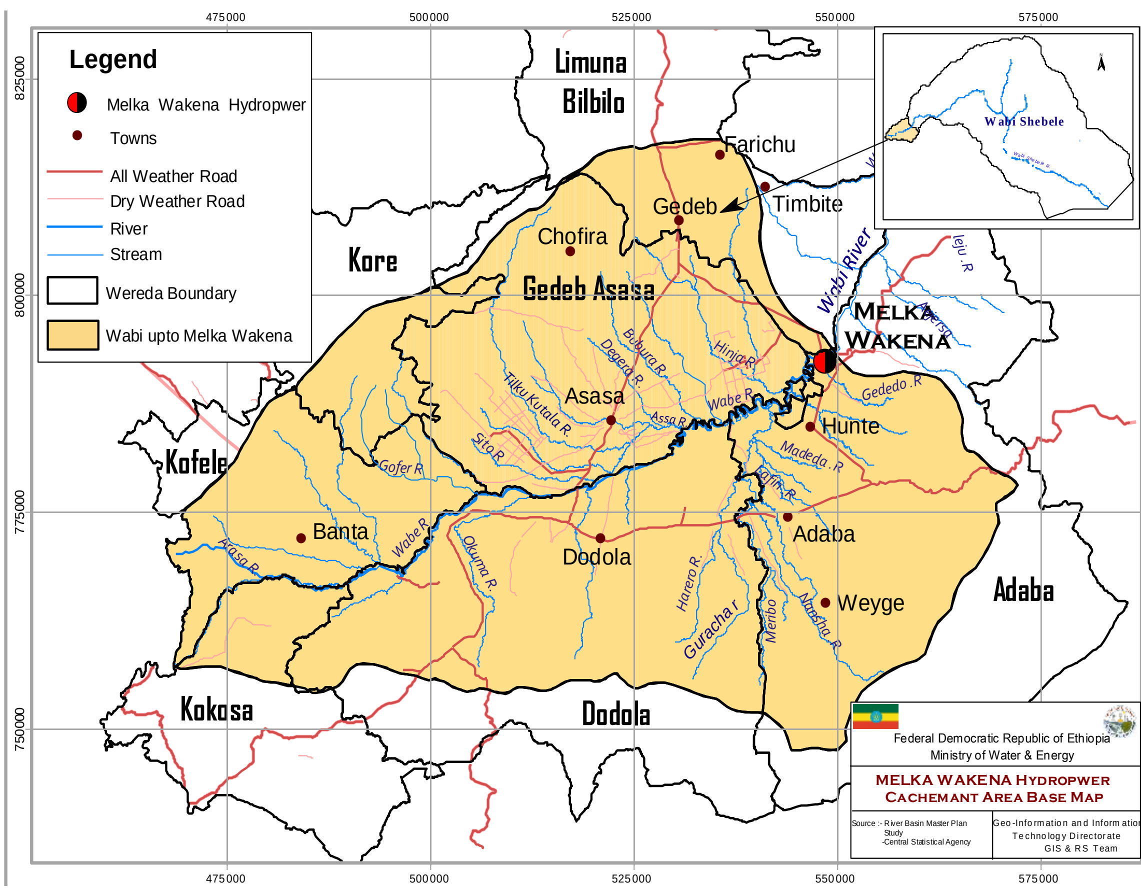


Figure 3.2: Location map of the Wabe-Melka Wakena.

Figure 3.21: Melka Wakena dam and Spillway

Rivers that completely drain to Wabe River are Marbio, Leliso, Ashiro, Gadedo, Hako, Fankaro, Farso, Tankaro, Sudo Ajoftu, Hersha, Bokina, Samera, Lagena, Qala, Ukuma and Hole Ashala while rivers Lensho, Kora, Sirbo, Lagena, Wolte Burka, Gadisa Terara, Dese Bilblo, Weltayi Negaya & Faricho drain partially to the sub-basin. Most of the Lemu and Belbilo Woreda rivers drain to the Zeway sub- basin.

a)Fruna **b)Leliso**

c)Herero d)Meribo

Figure 3.22: Rivers in the Melka Wakena Sub-basin

Table 3.3: Melka Wakena hydropower plant features (EEPCO, 2004)

1. Melka Wakena Reservoir	
Watershed (catchment) Area	5,300 sq.Km
Lake (Surface) Area	8,160 hectares
Storage capacity	763 Mm3 (million cu. meters)
Operation Storage (Water on duty)	606 Mm3
Mean over year flow of suspended particles	81,400 tones/Year
(Average annual silt deposit)	
2. Dam	
Type	Rock & earth fill dam
Height	42 meters
Length of the crust	2,000 meters
3. Bottom Water Outlet of the Dam	
Length	204.80 meters
Discharge	30 m3/sec.
4. Flood Control Spillway	
Length	262 meters
Water Discharge	530/480 m3/sec.

5. Water Intake of Head Race Canal	
Discharge	60 m3/sec
6. Head Race Canal	
Length	7.2 Km
Discharge	60 m3/sec.
Length of Emergency Spill way	100 meters
7. Penstock	
A) Vertical Shaft	
Height/ Depth	300 meters
Inner Diameter	4.2 meters
B) Tunnel	
Length	535 meters
Inner Diameter	4.2 meters
C) Tunnel Intake	
Length	113 meters
Inner Diameter	5 meter
8. Power House	
Head	300 meters
Mean Annual Power Output Capacity	543KWh
Number of Generators & Turbines	4
Type of Turbines	Francize
Runner’s Diameter	1.90 meters
Capacity	153 MW

3.1.2 Location and Description of the GODE Irrigation Project.

The project area is situated in the wabe shebelle basin in south east Ethiopia.one of the potential irrigable sites is located in Gode with a potential irrigable land of 27,600 ha, consisting of 7,600 ha in West Gode (Berano district) and 20,000 ha in South Gode. In West Gode (Berano) there is a gravity irrigation scheme consisting of a 13.6 km main canal of 15 m width, with design discharge of 46.6 m3/s networked with primary, secondary, tertiary and field intake and drainage canals along with cross regulators on the main canal and off-take sluice.

The scheme developed some 3,000 ha for irrigated agriculture beginning in 2006, and involved the settlement of 1,000 households in 2007 and a further 1,870 households in 2010, providing each household with 1 ha irrigable plot (total 2,870 ha). This is the largest gravity scheme undertaken by the government along the Shebelle Basin, with the intention of engaging former pastoralists in settled agricultural practices to increase food production in the region. The scheme has not been functioning for the last three years, although the ultimate objective is to expand the irrigable area to 7,600 ha in West Gode.

Table 3.4: Gode irrigation project features (MOWIE, 2004)

MAJOR STRUCTURE	DESIGN DISCHARGE(m^3/s)	LENGTH(m)	HEIGHT(m)	FREEBOARD(m)
Stone Masonry Weir	2100	26.7	4	1
Scouring Sluice	50			
Intake Structure	46.6			
Desalting Basin and Sediment Ejector	46.6			
Main Canal				
0-9750m	46.6	9750		
9750-13605	39.1	3855		
13605-27400	32.2	13795		
Main Off take				
MO1	3.7			
MO2	3.2			
MO3	3.2			
MO4	3.2			
Cross Regulator				

CR1	39.1			
CR2	32.2			
Rejection Spillways				
RS1	5.7			
RS2	8.9			
RS3	35			
Inverted Siphon	32.2			

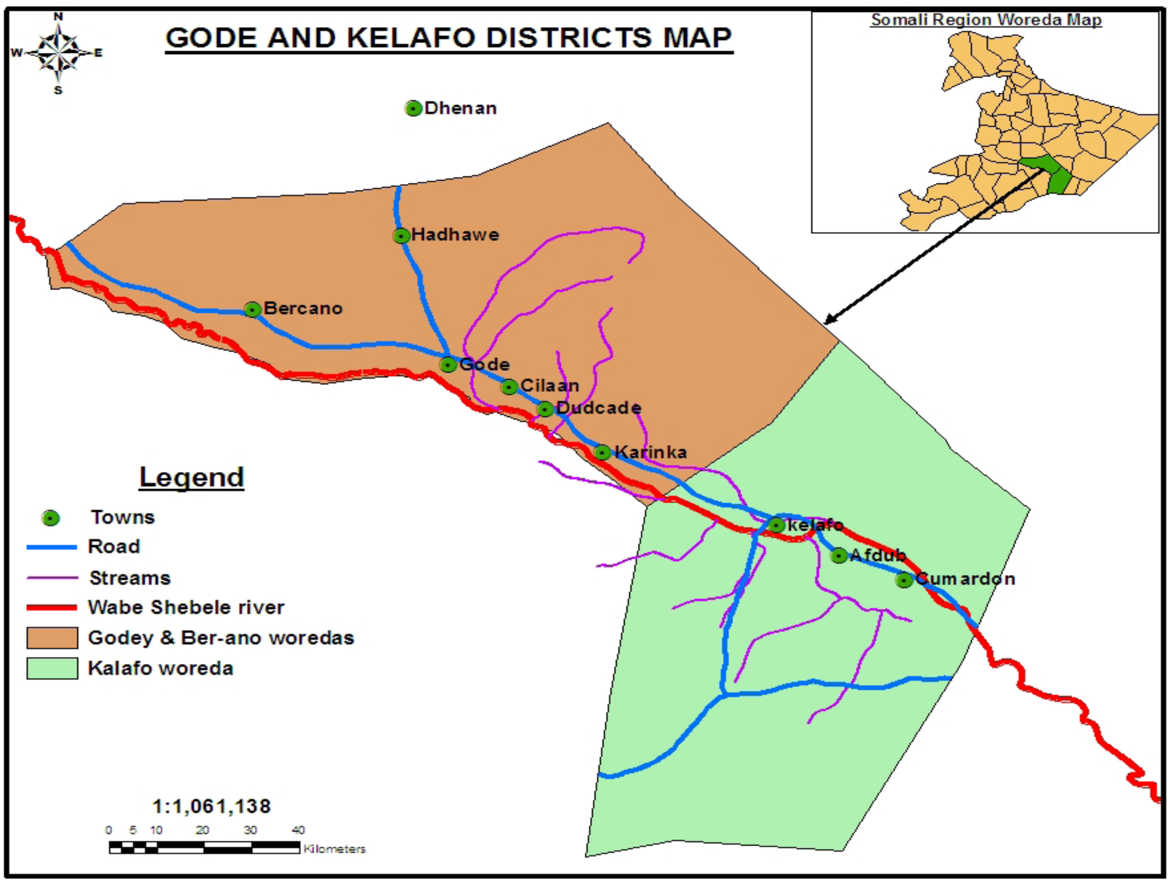


Figure 3.3: Location map of the Gode (livestock, crop and rural development bureau, 2013).

3.1.2 Location and Description of the GOLOCHA Irrigation Project.

The Gololcha River is located in the semi-arid area of the western Wabi Shebelle basin. The river flows generally in an easterly direction. The area of Gololcha catchment from its original plateaus to the dam site which is located in between 40015’16.13” to 40046’11.41” easting and 7012’58.85” to 7029’32.06” Nothing is 871.6 km2. The location of the old dam site is at 7024’16” North and 40045’58” East (or 694900 UTM N, 818900 UTM E) see Figure 3.1.

The water resource to be harness is that of Gololcha River or more commonly known as Dhare River locally. Dhare River originates east of Gassera town from the plateaus of 2400 masl altitude. It is known as Weran Genbo upstream of Delo-Serbo town and Gololcha thereafter until it reaches the area around the beginning of the very extensive plain lands of the Sawena Wereda which is at an altitude of about 1500 masl. From this area downstream it is known as Dhare River. (Feasibility Report Volume 3 Appendix I Hydrological a Water Resources Planning, June 2008)

The command area lies approximately between 40^0 47’ 53.14” to 40^0 58’ 49.5” easting and 70 22’ 23.9” to 70 29’ 57” Nothing and 1300 to 1500 masl see Figure 3.1 and finally the land slopes downwards on both banks towards the river Dhare.

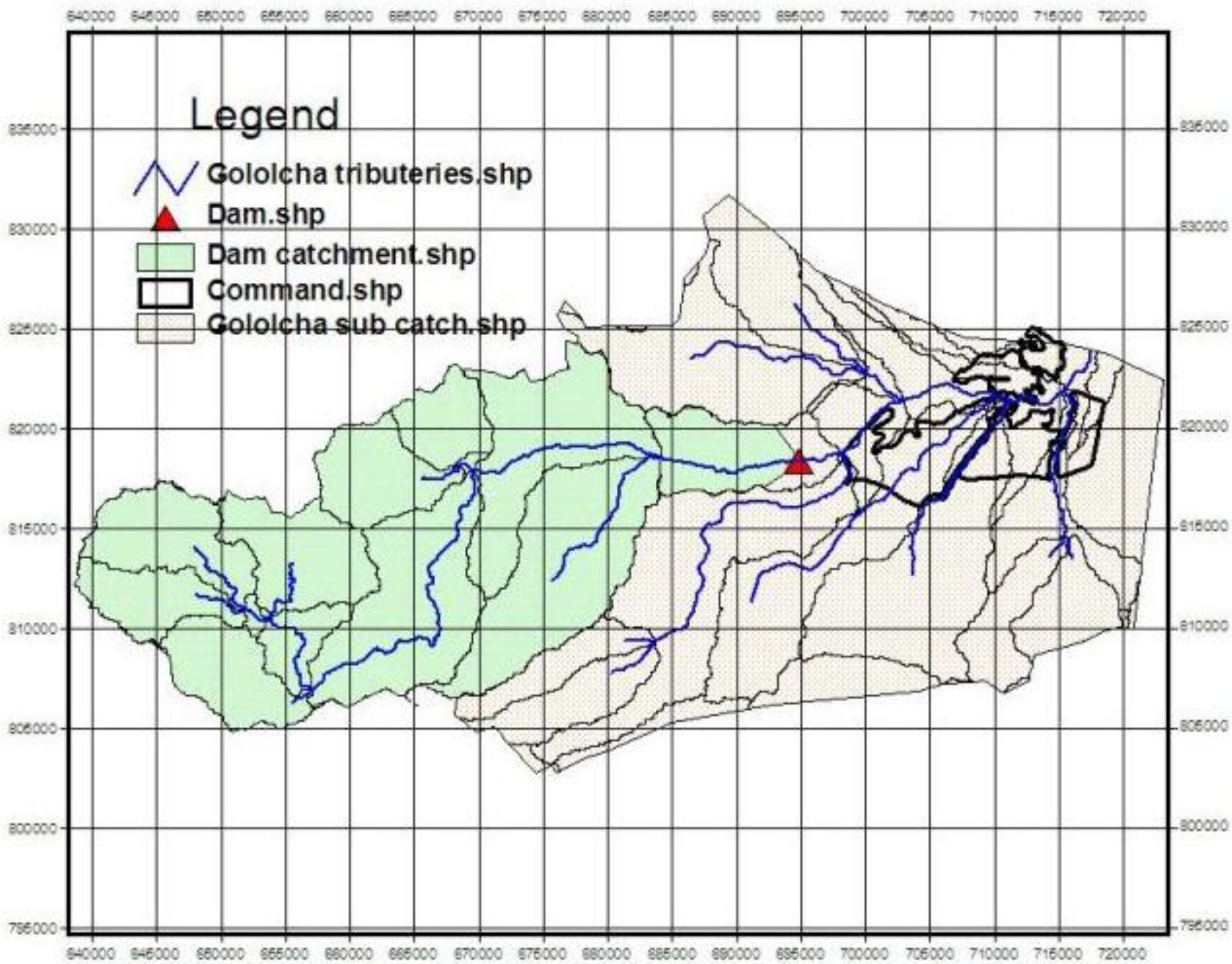


Figure 3.1: Location map of the Gololcha

3.1.2 Location and Description of the ERER Irrigation Project.

The Erer Irrigation Project is found in the Wabe Shebelle river basin, and the project has a storage (dam) facilitaty and an irrigation scheme, using the Erer river which is the tributary of Wabe shebelle river. Erer river is located in the semi-arid area of the north-eastern part of the basin. With its tributaries, it originates from Ejersa Goro and Waltaha connected to the Kombolcha mountain range which has a maximum altitude of 2670 m.a.s.l. in the North-East of Harar. The river flows South-east ward during rainy season and it is intermittent during dry season, with significant subsurface flow. The tributaries of Erer River in the Wabe Shebelle consist of the Abiyo, Yasakoy, Kebenawa, Ilimo and, Decheo stream and some field drainages systems. These stream and drainages cross the main and secondary canals of the Erer irrigation project. The area of Erer catchment from its head to the dam site is 419km2. Its annual rainfall ranges between about 650mm near the irrigation command area to about 800mm at the upper part of the catchment.

The proposed irrigation command area is about 3963ha which lies in Oromia and Harari Regional States. The project is located at about 19km south-east of Harar town and 11km from Babile town. The dam site is located at about 6km upstream of Harar-Jijiga road. The irrigation command area starts from some distance downstream of the dam and spreads on the right bank of Erer River. Its location is between coordinates 9o17’40” to 9o07’17” North Latitude and 42o12’ to 42o16’ East Longitude. The altitude of the command area lies approximately between 1280 to 1365masl.

The Erer irrigation project dam was designed to the maximum capacity of about 50.11MCM, with the full reservoir level of 1379.0m that will serve some 3960 hectares. According the feasibility study made by WWDSE, the annual catchmnet yield of the reservoir is about 60.4MCM.

3.2 Topography

Ethiopia can be divided into four major physiographic regions; the north western plateau, the south eastern plateau, the Main Ethiopian Rift and the Afar depression. The study area found maintains originating from one of this physiographic region which is south eastern plateau.

The Wabe Shebelle River emerges from the mountainous areas of the North Western borders of the river basin near a place called Hebeno. The basin is very relief-outstanding area; elevations range between 1500 to 4250 meters above sea level in the highlands of Bale to 150-300 meters above sea level in north of Mustahil in Somali region. From its source, the Wabe River flows eastward until it meets with another major component of the main river joining from Hareri region where most of the left bank tributaries originated and then and it changes its course to flow southwards .Downstream of Melka wakena hydropower dam site the river flows through a deep gorge up to north of Lmi and emerges in its lower valley .The lower valley is a vast alluvial plain stretching up to Somalia border with a very gentle slope of 0.25 to 0.35m/km, most of the tributaries after this portion do not add a substantial flow to the main water. The Ferer and Jerer watersheds are closed watershed.

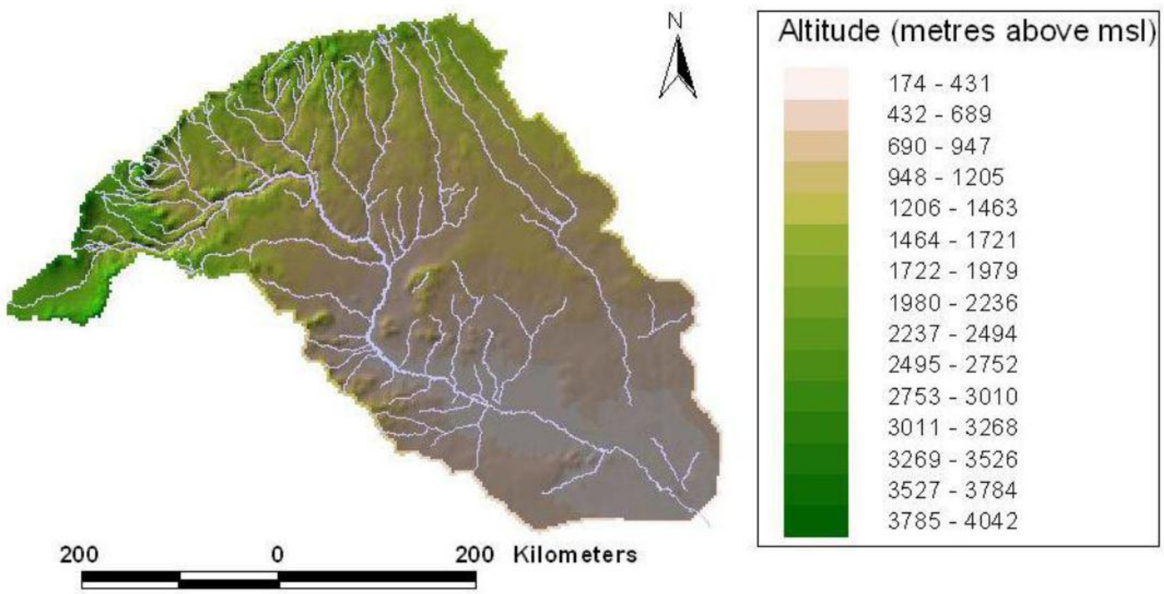


Figure 3.2: Topographic map of the Wabe-Shebelle River Basin

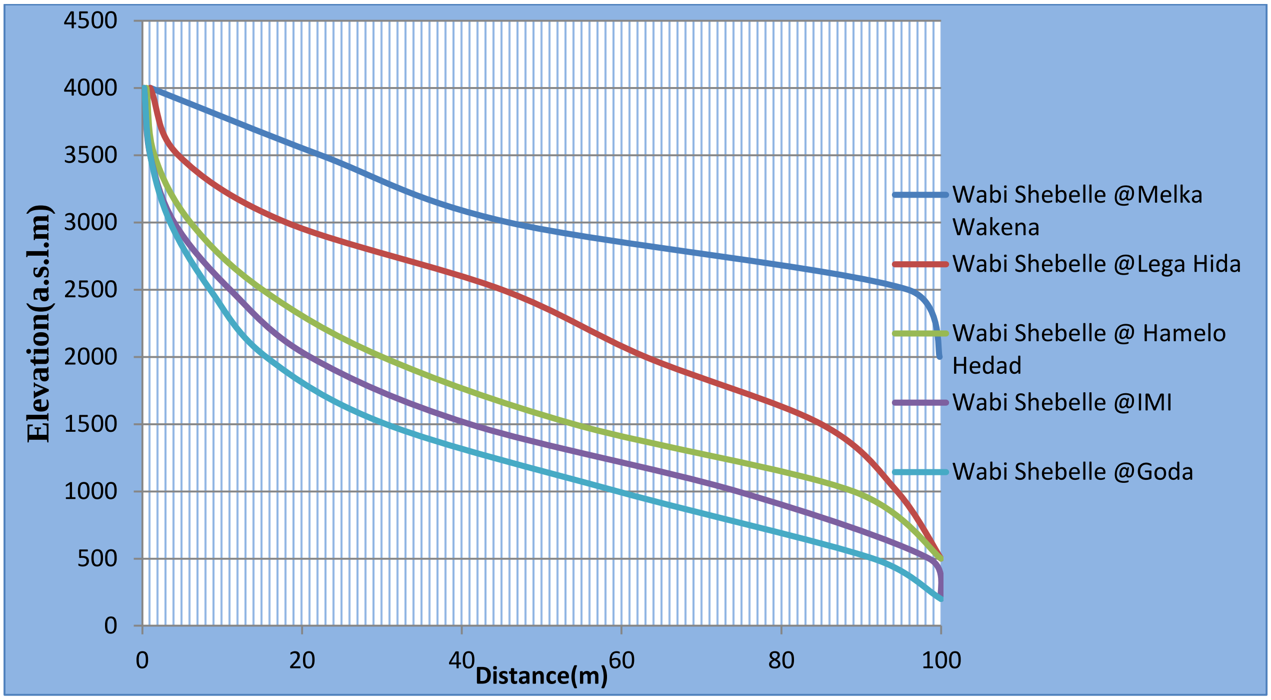


Figure 3.3: Hypsometric Curves of Some Wabe Shebelle River Basin (Source, Hydrological survey of Wabi Shebelle river basin)

3.3 Geology

The area is dominated by Mesozoic sedimentary formations, to some extent there are also volcanic rocks at the North West of the basin and isolated ridges and hills within the sedimentary basin. Metamorphic rocks outcrops in a small extent at the northern part of the study area. Alluvial deposits are also distributed linearly along the Wabe Shebelle Jerer and Fafen rivers and fan deposits of seasonal floods and stream beds. The volcanic rocks of Arsi-Bale basalt bordering the rift valley are highly fractured. Numerous springs outcrops along faults and fractures in this area and form substantial part s of the base flow of Wabe Shebelle River. The Southern part of the basin is over laid by thick gypsum and limestone. The water level monitoring for one hydro logic cycle on two wells at Gode showed that the water level is deep always lower than the river bed and the phreatic water level is practically the same during the hydrologic cycle and no interaction with Wabe Shebelle River water indicating the permeability is very low. On the other hand, at Kelafo there is interaction of the alluvial ground water with

Wabe Shebelle River. At Muslahil there is infiltration of the river flood waters in to the alluvial ground water.

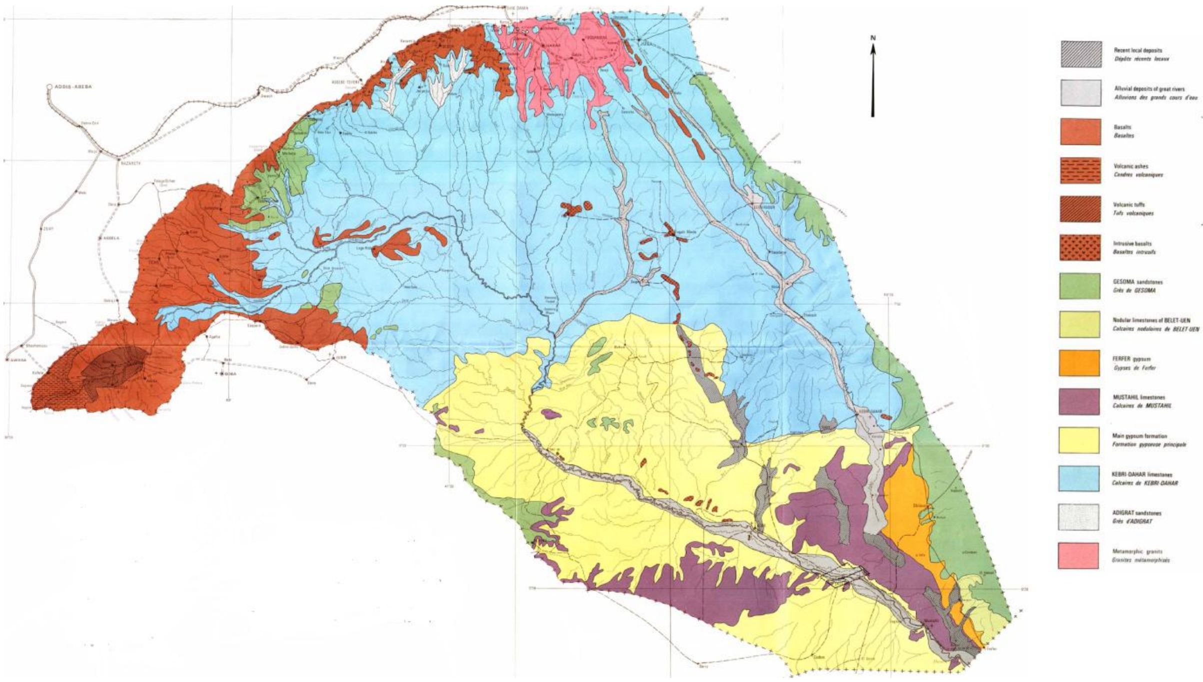


Figure 3.4: Geological map of the Wabi Shebelle River Basin

3.4 Land resources

The livelihoods of the people and their settlement patter in the Wabe-Shebelle River basin are strongly linked with the level of agricultural land suitability. In the highland areas of the sub basin, the high population pressure has been the major cause of land degradation which has resulted in deterioration of land resources and/or sedimentation in the reservoir or dam.

3.4.1 Land cover

Poor land use practices, improper management systems and lack of appropriate soil conservation measures have played a major role in causing land degradation problems in the basin. Only small dense forest is found at the North Western portion of the basin. Dense shrub land is the predominant land cover in the basin. The shrub land occurs mainly on the semi- arid parts and often consists of patches of shrubs interspersing grasslands with some scattered low trees. Patches of exposed rock or sand surface are found in parts of Bale and Hararghe lowlands in the south-east. Parts of central Arsi and northern Bale have afro-alpine and sub-afro alpine vegetation. These consist mostly of short shrub and heath vegetation used partly for sedentary grazing and browsing. Riparian woodland and bush land occur along the river banks and on floodplain sand are important in the semi-arid and arid parts of the basin where they are used for grazing and browsing and scattered seasonal crop cultivation on some of the flood plains.

3.4.2 Land use

The land use consists of large part of silvipastoral type. Areas of intensively cultivated land are found on the highlands of Arsi and parts of highland Harerge, and northern Bale. The major seasonal crops in the basin include maize, barley, wheat and sorghum while the perennial crops include coffee, chat and fruit trees.

3.4.3 Soils

The wide ranges of topographic and climatic factors, parent material and land use have resulted in extreme variability of soils (FAO, 1984). In different parts of the country, different soil forming factors have taken precedence. According to the Ministry of Agriculture about 19 soil types are identified throughout the country. (FAO, 2006)

The major soils of the basin are Cambisols (34.7%), Phaeozems (19.7%). Leptosols (12%), Regosols (11,6%),Luvisols (11.2%),Vertisols (4.53%),and Nitsol (3.5%) .Cambisols are distributed in the upper most parts of the watershed, especially areas on hills where the land is too steep. They are inevitably high- risk soils and occur wherever conditions are not favorable for other soil processes than weathering to take place. They are brown in color and shallow to moderately deep soil, phaeozems comprises 19.7% of the basin covering significant areas of the middle belt and downstream of the basin. Luvisols soil formed in the north to middle through south-west (large bell crossing from north-east west and west-north) of the watershed from the basaltic rock cap are deep, well structured, inherently well drained and relatively productive agricultural soil. Leplosols on the southern reach with some at the middle and very small on the northern part. This soil is common on mountainous region partly on continued hard rocks and partly gravels, the soil is limited in depth having calcareous material or cemented layer within 30 to 40cm depth. There are small pockets of vertisols particularly on southern part of basin and Fluvisols in valleys along rivers and streams.

3.5 Hydro meteorological condition:

3.5.1 Hydrology

The majority of the stream flow contributions are from the northern and north western catchments having greater elevation difference from the southern and south eastern part which have elevation range from 600 m to 166 m above sea level. The region has significant stream flow in two major river systems as well as numerous ephemeral rivers. Moreover, in some parts of the Basin, although surface water may not be available, substantial shallow and/or deep groundwater exists, though, depending on depth, at sometimes prohibitive cost. Economic rather than absolute scarcity of water is the greater determinant of access to the resource across the region. This has significant implications for how and where the region decides to invest in resource access improvements

The volume of water discharge of surface drainage of basin is determined by climatic condition, while its relief controls the flow pattern of rivers. High seasonal fluctuation and variation of climatic condition characterize precipitation of the basin. So, the volume of discharge is subjected to high fluctuation, sporadic flash of flood as a result of torrential tropical rains in summer and dry channels for some rivers and streams in dry season. In general, the regional has a total of more than five major rivers (Wabe, Ramis, Geletti, Erer, Deceta, and Fafen) and many minor tributaries which form one of the largest basins and draining a total of 191146 square km of land.

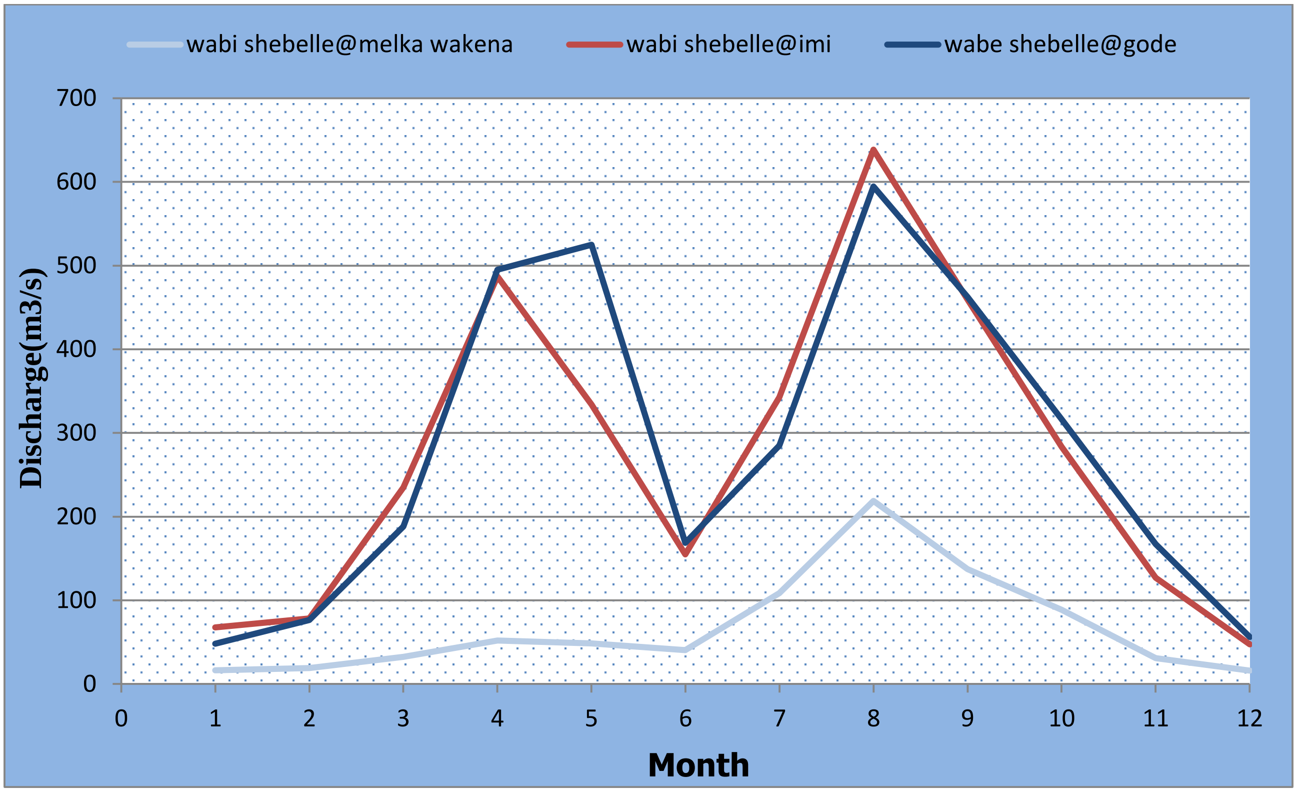


Figure 3.5: Mean monthly stream flow of Wabe Shebelle River at Melka Wakena, IMI and Gode station

Lakes/Reservoirs: Lake Haromaya and Adele, which are completely dried out recently, were the major natural lakes in the basin. Originally three lakes were located at a short distance from Harrar, (Lake Haromaya, Lake Adele, and Lake Lange) but the largest one, Lake Haromaya, has completely dried up, as it supposedly supplies the drinking water for the town and as it is used for irrigation by local farmers. Lake Adele is an adjoining lake to Haromaya. There had been a steady decline over the past decade in both the quality and quantity of water being delivered from this lake to the residents of Harar.

At present there is one large man made reservoir by Melkawakena dam that is commissioned in 1988 for hydropower generation. The river assumes a ravine character above the site and carries water through a vast trench suitable for creation of the reservoir. A rather large-capacity regulating reservoir with a volume of 763 million m3 was created by the construction of a relatively low dam with a maximum height of 38 m. Below the cataracts, which have a drop of the order of 80 m, the river flows into a deep and narrow canyon having significant slopes. The magnitude of the head at the hydroelectric plant is 300 m. Its rated capacity is 153 Mw. The mean annual electric-power generation at the plant is 543 million Kwh (Cheryachukin and Sitnin, 2000).

Hydrological setting

Most of the rivers in the area arise along the northern and north western margins of the basin (Arsi Bale and Hararghe Plateau) and descend with a steep gradient into the eastern and south eastern direction and joining to the Wabi Shebelle river which flow first to eastern direction and then south eastern and finally to Somalia territory.

Currently some areas in the upper catchments have gauging station. According to MoWIE, the lower catchments are remote areas and not accessible to have gauging station. There are fewer than 50 stream gauging stations in the basin. Only less than 30 are operational at present, a significant portion of which have operated intermittently. In the upper catchment there are more than 15 stations, among these Lelisso, Hararo, Assassa, Weyib at Agarifa, Ukuma, Maribo near Adaba, Jewis near Bedesa, Wabi at bridge and Wabi at Melkawakena, Robe station at Robe town, Jijiga River at Jijiga and Lake Adelle at Adelle are operational stations. MoWR (2003) provides monthly flow data generated by rainfall-runoff relationships at 13 stations in the basin.

3.5.2 Meteorology

Rainfall is the most important part of the atmospheric precipitation in the hydrologic cycle that falls on the earth surface in the form of water droplets and its amount is one of the most fundamental factors to determine the density and distribution of vegetation. The rainfall in Wabi Shebelle River Basin varies from less than 200 mm in arid zones (the south east part) to 1250mm in upper catchment. This is due to altitude variations over the basin from about 166m above sea level in the south east border up to 4250m above mean sea level in the Arsi- Bale Mountain Massif.

Meteorological setting

The distribution of the meteorological stations is not well integrated reducing the credibility of such data. There are about 48 meteorological stations in the basin. Most of them are clustered in or near urban centers of the upper portion of the basin. Meteorological data are taken from the station based on their availability within the recording year. The stations are not evenly distributed and sometime lack continuous meteorological records. However, long term records of values of meteorological parameters are enough for the purpose of this study.

There are meteorological stations that measures different meteorological parameters in the basins. According to national meteorological agency of Ethiopia there are four class of station in the country. These are First class (synoptic station), second class (principal station), third class (ordinary station), and fourth class (rainfall recording stations). The distribution of these stations depends on the topographical point and accessibility. On the study area the meteorological station distribution is parallel with the population distribution and are condensed upper catchments.

3.6 Socio-economics

There are about 76 administrative woredas that lie within the basin. About 7% of the population is urban. The major accesses to the basin are a gravel road along the highlands of the Bale mountains and the recently completed asphalt road to Harar. The density of feeder roads is quite low in the lowlands (See Annex Figure A.6).

3.6.1 Population and Settlement

As per the census of 1997, the total population of the basin is about 5.8 million. Out of this, 70.1% of the population belongs to parts of four zones of Oromiya region while about 27.4% are that of Somali region. The rest is that of Harari and SNNP regions. Population density is the highest in Arsi (78.5 people/Km2) whereas the lowest is in Warder Zone (4.2 people/Km2). Large percentage of the population in the highlands depends on agriculture while the lowlanders in general are pastoralists. About two-third of the area is populated with less than 20 person/Km2. Most of the less populated area lies in the arid to semi-arid lowland areas.

3.6.2 Water Consumption

Currently there are about 10 state farms in the basin involved in mechanized large scale rainfed agriculture. There are over 334 traditional irrigation schemes covering an estimated area of 12,000 ha. A total of 72 small and medium modern irrigation schemes with an estimated irrigable area of 7045 ha exist in the basin (MoWR, 2003). The only existing dam under operation on the Wabi Shebele River is the Melka Wakena hydropower dam. There is a large scale irrigation project at Gode but it is not functional. About 140 medium and small scale potential irrigation sites have been identi_ed in MoWR (2003). Higher population density is observed in the upstream portion of the basin and large irrigation schemes are clustered in the downstream portion (Figure 2.8). The deficiency of sufficient water for hydropower generation has inclined some consultants to contemplate inters basin water transfer for regulation of a proposed hydropower production scheme at Kuldash from Weyib river (WAPCOS, 1995). Sometimes at places where the number of good quality flow records is insufficient for an analysis to precede, stream flow naturalization procedures may be important to convert gauged flows to natural flows that would have occurred in the absence of water users and water management facilities. The procedure requires a systematic record of the influences, including times, rates and durations of the abstractions, discharges and compensation flows and adjusting the observed flow accordingly. The adjustments are governed largely by data availability. However, these data are not available for numerous smaller reservoirs.

4. METHODOLOGY

4.1 General

To fulfill our objectives of the study it is mandatory to search and collect basic inputs data's to be used for simulation of the basin. Reliability of the collected raw data significantly affects quality of the model input data. The model needed intensive data for simulation of optimal reservoir operations in the Wabe Shebelle main river channel and tributaries.

The following data are collected for the simulation of Wabe Shebelle River basin to achieve the main objective of the study:

1. Time series data which contain computed inflow and incremental local flow hydrographs, observed flow hydrographs, observed reservoir pool elevations and releases

2. Physical data which comprise reservoir pool storage definition like elevation-area-storage tables, dam elevation and length, outlet capacity curves, hydropower plant data (outflow and generation capacities, turbine efficiency, and hydraulic losses).

3. Operational reservoir data which take account of specifying the operation zones or levels.

Materials used

The materials used for this research are Arc view GIS tool to obtain hydrological and physical Parameters and spatial information, ArcMap10 software to delineate the basin of the study area, HEC-ResSim model for basin simulation and Microsoft EXCEL 2010 to analyze HEC-ResSim outputs. And that should be kept in HEC-DSSVue storage system. HECDSSVue (HEC-DSS Visual Utility Engine) is the U.S. Army Corps of Engineers' Hydrologic Engineering Center Data Storage System, or HEC-DSS. It is a database system designed for efficiently store and retrieve scientific data that is typically sequential.

4.2 Data collection and Analysis

For any river basin simulation, the first step is to search and collect Relevant and appropriate data for principal simulation components to be used for the proper simulation of the basin. Different data were collected from institutions such as Ministry of Water, Irrigation and Electricity (MOWIE), National Meteorological Agency (NMA), Ethiopian Electric Power Corporation (EEPCO), WWDSE and from review of previous studies.

After collecting the necessary data for this research, 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.

4.2.1 Meteorological Data

The meteorological data have been collected from National Meteorological Agency (NMA). The availability and quality of meteorological data such as rainfall, temperature, sunshine hours, wind speed, and relative humidity are vital for any water resource study.

There are number of Meteorological stations in the river basin, especially in the upper part of the basin, with quite long time series of observation. But only the stations listed in table 4.1 which is applicable to this study are collected and analyzed. The criterions for the selection of the metrological data were based on the availability of data, the data quality and possibly whether the station is within the sub-basin or nearby. The data collected covers a period of 1967-2008.Except few of the station most of the station data are incomplete and short. Table 4-1 below shows of selected meteorological station with their respective location and sub basin. Meteorological data analysis carried in this study is mainly based on rainfall data and summary the selected rainfall stations are also presented in Table 4.1.

Table 4.1: Summary of selected Metrological stations

No	Station Code	Nearby town	Installed Year	Latitude(degree)	longitude(degree)	altitude(m.a.s.l)
1	39070101	Adaba	1955	7.01	39.24	2420
2	39070011	Assassa	1960	7.07	39.11	2350
3	42090043	Babile	1968	9.13	42.2	1600
4	40080244	Bedessa	1962	8.55	40.46	1820
5	42080054	Fedis	1968	9.08	42.03	1700
6	41090061	Grawa	1988	9.08	41.5	2100
7	43050021	Gode	1967	5.54	43.35	295
8	42060011	Imi	1984	6.28	42.09	1100
9	40070224	Jarra	1850	7.27	40.46	1960
10	42090011	Jijiga	1952	9.2	42.47	1775
11	39070103	Sedik	1988	7.09	39.8	2320

4.2.1.1 Checking homogeneity of selected rainfall station

Homogeneous means that the measurements of the data are taken at a time with the same instruments and environments. Homogeneity is an important issue to detect the variability of the data however; it is a hard task when dealing with rainfall data because it is always caused by changes in measurement techniques and observational procedures, environmental characteristics and structures, and location of stations.

One of the methods to check homogeneity of the selected stations in the watershed is the non-dimensional rainfall records and plotted to compare the stations with each other

Non dimensional value Monthly precipitation of each station can be computed by:

$$\mathrm{Pi} = \frac{\mathrm{Pi,ave}}{\mathrm{Pave}} * 100 \qquad \text{...4.1}$$

Where, Pi ……………. is non-dimensional value of rainfall for month i,

P......................Over year-averaged monthly rainfall at the station i,

P ……………..The over year -average yearly rainfall of the station

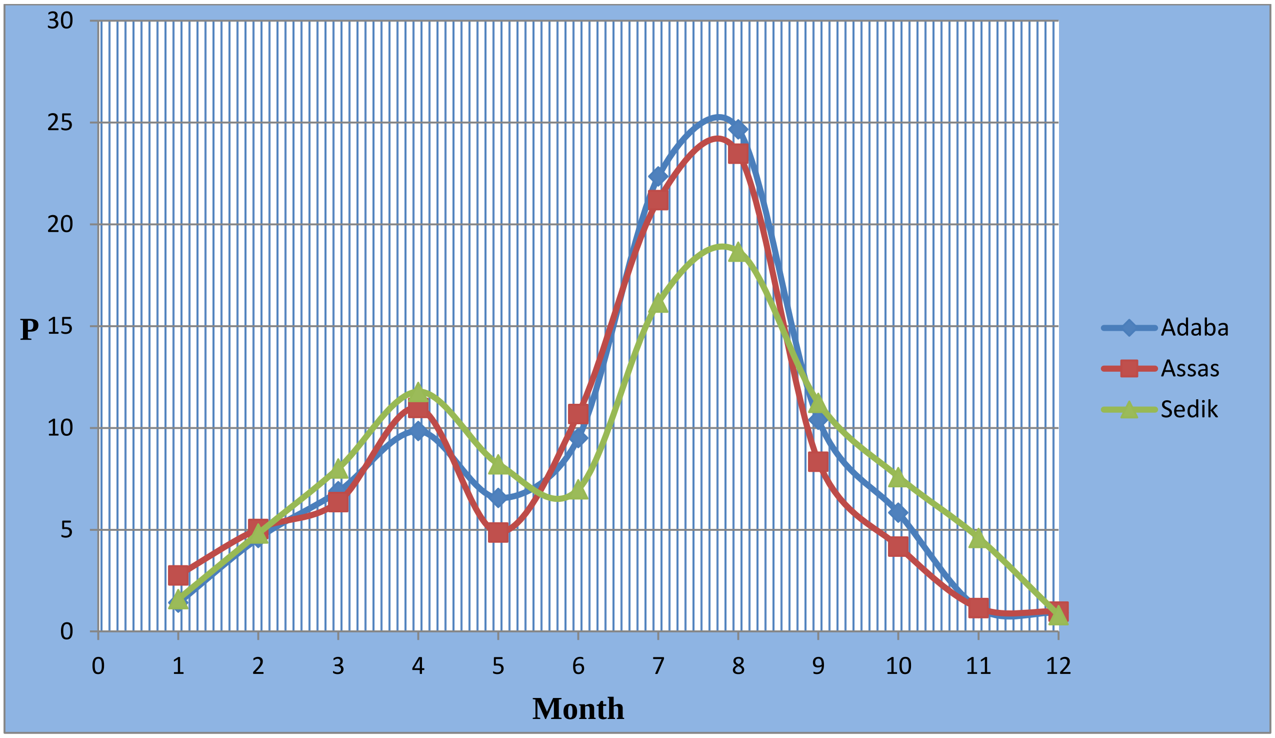


Figure 4.3: Homogeneity test for Adaba, Assas, and Sekoru and Sedik

4.2.1.2 Checking consistency and adjustment of rainfall data

A consistent record is the one where the characteristic of the record has not changed with time. Adjusting for gage consistency involves the estimation of an effect rather than a missing value. The consistency of rainfall records on selected stations is commonly checked by double mass curve analysis. Double mass curve is a graphical method for identifying and adjusting inconsistency in a station record by comparing its time trend with those of adjacent stations. 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. This inconsistency can be differentiated from the time significant change took place. If significant change in the regime of the curve is observed, it should be corrected by using Equation 4.2. The stations used in this study have not undergone significant changes during the base line period (R-square value greater than 0.98) of the study. (Detail curve data will discuss in appendix).

$$\text{Pcx} = \text{Pc} * \frac{\text{Mc}}{\text{Ma}} \qquad 4.2$$

Where Pcx is corrected precipitation at any time t

Pc is original recorded precipitation at a time period

Mc is corrected slop of a double mass

Ma is original slop of double mass curve

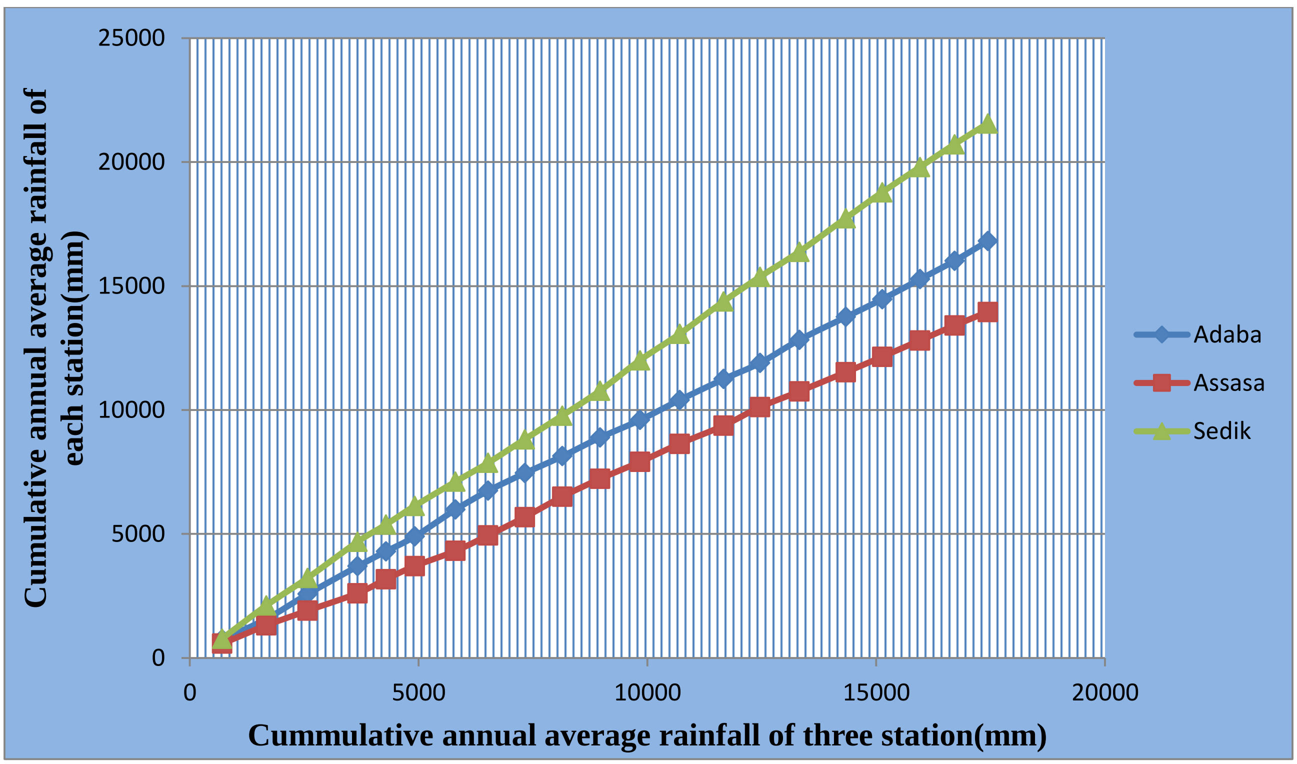


Figure 4.4: Double mass curves for selected meteorological stations

4.2.1.3 Filling missing rainfall data

Absence of observation and recorded from a station causes short break in the record of rainfall at the station. These gaps should be filled before using the rainfall data for analysis. The surrounding stations located within the basin help to fill the missing data on the assumption of hydro meteorological similarity of the group of stations

Normal – Ratio Method

The normal ratio method is preferred to be used where the mean annual precipitation of any of the adjacent stations exceed the station in question by more than 10% and it is Normal ratio methods are expressed by the following relationship:

$$Px = \frac{Nx}{N}\left(\frac{P1}{N1} + \frac{P2}{N2} + \frac{P3}{N3} \ldots\ldots + \frac{Pn}{Nn}\right) \ldots\ldots 4.3$$

Where,

P_x =Missing value of precipitation to be computed.

N_x = Average value of rainfall for the station in question for recording period.

N_1 ,N_2………Nn= Average value of rainfall for the neighboring station 1,2,…n..

P_1,P_2....P_n = Rainfall of neighboring station 1,2,…n during missing period

N= Number of stations used in the computation.

4.2.1.4 Estimation of Areal Rainfall

Rain gauged station recorded point rainfall.in practice hydrological analysis required knowledge the precipitation over the area.

There are Three common method used for estimate areal rainfall from point rainfall.

- **Isohyetal method**: - isohyets are line joining places of equal rainfall intensities over a basin. An Isohyet map represents an accurate picture of the rainfall distribution over the basin. If the network rainfall stations within the storm area are sufficiently dense, the Isohyet map will give a reasonably accurate indication of the rainfall distribution zones.

- **Arithmetic average method**: When the rainfall is uniformly distributed over the area, the average rainfall may be taken as the arithmetic average of the recorded rainfall.
- **Thiessen polygon method**: Rainfall varies in intensity and duration from place to place. Hence the rainfall recorded by each rain gauge station should be weighted according to the area it is assumed to represent. In this thesis Thiessen polygon method was used to determine the average areal precipitation over the whole basin from rain gauge measurements.

However, the Thiessen polygon was used for this study for its sound theoretical basis and availability of computational tools.

Average rainfall over the catchment was calculated by

$$\text{Pave} = \frac{\text{P1A1} + \text{P2A2} + \text{P3A3} - - - - - - - - - + \text{PnAn}}{\text{A1} + \text{A2} + \text{A3} - - - - - - - - - - - - - - - + \text{An}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \ldots 4.4$$

Where Pav average areal rainfall (mm),p1,p2,p3……Pn precipitation of station 1,2,3…n, respectively and A1,A2,A3…..An is area coverage of station 1,2,3…n respectively in the Thiessen polygon.

4.2.2 Hydrological Stream Flow Data

Stream flows for gauging stations in the Wabe Shebelle River Basin are mainly maintained by the hydrology department of the Ethiopian Ministry of Water, Irrigation and Energy (MOWIE) which is responsible for the operation of the hydrometric network throughout Ethiopia. But many of these gauges are situated in the upper part of the basin (list of Gauged station are listed in table 4.2) and there is lack of gauging stations in the lower Wabe Shebelle river basin and well gauged during BCEOM study of the basin (1967-1972). After 1972 the stations become abandoned, except for the Gode station, which has intermittent data up to now. Thus for such case, it is unavoidable to use the rainfall data and extension of month flow record to estimate the surface runoff flows to the reservoirs from each catchment, Extension of monthly flow records has to depend on rainfall runoff relationship and gauged stations data of the 1962 to 1972. Table

(4.3-4.5) gives rainfall-runoff model coefficient used for generating monthly flow. For 13 station monthly flow data (1967-2007) have generated using rainfall runoff relationship of the station, keeping the statically properties of the data in generated series. The generated mean monthly flow for 13 stations are given in table 6.the generated mean monthly flow over the period of 1967-2008 for 13 stations are listed in appendix.

Table 4.2: Summary of selected Hydrometric stations

No	Station Code	Station Name	Near By Town	Latitude(degree)	longitude(degree)	Installed Year
1	610001	Lelisso	Adaba	7	39.383	10/1/1967
2	610002	Maribo	Adaba	7	39.333	24-1-67
3	610003	Ukuma	Dodola	7.017	39.05	25-1-67
4	610004	Wabi	at Bridge	7.017	39.033	30-1-67
5	610005	Assassa	Assassa	7.1	39.217	25-2-67
6	610006	Wolkessa	Azazera	7.83	39.55	25-2-67
7	610007	Ulul	Azazera	7.83	39.855	25-2-67
8	610008	Harerghe	Assa			25-2-67
9	61012	Robe	Robe	7.85	39.633	8/3/1969
10	61014	Herero	at Herero	7	39.317	24-1-67
11	61015	Maribo	Kara			
12	61016	Fruna	Adaba			
13	62007	Hamaressa	Harer	9.333	42.083	26-11-80
14	62008	Bissidimo	Bissidimo			
15	62013	Upper Erer	Erer	9.233	42.25	4/2/1983
16	62016	Jijiga	at Jijiga	9.35	42.8	11/3/1985

The rainfall runoff relation is established as follows. The Wabi Shebelle at Melka Wakena is considering as a base flow data.

- Monthly flow of Wabi Shebelle at Legahida = constant + k_1 * previous monthly flow at Melka Wakena + k_2 * areal rainfall over the catchment between Melka Wakena and Legahida + k_3*current monthly flow at Melka Wakena.
- Monthly flow of Wabi Shebelle at Hamaro Hadada = k_2*areal rainfall over the catchment between Legahida and Hamaro Hadada + k_3 * current monthly flow at Legahida.
- Monthly Wabi Shebelle at Imi = monthly runoff factor * Wabi Shebelle at Hamaro Hadada.
- Monthly Wabi Shebelle at Gode = monthly runoff factor * Wabi Shebelle at Hamaro Hadada.

Note that the monthly factor is derived from the concurrently measured data of the BCEOM.

Rainfall runoff model coefficient used for generating flows (from Master plan of Wabe Shebelle river basin integrated development master plan)

Table 4.3: Melkawakena-Legahida monthly runoff-rainfall model coefficient

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Constant	0	0	0	59.1	14.8	28.3	87.2	0	0	0	0	7.06
k1	0	0	0	0	0	0	0	0	0	0	0	0.27
k2	0	0	0.1	0	0	0	0	1.4	0	0	0	0.12
k3	1.7	0.99	1.8	2.19	2.49	1.78	1.72	1.06	2.35	1.8	2.68	0.8

Table 4.4: Legahida-Hamaro monthly rainfall runoff model coefficient

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
k2	0	0	0.5	0.35	0.24	0.1	0.4	0.95	0.45	0.1	0	0
k3	2.6	4.25	3.4	2.45	2.12	1.7	1.2	1.34	1.25	1.35	1.5	1.7

Table 4.5: Monthly runoff factor for multiplying Wabi Shebelle at Hamaro to get:

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Imi	0.96	0.98	1.03	1.14	1.09	0.88	0.98	0.99	1.02	1.16	1	0.93
Gode	0.68	0.95	0.82	1.3	1.26	0.96	0.82	0.9	1.03	1.29	1.24	1.08

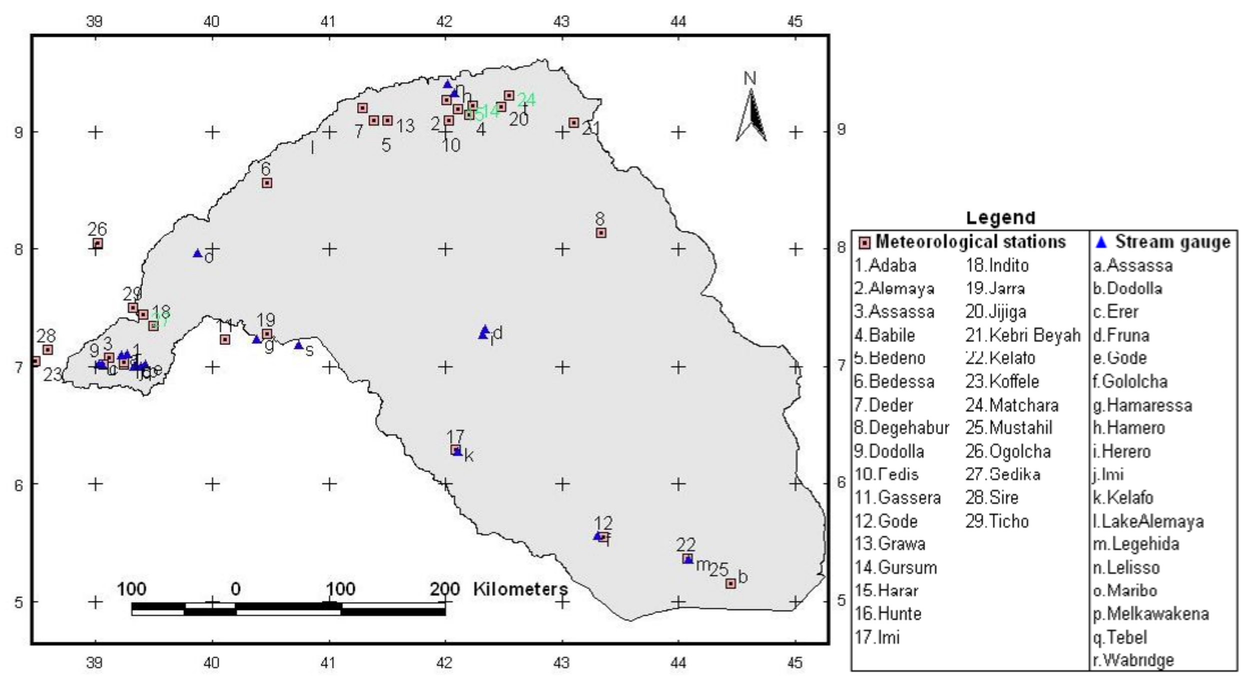


Figure 4.5: Location of some of the hydro meteorological gauging stations.

4.2.3 Evaporation Data

There are just two main aspects for estimating evaporation. The first one is evaporation of water from an open water surface, and this contains the direct transfer of water from lakes, reservoirs and rivers to the atmosphere. This can be comparatively easily estimated if the water body has known capacity and does not possess leakage and seepage. The second form of evaporation occurs from the transpiration from vegetation. The combined of these two losses of water is generally called evapotranspiration, because losses occur by direct evaporation of intercepted precipitation and transpired water on plant surfaces. For this study mean monthly evaporation data for each existing and proposed reservoirs were obtained from their respective study documents

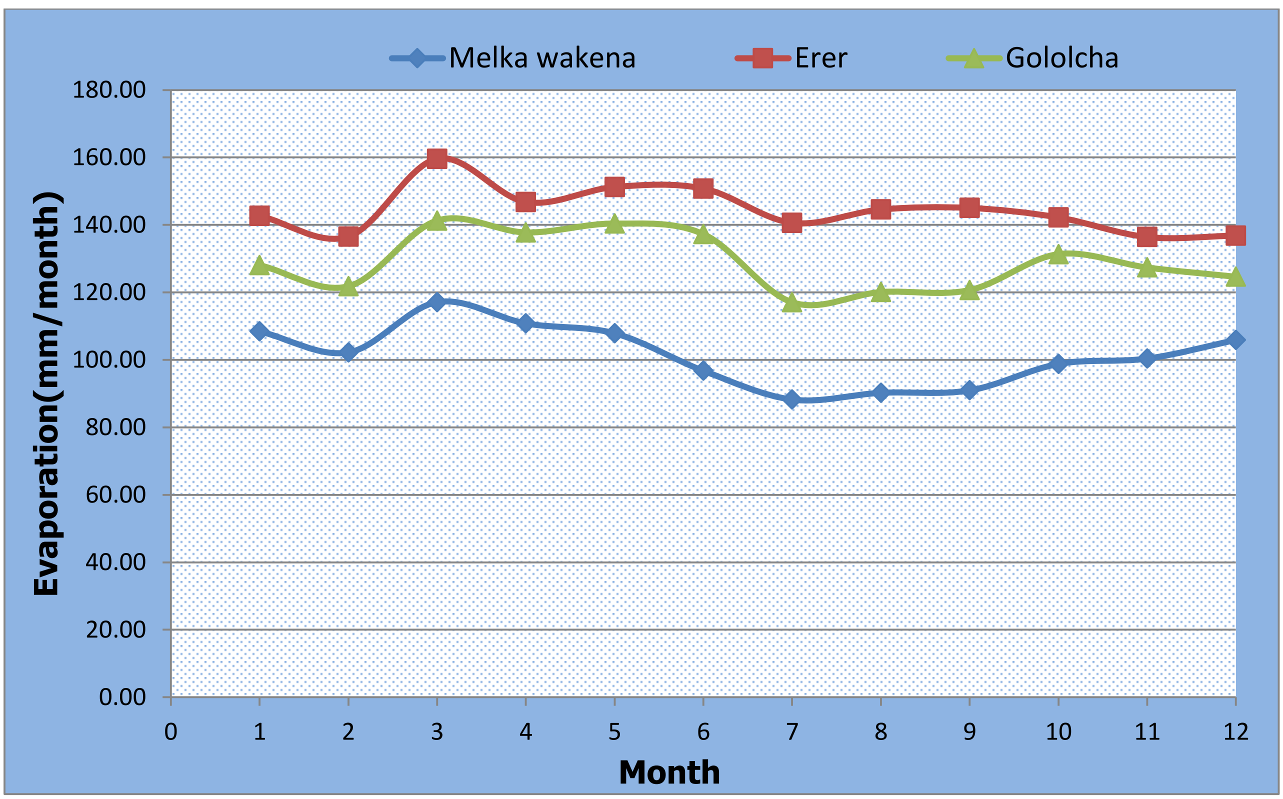


Figure 4.6: Reservoir evaporation for existing and proposed scheme

4.2.4 The Reservoirs physical characteristics data

The reservoirs physical characteristics data were the scantiest and important part of the data. Searching these data was also the most difficult work faced in this research work and it was not possible to get the original design documents of the reservoirs due the restructuring of the governmental organization to handle such type of documentation in the past decades. The design and construction of the Melka Wakena Hydropower plant and Gode irrigation Project were during the 'Hailselase' regime. The most important parts of the reservoirs physical characteristics data such as data at dead storage, at spillway level and at top level were obtained from the Ethiopian Ministry of Water, Irrigation and Electricity (MOWIE). On the other hand, the area and storage Elevation curve of the reservoirs obtained from EEPCO and WWDSE.

4.2.4.1 Power plant data

In the scope of long term system management, the monthly demands regarding electricity generation for existing power plant should be specified for simulation. Recorded energy generated listed in table 4.4.

Table 4.6: Recorded system energy at Melka Wakena(EEPCO,2004)

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Energy (GWh)	38.5	37.8	40.5	34.8	35.75	35.5	32.5	34	41	37.75	42	40.25

4.2.5 Irrigation Land data

Both the existing and potential land under the reservoir system data has been collected from the Ethiopian Ministry of Water, Irrigation and Electricity (MOWIE).

Table 4.7: potential Irrigation land at different site

Project Name	Location	Gross Irrigation area	Net Irrigation area	Head Work Type	Latitude	Longitude
Gololcha 1	Bale	11500	10000	Dam	$7^0$24'	$40^0$46'
Gololcha 4		9200	8000	Dam	$7^0$32'	$41^0$16'
Gode south	Gode	10000	8300	DW	$6^0$08'	$43^0$08'
Gode West	Gode	23000	18800	Syphon	$6^0$08'	$43^0$08'
Erer	E.Hararghe	4600	4000	Dam	$9^0$16'	$42^0$05'

4.2.6 Ecological flow

Water storage reservoirs typically provide multiple benefits viz. hydropower, water supply (municipal, industrial and agricultural), flood control and recreational opportunities. An environmental flow is the water regime provided within a river, wetland or coastal zone to maintain ecosystems and their benefits where there are competing water uses and where flows are regulated. In order to maintain the ecological services as well as the natural channel habitat associated to the historic flow regimes of the Wabi Shebelle River, a certain reserve flow has to be maintained and could be considered as a sectoral demand on its own.

An environmental flow that corresponds to low flow of 95% exceedance has been used in this study.

4.3 HEC-ResSim Model Framework of Wabe Shebelle River Basin

The model has three distinctive modules which have their own structure and operation to run the model and fulfill a certain task. In addition to this, the modeler or the engineer has an option to establish his own framework that simplifies the complexity of the work. The framework is an essential skeleton that shows distinct steps of the work with the aim of achieving a certain endeavor. In order to realize the specific objective of the study, the framework (Figure 4.2) of the study area was formulated.

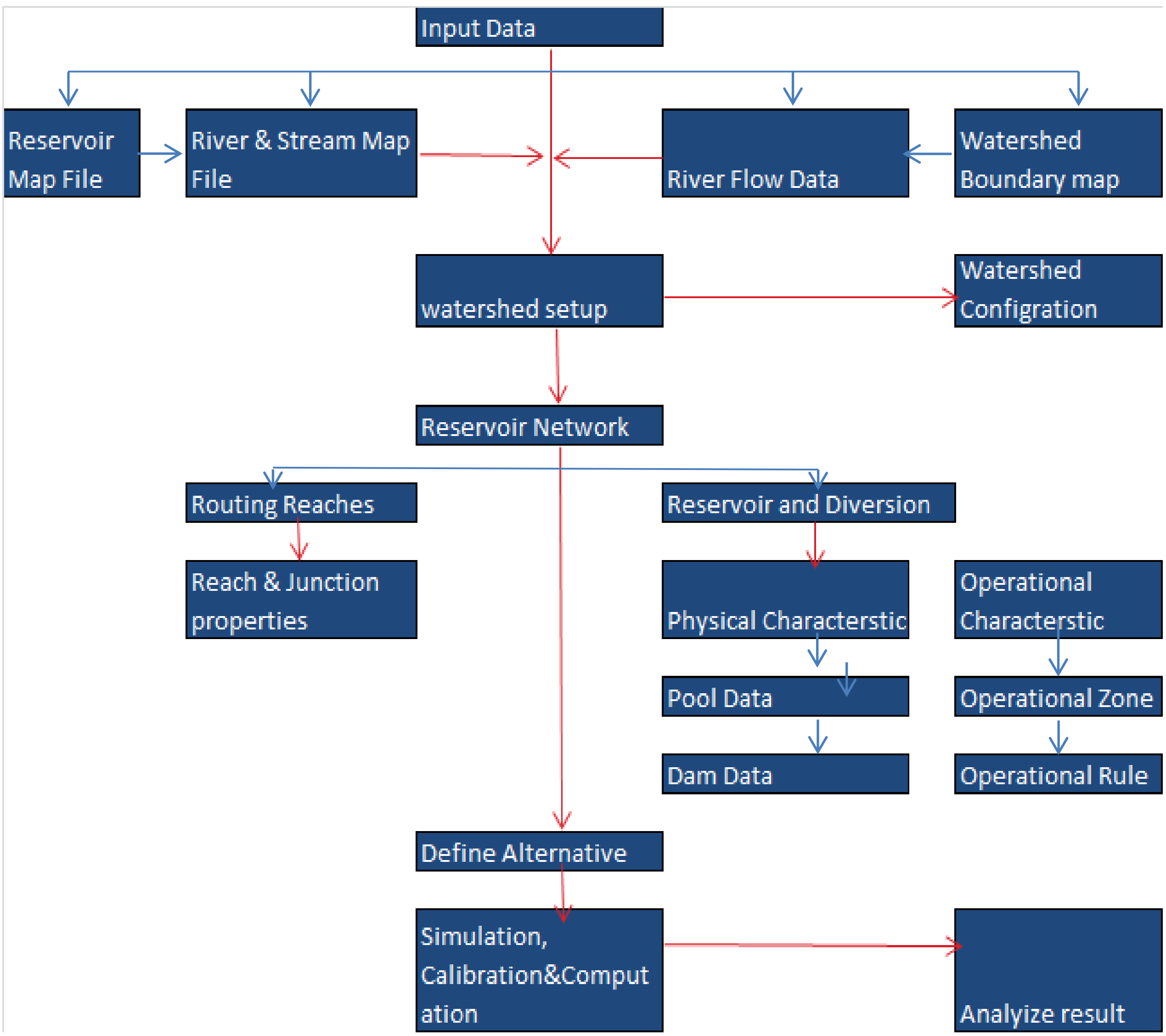


Figure 4.7: Framework of HEC-ResSim Model for Wabe Shebelle River Basin

5. DEVELOPMENT OF HEC- ResSim FOR WABE SHEBELLE RIVER BASIN

5.1 General

Water resources management is a complex and involving varied subject that requires consideration of a broad range of social, economic, political and environmental interests. As the world's water resources become increasingly stressed, effective tools for management become more important. One tool often used in water resources management is decision support systems.

HEC-ResSim is a computer program applicable in hydrologic and hydraulics of reservoir system simulation model used for research in water resources management. HEC-ResSim is planning and real time decision-support tool for single and multi-reservoir system management. This software performs hydrologic routing and determines reservoir releases based on a rule curve approach plus user-specified operating rules to meet multipurpose, seasonal, at-site and downstream operational goals, including flood reduction, water supply, hydropower generation and stream flow generation.

Typically, the model involves three separate modules that provide access to specific types of data within a watershed in which each of them has distinct features and have been conducted step by step.

The first one is model development which began with the establishment of a HEC-ResSim watershed. HEC-ResSim allows users to import an ArcGIS Shape files as a background layer. This can be characterized through the development of a stream alignment that serves as the framework or skeleton upon which the model schematic is set up. The second step in model development was the establishment of a reservoir network, defining alternatives and scenario setting in the reservoir network module. A reservoir network represents a collection of watershed elements connected by routing reaches. The network includes reservoirs, reaches and junctions needed for the. The final step in model development was computation of the different simulations and analyzing results in the simulation window.

5.2 Watershed Setup Module

The purpose of this module is to deliver a common framework for watershed creation and definition. The HEC-ResSim watershed for this study is named Wabe Shebelle River Basin. On this watershed module different digital background maps are overlaid. The watershed may include all of the streams, projects (e.g., reservoirs, irrigation diversions), Computation points, impact areas, time-series locations, and hydrologic and hydraulic data points for a specific area.

The physical arrangement of the streams network and layers containing additional information about the watershed is imported from ArcGIS file of the basin. This helps to draw the stream alignment properly and put the reservoir dams, diversion weir and its computation points at the appropriate positions. Once all these background maps overlaid and configured together, then the watershed framework is established. After importing the stream network, stream alignment and configuration are made, Project elements such as reservoirs and computational points were positioned in to the configuration on their respective coordinate location. Figure displays a list of all of the map layers that are included in the watershed and that are available for selection.

Stream Alignment

The orange lines in this map are streams of the stream alignment. Green dots represent stream nodes which are utilized to specify the stream stationing and the lighter green "halos" represent the stream junctions or confluences.

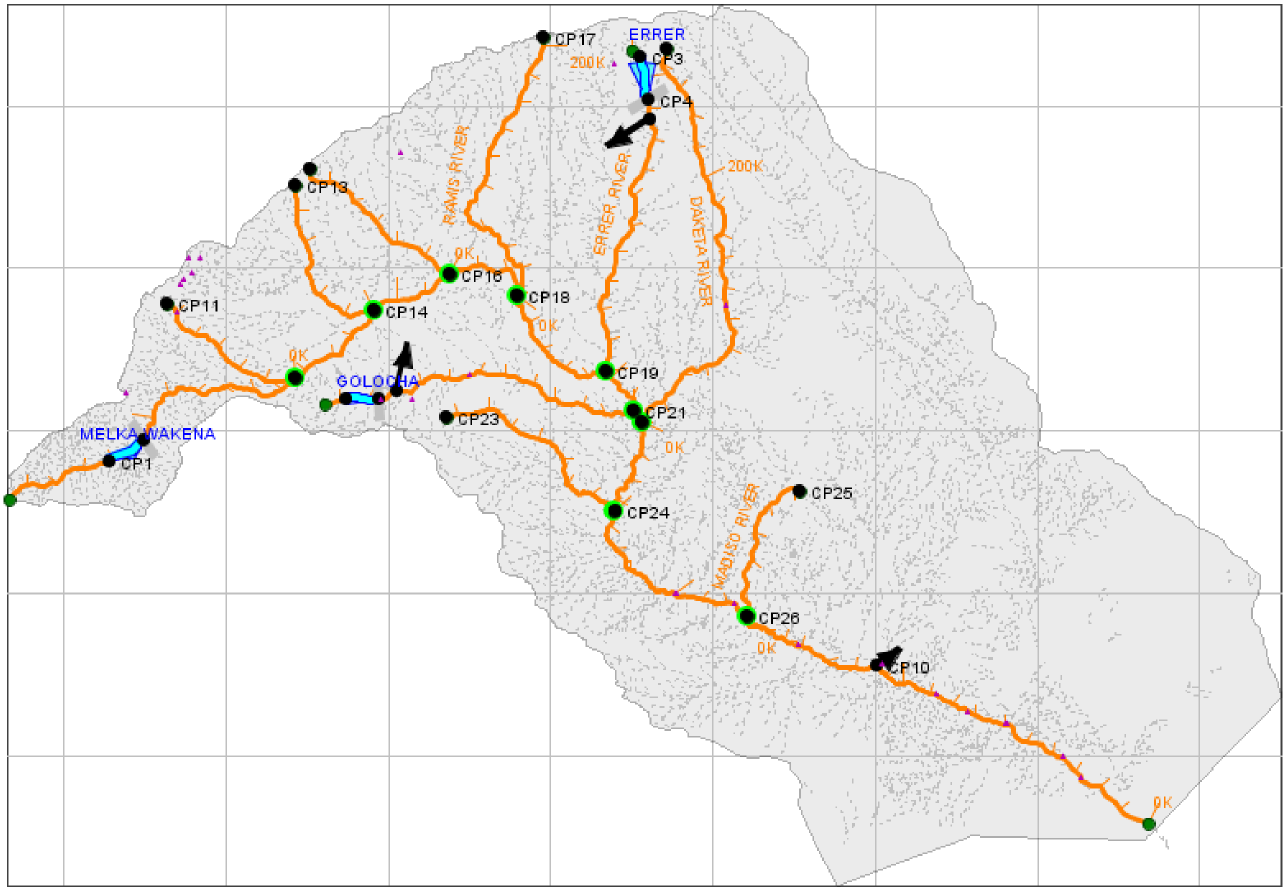


Figure 5.1: Watershed Setup for Wabe Shebelle reservoir system

Watershed Configurations

A watershed configuration is a specific physical arrangement of the project and computational point that will be modeled for the study of watershed. A watershed configuration includes projects (i.e., reservoirs and diversions), gauge location and computation points.

For this study two configurations are established, named baseline and future development scenario were needed for the Wabe Shebelle River Basin model. The first configuration is that includes two projects, and the second one is includes four projects.

5.3 Reservoir Network

Reservoir network represent the collection of watershed element connected by routing reach. The reservoir network module assists the establishment of the network schematic, adding description of the physical and operational elements of the reservoir model and develop the alternatives that to be Analyzed. The modeling elements that make up a reservoir network include reservoirs, reaches, junctions, diversions, and reservoir systems. Each of these elements required their own physical and operational data.

The main modeling element in reservoir network is the reservoirs. Reservoirs are connected to the river network as well as to diversions or junctions using routing reaches. After finalizing the connecting network schematic, physical and operational data for each network element are defined. The principal criteria for the release decision of reservoir normally depends on the discrete pool heights, power production levels and the reservoir operation release rules applied. Finally, the management alternatives are set up to compare the different simulation results using the defined model schematics, i.e. physical properties, operation sets, inflows, and initial conditions.

5.3.1 Reservoir network elements

Modeling element in HEC-ResSim that makes up each of the reservoir network 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.

5.3.1.1 Junctions

The junction’s elements are the main elements that inter connect all the model elements together. Junctions represent stream confluences or points where external flows enter the system. Since HEC-ResSim does not calculate runoff, all local flows must be introduced at junctions as external flows. At junction that the model calculates the inflow and outflow balance, stage of the river and rating curves. The flow out of a junction is simply the sum of the flows into the junction. For reservoir network model is being properly simulated, the connection between network elements utilizing the junction should be approved.

Depending on the place where the inflow joints to the river network, junction can be categorized into two namely boundary junctions and interior junctions. Boundary junctions are placed at the beginning of the reach and normally at the upstream reach of the river where a single gauge is located. Whereas interior junctions are located at the middle reach of the river where it combines the inflow routed from upstream with incremental local flow before passing the total flow on to the downstream element.

5.3.1.2 Routing Reaches

Routing reaches represent the natural streams in the system. The lag and attenuation of flow in a reach is computed by one of a variety of available standard hydrologic routing methods, such as Muskingum, Modified Puls, Coefficient, or Muskingum-Cunge. Losses through seepage can be specified for each routing reach. Among the seven hydrologic routing options available in HEC-ResSim, only two of them were applied for flow routing in the Wabe Shebelle River Basin. These two methods namely null (direct translation or no lag and attenuation) and Muskingum methods were selected based on the availability of data in this study region. Null routing was used for very short reaches that have no appreciable impact on the flow that can be represented in one-hour time step. While the remaining reaches were routed using the Muskingum routing method which required only two storage constants i.e., K and X parameters for routing of flow in a long reach of Wabe Shebelle River system. For more detail how to estimate the parameter of K and X for Muskingum method.

Muskingum Hydrologic Routing Method

The Muskingum method is a hydrological flow routing model that utilized storage constants which describe the transformation of discharge waves in a river bed (Linsley et al., 1982). Flow routing along the main and tributaries of the rivers have been internally handled applying the Muskingum routing method. This method applied two well-known equations namely the continuity equation (which is conservation of mass) and the discharge storage equation.

The two main parameters that should be needed in Muskingum methods are K and X. K means travel time in hours at a point on a watercourse from known or assumed hydrographs. Whereas X means storage constant, normally taken from the recommended values of commonly known rivers characteristics. The most critical part of the calculation is to estimate suitable values of K and X. The recommended values of attenuation coefficient X has been taken which usually ranges from 0 to 0.5 (HEC, 2010). A value of 0 specifies there is maximum attenuation of wave through the reach and a value of 0.5 designates a direct translation or no attenuation through the reach. However, in this study, K is approximated using the kirpich's formula:

K=0.0078L0.77S-0.385 ……………………………………………………………………….. 5.1

Where K=travel time for drop of water to travel from the remotest point outlet (minute)
L-Length of channel/ditch from head water to outlet in ft and S- average watershed slope, ft /ft.
The computed (K) in hr, X and the number of sub-reach values have been entered as an inputs to reach editor of the reservoir network model.

5.3.1.3 Diversion

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. For this study there is three diversions Gode, Erer and Gololcha.

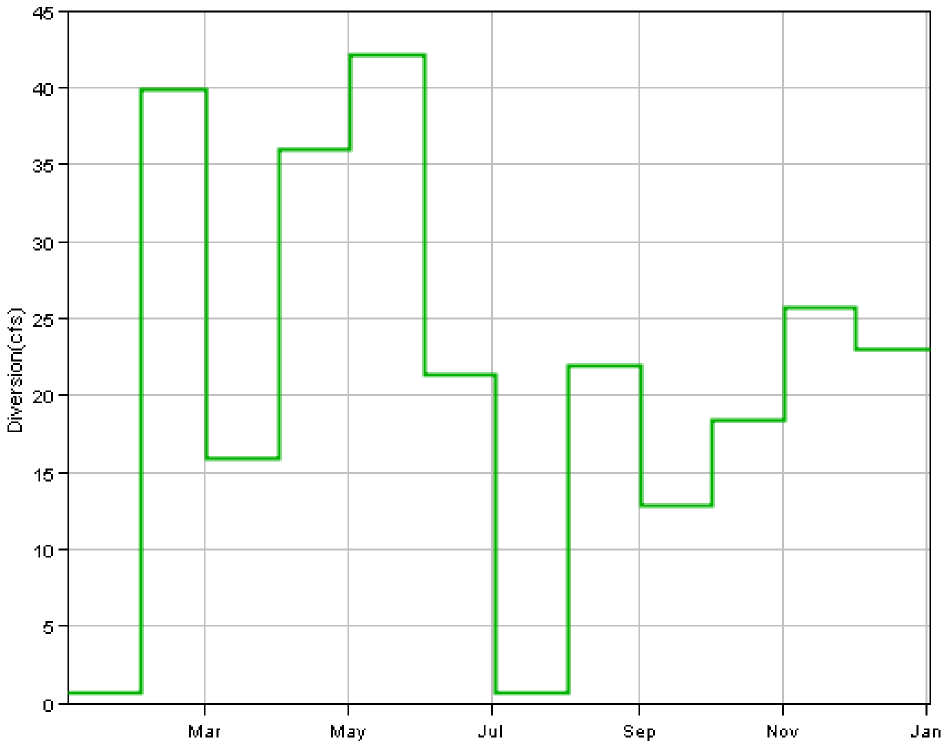


Figure 5.2: Diverted water for different month for Gode Irrigation Project

5.3.1.4 Reservoirs

A reservoir is the most complex element of the reservoir network and is composed of a pool and a dam. HEC-ResSim assumes that the pool is level (i.e., it has no routing behavior) and its hydraulic behavior is completely defined by an elevation-storage-area table, evaporation and seepage losses (Wakena, 2006).

The dam is the root of an outlet hierarchy or “tree” which allows the user to describe the diversion weir, controlled and uncontrolled outlets structures which are different appurtenant hydraulic structures constructed for distinct purposes. There are two basic and two advanced outlet types. The basic outlet types are controlled and uncontrolled. An uncontrolled outlet can be used to represent an outlet of the reservoir, such as an overflow spillway, that has no control structure to regulate flow. Controlled outlets can be used to represent any outlet, such as a gate or valve, capable of regulating flow. The advanced outlet types are power plant and pump, both of which are controlled outlets with additional features to represent their special purposes. The power plant adds the ability to compute energy production to the standard controlled outlet. The dimensions and configuration of all these physical structures are required in HEC-ResSim model for example the top of the dam, length of the crest, number of gates, the maximum and minimum releasing capacity of the outlets.

Reservoir elements are also contained the operational data. Operational data represent the different zones, and the goals and constraints that guide the release decision process. An operation set is the collection of all these operational data as a group. A number of multiple operation sets can be defined in reservoir, but only one operation set per reservoir may be employed in an alternative (HEC, 2007). The operation set is made up of a set of operating zones. Each of them contains a prioritized set of rules. Rules describe a minimum or maximum constraint on the reservoir releases. The model of the Wabe Shebelle River Basin was established to analyze the operation of the system during each day of the year.

5.3.2 Reservoir Physical and Operational Components

The general data requirements for this model were the physical and operational characteristics data of Melka Wakena hydropower plants, Erer and Gololcha irrigation project and their reservoirs. These data included reservoir pool definition (elevation-area-storage tables), outlet capacity curves, hydropower plant data, operational zones, and minimum and maximum release requirements of each project, and they were extracted from their respective feasibility and detail engineering design documentations.

5.3.2.1 Physical Components

Definition of physical parts is one of the most important parts in HEC model. Even small changes affect significantly the system behavior and the impacts deteriorate or meliorate the result in the simulation part. Input that should be considered for the physical part consists of the reservoir pool characteristics which are defined by the storage-elevation-area curve and the dam properties that consist of uncontrolled and controlled outlets along with tail water elevation and the downstream control.

a) Storage-Elevation-Area

The elevation storage area curve is the main characteristics of the reservoir pool defining the surface area and the volume of storage at the respective elevation. The reservoir surface area is mainly utilized to compute the reservoir evaporation loss, and the storage is used to estimate the stage or elevation at any time based on the storage equation. Reservoir stage-area-storage data for Melka Wakena, Gololcha and Erer reservoirs are presented in figures 8.4, 8.5 and 8.6.

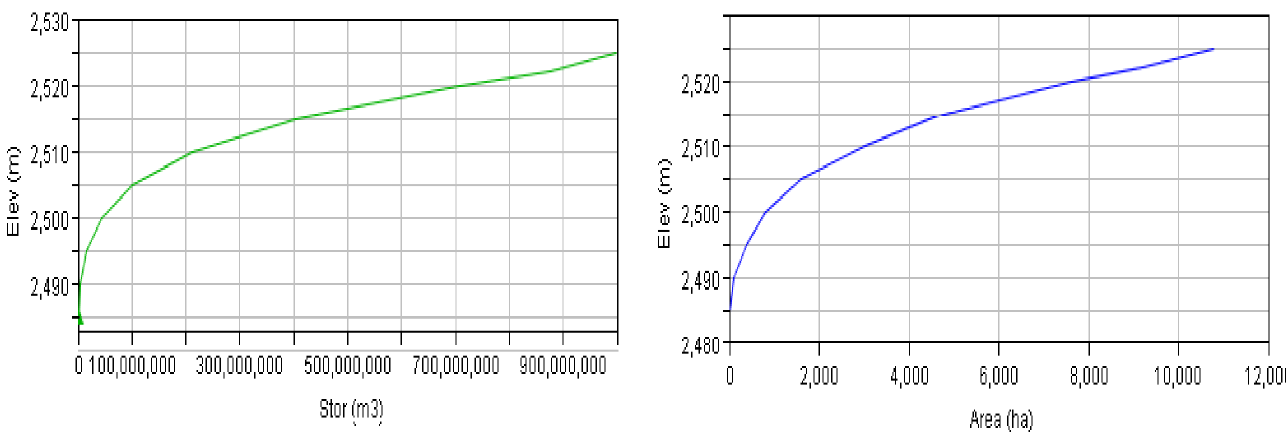


Figure 5.3: Reservoir stage-area-storage curve for Melka Wakena

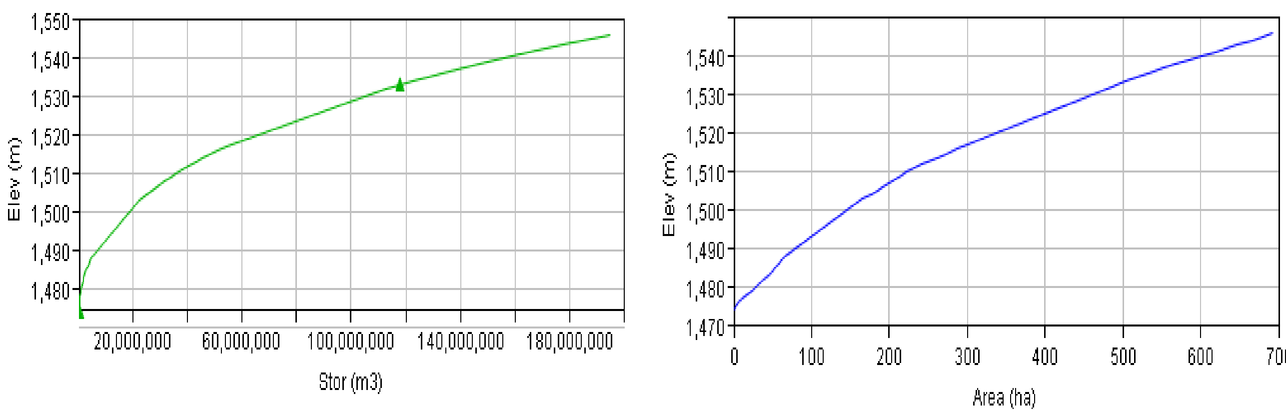


Figure 5.4. Reservoir stage-area-storage curve for Gololcha

b) Controlled Outlet

Controlled outlets can be used to represent any outlet, such as a gate or valve, capable of regulating flow. The advanced outlet types are power plant and pump, both of which are controlled outlets with additional features to represent their special purposes. The power plant adds the ability to compute energy production to the standard controlled outlet.

c) uncontrolled Outlet (Spillway)

Spillways are structures constructed to provide safe release of floods pass a dam to a downstream river stretches. Every reservoir has a certain capacity to store water. If the reservoir is full and high flows enter the same, the reservoir level increases and may eventually result in over-topping of the dam. To avoid this situation, the flood has to be passed to the downstream side and this is done either through the spillway or turbine intakes. A spillway can be a part of a concrete or connected to an embankment dam.

The elevation versus maximum capacity relation for the spillway of reservoirs will be computed for the various elevations above the spillway crest from the well-known broad crest weir formula, equation 5.2. ResSim has two way of data entry for the uncontrolled outlet. The first is using weir equation that requires the wearing coefficient, outlet elevation and crest length of the spillway. The second option is using a rating curve of elevation versus outflow. The first option is used in this study.

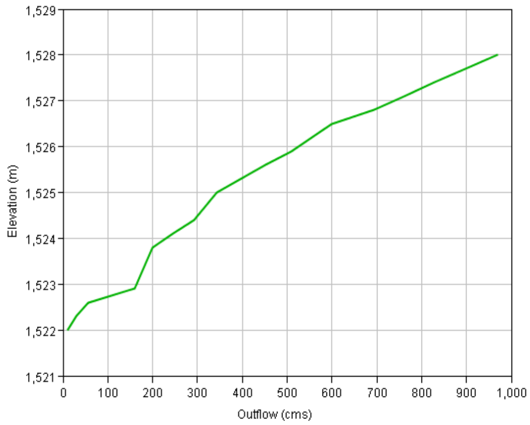


Figure 5.5 a

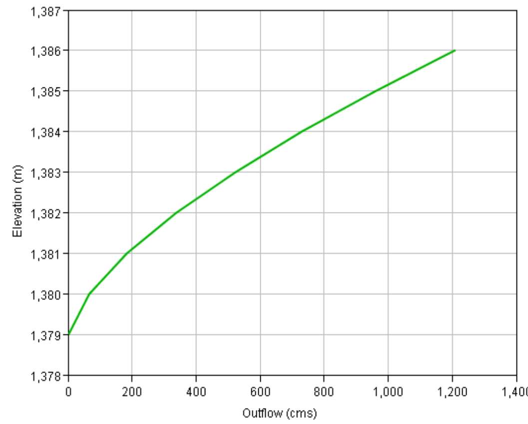


Figure 5.5 b

Figure 5.5: Spillway Elevation –outflow Relation a) for Golocha and B) for Errer

d) 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 Melka Wakena plant is 153 MW, station Use 0, total head loss 5.5m, overall efficiency 92% and the average tail water elevation used is 2218 masl.

5.3.2.2 Operation Component

In a manner similar to the methods an operator may use, each reservoir in ResSim network must determine the quantity of water to release at each time step of a simulation run. For this to happen, scheme upon release decisions can be made or an operation plan should be described. This plan is called an Operation Set. (HEC, 2013). An operation set consists of three basic features: Zones, Rules and the identification of the Guide curve.

Zone

Zones are operational subdivisions of the reservoir pool. Each zone is defined by a curve describing the top of the zone. When an operation set is created, ResSim establishes a default set of zones within the operation set. These zones are Flood Control, Conservation and the Inactive. However additional zone could be added when necessary. Additional Minimum Operation zone is added in between the conservation and Inactive zone for this study.

Rule

Operating rules describe the goal and constraint upon storing or releasing water. Dam planning and operation requires decisions to be made about the magnitude and timing of releases. Rules are applied to selected zones of the reservoir to describe the different factors influencing the release decision when the reservoir elevation is within each zone.

The following operational rules were implemented on the reservoir pool and hydropower plant to define two alternatives based on the availability and feasibility of the data on this study. These include: **The Downstream Control Function Rule and Hydropower schedule operation Rule**. Downstream Control Function Rule can be assigned only to the reservoir (pool), because only Reservoir can account all release from reservoir outlet that could influence the flow at the downstream control point but on Hydropower schedule operation Rule can be assigned to reservoir element (pool or outlet).

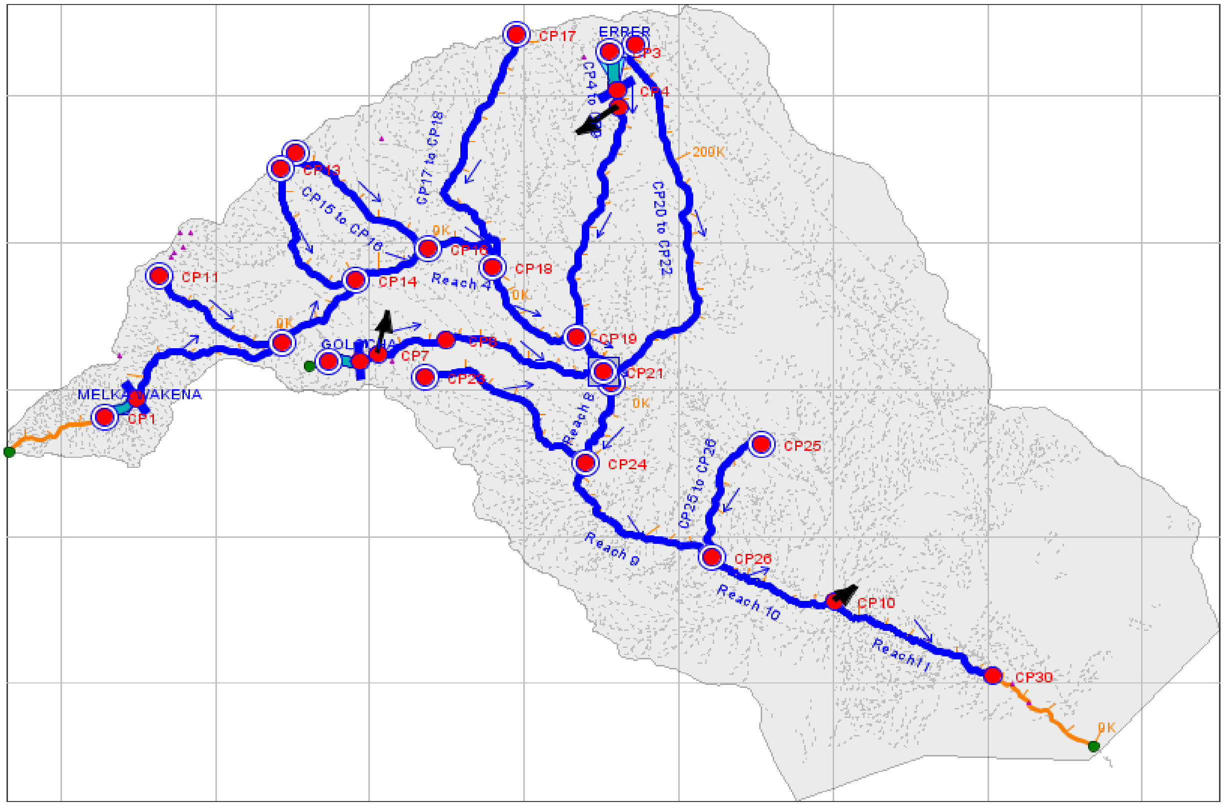


Figure 5.6: Reservoir Network setup Melka Wakena, Gololcha and Erer Reservoir System

5.3.3 Guide Curve

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). Guide curve operation oversees releases to maintain that storage level. For this study guide curve set in conservation zone.

5.3.4 Scenario Setting in Reservoir Network

Scenarios were set to evaluate the possible most likely events especially what was and/or will be happened based on different conditions in the study area. After alternatives were defined based on the two reservoir operation rules applied on the reservoir pool and hydropower plant, two scenarios are set based on the past and future conditions of the projects on the reservoir module. These are:

5.3.4.1 A baseline scenario (Scenario-1)

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 and generated flow data as input.

This Scenario considered the time until 2017 and included projects are only Melka Wakena Hydro power plant and Gode Irrigation project. This scenario has been set up to evaluate the water availability in dry season and flooding in summer season at Gode and downstream site.

5.3.4.2 Future development scenario (Scenario-2)

This considered the time from the future project will implemented and included projects in scenario one and design project Erer and Gololcha Irrigation Project. This scenario has been set up to evaluate the effect of water management in the near future of the basin based on likely future developments currently anticipated being implemented. In addition, this scenario was applied to develop reservoir and power guide curves which is the main target of the next chapter.

The main target of scenario development is to compare the different condition of the basin, considering the hydrologic condition and future Irrigation project development.

5.3.5 Transferring data to HEC-Dss tools

HEC-DssVue is a tool for transferring time series data from HEC-DSS database storage to a working space or it allows to access data stored in HEC-DSS database. The tool is comprised of two visual basic executables that utilize an object library and object classes within the database structure (DSS catalogs) and contains all relevant records and descriptors to automatically transfer the time series data during simulation process. The time series data of the reservoirs have been stored in HEC-DssVue file. This data is the runoff flows to the reservoirs and runoff from tributaries from the year 1967 to 2007.

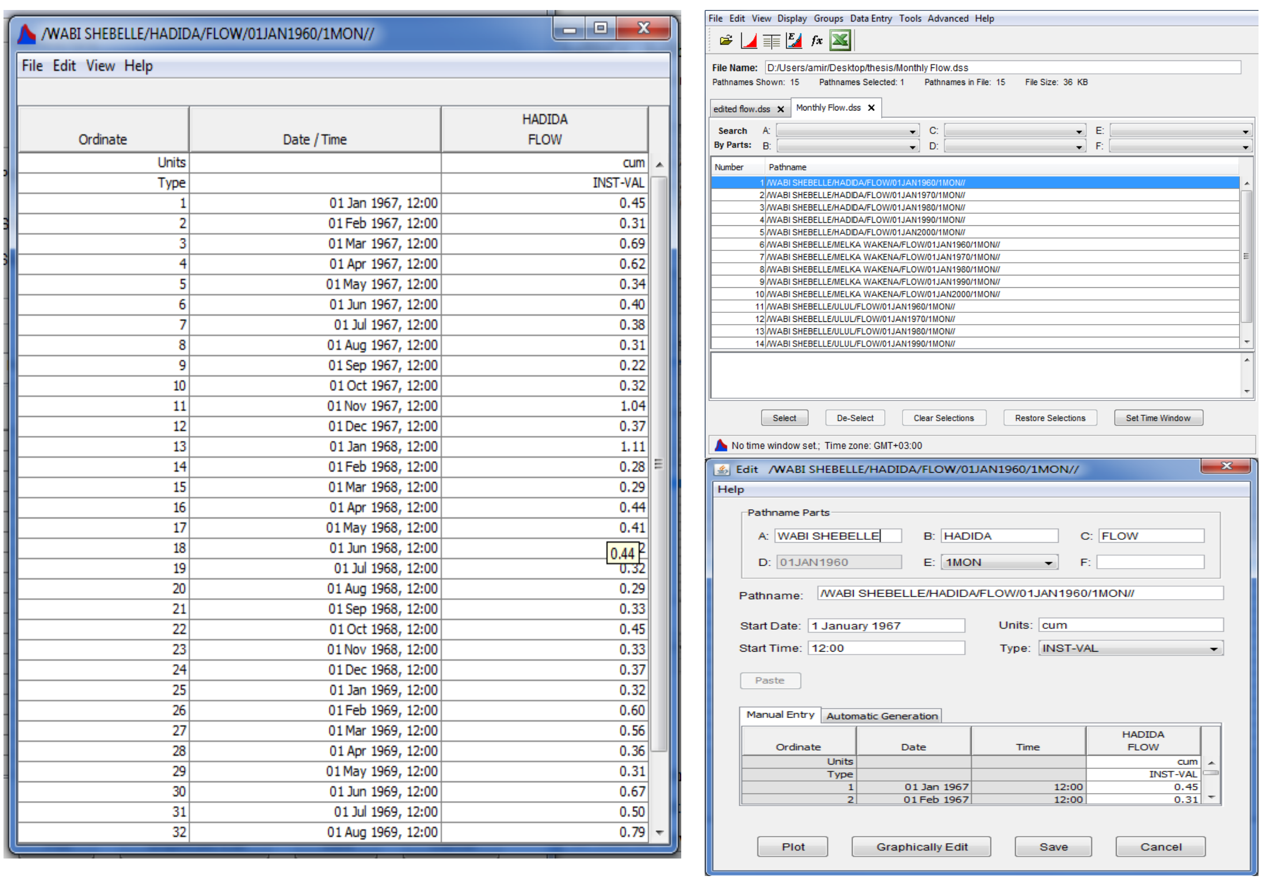


Figure 5.7: Time series transfer database and HEC-DSS

A key step in transferring a time series data from the database storage in to the DSS format is the creation of DSS catalog inside the database. DSS catalog is the object class table within the database that contains the information related to the DSS data and its pathname. The DSS pathname consists of six parts in the following format.

A/B/C/D/E/F

Where:

A - Group name for the data such as a watershed name, study name, or any identifier which allows the records to be recognized as belonging to a group.

B - The location identifier for the data. The location identifier may be a site name or organization ID such as NMSA gage name.

C – The parameter of the data such as flow, precipitation, storage or evaporation.

D – The start date of the time series.

E – The time interval for regular data or the block length for irregular interval data.

F – An optional descriptor that can be used for additional information about the data.

5.3.6 Defining Alternatives in Reservoir Network

An alternative was put in place in the reservoir network module in which distinct feasible reservoir operation rules are defined on the forehand reservoir network configuration. The following endeavors were accomplished on alternatives in the reservoir network. These include the setting of an operation for each reservoir in the network, setting of a storage balance for each reservoir in the network, defining of the initial (lookback) condition, and mapping of all the time series records to already identified local inflows. The alternatives for this study were set using the two reservoir operation rules utilized for each zone to optimize the water resources management.

6. RESULTS AND DISCUSSIONS

6.1 General

The objective of reservoirs simulation was to select the best reservoir operational rule that optimize water management for hydropower energy generation taking into account flood control in summer season and availability of water in dry season for Gode Irrigation and downstream users and to show the effect of future development Irrigation project (Erer and Gololcha). Simulation was performed proceeding defining two reservoir operation alternatives for two scenarios based on considering the existing project and future expansion Project (Erer and Gololcha Irrigation Project). Based on this fact, the first scenario was simulated for existing project (Melka Wakena Hydropower Plant and Gode Irrigation project); and the second scenario considering Erer and Gololcha irrigation Project addition to the first scenario.

6.2 Calibration and Verification of the Model

The overall goal of calibration procedure was to evaluate whether flow routing through HEC-ResSim represents the actual river morphology of the basin or not. The model calibration was performed at two sections of the river namely: at the upper reach Wabe Shebelle and at the Imi station (Figure 6.1).

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, good overall agreement of the shape of the hydrograph and time series is observed.

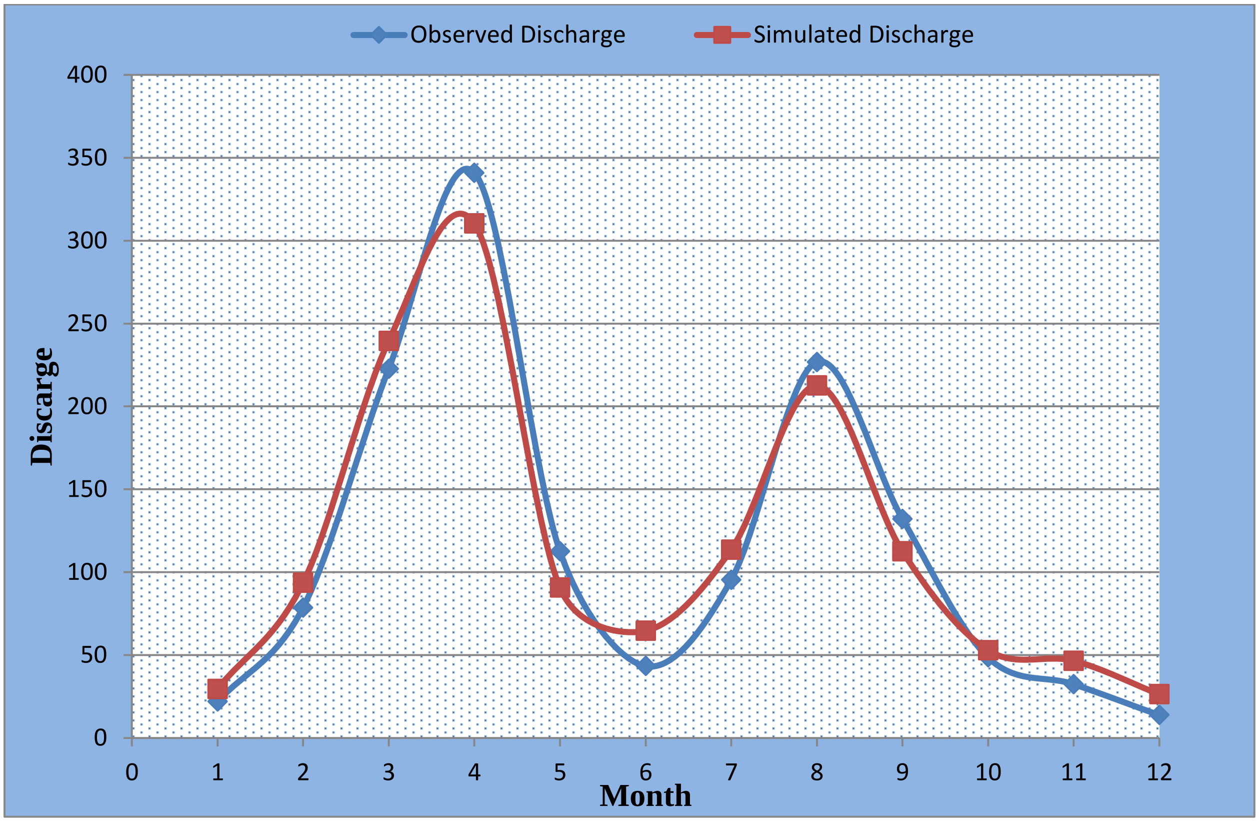


Figure 6.1**:** Comparison of measured and simulated hydrograph at Imi

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

$$\mathrm{EFF} = 1 - \frac{\sum(\mathrm{Qobs} - \mathrm{Qsim})2}{\sum(\mathrm{Qobs} - \mathrm{Qbar})2}$$

Where; Qbar is the observed mean monthly flow and Qsim is simulated monthly flow. An efficiency criterion of 1 means that observed and simulated values are in perfect agreement, the Nash-Sutcliffe coefficient computed at the Imi station is 0.86 hence the model ability and efficiency is acceptable

6.3 A baseline scenario (Scenario-1)

In this system of operation, one dam (Melka Wakena Hydropower Plant) and one diversion weir (Gode Irrigation Project) were configured. The reservoirs network configuration of Melka Wakena Hydropower Plant and Gode Irrigation Project for the first scenario is shown in figure 6.10.

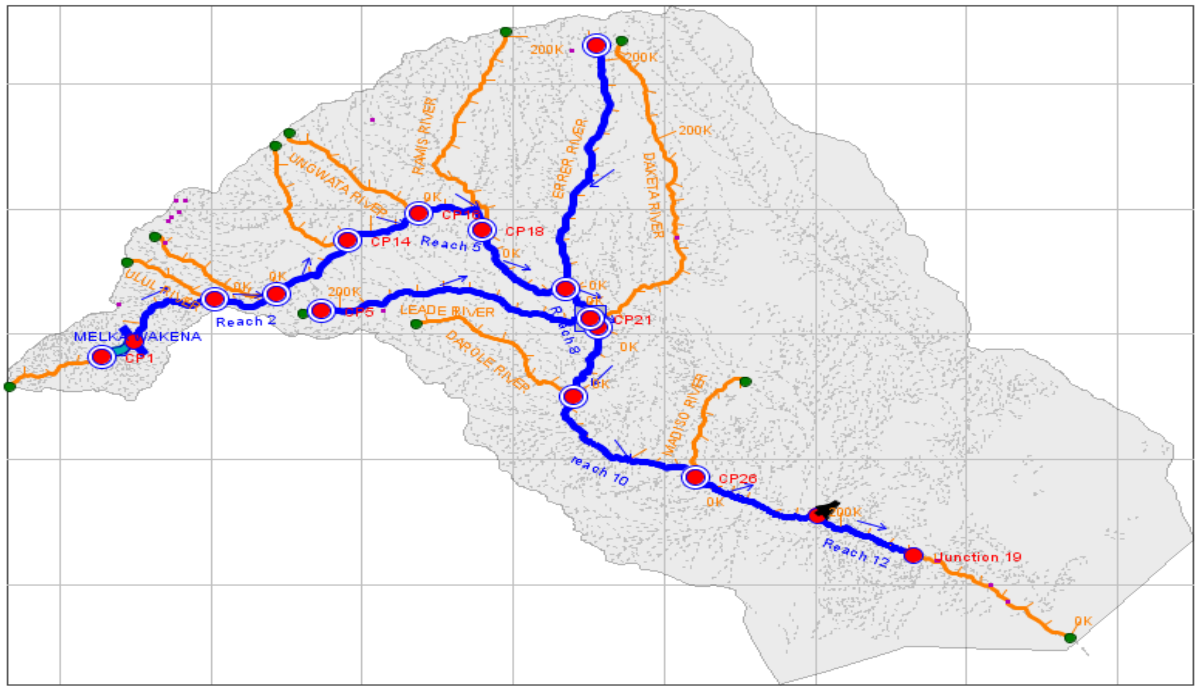


Figure 6.2: Melka Wakena Hydropower Plant and Gode irrigation Project operation for scenario one

In this scenario, the levels of reservoir operation zones (i.e., flood control zone, conservation zone, and inactive storage zone) are set or defined based on the data obtained from engineering design (EEPCO, 2004 and 2006).

Two alternatives were evaluated to select the best reservoir operation rule which provides maximum power generation of the hydropower plant and availability of water at Gode Irrigation Project as the main objective function considering environmental flow at downstream.

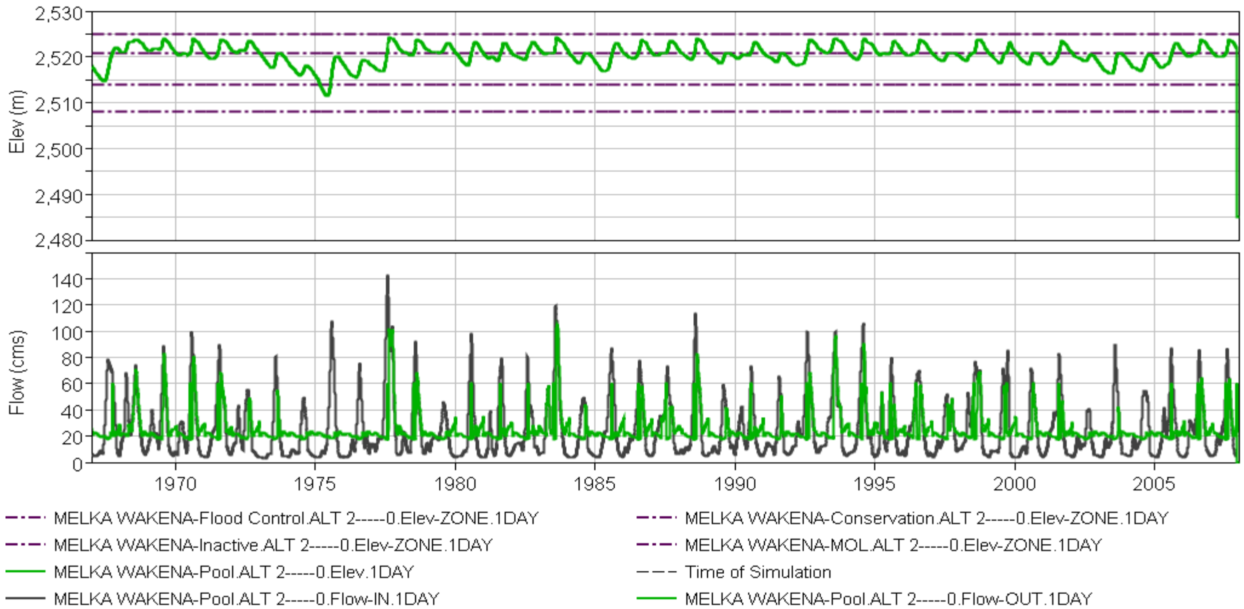


Figure 6.21.: Downstream Control Function Rule for Melka Wakena reservoir levels- (upper plot): computed reservoir (green), conservation, inactive, flood control, top of dam (dark purple dotted lines), and Flows (lower plot): inflow (black) and outflow (dark green) hydrographs

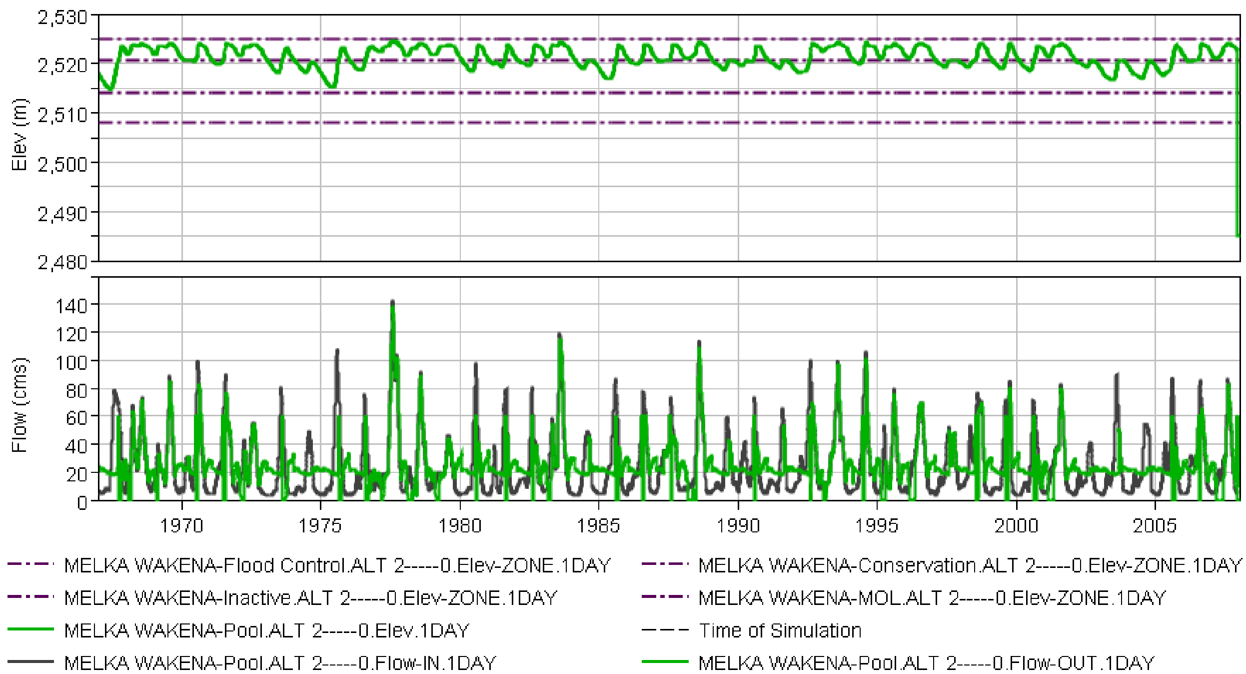


Figure 6.22: Hydropower schedule operation Rule for Melka Wakena reservoir levels- (upper plot): computed reservoir (green), conservation, inactive, flood control, top of dam (dark purple dotted lines), and Flows (lower plot): inflow (black) and outflow (dark green) hydrographs

The upper plots of figures 6.21 and 6.22 show graphical representations of reservoir levels with respect to time and depict dam crest, flood control, conservation, computed reservoir pool, and inactive levels in the order from top to down of reservoir elevation curves for Melka Wakena. As one can observe from these figures, the computed reservoir pool is within the required operating zone (i.e. conservation zone) to meet the monthly energy requirement and availability of water throughout the simulation period. The upper conservation level is the designed or target level where ResSim try to keep while the computed level is the actual reservoir pool determined on the basis of inflows, water release for the different activities and operation of the reservoir. The lower plots show in the inflow and the outflow from the reservoir during the operation of the reservoirs with respect to the simulation period. The Downstream Control Function Rule reservoir operation rule has best performance in system balance storage in the reservoir. This doesn't mean that this rule best achieved the release requirement to produce hydropower. Hence, to select the best operation rule which performs well in optimizing the reservoir operation, better to see the power generation curve of each project.

6.3.1 Power and Energy Computation for Melka Wakena Hydropower Plant

The power required for Melka Wakena hydropower plant was derived from the energy requirement collected from the engineering design documentation and entered the physical data of the reservoir network. The regular energy requirement was applied to the model in the monthly basis so that these values are constant throughout the designed period of the hydropower plant. The power required, power computed and power capabilities of the plant during the simulation period are shown in figures (6.31-6.32).

Power capability or capacity of the plant means the maximum electric output a generator can produce under specific conditions. For this case, installed capacity is 153 MW and represents the nameplate capacity for the power plant. Nameplate capacity is determined by the generator's manufacturer and indicates the maximum output a generator can produce without exceeding design thermal limits. Generators do not operate at their full capacity all the time and they may vary their output according to conditions at the power plant. The daily energy requirement of the designed system is obtained from the monthly values, internally converted by the model with the assumption that the energy produced equally per weeks. Based on the input data supplied to the model, the simulation results of the two operational rules for Melka Wakena hydropower Plant were presented using the power curves in figures 6.31-6.32 below.

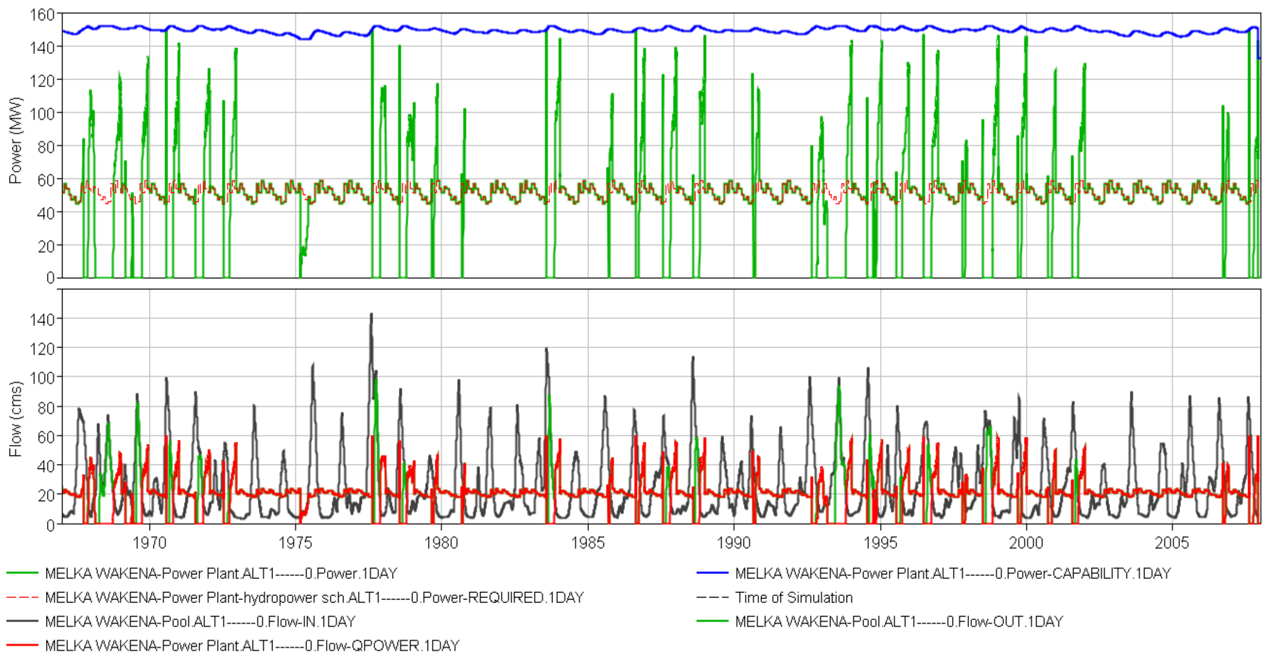


Figure 6.31: Downstream Control Function Rule power plant (upper plot): power required (red), computed power (dark green), power capability (blue), and Flows: inflow (black), turbine flow (red) and outflow (Dark green) hydrographs.

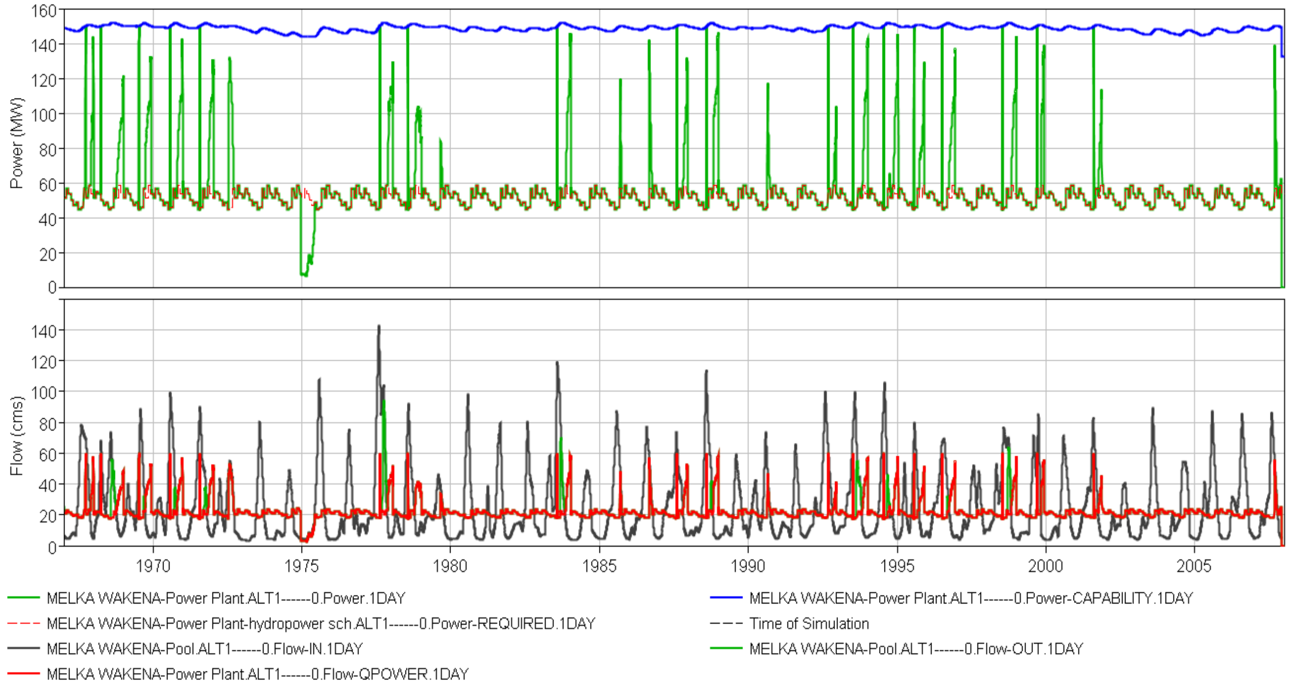


Figure 6.32: Hydropower schedule operation Rule power plant (upper plot): power required (red), computed power (dark green), power capability (blue), and Flows: inflow (black), turbine flow (red) and outflow (Dark green) hydrographs.

The evaluation of the power production of Melka Wakena Hydropower Plant for the simulations of reservoirs using the two reservoir operation rules are based on the computed power curve. As one can observe from Figure 6.31, the computed power follows an irregular trend pattern. Power production is higher, lower and sometimes zeroes in the simulation period. This suggests that the system doesn’t release water through the turbine when the pool level is below the conservation level. Since the system gives more priority for system storage balance, optimizing the release through the turbine is not sufficient to produce the required energy. Hence, this leads to minimal daily power production even though there is water in the conservation zone. For figures 6.32, the computed power curves are higher for almost all simulation periods. This indicates that the hydropower rules strive to release water through the turbine with the hydropower schedule operation rule for better performance.

From the above information, the downstream control Function Rule has intermittent power productions which will lead to interruption of electricity in the simulation periods. Whereas for the hydropower schedule operation rule, the uniformity of daily energy productions with respect to the simulation period is nearly regular and good distribution. For most of the simulation period, the computed power is equal or above the monthly power required which are calculated by the HEC-ResSim model from the monthly energy requirement supplied from the design engineering documentation of project.

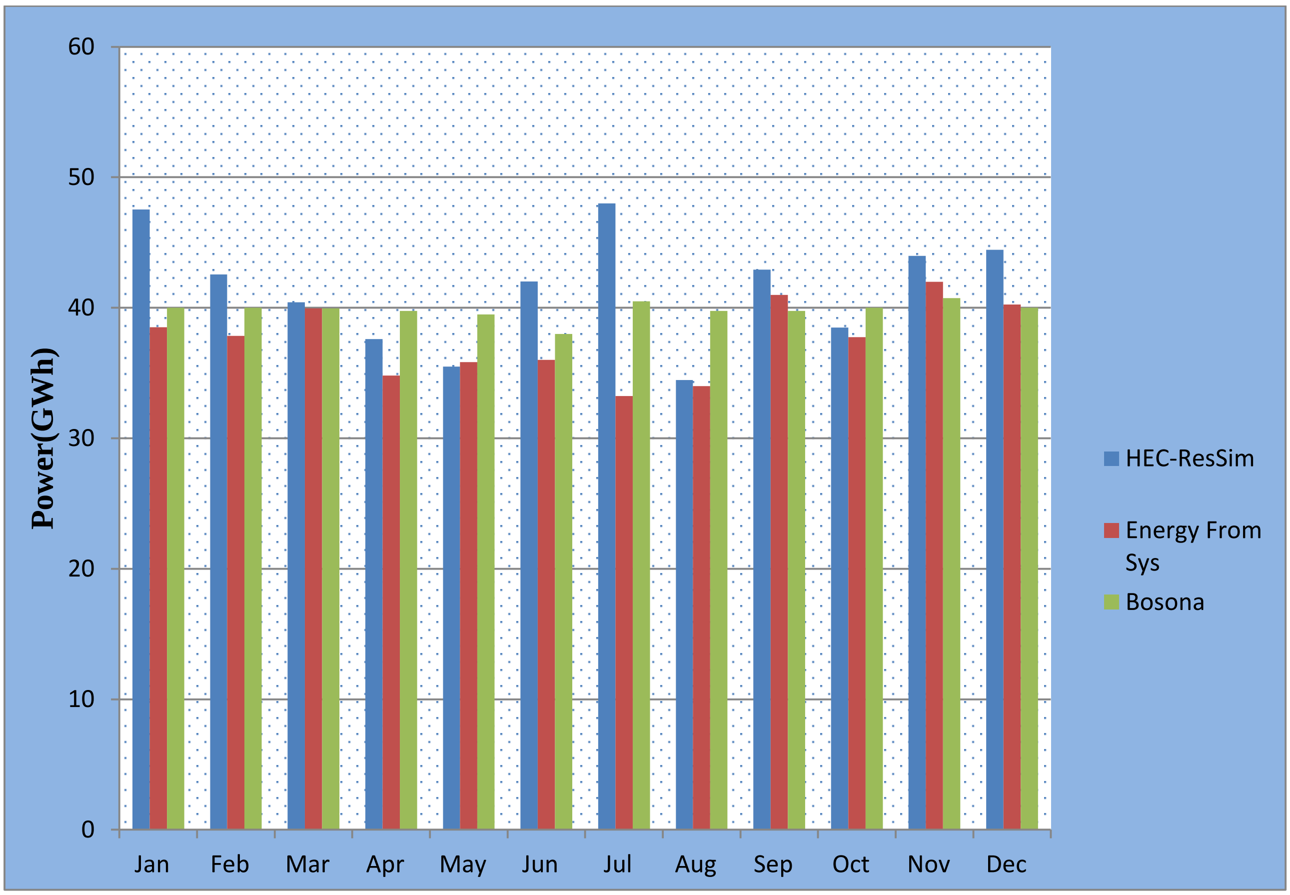


Figure 6.33: Energy generated using HEC-ResSim and EEPCO and Bosona (2006) studies

6.3.2 Evaluation Water Availability at downstream of Melka Wakena

Water Availability at downstream of Melka Wakena was the main goal for reservoir operation on Melka Wakena Hydropower plant. For downstream of Melka Wakena, the highest and lowest flow occur during the month of August and between the months of January and March (Figure 6.41 and Figure 6.42), respectively. For the simulation of the stream flows, the maximum flow will be occurred during the month of August 1983, and it is obvious that the water level rises in the reservoir. Nonetheless, during the operation of the reservoirs when the water level rises up above design guide curve (i.e., the maximum level 2525 m) due to unexpected extreme flood event, possibly water pool might be raised up over the design guide curve. In this case, the reservoir operating rule will start operating to regulate the flood and try to keep the pool at the desired guide curve. This strategy is achieved by giving the first priority to release water safely through the main and emergency spillways and other outlet facilities provided on the dams, and then later to release the remaining to the turbine and environmental flow.

However, in the low flood event that means when the water level is below the minimum design guide curve, then the reservoirs stop release water rather it attempts to increase the water pool utilizing the operating rule. In this case, the mechanism is achieved by releasing the critical water demands for instance the first release priority is given to environmental flow and then subsequently to the turbine.

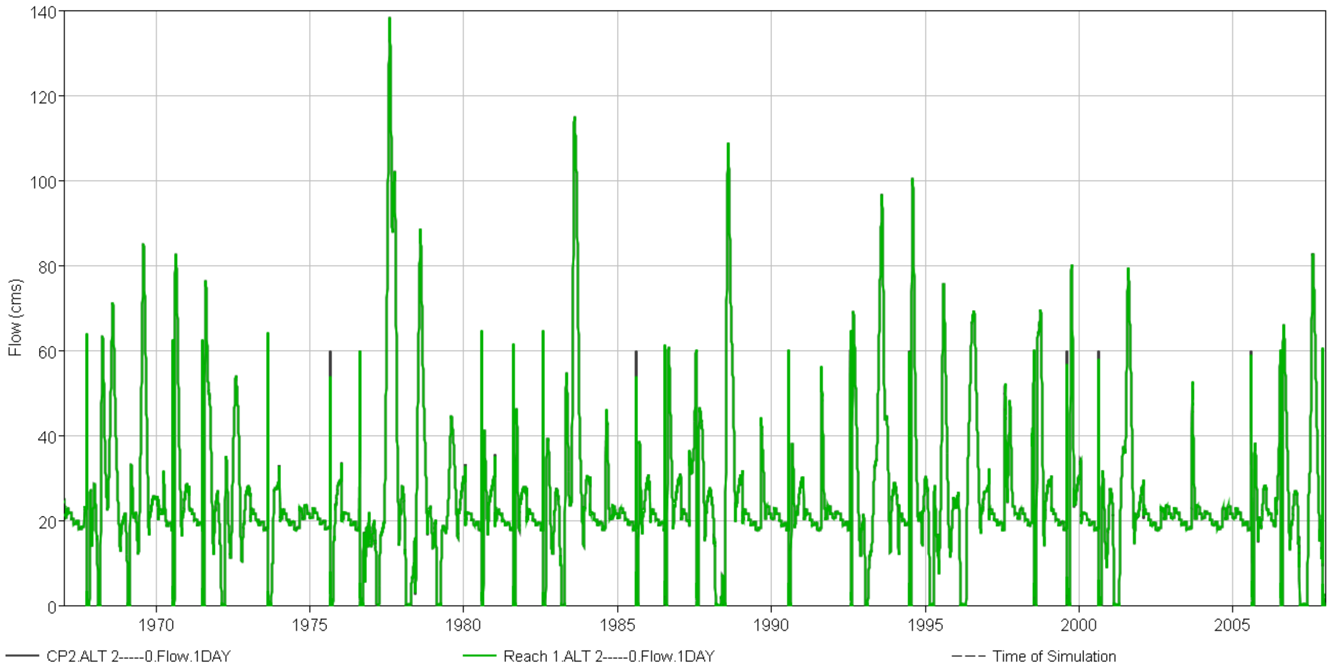


Figure 6.41.: Simulated flow at downstream of Gode Irrigation Project by using Downstream Control Function Rule.

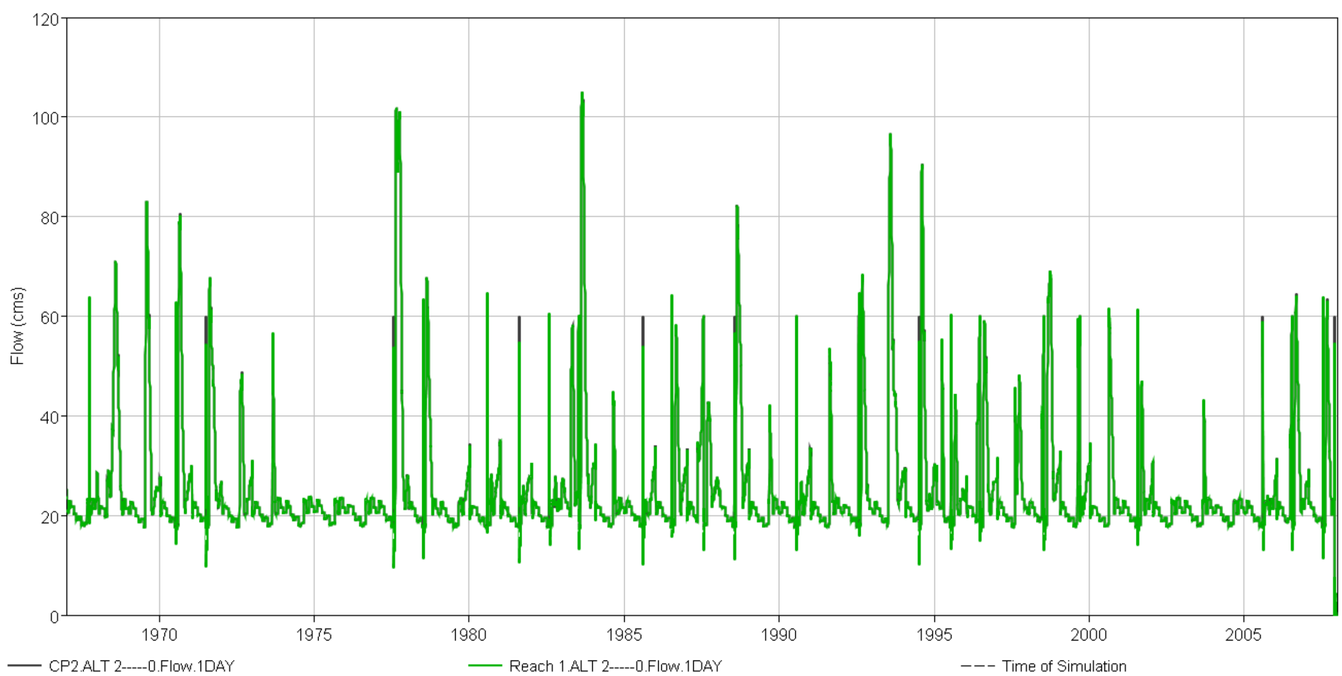


Figure 6.42: Simulated flow at downstream of Melka Wakena Hydropower Project by using Hydropower schedule operation Rule power plant.

As we see from Figure 6.41 and Figure 6.42, the two operational rules provide different stream flows at the downstream of the dam. This clearly indicates that the hydropower schedule operation rule releases the water at good distribution throughout the simulation period than the others at the downstream of the dam. For example, Downstream Control Function rule releases extremely high stream flows than the unregulated flow in August 2, 1983 (i.e., 137.56m3/s). On the other side, the system doesn't release stream flows during the months of March and February in the simulation periods.

In the evaluation of high stream flow event (Figure 6.41 and Figure 4.42) which means in August 1983 during the operation of reservoirs using the two operational rules, the hydropower schedule operation rule decreases the maximum flood. Hydropower operation rule cutbacks the maximum flood from 137.56m3/s to the 104 m3/s during the operation of the reservoirs. Whereas during the low flood event (Figure 6.41 and Figure 4.42) that means dry season, the Downstream Control Function rule the system doesn't release stream flows during the months of March and February in all the years of the simulation periods. hydropower schedule operation rule increases the daily stream flow in the river above the required release of environmental flow which is in this case above 17m3/s. This clearly indicates that hydropower operational rules satisfied the minimum release requirement of the environmental release flow.

6.3.2 Evaluation Flooding and Water Availability at Gode Irrigation Project

Flood control and water availability at Gode Irrigation Project also the main goal of reservoir operation on Melka Wakena Hydropower plant. At Gode Irrigation Project, the highest and lowest floods occur during the month of April and August and between the months of December and February (Figure 6.51 and Figure 6.52), respectively. For the simulation of the stream flows, the maximum flood will be occurred during the month of August, and it is obvious that the water level rises in the reservoir.

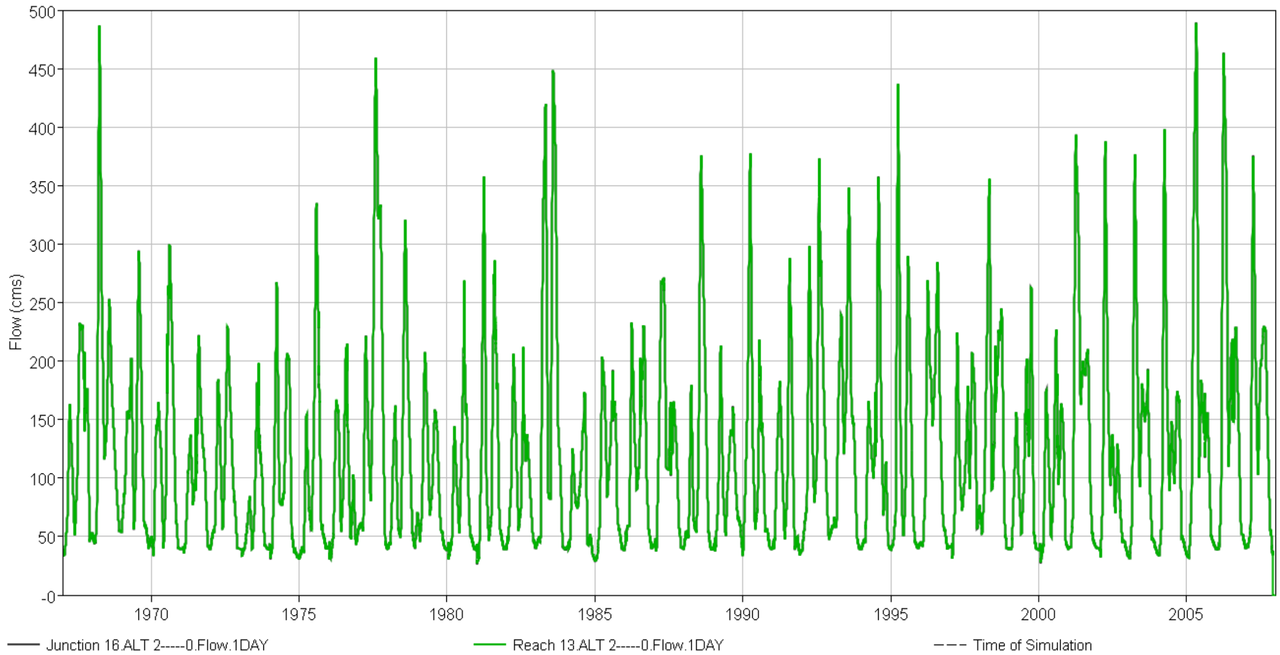


Figure 6.51: Simulated flow at Gode Irrigation Project by using Downstream Control Function Rule.

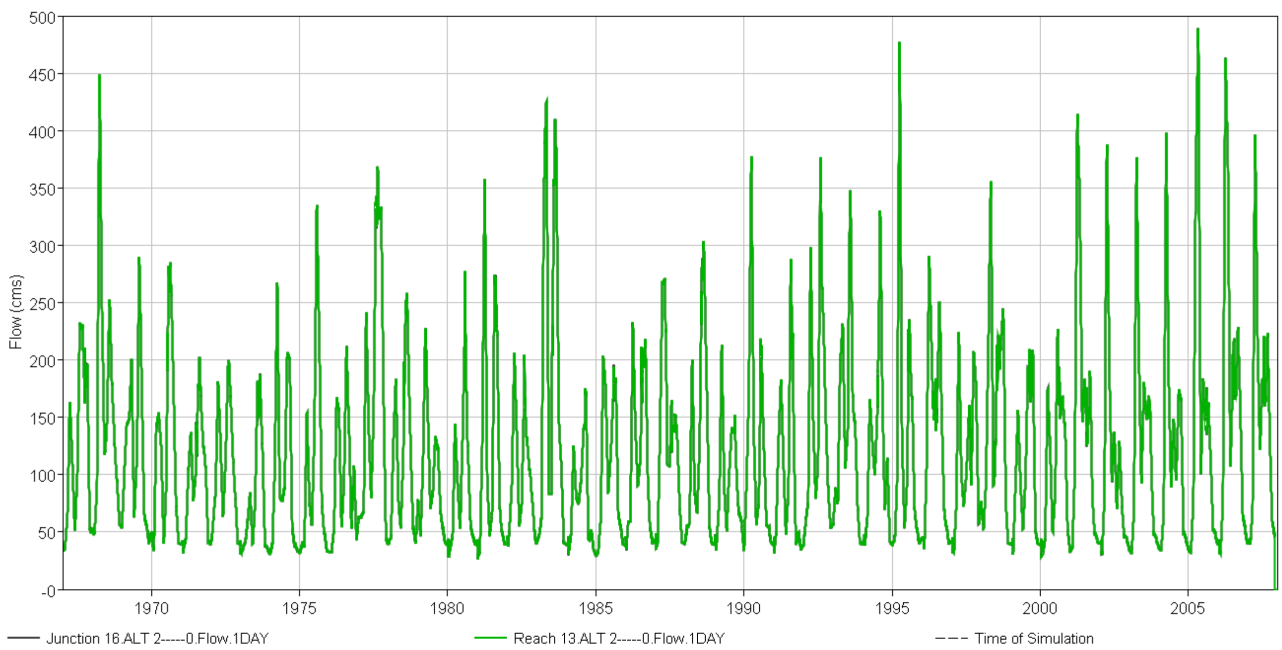


Figure 6.52: Simulated flow at downstream of Gode Irrigation Project by using Hydropower schedule operation Rule power plant.

As we see from (Figure 6.51 and Figure 6.52), the two operational rules provide different stream flows at Gode Irrigation project. This clearly indicates that the hydropower schedule operation rule releases the water at good distribution throughout the simulation period than the other at the downstream of the dam. For example, Downstream Control Function rule releases extremely high stream flows than the unregulated flow in April 1, 1968 and April 29, 2001 (i.e., 486m3/s) and in august 1977 (i.e., 457m3/s). On the other side, the stream flows is low during the months of December and January in all the years of the simulation periods.

In the evaluation of high stream flow event (Figure 6.51 and Figure 6.52), which means in April, 2001, April, 1968 and August 1977 during the operation of reservoirs using the two operational rules, the hydropower schedule operation rule decreases the maximum flood on 1968 April from 486.8m3/s to the 447 m3/august 1977 from 457 m3/s to 395.2 m3/s and 2001 April from 486.58m3/s to 480 m3/s during the operation of the reservoirs. Whereas during the low flood event (Figure 6.51 and Figure 6.52), that means dry season, the Downstream Control Function rule the system release low flow during the months of January and December in all the years of the simulation periods. In Hydropower reservoir operational rules increase the daily stream flow in December 1968 from 43.2 to 48.56, December 1974 from 33.2 to 36.69 and December 1992 from 47.23 to 52.37. This clearly indicates that hydropower schedule operation rule better than downstream control function to satisfy the minimum water requirement of the Gode Irrigation Project.

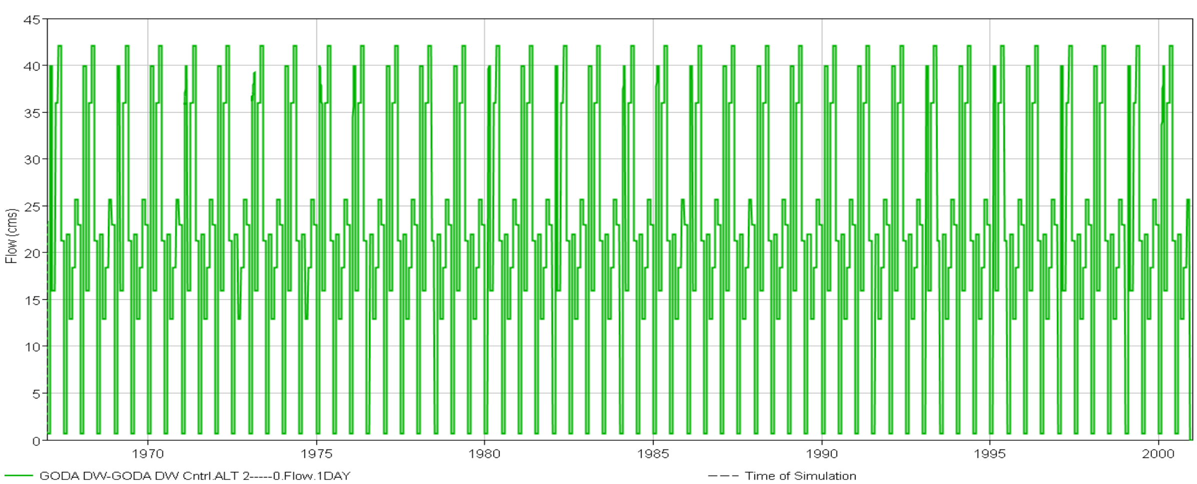


Figure 6.53: Diverted water at Gode Irrigation Project by using Hydropower schedule operation Rule power plant.

6.4 Future development scenario (Scenario-2)

This considered the time from the future project will implemented and included projects in scenario one and design project Erer and Gololcha Irrigation Project. This scenario has been set up to evaluate the effect of water management in the near future of the basin based on likely future developments currently anticipated being implemented. this scenario was applied to develop reservoir guide curves for Erer and Gololcha irrigation project. In addition, the main target of this scenario development is to compare the different condition of the basin, considering the hydrologic condition and future Irrigation project development.

The reservoir operations are defined by the same rules as scenario one (i.e., Downstream Control Function Rule and hydropower schedule operation rule). In order to analyze the effects due to Erer and Gololcha Irrigation Project and its reservoir, the model should be simulated with the same alternatives defined for the operation of reservoirs. All the physical and operational data inserted in the HEC-ResSim model were in the same procedure with scenario one.

6.4.1 Power and Energy Computation for Melka Wakena Hydropower Plant

The power required, power computed and power capabilities of the plant during the simulation period are shown in figures (6.61-6.62) are similar to scenario one. The power required for Melka Wakena hydropower plant was derived from the energy requirement collected from the engineering design documentation and entered the physical data of the reservoir network

Power capability or capacity of the plant means the maximum electric output a generator can produce under specific conditions. Also for this scenario, installed capacity is 153 MW and represents the nameplate capacity for the power plant. Nameplate capacity is determined by the generator's manufacturer and indicates the maximum output a generator can produce without exceeding design thermal limits. Generators do not operate at their full capacity all the time and they may vary their output according to conditions at the power plant. The daily energy requirement of the designed system is obtained from the monthly values, internally converted by the model with the assumption that the energy produced equally per weeks. Based on the input data supplied to the model, the simulation results of the two operational rules for Melka Wakena hydropower Plant were presented using the power curves in figures 6.61-figure6.62 below.

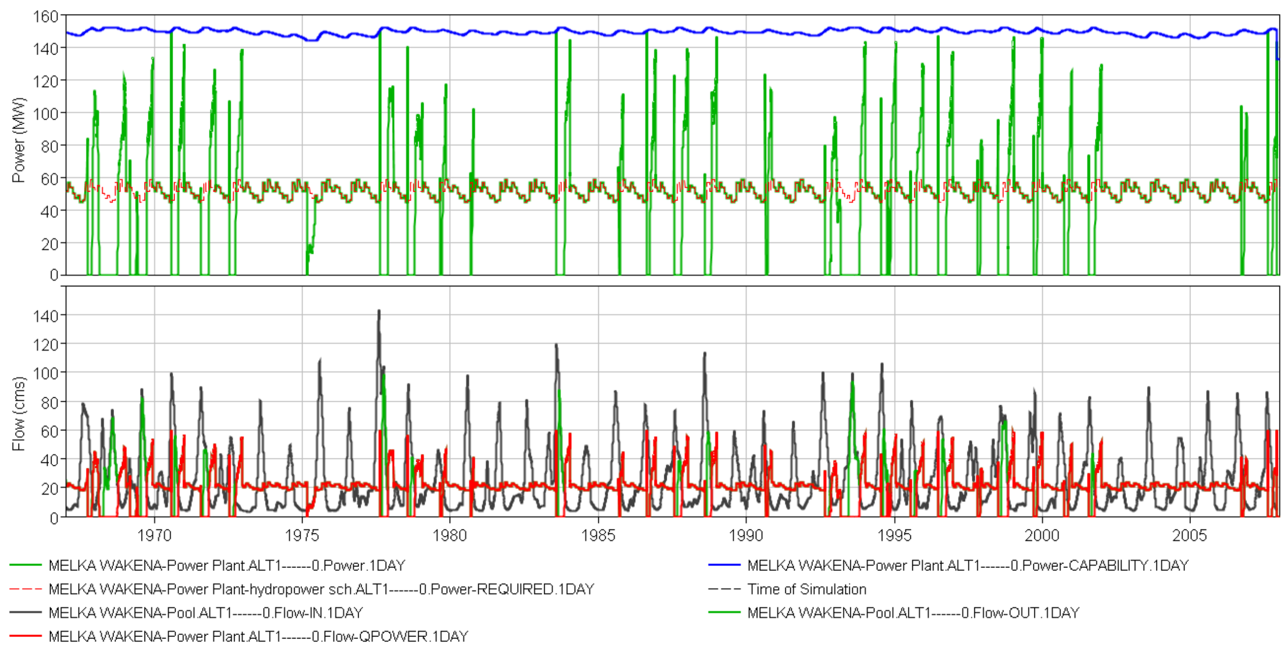


Figure 6.61: Downstream Control Function Rule power plant (upper plot): power required (red), computed power (dark green), power capability (blue), and Flows: inflow (black), turbine flow (red) and outflow (Dark green) hydrographs.

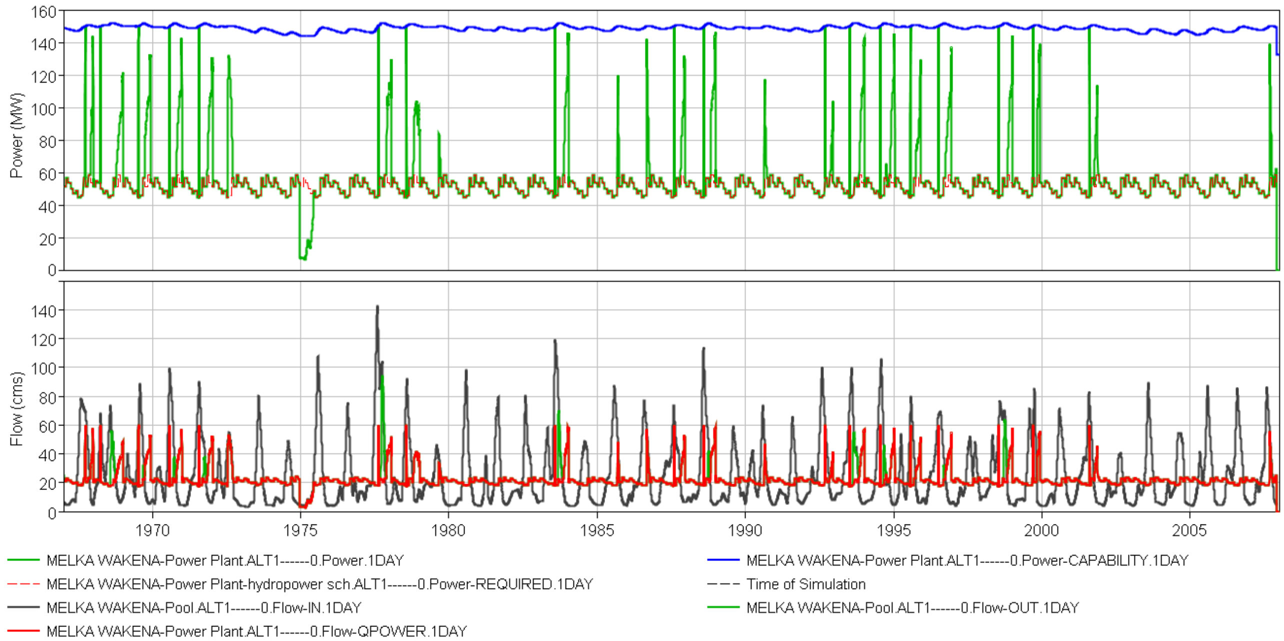


Figure 6.62: Hydropower schedule operation Rule power plant (upper plot): power required (red), computed power (dark green), power capability (blue), and Flows: inflow (black), turbine flow (red) and outflow (Dark green) hydrographs.

The evaluation of the power production of Melka Wakena Hydropower Plant for the simulations of reservoirs in this scenario using the two reservoir operation rules are based on the computed power curve are the same as scenario one. As one can observe from Figure 6.61, the computed power follows an irregular trend pattern. Power production is higher, lower and sometimes zeroes in the simulation period. This suggests that the system doesn't release water through the turbine when the pool level is below the conservation level. Since the system gives more priority for system storage balance, optimizing the release through the turbine is not sufficient to produce the required energy. Hence, this leads to minimal daily power production even though there is water in the conservation zone. For figures 6.62, the computed power curves are higher for almost all simulation periods. This indicates that the hydropower rules strive to release water through the turbine with the hydropower schedule operation rule for better performance.

From the above information, the downstream control Function Rule has intermittent power productions which will lead to interruption of electricity in the simulation periods. Whereas for the hydropower rules, the uniformity of daily energy productions with respect to the simulation period is nearly regular and good distribution. For most of the simulation period, the computed power is equal or above the monthly power required which are calculated by the HEC-ResSim model from the monthly energy requirement supplied from the design engineering documentation of each project.

6.4.2 Evaluation Water Availability at downstream of Melka Wakena

Flood control also the main goal for reservoir operation on Melka Wakena Hydropower plant in this scenario. For downstream of Melka Wakena, the highest and lowest flow occur during the month of August and September and between the months of April and May (Figure 6.4), respectively are similar to scenario one result. For the simulation of the stream flows, the maximum flow will be occurred in this scenario also the same as scenario one during the month of August 1983, and it is obvious that the water level rises in the reservoir as discussed in scenario one.

However, in the low flood event that means when the water level is below the minimum design guide curve, then the reservoirs stop release water rather it attempts to increase the water pool utilizing the operating rule. In this case, the mechanism is achieved by releasing the critical water demands for instance the first release priority is given to environmental flow and then subsequently to the turbine.

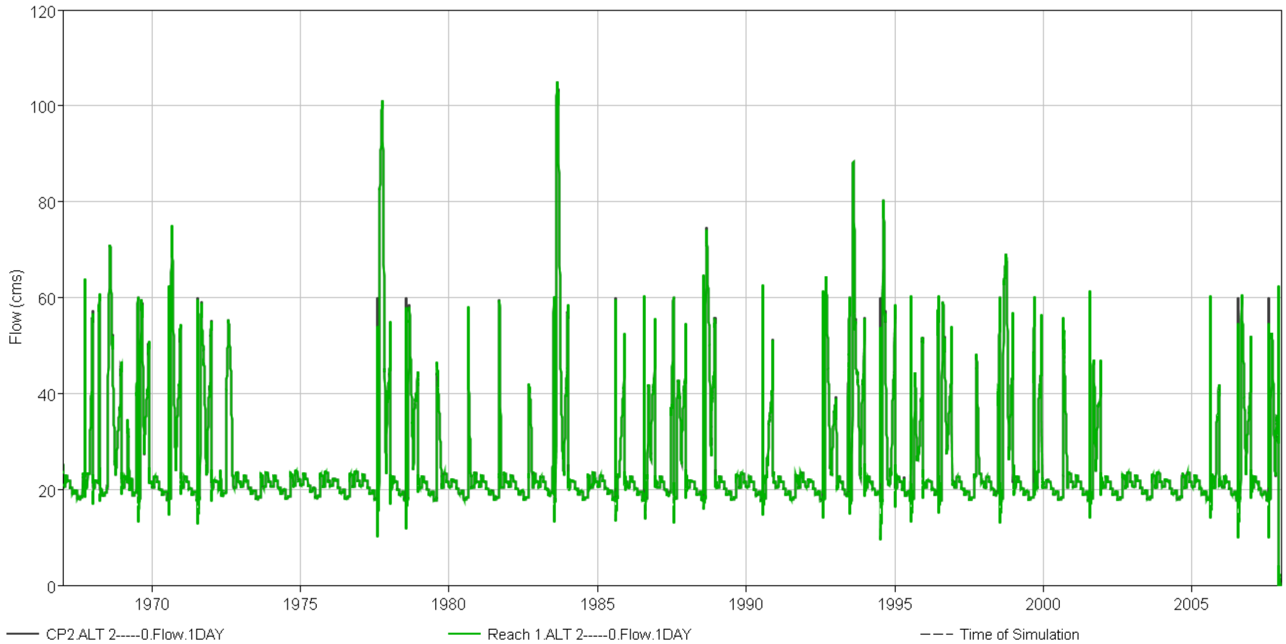


Figure 6.71: Simulated flow at downstream of Melka Wakena Hydropower Project by using Hydropower schedule operation Rule power plant.

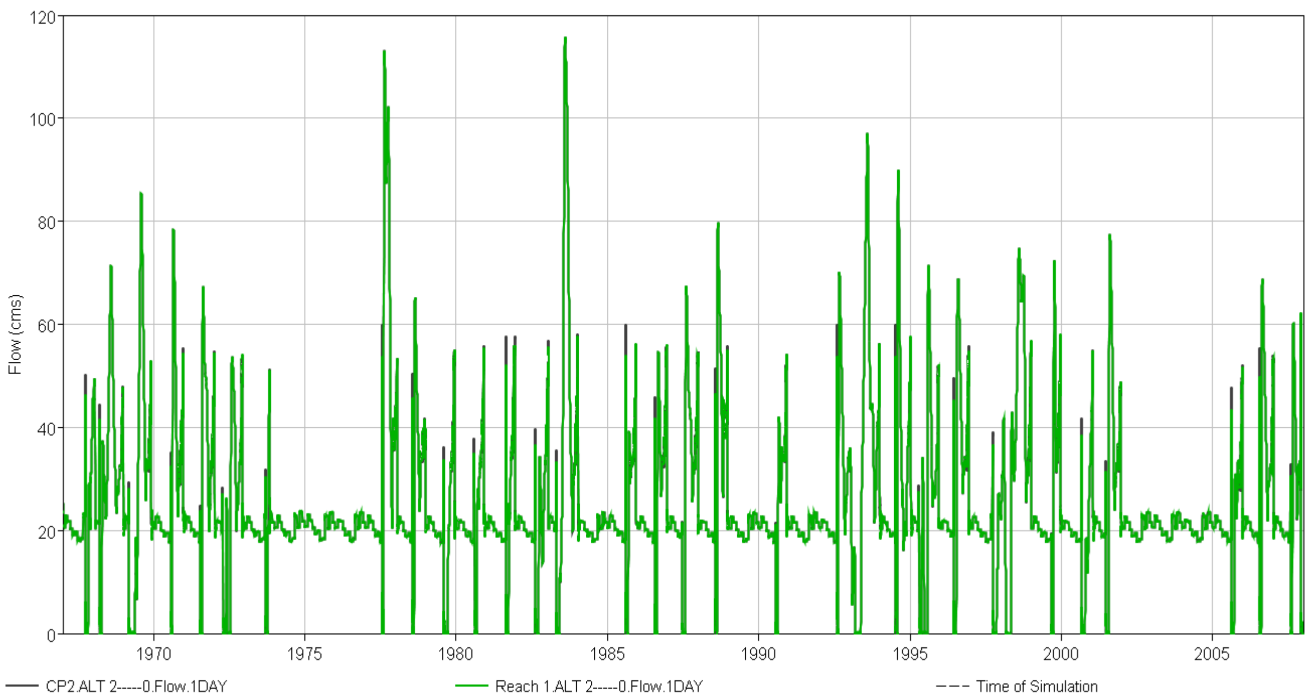


Figure 6.72: Simulated flow at downstream of Gode Irrigation Project by using Downstream Control Function Rule.

As we see from figure 6.71 and figure 6.72, the two operational rules provide different stream flows at the downstream of the dam. This clearly indicates that the hydropower schedule operation rule releases the water at good distribution throughout the simulation period than the others at the downstream of the dam. For example, Downstream Control Function rule releases extremely high stream flows than the unregulated flow in August 5, 1983 (i.e., 114m3/s). On the other side, the system doesn't release stream flows during the months of July and August in all the years of the simulation periods. In case of hydropower guide curve rule is better than Downstream Control Function rule but still has some high stream flows during the month of December.

In the evaluation of high stream flow event (Figure 6.7) which means in August 1983 during the operation of reservoirs using the two operational rules, the hydropower operational rules decrease the maximum flood from 115m3/s to the 104 m3/s and during the operation of the reservoirs. Whereas during the low flood event (Figure 6.7) that means dry season, the Downstream Control Function rule the system doesn't release stream flows during the months of July and August in all the years of the simulation periods. Hydropower reservoir operational rules increase the daily stream flow in the river above the required release of environmental flow which is in this case above 17m3/s. This clearly indicates that hydropower reservoir operational rules satisfied the minimum release requirement of the environmental release flow.

6.4.3 Evaluation Flooding and Water Availability at Gode Irrigation Project

Flood control and water availability at Gode Irrigation Project also the main goal of reservoir operation on Melka Wakena Hydropower plant and Gololcha and Erer irrigation project in this scenario. At Gode Irrigation Project, the highest and lowest floods occur during the month of April and August and between the months of December and February (Figure 6.8), respectively but. For the simulation of the stream flows, the maximum flood will be occurred during the month of August, and it is obvious that the water level rises in the reservoir.

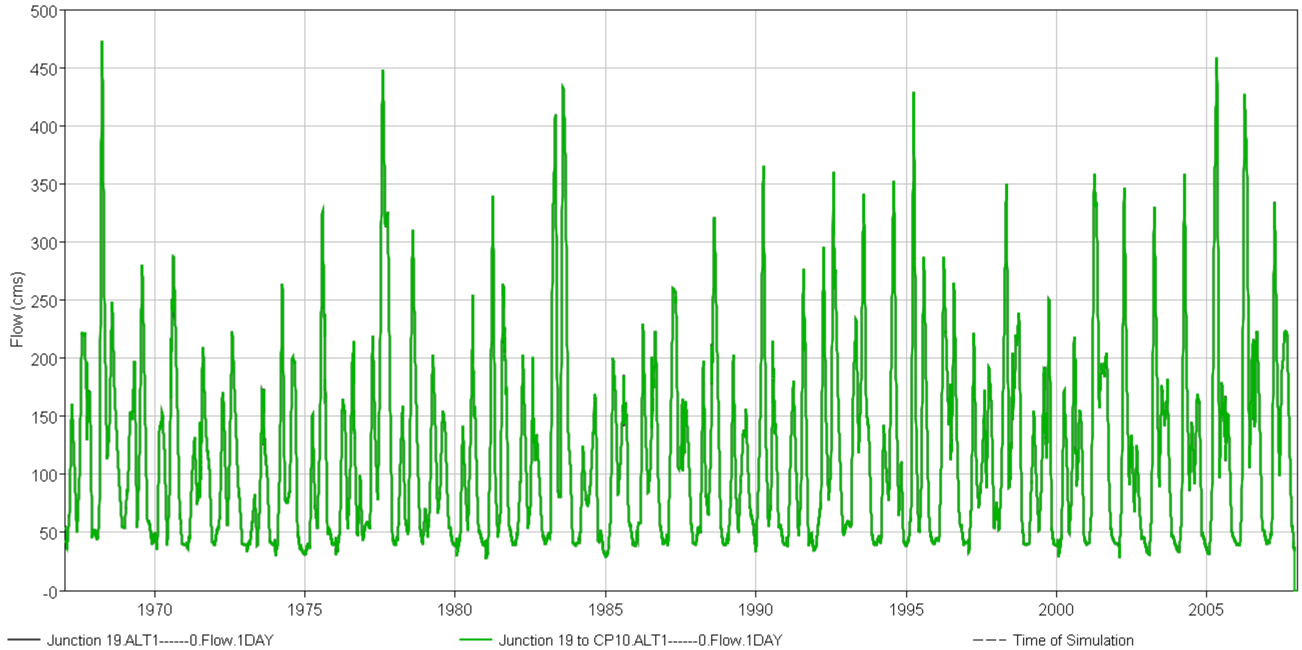


Figure 6.81: Simulated flow at Gode Irrigation Project by using Downstream Control Function Rule.

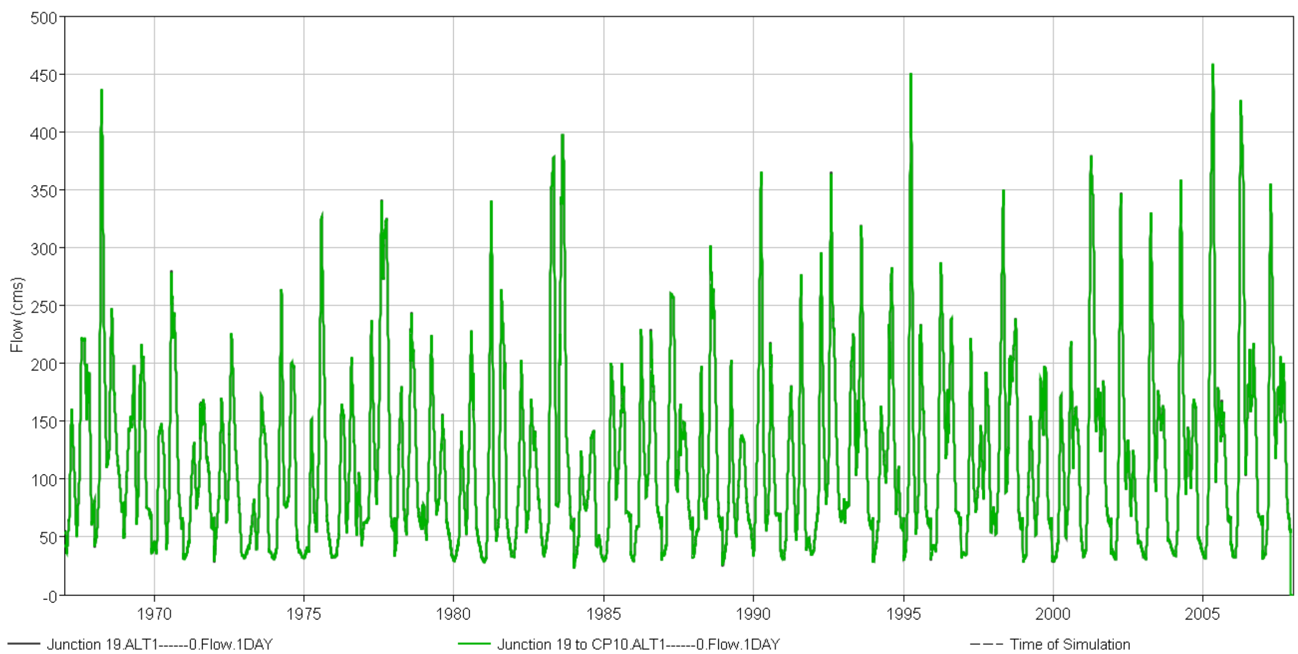


Figure 6.82: Simulated flow at Gode Irrigation Project by using Hydropower schedule operation Rule.

As we see from figure 6.81, the two operational rules provide different stream flows at Gode Irrigation project. This clearly indicates that the hydropower schedule operation rule releases the water at good distribution throughout the simulation period than the others at the downstream of the dam. For example, Downstream Control Function rule releases extremely high stream flows than the unregulated flow in April 29, 2001 (i.e., 486m3/s). On the other side, the stream flows is low during the months of December and January in all the years of the simulation periods. In case of hydropower guide curve rule is better than Downstream Control Function rule but still has some high stream flows during the month of August and April.

In the evaluation of high stream flow event in this scenario (Figure 6.8) which means in April, 2001and Mach, 1968 during the operation of reservoirs using the two operational rules, the hydropower operational rules decrease the maximum flood on 1968 March from 473.67m3/s to the 428.26 m3/s and 1977 August from 445.58m3/s to the 356 m3/s during the operation of the reservoirs. Whereas during the low flood event (Figure 6.8) that means dry season, the Downstream Control Function rule the system doesn’t release stream flows during the months of July and August in all the years of the simulation periods. Hydropower reservoir operational rules increase the daily stream flow in the river above the required release of environmental flow which is in this case above 17m3/s. This clearly indicates that hydropower reservoir operational rules satisfied the minimum release requirement of the environmental release flow.

6.4.5 Effect of Erer and Gololcha Irrigation on Gode Irrigation project and downstream users

As discuss previously Wabi Shebelle River flow from Kaka Mountain to Somalia region in Ethiopia, the Erer-Gololcha river system contributes 12% of it, which is mean inflow of 12.6m3/s or 389.445MCM per annum. Therefore, the Erer-Gololcha Irrigation project will be smoothly influence monthly flow contributions from this catchment on Wabi Shebelle River at Gode. This due to diverted water for irrigation and also be a slight reduction evaporation loss from the Erer-Gololcha artificial lake. These effects are illustrated, for the average year, on Figure 6.3. The modified flows at of Gode irrigation project will have two components; discharge from the power station tailrace and discharge from the dam spillway.

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 effect of Erer-Gololcha Irrigation project surface water resources of the Wabe Shebelle River for different future levels of irrigation development and impacts on the total volume of water leaving basin.

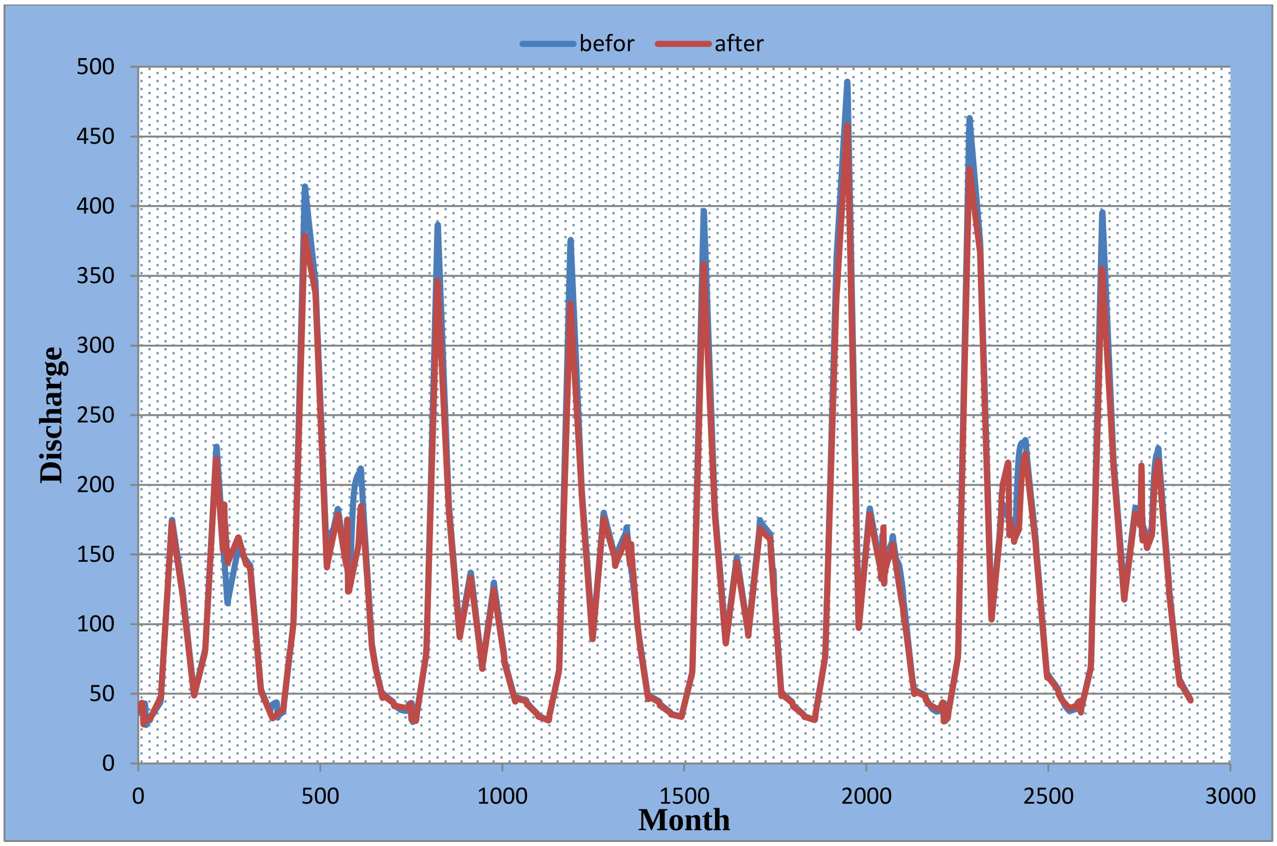


Figure 6.83: Simulated flow at Gode Irrigation Project by using Hydropower schedule operation Rule before and after implementation of Erer-Gololcha irrigation project.

As describe in the figure the development of Erer and Gololcha irrigation project will affect water availability on Gode irrigation project, also it has positive effect on summer season by reduced flooding in Gode irrigation project.

The development of Erer-Gololcha irrigation project will reduced the flood occurred in Gode irrigation project in summer season and water availability in Gode, the effect of both project discussed in table 7.1 and 7.2.

Table 6.1: effect of Erer-Gololcha Irrigation Project on wabe Shebelle River on high flow conditions.

Date	After	Before	flood reduction (%)
July 1, 2001	207.5	221.8	6.45
April 1, 2001	372.56	411	9.35
April 1, 2003	324.07	374.45	13.45
April 1, 2004	352.87	395.65	10.81
April 1, 2005	449.33	486.58	7.66
April 1, 2006	425.84	459.3	7.28
April 1, 2007	348.98	394.03	11.43

Table 6.2: effect of Erer-Gololcha Irrigation Project on wabe Shebelle River on low flow conditions.

Date	after	before	reduction of water availability (%)
December 1, 2000	36.24	38.22	5.18
December 1, 2001	41.88	43.62	3.99
December 1, 2002	44.33	45.12	1.75
December 1, 2003	42.49	44.28	4.04
December 1, 2004	42.88	43.65	1.76
December 1, 2005	44.05	46.65	5.57
December 1, 2006	44.47	46.19	3.72

7. CONCLUSION AND RECOMMENDATION

7.1 Conclusion

The principal aim of the study is to increase the power and energy generation of Melka Wakena hydropower projects by considering availability of water throughout the year and flood controlling in summer season by using Hec-ResSim3.1 model, considering annual and seasonal hydrological variations contained in the inflow series, reservoir characteristics and operation rules, evaporation losses and downstream water requirements.

HEC-ResSim was applied to simulate dams and reservoirs operation to optimize water for hydropower energy production, flood management as well as environmental flows. This can be achieved by using rapid simulation of reservoir operations and stream flow routing to reproduce the decision making process that human reservoir operators must use to set releases through a comprehensive reform of reservoir operating policy. To control the model two scenarios were simulated: scenario one (existing project) and scenario two (existing and future project) based on the simulation period to incorporate the parameters that may influence flow requirements at a reservoir include time of year, hydrology conditions, and simultaneous operations by other reservoirs in a system.

Two alternatives were established for two scenarios to model dams and reservoirs operation so that the best reservoir operational rule that optimizes the water release allocation was selected for modeling. The criterion for selection of the best reservoir operation rule is based on the simulation results of average energy generation per daily time step considering its effect on the availability of water at downstream flow. According to the simulation results obtained from the two scenarios, hydropower schedule operation rule shows maximum average energy generation, maximum availability of water distributed throughout the year, and better control of flood at the downstream of the river. Hence, hydropower schedule operation rule was selected to model dams and reservoirs operation in Wabi Shebelle River Basin.

Table 7-1 Main Outputs of the model and corresponding value from existing system.

Description	From existing system	Bosona	Hec - ResSim	Remark
Average annual energy production in GWh	450.71	476.68	497.933	Improved by 9.76%
As percentage of Annual average design Energy production (543GWh), %	83.01	87.79	91.70	

As per Table 7.1 above The results of simulation indicated that the average yearly energy production using hydropower schedule operation Rule will have improved by 9.76%. Downstream control function rule has an advantage in system storage balance distribution but ineffective in releasing water to the hydropower plants. Whereas the hydropower schedule rule has good in releasing water to the hydropower plants, and on averagely good in storage distribution

The model was attempted to represent the physical behavior of reservoirs in the basin with its high speed hydraulic computations for flows through control structures, and hydrologic routing to represent the lag and attenuation of flows through the main and its tributaries of the river. Hence, the model results suggest that the new reservoir operation rule selected for modeling of the dams and reservoirs operation enhances average energy production of the designed reservoir operation systems of the basin.

Hydrology flood simulation results reveal that the latest operation system will increase water availability in the dry season and decrease flooding in the wet season. The study has determined the new reservoir operation system will evenly allocate and release the available water in real time during day-to-day and an emergency operation throughout the year.

The likely future development scenarios in Wabi Shebelle river basin are the Erer-Gololcha Irrigation Project projects on Erer and Dhare river Respectively which are located upstream of Gode irrigation project. However, their construction and operation would alter the natural flow regime downstream of the dam. So the water availability at Gode irrigation project will be influenced by the two near future development projects.

Table 7.2: effect of Erer-Gololcha Irrigation Project on wabe Shebelle River on high flow conditions.

Description	before	after	% of water availability reduction
low flow condition	43.93	42.144	4.01
high flow condition	391.83	354.45	9.49

Finally, the model has provided overall operation strategies for reservoir releases according to the reservoir level, hydrological conditions and the time of year and develops a unique reservoir and power guide curve for Melka Wakena hydropower plant, Erer and Gololcha irrigation projects.

7.2 Recommendations

The study has recommended the following points to be included in the future reservoir operation and studies for better water based development plan in the basin.

- ✓ The work conducted in this thesis was by employing HEC-ResSim 3.1 which still 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.

- ✓ The HEC-ResSim optimal result is based two operational rules that are not fully guaranteed for the optimal value. Hence it is recommendable to recheck using optimization models.

- ✓ 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 observed historic hydrological data.

- ✓ The results of the study are specifically intended to inform policy makers, water resource managers, and other interested stakeholders to make effective and economically viable plans for sustainable future development in the Wabi Shebelle River Basin.

- ✓ Implementation of hydrological gauges that can measure the inflows to the reservoirs is recommended. In practice, there were no gauged data most of river in lower reach, which supplies data that can be used directly for estimation of hydrology of the proposed hydropower projects and irrigation project. Thus it is recommended to establish more gauging station on the lower reaches of Wabi Shebelle River basin so that better validation and calibration of the HEC-ResSim or any applicable model can be made.

REFERENCES

AWULACHEW SB, YILMA AD, LOULSEGED M, LOISKANDI W, AYANA M, ALAMIREW T. 2007. Water Resources and Irrigation Development in Ethiopia. Working Paper 123, International Water Management Institute, Colombo, Sri Lanka.

ADANE, A. 2009**.** Hydrological drought analysis -occurrence, severity, ,risks: the case of wabe shebelle river basin , Ethiopia. MSc Thesis. University of Siegn.

BERGKAMP, G. 2000. Dam, Ecosystem Functions and Environmental Restoration. Thematic Review II.1, prepared as an input to the World Commission on Dam, Cape Town, www.dams.org

BCEOM_ORSTOM_EDF. 1973. Hydrological Survey of the Wabi Shebelle Basin.

BCEOM_ORSTOM_EDF. 1973. Geological Survey of the Wabi Shebelle Basin.

CHEN, J., GUO, S., LI, Y., LIU, P. & LI, T. 2011. Joint operation of the multi-reservoir system of the Three Gorges and the Qingjiang cascade reservoirs. Energies, 4**,** 1036-1050.

DANIEL ASEFA. 2011. Water use and operation analysis of water resource Systems in omo gibe river basin .MSc. Thesis Addis Ababa University, Ethiopia

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. 2010. 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.

KINDIE ENGDAW. 2016**.** Assessment of surface water potential and demands of Wabi shebelle basin in Ethiopia. MSc Thesis Addis Ababa University, Ethiopia

KLIPSCH, J. & HURST, M. 2007. HEC-ResSim reservoir system simulation user's manual version 3.0. USACE, Davis, CA**,** 512.

LIVESTOCK, CROP AND RURAL DEVELOPMENT BUREAU, 2013. The Lower Shebelle Irrigation Scheme in Ethiopia: An assessment of productive options. Ethiopian Somali Regional State , Jigjiga.

MADANI, H. 2013. "Application of reservoir simulation and flow routing models to the operation of multi-reservoir system in terms of flood controlling and hydropower's regulation"

MAASS, A. 1962. Design of water resource system; new technique for relating economic objective. Engineering anal

MCCARTNEY, M. P. 2007. Decision support systems for large dam planning and operation in Africa. International Water Management Institute Colombo,, Sri Lanka.

MCCARTNEY, M. P. 2007. Decision Support Systems for Large Dam Planning & Operation in Africa. Colombo, Sri Lanka: International Water Management Institute. (IWMI Working Paper 119).

MCCULLY, P. 2001. Silenced Rivers: The Ecology and Politics of Large Dams. Enlarged and Updated Edition. London, New Jersey.

MULU SEWINET, K. 2009. Optimal Reservoir operational planning of proposed Desesa Hydropower Development. Arbaminch University.

MOWR. 2003**.** Wabi Shebelle river basin integrated master plan study project vol I-XII. Technical report, Ministry of Water Resources

OLIVEIRA, R. & LOUCKS, D. P. 1997. Operating rules for multi reservoir systems. Water resources research, 33**,** 839-852.

SIMONOVIC, S. 1996. Decision Support Systems for Sustainable Management of Water Resources :General Principles. Water International, 21.

SUBRAMANYA, K. 1994. Engineering hydrology, Tata McGraw-Hill Education.

WAKENA, T. 2006. Operational Analysis of the Cascaded Wadecha-Belbela Reservoir System in Ada'a-Liben woreda (Oromia Regional State). Master Thesis, Arbaminch university, Ethiopia.

WILLIS, C.M. & GRIGGS, G.B. 2003. Reductions in Fluvial Sediment Discharge by Coastal Dams in California and Implications for Beach Sustainability. Journal of Geology, 111.

YEH, W. W. G. 1985. Reservoir management and operations models: A state-of-the-art review. Water resources research, 21**,** 1797-1818.

-

APPENDIX

APPENDIX-A Measured and Generated Stream Flow Data

Table A-1 Mean monthly flow at Wabi Shebelle river @Melka Wakena hydrometric station [m^3/s]

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1967	6.2	4.6	4.4	6.4	8.8	6.4	35.0	78.7	72.8	68.4	43.0	8.8
1968	4.2	16.2	21.1	68.5	32.8	20.3	43.9	74.3	43.0	23.2	9.6	5.9
1969	9.5	17.7	40.5	19.3	22.3	9.4	43.2	89.2	50.2	14.0	6.6	5.0
1970	8.5	5.2	29.3	31.0	16.4	6.6	28.7	99.8	74.2	34.5	10.8	4.6
1971	4.6	4.1	4.6	12.9	22.7	25.9	57.5	90.2	52.3	47.3	12.4	7.3
1972	5.5	13.8	14.8	43.7	18.9	9.0	39.2	55.5	42.9	9.3	7.8	4.8
1973	3.9	3.6	3.3	3.3	6.4	6.1	31.4	80.9	50.9	16.0	4.5	4.4
1974	4.6	3.8	9.7	8.9	6.0	7.3	31.1	49.4	33.3	9.0	6.4	5.0
1975	4.0	4.3	3.7	8.8	6.5	13.9	46.0	108.0	76.4	24.9	6.8	3.4
1976	4.4	3.9	4.4	6.4	17.7	7.7	34.8	75.8	42.1	10.4	21.2	6.5
1977	14.3	13.5	7.9	18.3	17.3	20.4	74.2	143.7	84.2	104.5	29.5	5.5
1978	5.2	8.0	24.1	13.2	6.9	7.9	51.4	92.3	52.2	32.1	7.7	6.6
1979	15.3	8.3	17.0	20.0	18.8	16.6	26.3	46.3	36.5	21.8	7.9	4.7
1980	3.9	4.7	4.3	5.4	9.2	7.8	56.1	98.8	38.4	19.2	5.8	4.3
1981	4.0	3.9	10.6	39.1	9.5	4.9	14.2	62.8	79.6	22.7	6.6	4.5
1982	6.0	10.2	14.2	14.3	15.3	9.0	23.7	81.2	43.4	37.1	11.9	12.0
1983	5.7	7.4	7.2	37.8	58.6	21.9	24.8	119.8	97.1	41.1	20.0	6.7
1984	4.4	3.8	3.8	3.9	6.3	18.9	38.9	49.0	42.1	9.9	7.2	5.3
1985	4.4	4.2	4.2	12.2	23.0	23.8	55.8	87.5	60.6	21.4	8.2	4.7
1986	4.0	11.7	7.2	18.0	16.9	22.2	44.3	77.6	57.9	30.0	7.5	5.3
1987	4.6	6.7	21.7	24.6	35.6	30.9	38.1	73.7	45.9	40.4	11.5	6.3
1988	6.2	10.1	6.7	12.0	8.6	14.5	44.8	114.3	68.9	49.5	7.8	4.8
1989	4.5	7.2	7.4	12.9	8.2	6.4	21.6	59.6	43.6	30.5	10.7	13.2
1990	5.1	19.1	31.6	42.6	16.6	9.8	25.0	74.0	40.2	16.3	8.1	4.9
1991	4.4	9.6	15.2	12.1	11.9	5.4	22.1	66.0	42.8	8.2	6.7	5.2
1992	8.3	12.3	12.7	31.6	19.2	21.5	51.1	100.5	66.4	43.7	15.8	7.5
1993	7.7	12.8	12.3	13.1	32.9	34.7	68.3	100.1	42.2	44.9	11.5	5.6
1994	5.0	6.7	7.9	8.1	14.0	32.5	73.3	106.4	43.5	18.0	22.7	6.9

1995	4.2	5.6	11.3	54.2	17.0	8.1	27.0	80.4	47.1	16.2	6.0	5.7
1996	9.3	4.8	15.4	27.5	27.4	43.7	66.7	69.6	43.6	21.3	8.1	4.9
1997	6.9	3.6	6.2	16.6	10.8	16.7	42.0	52.2	23.9	48.5	23.6	7.9
1998	10.9	10.0	14.3	17.3	53.6	26.9	42.7	76.8	63.4	70.5	12.7	5.2
1999	5.2	3.6	8.9	8.0	9.0	7.0	29.9	72.1	44.1	86.2	7.1	4.5
2000	3.9	3.4	4.4	10.2	12.9	5.9	27.0	72.0	54.8	35.3	12.5	6.0
2001	4.1	5.7	12.5	23.3	25.9	38.1	35.4	83.4	54.7	18.7	6.5	5.5
2002	5.2	3.4	8.1	20.9	9.8	14.0	12.7	38.6	40.8	15.9	5.8	5.9
2003	4.7	3.5	5.6	18.8	11.0	14.7	30.8	90.0	54.2	25.1	6.2	6.3
2004	5.2	4.5	5.5	21.0	9.4	13.7	17.5	54.2	54.7	46.6	6.6	5.1
2005	4.5	3.7	7.6	17.5	41.7	17.9	33.9	87.8	51.9	28.2	7.1	4.9
2006	4.2	4.2	7.6	32.0	29.1	21.3	36.0	86.0	59.7	37.4	9.9	7.2
2007	4.5	5.3	6.0	22.4	13.3	26.7	32.9	87.0	58.9	29.5	7.6	4.6

Table A-2 Mean monthly flow at Wabi Shebelle river @Lega Hida hydrometric station [m^3/s]

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1967	11.1	6.7	9.2	23.3	21.4	16.7	77.5	152.7	151.3	126.2	96.0	18.4
1968	7.5	23.5	39.5	147.8	72.8	41.9	93.4	133.4	89.4	42.8	21.5	11.1
1969	16.9	25.7	75.5	49.1	50.3	22.1	92.2	156.1	104.3	25.8	14.8	8.8
1970	15.2	7.5	55.5	73.7	41.4	14.0	66.8	231.5	151.3	75.6	23.7	8.8
1971	8.3	7.2	10.2	34.8	48.5	52.8	109.8	163.7	97.2	85.3	37.0	13.8
1972	9.8	18.8	27.9	95.9	43.7	23.2	88.9	118.5	88.7	30.5	19.6	8.5
1973	8.0	6.9	6.1	7.0	15.9	13.0	62.8	135.1	99.7	46.0	9.4	7.8
1974	8.0	6.4	21.5	43.5	15.1	25.2	70.2	119.8	103.8	20.3	11.8	8.0
1975	6.3	6.8	5.5	25.5	15.5	27.2	109.5	225.7	158.8	45.9	15.1	6.7
1976	7.9	5.6	9.2	23.2	40.4	19.0	77.2	144.4	87.7	19.3	47.3	12.6
1977	25.5	19.6	15.4	47.2	39.5	42.1	147.7	261.9	175.0	192.6	65.9	12.7
1978	9.2	11.7	44.0	37.0	17.2	19.4	106.8	174.6	108.6	59.3	17.1	11.2
1979	27.3	12.0	32.0	50.6	42.8	35.2	62.0	87.9	75.9	40.2	17.5	8.7
1980	7.0	6.8	8.3	21.2	22.2	19.1	115.3	178.2	79.9	35.4	12.9	7.8
1981	7.2	5.6	22.8	88.7	22.9	14.0	40.3	150.9	165.5	41.8	14.7	8.3
1982	10.7	14.8	26.6	39.2	35.3	21.3	57.3	138.1	90.3	68.5	161.0	19.2

1983	10.1	10.7	14.4	86.3	128.1	44.8	59.3	235.6	202.9	75.8	44.6	12.8
1984	7.9	5.5	8.5	18.2	16.1	39.3	84.5	95.0	87.5	18.3	16.0	9.6
1985	7.8	6.1	8.3	35.0	51.8	48.3	114.8	147.6	126.0	39.5	18.3	8.7
1986	7.1	17.1	13.6	46.7	38.8	45.4	94.1	140.6	120.4	55.4	16.8	9.4
1987	8.2	9.7	41.7	59.7	78.8	61.2	83.0	124.3	95.5	74.6	25.7	11.2
1988	11.1	14.7	12.6	34.5	20.9	31.3	95.1	206.3	143.2	91.3	17.4	8.8
1989	8.1	10.4	15.2	36.4	20.2	16.6	53.7	106.2	90.6	56.3	23.9	21.4
1990	9.2	27.8	59.3	95.9	38.0	22.9	59.6	143.3	83.5	30.0	18.0	8.9
1991	7.9	14.0	30.6	34.7	28.1	14.8	54.5	164.5	89.0	15.1	14.9	9.2
1992	14.7	17.9	23.3	73.8	43.6	44.0	106.4	210.0	138.1	80.7	35.3	13.9
1993	13.8	18.7	22.4	36.8	73.1	68.1	137.2	193.9	87.8	82.9	25.6	10.3
1994	8.9	9.7	15.1	26.7	32.5	64.2	146.1	190.4	90.4	33.2	50.6	13.5
1995	7.5	8.1	22.7	119.1	38.9	19.7	63.2	156.4	97.8	29.9	13.4	9.9
1996	16.6	7.0	29.7	65.6	61.2	84.5	134.1	138.6	90.6	39.3	18.0	8.9
1997	12.3	5.3	13.2	43.8	25.7	35.5	90.0	102.7	49.6	89.4	52.7	14.9
1998	19.4	14.5	26.9	45.2	117.5	54.0	91.4	144.5	131.8	130.0	28.3	9.9
1999	9.3	5.3	17.8	26.5	21.8	17.8	68.4	133.7	91.7	158.9	15.8	8.2
2000	7.0	5.0	8.5	30.9	30.1	15.9	63.2	141.7	93.8	80.1	44.9	15.2
2001	7.0	5.6	24.7	110.1	79.4	96.2	148.0	89.6	128.5	34.4	17.3	15.3
2002	8.8	3.4	16.7	104.9	39.1	53.3	109.1	42.1	95.8	29.3	15.4	15.5
2003	8.0	3.5	12.1	100.3	42.3	54.5	140.2	96.6	127.3	46.1	16.5	15.9
2004	8.9	4.4	11.9	105.1	38.2	52.8	117.3	58.7	128.5	85.7	17.7	15.1
2005	7.7	3.6	15.7	97.5	118.6	60.2	145.5	94.3	122.0	51.8	19.1	18.0
2006	7.2	4.1	15.8	129.1	87.2	66.2	149.2	92.3	140.3	68.8	26.4	17.7
2007	7.7	5.2	13.0	108.2	47.8	75.9	143.7	93.4	138.3	54.3	20.3	15.0

Table A-3 Mean monthly flow at Wabi Shebelle river @Hamelo Hedad hydrometric station [m^3/s]

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1967	27.6	19.3	52.6	110.6	76.8	39.0	126.3	257.6	249.8	173.4	173.1	35.5
1968	18.7	47.1	86.2	371.0	193.0	119.0	136.0	242.0	164.0	100.0	66.1	37.5
1969	29.1	102.0	187.0	108.0	160.0	46.3	119.0	240.0	160.0	47.4	32.6	14.4

1970	25.9	18.6	177.6	120.0	81.3	22.6	78.7	317.0	228.0	132.0	48.4	17.3
1971	12.9	10.8	16.3	70.1	110.0	79.0	118.0	202.0	155.0	98.5	74.2	24.8
1972	25.9	53.8	41.8	145.9	93.7	55.0	154.8	201.1	150.7	81.5	52.4	14.0
1973	23.1	9.8	5.7	30.9	55.8	27.2	90.4	199.5	145.0	90.3	16.0	12.4
1974	19.2	24.0	111.4	191.4	52.7	67.8	114.4	232.8	206.8	34.0	17.7	11.2
1975	13.3	23.2	15.9	106.2	50.0	52.2	181.2	361.9	239.0	62.6	27.2	12.1
1976	19.6	16.2	42.2	113.7	120.4	44.2	121.8	242.6	140.2	30.2	85.2	22.7
1977	63.5	56.6	62.9	179.1	110.0	83.8	203.3	386.1	262.8	267.5	118.9	26.6
1978	22.9	33.7	151.6	130.7	52.3	43.8	157.6	275.4	169.1	84.7	30.9	17.1
1979	67.9	34.7	121.8	169.9	119.5	70.6	103.4	142.1	116.3	56.1	31.6	15.1
1980	17.3	19.7	35.1	95.9	64.7	43.0	158.9	254.7	124.3	48.8	23.3	12.9
1981	17.8	16.2	131.5	282.5	68.3	33.8	74.3	287.8	249.6	57.6	26.5	14.2
1982	26.6	42.7	98.9	149.2	104.4	46.6	94.6	190.4	136.9	95.7	47.9	26.7
1983	25.1	30.9	55.8	277.7	335.9	86.9	98.9	374.0	350.7	103.9	80.5	22.6
1984	19.6	16.0	36.1	80.4	53.6	77.1	124.4	154.7	158.9	25.5	28.9	16.0
1985	19.5	17.5	50.4	145.6	140.8	91.3	165.9	192.8	217.1	54.0	33.0	14.7
1986	17.6	49.3	51.5	172.5	109.9	88.3	135.1	203.7	178.8	75.3	30.3	15.1
1987	20.4	28.0	160.3	202.0	224.2	112.9	119.8	171.8	144.3	102.2	46.4	18.3
1988	27.7	42.4	50.9	143.8	58.9	64.1	142.3	297.2	223.9	124.6	31.4	14.8
1989	20.1	30.1	74.4	154.1	60.9	39.3	93.1	165.5	142.3	79.1	43.2	30.4
1990	22.8	80.3	215.1	299.6	103.3	49.1	97.1	228.2	129.2	42.0	32.5	14.8
1991	19.7	40.4	145.0	129.4	82.0	35.2	89.7	302.0	133.6	21.2	26.8	15.0
1992	36.6	51.6	80.0	231.5	118.5	85.0	154.3	350.7	212.4	110.5	63.7	23.4
1993	34.3	53.9	76.0	142.9	192.4	125.8	186.7	299.7	136.7	114.6	46.2	17.5
1994	22.1	28.1	55.6	114.0	96.1	118.2	210.9	271.5	144.3	46.3	91.2	24.4
1995	18.6	23.4	96.1	370.3	105.4	43.9	106.9	246.7	145.9	41.3	24.1	15.7
1996	41.2	20.3	125.4	222.3	170.4	153.6	187.4	236.6	139.5	53.2	32.5	15.0
1997	30.5	15.3	66.6	165.0	73.5	72.9	135.7	167.2	75.1	128.2	95.1	25.9
1998	48.3	42.0	98.3	158.5	307.7	101.4	137.7	216.9	200.2	177.0	51.0	17.5
1999	23.0	15.3	94.2	106.8	64.7	41.4	110.7	207.8	137.2	217.7	28.6	13.7
2000	17.3	14.3	31.6	123.2	91.0	37.4	101.7	228.8	120.7	133.8	106.1	33.9
2001	18.1	24.0	94.5	291.8	175.8	163.6	179.1	120.9	164.4	52.0	26.0	26.1

2002	22.9	14.5	67.2	279.3	90.4	90.7	132.4	57.2	123.4	45.1	23.2	26.3
2003	20.7	14.9	51.9	267.9	97.1	92.8	169.7	130.2	162.8	67.8	24.8	27.0
2004	23.2	18.8	51.2	279.5	88.5	89.8	142.2	79.4	164.3	121.2	26.5	25.6
2005	20.0	15.5	64.1	261.0	258.9	102.4	176.0	127.1	156.3	75.5	28.6	30.6
2006	18.8	17.5	64.2	338.5	192.3	112.6	180.5	124.6	179.1	98.4	39.6	30.0
2007	20.1	22.2	54.7	287.1	108.8	129.1	174.0	126.0	176.6	78.9	30.5	25.4

Table A-4 Mean monthly flow at Wabi Shebelle river @Imi hydrometric station [m^3/s]

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1967	26.5	18.9	54.5	125.8	83.8	34.4	124.0	256.0	255.4	200.9	172.9	33.1
1968	17.9	46.1	89.2	422.3	210.4	105.0	133.5	240.5	167.7	115.8	66.0	34.9
1969	27.9	99.9	180.0	106.0	147.0	36.2	108.0	222.0	152.0	50.2	31.6	15.6
1970	25.2	17.0	175.0	148.0	107.0	19.9	73.7	330.0	249.0	154.0	4.7	13.6
1971	12.2	11.3	18.9	84.1	114.0	77.8	130.0	205.0	159.0	123.0	79.3	23.1
1972	24.8	52.7	43.3	166.1	102.5	48.6	152.0	199.8	154.1	94.4	52.3	13.0
1973	22.2	9.6	5.9	35.2	60.9	24.0	88.8	198.2	148.3	104.6	16.0	11.6
1974	18.4	23.5	115.3	217.9	57.5	59.8	112.3	231.3	211.5	39.4	17.6	10.4
1975	12.8	22.7	16.5	120.9	54.5	46.1	177.9	359.6	244.4	72.5	27.2	11.3
1976	18.8	14.3	43.7	129.4	131.2	39.0	119.6	241.1	143.4	35.0	85.1	21.1
1977	60.9	55.4	65.1	203.8	120.0	73.9	199.6	383.7	268.7	309.8	118.8	24.8
1978	22.0	33.0	156.9	148.8	57.0	38.7	154.8	273.6	172.9	98.1	30.9	15.9
1979	65.0	34.0	126.0	193.2	130.3	62.3	101.5	141.2	119.0	65.0	31.6	14.1
1980	16.6	19.2	36.3	109.1	70.6	38.0	156.0	253.1	127.1	56.5	23.2	12.0
1981	17.1	15.8	136.1	321.5	74.5	29.8	73.0	286.0	255.2	66.7	26.5	13.2
1982	25.5	41.8	102.4	169.8	113.8	41.1	92.9	190.3	140.0	100.7	47.8	24.8
1983	24.1	30.2	57.8	316.1	366.3	76.7	97.1	371.6	358.6	120.4	80.4	21.0
1984	18.8	15.7	37.3	91.6	58.4	68.1	122.2	153.7	162.5	29.5	28.8	14.9
1985	18.7	17.1	52.1	165.7	153.5	80.5	163.0	191.6	222.0	62.5	33.0	13.7
1986	15.8	48.2	53.3	196.4	119.9	77.9	132.7	202.4	182.8	87.2	30.3	14.1
1987	19.5	27.4	165.9	229.9	244.5	99.6	117.6	170.7	147.5	118.4	46.4	1.7
1988	26.5	41.6	52.6	163.6	64.3	56.6	139.7	295.3	228.9	144.3	31.3	13.8
1989	19.3	29.5	77.0	175.5	66.4	34.7	91.5	164.4	145.5	91.6	43.1	28.3

1990	21.9	78.6	222.7	341.0	112.7	43.3	95.3	226.8	132.2	48.6	32.4	13.8
1991	18.9	39.6	150.1	147.4	89.5	31.0	88.0	300.1	136.6	24.6	26.8	14.0
1992	35.2	50.6	82.8	263.5	129.3	75.0	151.5	348.5	217.2	128.0	63.6	21.8
1993	32.9	52.8	78.6	162.6	209.8	111.0	183.4	297.8	139.7	132.7	46.1	16.3
1994	21.2	27.5	57.6	129.8	104.8	104.3	207.1	269.8	147.3	53.6	91.1	22.7
1995	17.9	22.9	99.4	421.5	115.0	38.7	105.0	245.1	149.2	47.9	24.1	14.6
1996	39.5	19.9	129.7	253.0	185.8	135.6	184.0	235.1	142.7	61.6	32.4	13.9
1997	29.3	15.0	68.9	187.8	80.5	64.3	133.3	166.1	76.8	148.5	95.0	24.1
1998	46.4	41.1	101.8	180.5	335.5	89.5	135.2	21.4	204.7	204.7	50.7	16.3
1999	22.1	14.9	97.5	121.6	70.5	36.5	108.7	206.4	140.3	252.1	28.5	12.7
2000	16.6	14.0	32.7	140.2	99.2	33.0	99.8	227.4	123.5	155.0	50.9	31.6
2001	17.4	23.5	97.3	332.7	191.6	144.0	175.5	119.7	167.7	60.3	26.0	24.2
2002	21.9	14.2	69.2	318.4	98.5	79.8	129.8	56.6	125.9	52.3	23.2	24.4
2003	19.9	14.6	53.4	305.4	105.8	81.6	166.3	128.9	166.1	78.6	24.8	25.1
2004	22.3	18.4	52.7	318.7	96.5	79.0	139.3	78.6	167.6	140.6	26.5	23.8
2005	19.2	15.2	66.0	297.5	282.2	90.1	172.5	125.9	159.4	87.6	28.6	28.4
2006	18.0	17.1	66.1	385.9	209.6	99.1	176.9	123.3	182.7	114.2	39.6	27.9
2007	19.3	21.7	56.3	327.3	118.6	113.6	170.5	124.7	180.1	91.5	30.5	23.6

Table A-5 Mean monthly flow at Wabi Shebelle river @Gode hydrometric station [m^3/s]

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1967	18.8	18.4	43.3	144.0	96.8	37.6	103.1	232.8	257.5	223.8	215.1	38.3
1968	12.8	45.0	70.9	483.2	243.2	114.7	111.0	218.7	169.1	129.0	82.1	40.4
1969	19.9	97.4	153.8	140.7	201.6	44.6	97.1	216.9	164.9	61.1	40.5	15.6
1970	17.7	17.8	146.4	156.3	102.4	21.8	64.2	286.5	235.0	170.3	60.6	18.7
1971	8.8	10.3	13.4	91.3	138.6	76.1	96.3	182.6	159.8	127.0	92.2	26.7
1972	17.6	51.4	34.4	190.1	118.5	53.0	126.3	181.7	155.3	105.1	65.1	15.1
1973	15.8	9.3	4.7	40.2	70.3	26.2	73.8	180.3	149.5	119.9	19.8	13.4
1974	13.1	23.0	91.7	249.3	66.4	65.4	93.4	210.4	213.2	43.8	21.9	12.0
1975	9.1	22.1	13.1	138.4	63.0	50.3	147.8	327.1	246.4	80.7	33.8	13.1
1976	13.4	15.5	34.7	148.1	151.6	42.6	99.4	219.3	144.6	39.0	105.9	24.5
1977	43.3	54.1	51.7	233.2	138.6	80.8	165.9	348.9	270.9	345.1	147.8	28.7

1978	15.6	32.2	124.7	170.2	65.9	42.3	128.6	248.9	174.3	109.3	38.4	18.4
1979	46.3	33.1	100.2	221.1	150.6	68.1	84.3	128.4	119.9	72.4	39.3	16.3
1980	11.8	18.8	28.8	124.8	81.5	41.5	129.7	230.2	128.1	62.9	28.9	13.9
1981	12.1	15.4	108.2	367.9	86.1	32.6	60.6	260.1	257.3	74.3	33.0	15.3
1982	18.1	40.8	81.4	194.3	131.5	44.9	77.2	172.1	141.2	123.4	59.4	28.7
1983	17.1	29.5	45.9	361.7	423.2	83.8	80.7	338.0	361.5	134.1	100.0	24.4
1984	13.3	15.3	29.7	104.8	67.5	74.3	101.5	139.8	163.8	32.9	35.9	17.2
1985	13.3	16.7	41.4	189.6	177.4	88.0	135.4	174.3	223.8	69.6	41.0	15.9
1986	12.0	47.0	42.4	224.7	138.5	85.1	110.3	184.1	184.3	97.2	37.4	16.3
1987	13.9	26.7	131.9	263.1	282.5	108.8	97.7	155.3	148.7	131.8	57.7	19.7
1988	18.9	40.5	41.8	187.2	74.3	61.8	116.1	268.6	230.8	160.7	38.9	16.0
1989	13.7	28.8	61.2	200.7	76.8	37.9	76.0	149.5	146.7	102.1	53.6	32.8
1990	15.5	76.7	177.0	390.2	130.2	47.3	79.2	206.3	133.2	54.1	40.3	16.0
1991	13.4	38.6	119.3	168.6	103.4	33.9	73.2	272.9	137.7	27.4	33.3	16.2
1992	25.0	49.3	65.8	301.5	149.4	81.9	125.9	317.0	219.0	142.6	79.1	25.2
1993	23.4	51.5	62.5	186.1	242.4	121.2	152.4	270.9	140.9	147.8	57.3	18.8
1994	15.1	26.9	45.8	148.5	121.1	113.9	172.1	245.4	148.5	59.7	113.3	26.3
1995	12.7	22.3	79.0	482.3	132.9	42.3	87.3	223.0	150.4	53.3	30.0	16.9
1996	28.1	19.4	103.1	289.5	214.7	148.0	152.9	213.9	143.8	68.6	40.3	16.1
1997	20.8	14.6	54.7	214.9	92.6	70.3	110.8	151.1	77.4	165.4	118.1	28.0
1998	33.0	40.1	80.9	206.5	387.6	97.7	112.4	196.1	206.4	228.0	63.3	18.9
1999	15.7	14.6	77.5	139.1	81.5	39.9	90.3	187.8	141.4	280.8	35.5	14.8
2000	11.8	13.7	26.0	160.4	114.6	36.0	83.0	206.8	124.5	172.6	131.8	36.6
2001	13.6	22.3	79.8	432.5	241.4	138.2	143.9	107.7	172.7	77.8	32.2	26.2
2002	17.1	13.5	56.8	413.9	124.1	76.6	106.4	51.0	129.7	67.5	28.7	26.4
2003	15.5	13.9	43.8	397.0	133.3	78.4	136.4	116.0	171.0	101.4	30.7	27.1
2004	17.4	17.5	43.2	414.3	121.6	75.9	114.3	70.8	172.6	181.4	32.9	25.7
2005	15.0	14.4	54.1	386.8	355.6	86.5	141.5	113.3	164.2	113.0	35.5	30.7
2006	14.1	16.3	54.2	501.7	264.1	95.1	145.1	111.0	188.2	147.3	49.1	30.1
2007	15.1	20.6	46.2	425.5	149.5	109.0	139.8	112.3	185.5	118.0	37.8	25.5

Table A-6 Mean monthly flow Ulul river at junction of Wabi Shebelle [m^3/s]

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1967	0.84	0.36	0.84	2.92	2.18	1.77	7.36	12.81	13.58	9.99	9.17	1.66
1968	0.57	1.27	3.19	13.72	6.93	3.74	8.57	10.22	8.02	3.39	2.06	0.90
1969	1.28	1.39	6.05	5.16	4.85	2.20	8.48	11.57	9.37	2.05	1.41	0.66
1970	1.15	0.41	4.53	7.39	4.33	1.28	6.59	22.79	13.34	7.11	2.23	0.73
1971	0.63	0.54	0.99	3.80	4.45	4.65	9.05	12.71	7.77	6.57	4.25	1.13
1972	0.74	0.87	2.27	9.04	4.28	2.46	8.59	10.90	7.92	3.67	2.05	0.65
1973	0.71	0.57	0.48	0.64	1.64	1.19	5.43	9.38	8.44	5.19	0.84	0.58
1974	0.59	0.45	2.05	5.98	1.58	3.09	6.77	12.17	12.19	1.94	0.93	0.52
1975	0.41	0.43	0.31	2.90	1.55	2.30	10.98	20.36	14.26	3.63	1.44	0.57
1976	0.60	0.31	0.83	2.92	3.94	1.96	7.33	11.87	8.02	1.53	4.51	1.06
1977	1.94	1.06	1.29	5.00	3.85	3.76	12.71	20.45	15.71	14.97	6.30	1.24
1978	0.70	0.63	3.46	4.11	1.79	1.99	9.59	14.24	9.75	4.70	1.64	0.80
1979	2.08	0.65	2.58	5.29	4.16	3.22	6.18	7.21	6.81	3.19	1.67	0.71
1980	0.53	0.37	0.69	2.75	2.25	1.97	10.24	13.74	7.17	2.80	1.23	0.60
1981	0.55	0.30	2.11	8.61	2.32	1.57	4.52	15.24	14.86	3.31	1.40	0.66
1982	0.81	0.80	2.14	4.30	3.47	2.14	5.81	9.84	8.11	5.42	2.53	1.25
1983	0.77	0.58	1.25	8.39	12.03	3.97	5.97	20.04	19.27	6.00	4.26	1.06
1984	0.60	0.30	0.82	2.48	1.69	3.54	7.90	7.98	7.85	1.45	1.53	0.75
1985	0.59	0.33	0.72	3.94	4.98	4.24	10.20	10.40	11.31	3.13	1.75	0.69
1986	0.54	0.92	1.12	4.95	3.79	4.01	8.62	10.90	10.81	4.39	1.60	0.71
1987	0.62	0.52	3.45	6.08	7.48	5.24	7.78	8.74	8.57	5.91	2.46	0.85
1988	0.84	0.79	1.03	3.90	2.13	2.92	8.70	15.91	12.85	7.22	1.66	0.69
1989	0.62	0.56	1.35	4.05	2.07	1.77	5.54	8.06	8.13	4.46	2.28	1.42
1990	0.69	1.50	4.79	9.22	3.62	2.26	5.99	11.98	7.50	2.37	1.72	0.69
1991	0.60	0.76	2.67	3.91	2.80	1.63	5.60	17.03	7.99	1.20	1.42	0.70
1992	1.12	0.97	1.83	7.30	4.23	3.91	9.56	18.94	12.40	6.39	3.37	1.09
1993	1.05	1.01	1.75	4.09	6.95	5.78	11.91	16.23	7.89	6.57	2.45	0.82
1994	0.67	0.52	1.23	3.22	3.21	5.47	12.59	14.53	8.12	2.63	4.83	1.14
1995	0.57	0.44	1.96	11.23	3.80	2.01	6.27	13.15	8.78	2.37	1.28	0.73
1996	1.26	0.38	2.48	6.59	5.86	7.06	11.67	11.93	8.13	3.11	1.72	0.70

1997	0.93	0.29	1.21	4.70	2.58	3.24	8.31	8.76	4.45	7.08	5.03	1.21
1998	1.47	0.79	2.16	4.83	11.05	4.68	8.42	11.72	11.83	10.30	2.70	0.82
1999	0.70	0.29	1.55	3.20	2.22	1.86	6.66	10.66	8.23	12.59	1.51	0.64
2000	0.53	0.27	0.70	3.58	2.98	1.71	6.27	12.05	6.75	7.75	5.62	1.59
2001	0.63	0.51	2.22	9.90	7.14	8.66	13.32	8.07	11.57	3.09	1.56	1.38
2002	0.79	0.31	1.50	9.44	3.52	4.80	9.82	3.79	8.62	2.64	1.39	1.39
2003	0.72	0.32	1.09	9.03	3.80	4.91	12.62	8.69	11.46	4.15	1.49	1.43
2004	0.80	0.40	1.07	9.45	3.44	4.75	10.55	5.28	11.56	7.71	1.59	1.36
2005	0.69	0.33	1.42	8.77	10.67	5.41	13.09	8.48	10.98	4.66	1.72	1.62
2006	0.65	0.37	1.42	11.62	7.85	5.95	13.43	8.31	12.63	6.19	2.38	1.59
2007	0.70	0.47	1.17	9.73	4.30	6.83	12.94	8.41	12.45	4.89	1.83	1.35

Table A-7 Mean monthly flow Robi river at junction of Wabi Shebelle [m^3/s]

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1967	0.45	0.19	0.45	1.57	1.17	0.95	3.94	6.85	7.27	5.35	4.91	0.89
1968	0.31	0.68	1.71	7.35	3.71	2.00	4.59	5.47	4.29	1.81	1.08	0.48
1969	0.69	0.74	3.24	2.76	2.60	1.18	4.54	6.19	5.02	1.09	0.76	0.35
1970	0.62	0.21	2.43	3.95	2.32	0.68	3.52	12.20	7.14	3.80	1.20	0.39
1971	0.34	0.29	0.53	2.03	2.39	2.49	4.85	6.80	4.16	3.52	2.28	0.60
1972	0.40	0.46	1.21	4.84	2.29	1.32	4.60	5.84	4.24	1.97	1.10	0.35
1973	0.38	0.30	0.25	0.34	0.88	0.64	2.91	5.02	4.52	2.78	0.45	0.31
1974	0.31	0.24	1.09	3.20	0.85	1.66	3.62	6.52	6.52	1.04	0.50	0.28
1975	0.22	0.23	0.16	1.55	0.83	1.23	5.88	10.89	7.63	1.95	0.77	0.30
1976	0.32	0.16	0.44	1.56	2.11	1.05	3.92	6.35	4.21	0.82	2.42	0.57
1977	1.04	0.57	0.69	2.67	2.06	2.01	6.80	10.95	8.41	8.17	3.37	0.66
1978	0.37	0.34	1.85	2.20	0.96	1.06	5.13	7.62	5.22	2.51	0.88	0.43
1979	1.11	0.35	1.38	2.83	2.23	1.72	3.30	3.86	3.65	1.71	0.90	0.38
1980	0.28	0.20	0.37	1.47	1.21	1.05	5.48	7.35	3.84	1.50	0.66	0.32
1981	0.29	0.16	1.13	4.61	1.24	0.84	2.42	8.16	7.95	1.77	0.75	0.35
1982	0.44	0.43	1.15	2.30	1.86	1.14	3.11	5.27	4.34	2.90	135.80	0.67
1983	0.41	0.31	0.67	4.49	6.44	2.12	3.19	10.73	9.70	3.21	2.28	0.56
1984	0.32	0.16	0.44	1.33	0.90	1.89	4.23	4.27	4.20	0.78	0.82	0.40

1985	0.32	0.17	0.39	2.11	2.67	2.27	5.46	5.57	6.05	1.68	0.94	0.37
1986	0.29	0.49	0.60	2.65	2.03	2.15	4.61	5.84	5.79	2.35	0.86	0.38
1987	0.33	0.28	1.85	3.26	4.00	2.80	4.16	4.68	4.59	3.16	1.32	0.46
1988	0.45	0.43	0.55	2.08	1.14	1.56	4.66	8.52	6.88	3.96	0.89	0.37
1989	0.33	0.30	0.72	2.17	1.11	0.95	2.96	4.31	4.35	2.39	1.22	0.76
1990	0.37	0.81	2.56	4.93	1.99	1.21	3.21	6.41	4.01	1.27	0.92	0.37
1991	0.32	0.41	1.43	2.09	1.50	0.87	3.00	9.12	4.27	0.64	0.76	0.38
1992	0.60	0.52	0.98	3.91	2.26	2.09	5.11	10.14	6.64	3.42	1.81	0.59
1993	0.56	0.54	0.94	2.19	3.72	3.09	6.37	8.69	4.22	3.51	1.31	0.44
1994	0.36	0.28	0.66	1.72	1.72	2.93	6.74	7.78	4.34	1.41	2.58	0.61
1995	0.31	0.24	1.05	6.01	2.03	1.08	3.36	7.04	4.70	1.27	0.68	0.39
1996	0.67	0.20	1.33	3.53	3.14	3.78	6.25	6.39	4.35	1.67	0.92	0.37
1997	0.50	0.15	0.65	2.52	1.38	1.73	4.45	4.68	2.38	3.79	2.66	0.65
1998	0.79	0.42	1.16	2.58	5.91	2.50	4.50	6.27	6.33	5.51	1.44	0.44
1999	0.38	0.15	0.83	1.71	1.19	1.00	3.57	5.70	4.41	6.74	0.81	0.34
2000	0.28	0.14	0.38	1.92	1.60	1.04	3.36	6.45	3.61	4.15	3.01	0.85
2001	0.35	0.28	1.23	5.50	3.97	4.81	7.40	4.48	6.43	1.72	0.87	0.77
2002	0.44	0.17	0.83	5.25	1.95	2.66	5.46	2.10	4.79	1.47	0.77	0.77
2003	0.40	0.18	0.61	5.01	2.11	2.73	7.01	4.83	6.36	2.30	0.83	0.79
2004	0.45	0.22	0.60	5.25	1.91	2.64	5.86	2.93	6.42	4.28	0.88	0.75
2005	0.38	0.18	0.79	4.87	5.93	3.01	7.27	4.71	6.10	2.59	0.95	0.90
2006	0.36	0.21	0.79	6.46	4.36	3.31	7.46	4.62	7.02	3.44	1.32	0.88
2007	0.39	0.26	0.65	5.41	2.39	3.79	7.19	4.67	6.92	2.72	1.02	0.75

Table A-6 Mean monthly flow Manya river at junction of Wabi Shebelle [m^3/s]

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1967	3.58	1.53	3.56	12.41	9.26	7.53	31.24	54.36	57.67	42.42	38.91	7.05
1968	2.42	5.38	13.53	58.24	29.41	15.90	36.36	43.38	34.06	14.39	8.72	3.82
1969	5.45	5.90	25.68	21.92	20.59	9.33	35.99	49.10	39.76	8.68	5.99	2.81
1970	4.88	1.72	19.24	31.36	18.38	5.43	27.95	96.77	56.64	30.18	9.48	3.10
1971	2.70	2.33	4.18	16.12	18.91	19.72	38.44	53.95	32.97	27.92	18.04	4.79
1972	3.14	3.68	9.62	38.37	18.18	10.43	36.48	46.27	33.63	15.60	8.70	2.77

1973	2.99	2.40	2.03	2.73	6.97	5.05	23.06	39.80	35.83	22.04	3.59	2.47
1974	2.49	1.91	8.68	25.41	6.72	13.14	28.73	51.66	51.73	8.24	3.97	2.21
1975	1.72	1.84	1.31	12.31	6.60	9.75	46.63	86.41	60.53	15.42	6.11	2.41
1976	2.54	1.29	3.54	12.38	16.70	8.31	31.12	50.37	33.37	6.48	19.16	4.50
1977	8.23	4.49	5.49	21.20	16.36	15.95	53.96	86.81	66.69	64.90	26.74	5.28
1978	2.97	2.68	14.67	17.44	7.62	8.46	40.71	60.44	41.37	19.93	6.94	3.39
1979	8.81	2.75	10.96	22.47	17.65	13.68	26.21	30.59	28.93	13.53	7.11	3.00
1980	2.24	1.56	2.95	11.66	9.56	8.35	43.46	58.31	30.43	11.89	5.23	2.56
1981	2.31	1.29	8.93	36.41	9.85	6.65	19.19	64.70	63.04	14.06	5.96	2.82
1982	3.45	3.39	9.09	18.26	14.72	9.07	24.68	41.78	34.41	23.03	10.76	5.29
1983	3.26	2.45	5.29	35.62	51.06	16.83	25.33	85.06	76.89	25.48	18.09	4.48
1984	2.54	1.27	3.48	10.55	7.16	15.02	33.52	33.70	33.33	6.15	6.49	3.17
1985	2.52	1.39	3.07	16.71	21.15	18.01	43.31	44.15	48.01	13.29	7.42	2.92
1986	2.28	3.91	4.75	21.01	16.07	17.03	36.60	46.27	45.88	18.62	6.81	3.00
1987	2.64	2.22	14.66	25.83	31.74	22.25	33.02	37.12	36.38	25.09	10.44	3.63
1988	3.59	3.37	4.36	16.54	9.06	12.39	36.93	67.54	54.58	30.68	7.05	2.93
1989	2.61	2.39	5.72	17.22	8.77	7.50	23.51	34.20	34.51	18.94	9.70	6.03
1990	2.95	6.38	20.36	39.14	15.80	9.60	25.43	50.86	31.82	10.08	7.30	2.94
1991	2.55	3.21	11.35	16.59	11.89	6.91	23.78	72.31	33.90	5.08	6.03	2.98
1992	4.75	4.10	7.76	31.01	17.96	16.59	40.57	80.41	52.62	27.13	14.32	4.64
1993	4.45	4.28	7.45	17.38	29.52	24.55	50.55	68.90	33.47	27.87	10.38	3.46
1994	2.86	2.23	5.23	13.65	13.61	23.24	53.44	61.67	34.46	11.17	20.51	4.84
1995	2.42	1.86	8.33	47.69	16.12	8.53	26.61	55.82	37.27	10.05	5.42	3.11
1996	5.34	1.62	10.53	27.97	24.86	29.97	49.57	50.66	34.52	13.20	7.30	2.97
1997	3.96	1.21	5.14	19.95	10.95	13.75	35.27	37.09	18.90	30.07	21.38	5.14
1998	6.26	3.33	9.18	20.48	46.90	19.87	35.72	49.73	50.23	43.71	11.45	3.47
1999	2.98	1.21	6.57	13.58	9.43	7.89	28.28	45.25	34.95	53.43	6.42	2.71
2000	2.24	1.14	2.98	15.21	12.67	7.24	26.61	51.17	28.67	32.89	23.84	6.73
2001	2.92	2.37	10.37	46.22	33.34	40.40	62.17	37.65	53.99	14.44	7.28	6.44
2002	3.69	1.43	7.00	44.08	16.42	22.38	45.83	17.68	40.23	12.31	6.48	6.49
2003	3.34	1.47	5.10	42.12	17.75	22.89	58.88	40.56	53.46	19.36	6.93	6.67
2004	3.74	1.86	5.01	44.12	16.05	22.16	49.25	24.64	53.96	35.98	7.43	6.33

2005	3.23	1.53	6.60	40.94	49.81	25.26	61.09	39.59	51.26	21.76	8.01	7.55
2006	3.03	1.73	6.62	54.23	36.61	27.79	62.66	38.79	58.94	28.89	11.09	7.41
2007	3.25	2.19	5.45	45.42	20.08	31.86	60.37	39.24	58.09	22.81	8.54	6.28

Table A-8 Mean monthly flow Unguata river at junction of Wabi Shebelle [m^3/s]

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1967	1.80	2.62	7.13	19.31	11.72	2.96	9.08	46.00	40.00	9.48	18.31	7.23
1968	1.21	5.73	18.40	71.25	37.25	6.25	50.26	50.78	23.63	3.21	6.02	5.42
1969	2.23	8.21	32.13	30.08	26.44	6.81	10.46	41.55	27.58	3.10	2.82	3.18
1970	1.74	3.10	17.34	35.24	19.86	3.56	8.87	55.20	37.87	6.09	4.22	3.61
1971	1.61	3.17	5.32	17.72	20.76	6.33	11.27	36.56	18.16	3.27	5.79	3.63
1972	1.50	4.35	13.97	48.73	23.02	4.10	10.60	39.17	23.33	3.48	4.09	2.83
1973	1.50	3.32	5.40	8.33	8.83	1.99	6.70	33.69	24.85	4.92	1.69	2.52
1974	1.25	2.92	12.92	34.03	8.51	5.17	8.35	43.72	35.88	1.84	1.87	2.27
1975	0.87	2.86	4.58	19.19	8.36	3.84	13.55	73.13	41.99	3.45	2.87	2.46
1976	1.27	2.42	7.10	19.27	21.15	3.27	9.05	42.63	23.15	1.45	9.01	4.60
1977	4.13	5.01	9.31	29.27	20.71	6.28	15.68	73.47	46.25	14.48	12.58	5.40
1978	1.49	3.54	19.68	25.00	9.65	3.33	11.83	51.15	28.70	4.45	3.27	3.47
1979	4.41	3.60	15.49	30.70	22.35	5.38	7.62	25.88	20.07	3.02	3.34	3.07
1980	1.12	2.64	6.43	18.45	12.11	3.28	12.63	49.35	21.11	2.65	2.46	2.62
1981	1.16	2.41	13.20	46.67	12.47	2.62	5.58	54.76	43.75	3.14	2.80	2.88
1982	1.73	4.12	13.38	25.93	18.64	3.57	7.17	35.36	23.87	5.14	5.06	5.41
1983	1.63	3.36	9.08	45.60	64.65	6.62	7.36	71.99	53.34	5.69	8.51	4.58
1984	1.27	2.41	7.03	17.20	9.07	5.86	9.74	28.67	23.12	1.37	3.06	3.24
1985	1.27	2.50	6.58	24.18	26.78	7.08	12.59	37.36	33.30	2.97	3.50	2.98
1986	1.14	4.54	8.47	29.05	20.36	6.70	10.64	39.16	31.82	4.16	3.20	3.07
1987	1.33	3.17	19.67	34.51	40.19	8.75	9.60	31.41	25.23	5.60	4.91	3.71
1988	1.80	4.10	8.03	23.98	11.47	4.87	10.73	57.16	37.86	6.85	3.31	3.00
1989	1.31	3.31	9.57	24.75	11.11	2.95	6.83	28.94	23.94	4.23	4.56	6.16
1990	1.48	6.54	26.11	49.59	20.02	3.78	7.39	43.04	22.08	2.25	3.43	3.01
1991	1.28	3.97	15.93	24.04	15.05	2.72	6.91	61.20	23.51	1.14	2.84	3.05
1992	2.38	4.69	11.88	40.38	22.74	6.52	11.79	68.06	36.50	6.06	6.74	4.74

1993	2.23	4.84	11.52	24.94	37.38	9.66	14.69	58.31	23.21	6.23	4.88	3.54
1994	1.43	3.18	9.01	20.71	17.24	9.14	15.53	52.19	23.90	2.49	9.65	4.95
1995	1.21	2.88	12.52	59.28	20.42	3.36	7.73	47.24	25.85	2.24	2.55	3.18
1996	2.67	2.68	15.00	36.93	31.49	11.79	14.40	42.88	23.94	2.95	3.43	3.04
1997	1.98	2.36	8.91	27.85	13.87	5.41	10.25	31.39	13.11	6.72	10.06	5.26
1998	3.14	4.07	13.49	28.45	59.40	7.82	10.38	42.09	34.84	9.76	5.39	3.55
1999	1.49	2.36	10.54	20.63	11.94	3.11	8.22	38.30	24.24	11.94	3.02	2.78
2000	1.12	2.30	6.47	22.47	16.05	2.85	7.74	43.31	19.88	7.35	11.22	6.88
2001	2.35	3.12	12.29	37.93	22.85	21.27	23.29	15.72	21.37	6.76	3.38	3.39
2002	2.97	1.89	8.74	36.31	11.75	11.79	17.21	7.44	16.05	5.87	3.01	3.42
2003	2.69	1.94	6.74	34.82	12.62	12.06	22.06	16.93	21.17	8.81	3.22	3.51
2004	3.01	2.44	6.65	36.34	11.51	11.68	18.48	10.33	21.36	15.76	3.45	3.33
2005	2.60	2.01	8.33	33.93	33.66	13.31	22.88	16.53	20.31	9.82	3.72	3.97
2006	2.44	2.27	8.34	44.01	25.00	14.64	23.47	16.19	23.28	12.80	5.15	3.90
2007	2.61	2.88	7.11	37.33	14.15	16.78	22.62	16.38	22.96	10.25	3.97	4.63

Table A-9 Mean monthly flow Ramis river at junction of Wabi Shebelle [m^3/s]

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1967	2.67	2.10	6.41	14.34	10.79	2.96	6.22	27.76	35.99	15.28	13.68	5.91
1968	1.81	4.61	16.01	54.68	34.30	6.45	34.41	75.75	21.97	5.18	4.65	4.45
1969	3.32	6.60	27.95	23.09	24.35	7.03	7.16	25.08	25.65	5.00	2.18	2.64
1970	2.59	3.32	15.09	27.04	18.28	3.67	6.07	33.31	35.21	9.81	3.26	2.97
1971	2.40	2.55	4.63	13.60	19.12	6.53	7.72	22.07	16.89	5.28	4.48	2.98
1972	2.24	3.50	12.16	38.17	21.20	4.23	7.26	23.64	21.69	5.62	3.16	2.32
1973	2.23	2.67	4.69	6.40	8.13	2.05	4.59	20.33	23.11	7.94	1.30	2.07
1974	1.86	2.35	11.24	26.12	7.84	5.33	5.72	26.39	33.36	2.97	1.44	1.86
1975	1.29	2.30	3.99	14.73	7.69	3.96	9.28	44.13	39.04	5.55	2.22	2.02
1976	1.89	1.95	6.18	14.79	19.48	3.37	6.19	26.39	21.52	2.33	6.96	3.77
1977	6.14	4.03	8.09	22.46	19.07	6.47	10.74	44.34	43.01	23.24	9.71	4.43
1978	2.21	2.85	17.13	19.19	8.89	3.43	8.10	30.87	26.68	7.18	2.52	2.84
1979	6.57	2.90	13.47	23.56	20.58	5.55	5.22	15.62	18.66	4.87	2.58	2.52
1980	1.67	2.12	5.60	14.16	11.15	3.39	8.65	29.78	19.63	4.28	1.90	2.15

1981	1.72	1.94	11.48	35.82	11.48	2.70	3.82	33.05	40.68	5.06	2.16	2.36
1982	2.57	3.32	11.64	19.90	17.16	3.68	4.91	21.34	22.27	8.29	3.91	4.44
1983	2.43	2.70	7.90	35.00	59.54	6.83	5.04	43.45	49.59	9.18	6.57	3.76
1984	1.89	1.93	6.12	13.20	8.36	6.10	6.67	17.30	21.50	2.21	2.36	2.66
1985	1.88	2.01	5.72	18.56	24.66	7.31	8.62	22.55	30.96	4.79	2.70	2.45
1986	1.70	3.65	7.37	22.30	18.74	6.91	7.28	23.63	29.59	6.71	2.47	2.52
1987	1.97	2.55	17.11	26.49	37.01	9.03	6.57	18.96	23.46	9.04	3.79	3.04
1988	2.67	3.30	6.99	18.40	10.56	5.03	7.35	34.50	35.20	11.05	2.56	2.46
1989	1.95	2.67	8.32	19.00	10.23	3.04	4.68	17.47	22.26	6.82	3.52	2.50
1990	2.20	5.26	22.72	38.06	18.43	3.90	5.06	25.98	20.52	3.63	2.65	2.46
1991	1.90	3.20	13.86	18.46	13.86	2.80	4.73	36.93	21.86	1.83	2.19	2.50
1992	3.54	3.77	10.33	31.00	20.94	6.73	8.07	41.07	33.94	9.77	5.20	3.89
1993	3.32	3.89	10.02	19.14	34.42	9.96	10.06	35.19	21.59	10.04	3.77	2.90
1994	1.95	2.56	7.84	15.90	15.87	9.43	10.63	31.50	22.22	4.02	7.45	4.06
1995	1.80	2.31	10.89	45.50	18.80	3.46	5.29	28.51	24.04	3.62	1.97	2.61
1996	3.98	2.16	13.05	28.34	28.99	12.16	9.86	25.88	22.26	4.75	2.65	2.49
1997	2.95	1.90	7.75	21.38	12.77	5.58	7.02	18.94	12.19	10.83	7.77	4.32
1998	4.67	3.27	11.73	21.84	54.70	8.06	7.11	25.40	32.39	15.74	4.16	2.91
1999	2.23	1.90	9.17	15.84	10.99	3.20	5.63	23.11	22.54	19.24	2.33	2.28
2000	1.67	1.85	5.63	17.25	14.75	2.94	5.29	26.14	18.49	11.84	8.66	5.65
2001	2.35	3.12	12.29	37.93	22.85	21.27	23.29	15.72	21.37	6.76	3.38	3.39
2002	2.97	1.89	8.74	36.31	11.75	11.79	17.21	7.44	16.05	5.87	3.01	3.42
2003	2.69	1.94	6.74	34.82	12.62	12.06	22.06	16.93	21.17	8.81	3.22	3.51
2004	3.01	2.44	6.65	36.34	11.51	11.68	18.48	10.33	21.36	15.76	3.45	3.33
2005	2.60	2.01	8.33	33.93	33.66	13.31	22.88	16.53	20.31	9.82	3.72	3.97
2006	2.44	2.27	8.34	44.01	25.00	14.64	23.47	16.19	23.28	12.80	5.15	3.90
2007	2.61	2.88	7.11	37.33	14.15	16.78	22.62	16.38	22.96	10.25	3.97	3.30

Table A-10 Mean monthly flow Golocha river at junction of Wabi Shebelle [m^3/s]

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1967	1.21	1.03	0.54	2.50	2.66	0.77	6.09	19.80	12.71	23.64	12.71	1.72
1968	0.84	2.03	1.53	23.66	9.60	3.72	4.69	12.70	8.94	8.11	1.52	1.21

1969	2.00	3.36	2.96	4.48	4.87	1.76	8.53	31.96	8.48	4.03	1.50	1.11
1970	1.48	1.41	3.17	10.29	5.85	1.18	4.57	28.09	11.57	9.43	1.77	1.05
1971	0.76	1.05	0.75	4.09	7.64	3.94	12.12	31.75	7.60	12.89	2.78	1.86
1972	1.39	6.08	2.26	20.52	7.36	1.42	7.80	14.02	7.22	2.91	1.83	1.49
1973	1.17	1.39	0.77	2.27	2.83	1.32	3.77	19.41	6.84	6.63	1.55	1.46
1974	1.15	1.46	1.46	3.07	2.07	1.10	5.22	8.16	5.54	3.71	1.74	1.40
1975	0.29	0.74	0.49	3.05	2.09	2.49	8.25	17.87	12.80	8.20	1.22	0.77
1976	0.97	0.92	0.66	2.30	2.94	1.49	3.61	16.13	6.45	3.48	3.43	1.30
1977	2.23	2.73	0.87	5.39	3.54	2.80	10.21	20.68	12.14	12.09	4.86	1.46
1978	0.81	1.69	2.29	3.89	4.91	1.73	5.05	20.75	8.14	15.30	1.94	1.72
1979	1.42	2.73	1.65	6.32	2.63	1.57	6.39	7.74	6.82	6.37	1.55	1.05
1980	0.88	0.95	0.74	3.67	5.05	1.71	10.78	13.51	4.51	6.17	1.28	0.92
1981	0.37	0.40	3.33	35.08	2.15	0.69	2.99	20.31	13.00	3.68	0.89	0.34
1982	0.39	0.36	0.28	6.11	9.34	1.42	2.03	9.30	1.88	7.99	2.57	4.57
1983	0.80	0.97	0.43	4.27	13.55	4.29	2.42	27.41	13.07	18.41	4.17	0.72
1984	0.29	0.23	0.22	0.27	0.68	0.84	3.17	5.12	10.21	1.20	0.46	0.27
1985	0.13	0.20	0.87	4.33	11.95	0.30	3.07	14.99	4.51	3.20	0.88	0.28
1986	0.18	0.21	0.36	5.03	9.99	11.30	7.89	18.00	9.90	5.35	0.70	0.45
1987	0.19	0.20	1.60	10.65	23.28	3.80	0.63	1.71	2.90	4.36	1.76	0.44
1988	0.22	0.24	0.39	3.16	1.25	0.64	12.67	23.32	9.74	17.72	1.28	0.45
1989	0.24	0.24	0.53	21.34	6.48	0.59	15.28	5.43	5.42	6.79	2.32	5.03
1990	0.96	5.46	7.31	21.75	1.62	0.50	1.16	14.04	2.35	2.36	0.67	0.56
1991	0.27	0.39	0.80	2.09	2.28	0.93	10.70	25.85	7.64	1.32	0.42	0.30
1992	0.37	1.20	0.22	0.40	1.01	0.84	2.68	38.58	5.24	21.33	6.42	5.84
1993	2.35	21.61	0.81	1.75	5.99	2.02	6.55	14.12	5.02	7.99	8.79	0.48
1994	0.89	1.08	0.84	2.50	5.95	5.58	12.01	22.54	6.10	7.42	6.59	0.94
1995	0.38	0.39	2.08	9.98	0.67	1.92	6.79	23.85	18.74	8.52	10.86	0.76
1996	0.72	0.39	0.31	1.71	6.85	9.23	13.54	24.01	4.90	3.58	0.71	0.39
1997	0.34	0.27	0.40	2.94	1.15	0.70	3.33	5.60	3.31	32.07	43.46	5.26
1998	12.34	2.17	1.70	3.40	4.75	0.80	7.43	34.10	11.55	39.18	5.03	0.88
1999	0.54	0.33	2.06	2.35	2.32	1.16	4.44	16.04	6.55	23.48	1.85	1.10
2000	0.79	0.95	0.47	3.35	2.87	0.94	3.45	19.94	8.39	11.00	3.13	1.64

2001	0.91	1.20	4.73	14.59	8.79	8.18	8.96	6.05	8.22	2.60	1.30	1.30
2002	1.14	0.73	3.36	13.96	4.52	4.53	6.62	2.86	6.17	2.26	1.16	1.31
2003	1.03	0.75	2.59	13.39	4.85	4.64	8.49	6.51	8.14	3.39	1.24	1.35
2004	1.16	0.94	2.56	13.98	4.43	4.49	7.11	3.97	8.22	6.06	1.33	1.28
2005	1.00	0.77	3.20	13.05	12.94	5.12	8.80	6.36	7.81	3.78	1.43	1.53
2006	0.94	0.87	3.21	16.93	9.62	5.63	9.03	6.23	8.96	4.92	1.98	1.50
2007	1.01	1.11	2.73	14.36	5.44	6.45	8.70	6.30	8.83	3.94	1.53	1.27

Table A-11 Mean monthly flow Golocha river at upper reach [m^3/s]

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1967	1.37	1.05	0.61	2.73	3.00	0.84	6.87	22.34	13.88	25.79	13.88	1.95
1968	0.94	2.07	1.73	25.83	10.83	4.08	5.28	14.32	9.75	9.15	1.66	1.36
1969	2.26	3.43	3.34	4.89	5.50	1.92	9.53	35.05	9.25	4.54	1.64	1.25
1970	1.67	1.44	3.57	11.23	5.50	1.29	5.15	31.59	12.54	10.54	1.93	1.19
1971	1.11	1.07	0.85	4.45	8.51	4.30	13.67	35.81	8.29	14.54	3.03	2.09
1972	1.57	6.20	2.55	22.41	8.30	1.55	8.80	15.82	7.88	3.29	2.00	1.80
1973	1.32	1.42	0.87	2.48	3.20	1.44	4.25	21.89	7.45	7.48	1.70	1.64
1974	1.29	1.49	1.65	3.35	2.33	1.20	5.88	9.20	5.05	4.19	1.90	1.58
1975	0.33	0.75	0.55	3.33	2.35	2.72	9.31	20.15	13.97	9.25	1.33	0.87
1976	1.10	0.93	0.75	2.51	3.32	1.63	4.07	18.19	7.05	3.92	3.75	1.47
1977	2.51	2.78	0.99	5.89	3.99	3.05	11.52	23.33	13.25	13.54	5.31	1.65
1978	0.91	1.72	2.59	4.25	5.53	1.89	5.70	23.41	8.89	17.25	2.12	1.95
1979	1.60	2.78	1.86	5.89	2.95	1.71	7.21	8.73	7.44	7.19	1.59	1.18
1980	0.99	0.97	0.83	4.01	5.70	1.87	12.15	15.24	5.00	6.96	1.39	1.04
1981	0.41	0.41	3.75	38.30	2.42	0.75	3.37	22.91	14.19	4.15	0.97	0.39
1982	0.44	0.37	0.32	5.57	10.54	1.54	2.29	10.49	2.05	9.02	2.80	5.15
1983	0.90	0.99	0.49	4.55	15.29	4.58	2.73	30.92	14.27	20.77	4.55	0.81
1984	0.33	0.24	0.25	0.30	0.77	0.92	3.57	5.78	11.15	1.35	0.50	0.31
1985	0.15	0.21	0.98	4.72	13.48	0.32	3.45	15.91	4.93	3.51	0.96	0.31
1986	0.20	0.21	0.41	5.49	11.27	12.34	8.89	20.31	10.81	5.04	0.77	0.51
1987	0.22	0.21	1.81	11.53	26.25	4.15	0.71	1.93	3.17	4.91	1.92	0.50
1988	0.25	0.24	0.44	3.45	1.42	0.59	14.29	26.30	10.53	19.99	1.40	0.46

1989	0.27	0.25	0.59	23.30	7.31	0.55	17.23	6.12	5.92	7.66	2.54	5.68
1990	1.09	5.57	8.24	23.74	1.83	0.54	1.31	15.84	2.50	2.66	0.73	0.63
1991	0.30	0.40	0.90	2.55	2.57	1.02	12.07	29.15	8.33	1.49	0.45	0.34
1992	0.42	1.22	0.25	0.44	1.14	0.92	3.02	43.53	5.72	24.07	7.01	6.59
1993	2.65	22.02	0.92	1.91	5.75	2.21	7.39	15.92	5.47	9.02	9.59	0.54
1994	1.00	1.10	0.95	2.73	5.71	5.09	13.54	25.43	6.39	8.37	7.19	1.07
1995	0.43	0.40	2.34	10.89	4.55	2.09	7.55	3.91	20.46	9.61	11.86	0.85
1996	0.81	0.40	0.34	1.87	7.73	10.08	15.25	27.09	5.35	4.04	0.77	0.44
1997	0.42	0.30	0.45	3.21	1.29	0.77	3.70	5.32	3.61	36.18	47.44	5.94
1998	13.91	2.21	1.92	3.71	5.36	0.87	5.30	38.47	12.51	44.19	5.50	0.99
1999	0.61	0.33	2.32	2.14	2.62	1.26	5.01	18.09	7.15	26.49	2.02	1.24
2000	0.89	0.91	0.53	3.55	3.66	1.02	3.89	22.50	9.16	12.41	3.42	1.87
2001	0.02	0.04	0.34	4.28	2.99	2.80	5.69	3.61	2.37	0.53	0.18	0.20
2002	0.03	0.03	0.24	4.09	1.54	1.55	4.20	1.71	1.78	0.46	0.16	0.20
2003	0.03	0.03	0.18	3.92	1.65	1.59	5.39	3.89	2.34	0.70	0.17	0.21
2004	0.03	0.04	0.18	4.10	1.51	1.54	4.51	2.37	2.37	1.24	0.18	0.19
2005	0.03	0.03	0.23	3.82	4.40	1.75	5.59	3.80	2.25	0.77	0.20	0.23
2006	0.03	0.03	0.23	4.96	3.27	1.93	5.73	3.72	2.58	1.01	0.27	0.23
2007	0.03	0.04	0.19	4.21	1.85	2.21	5.52	3.76	2.54	0.81	0.21	0.19

Table A-12 Mean monthly flow Errer river at junction of Wabi Shebelle [m^3/s]

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1967	2.17	1.56	2.39	5.72	5.32	2.29	2.39	7.17	14.95	12.77	10.22	3.95
1968	1.47	3.42	6.34	21.10	16.90	4.83	13.20	19.60	8.83	4.58	3.36	2.80
1969	2.70	4.89	11.06	8.91	12.00	5.26	2.75	6.49	11.08	4.42	1.57	1.76
1970	2.11	1.85	5.97	10.44	9.01	2.75	2.33	8.62	14.16	8.68	2.36	1.98
1971	1.95	1.89	1.83	5.25	9.38	4.89	2.96	5.71	6.79	4.67	3.23	1.99
1972	1.82	2.60	4.81	14.43	10.45	3.17	2.79	6.12	8.72	4.97	2.28	1.55
1973	1.81	1.98	1.86	2.47	4.01	1.53	1.76	5.26	9.29	7.03	0.94	1.38
1974	1.51	1.74	4.45	10.08	3.86	3.99	2.19	6.83	13.41	2.63	1.04	1.24
1975	1.05	1.71	1.58	5.69	3.79	2.96	3.56	11.42	15.69	4.91	1.60	1.35
1976	1.54	1.44	2.45	5.71	9.60	2.52	2.37	6.66	8.65	2.06	5.03	2.52

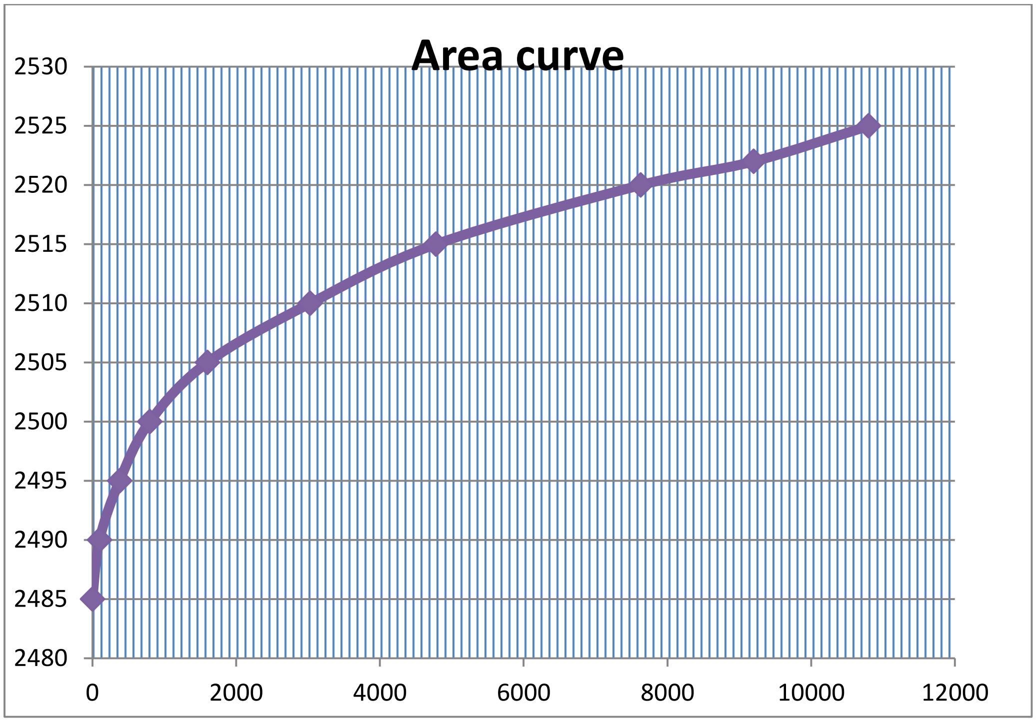
1977	4.99	2.99	3.20	8.67	9.40	4.85	4.12	11.47	17.29	20.66	7.02	2.95
1978	1.80	2.11	6.78	7.41	4.38	2.57	3.11	7.99	10.73	6.35	1.82	1.90
1979	5.34	2.15	5.33	9.09	10.14	4.16	2.00	4.04	7.50	4.31	1.87	1.68
1980	1.36	1.57	2.21	4.69	5.50	2.53	3.32	7.71	7.89	3.79	1.37	1.43
1981	1.40	1.44	4.54	13.82	5.66	2.02	1.46	8.55	16.35	4.48	1.57	1.58
1982	2.09	2.46	4.61	7.68	8.46	2.75	1.89	5.52	8.92	7.34	2.82	2.96
1983	1.98	2.00	3.13	13.54	29.34	5.11	1.93	11.24	19.94	8.12	4.75	2.51
1984	1.54	1.43	2.42	5.09	4.12	4.56	2.56	4.48	8.64	1.96	1.71	1.77
1985	1.53	1.49	2.26	7.16	12.15	5.47	3.31	5.84	12.45	4.24	1.95	1.64
1986	1.39	2.71	2.92	8.60	9.24	5.17	2.79	6.12	11.90	5.93	1.79	1.68
1987	1.60	1.89	6.77	10.22	18.24	6.76	2.52	4.91	9.43	7.99	2.74	2.03
1988	2.17	2.45	2.77	7.10	5.20	3.76	2.82	8.93	14.15	9.77	1.85	1.64
1989	0.84	1.98	3.29	7.33	5.04	2.28	1.80	4.52	8.95	6.03	2.55	3.38
1990	1.79	3.90	8.99	13.92	9.08	2.92	1.94	6.72	8.25	3.21	1.91	1.65
1991	1.55	2.37	5.48	7.12	6.83	2.10	1.81	9.56	8.79	1.62	1.59	1.67
1992	2.87	2.80	4.09	11.96	10.32	5.04	3.10	10.63	13.64	8.65	3.76	2.59
1993	2.70	2.89	3.97	7.39	16.96	7.46	3.86	9.11	8.68	8.88	2.72	1.94
1994	1.74	1.90	3.10	6.13	7.82	7.06	4.08	8.15	8.94	3.56	5.38	2.71
1995	1.46	1.72	4.31	17.56	9.26	2.59	2.03	7.38	9.66	3.20	1.42	1.74
1996	3.24	1.60	5.16	10.94	14.29	9.10	3.78	6.69	8.95	4.21	1.92	1.66
1997	2.40	1.41	3.07	8.25	6.29	4.18	2.69	4.90	4.90	9.58	5.61	2.88
1998	3.80	2.43	4.64	8.43	26.95	6.03	2.74	6.57	13.02	13.93	3.01	1.95
1999	1.81	1.41	3.63	6.11	5.42	2.40	2.16	5.98	9.06	17.03	1.69	1.52
2000	1.36	1.37	2.23	6.66	7.28	2.20	2.03	6.76	7.43	10.48	6.26	3.77
2001	1.27	1.68	6.62	20.43	12.30	11.46	12.54	8.46	11.51	3.64	1.82	1.82
2002	1.60	1.02	4.71	19.55	6.33	6.35	9.27	4.01	8.64	3.16	1.62	1.84
2003	1.45	1.04	3.63	18.75	6.79	6.49	11.88	9.12	11.40	4.75	1.73	1.89
2004	1.62	1.32	3.58	19.57	6.20	6.29	9.95	5.56	11.50	8.49	1.86	1.79
2005	1.40	1.08	4.48	18.27	18.12	7.17	12.32	8.90	10.94	5.29	2.00	2.14
2006	1.31	1.22	4.49	23.70	13.46	7.88	12.64	8.72	12.54	6.89	2.77	2.10
2007	1.41	1.55	3.83	20.10	7.62	9.04	12.18	8.82	12.36	5.52	2.14	1.78

Table A-13 Mean monthly flow Daketa river at junction of Wabi Shebelle [m^3/s]

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1967	0.00	0.00	6.50	19.44	43.09	0.96	0.00	0.00	4.49	7.89	7.05	0.00
1968	14.90	1.00	1.53	14.65	10.88	3.92	0.00	0.00	0.00	1.28	0.60	0.02
1969	13.81	0.10	0.09	1.11	4.00	6.15	0.00	0.00	0.00	3.70	2.07	0.00
1970	10.01	0.00	8.20	25.83	21.40	0.00	0.00	0.00	4.97	13.66	0.06	0.00
1971	0.00	0.00	2.21	9.34	20.20	3.65	0.00	0.00	0.61	0.06	1.40	0.00
1972	0.00	0.47	11.88	16.32	9.98	1.94	0.00	0.00	1.44	0.19	1.28	0.00
1973	0.00	0.00	0.83	10.27	19.18	1.16	0.00	0.00	0.06	4.97	0.34	0.00
1974	0.00	0.00	5.03	8.20	11.75	0.81	0.00	0.00	0.47	1.89	0.00	0.01
1975	4.07	0.62	0.00	15.83	17.03	2.45	0.00	0.00	0.92	1.71	0.00	0.00
1976	2.39	0.13	1.82	22.47	22.92	1.83	0.00	0.00	0.85	9.55	0.22	0.01
1977	12.75	0.26	1.32	24.51	10.93	3.85	0.00	0.00	1.17	19.28	0.23	0.00
1978	0.00	1.36	1.28	2.26	10.02	1.65	0.00	0.00	1.18	15.87	2.98	0.00
1979	27.30	0.10	2.49	0.59	17.23	2.33	0.00	0.00	0.11	0.03	0.16	0.00
1980	0.00	0.00	0.00	6.17	7.83	1.27	0.00	0.00	1.25	1.02	0.07	0.00
1981	0.00	0.03	15.91	10.11	8.75	0.39	0.00	0.00	1.07	1.72	1.15	0.04
1982	0.00	0.24	0.68	10.31	10.81	0.83	0.00	0.00	1.17	3.79	1.08	0.00
1983	0.81	0.00	0.00	11.29	26.52	2.79	0.00	0.00	10.39	3.80	0.00	0.00
1984	0.00	0.00	0.00	0.45	7.86	0.10	0.00	0.00	5.18	1.91	0.12	0.00
1985	0.00	0.00	9.91	24.32	9.47	0.55	0.00	0.00	0.61	1.63	0.00	0.00
1986	0.00	0.18	0.46	17.43	12.44	2.20	0.00	0.00	0.40	1.47	0.37	0.00
1987	4.33	0.00	1.46	7.18	50.07	0.63	0.00	0.00	0.22	3.38	0.92	0.00
1988	0.09	0.14	3.07	22.70	1.06	1.97	0.00	0.00	0.68	3.52	0.24	0.01
1989	0.00	0.13	2.76	19.60	13.46	0.85	0.00	0.00	0.38	7.99	0.43	0.03
1990	0.99	35.55	1.37	8.21	3.46	0.46	0.00	0.00	0.27	4.25	0.00	0.01
1991	0.60	0.10	11.85	5.38	14.46	0.50	0.00	0.00	0.23	0.40	0.12	0.00
1992	1.73	0.13	0.23	2.63	5.02	1.11	0.00	0.00	0.86	2.34	0.70	0.01
1993	15.87	0.14	0.03	8.23	8.94	4.04	0.00	0.00	0.49	4.02	0.00	0.00
1994	0.00	0.00	0.34	11.23	17.32	0.30	0.00	0.00	1.36	3.79	2.94	0.00
1995	0.00	0.13	1.90	17.71	3.92	0.86	0.00	0.00	0.35	2.34	0.98	0.01
1996	4.48	0.03	5.86	14.33	20.27	3.02	0.00	0.00	0.62	0.33	0.49	0.00

1997	2.34	0.00	4.62	18.91	4.67	4.21	0.00	0.00	0.14	17.07	2.67	0.00
1998	18.14	0.22	1.33	8.40	30.70	0.69	0.00	0.00	1.10	1.99	0.95	0.00
1999	0.00	0.02	11.26	6.13	8.59	0.96	0.00	0.00	0.18	4.92	0.47	0.00
2000	0.00	0.00	0.09	7.21	25.49	0.67	0.00	0.00	0.48	2.73	1.08	0.02
2001	0.00	0.00	11.98	22.70	17.62	3.53	0.00	0.00	3.01	2.74	1.06	0.00
2002	12.56	0.00	8.53	19.60	20.56	1.96	0.00	0.00	2.26	2.38	0.94	0.00
2003	0.00	0.00	6.58	8.21	19.50	2.00	0.00	0.00	2.99	3.58	1.01	0.00
2004	14.50	0.00	6.49	5.38	29.50	1.94	0.00	0.00	3.01	6.40	1.08	0.00
2005	0.00	0.00	8.12	2.63	31.50	2.21	0.00	0.00	2.87	3.99	1.16	0.00
2006	1.56	0.00	8.14	8.23	43.20	2.43	0.00	0.00	3.28	5.19	1.61	0.00
2007	3.21	0.00	6.93	11.23	39.50	2.79	0.00	0.00	3.24	4.16	1.24	0.00

APPENDIX-B Physical and Power plant characteristics of hydropower dams



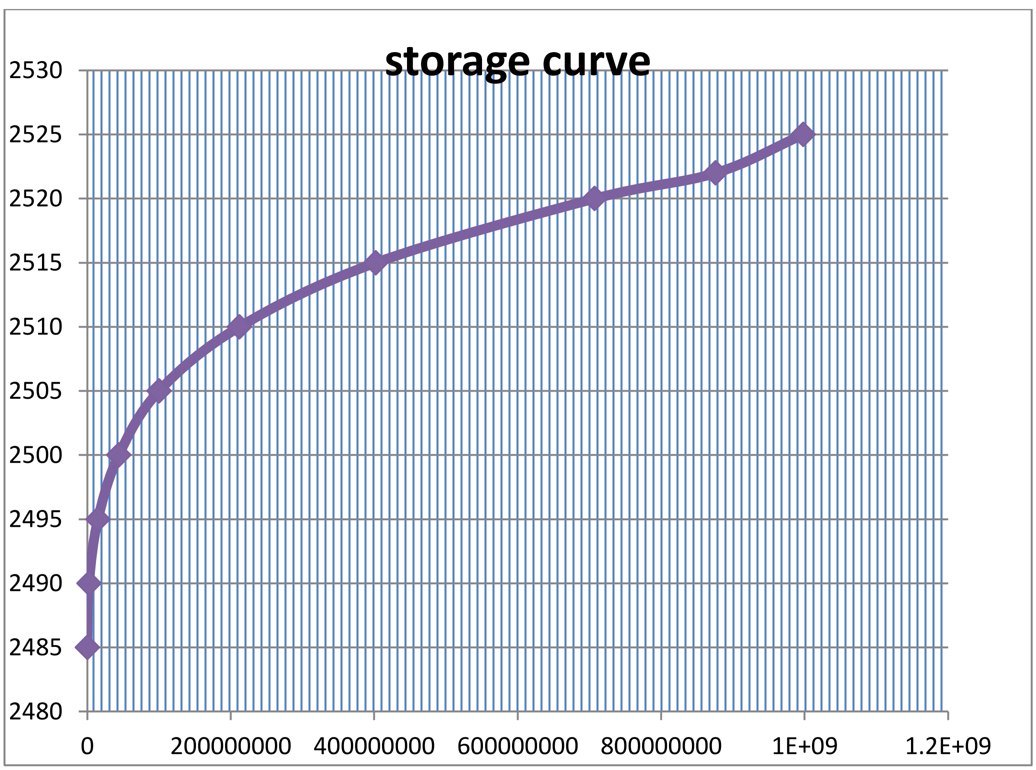
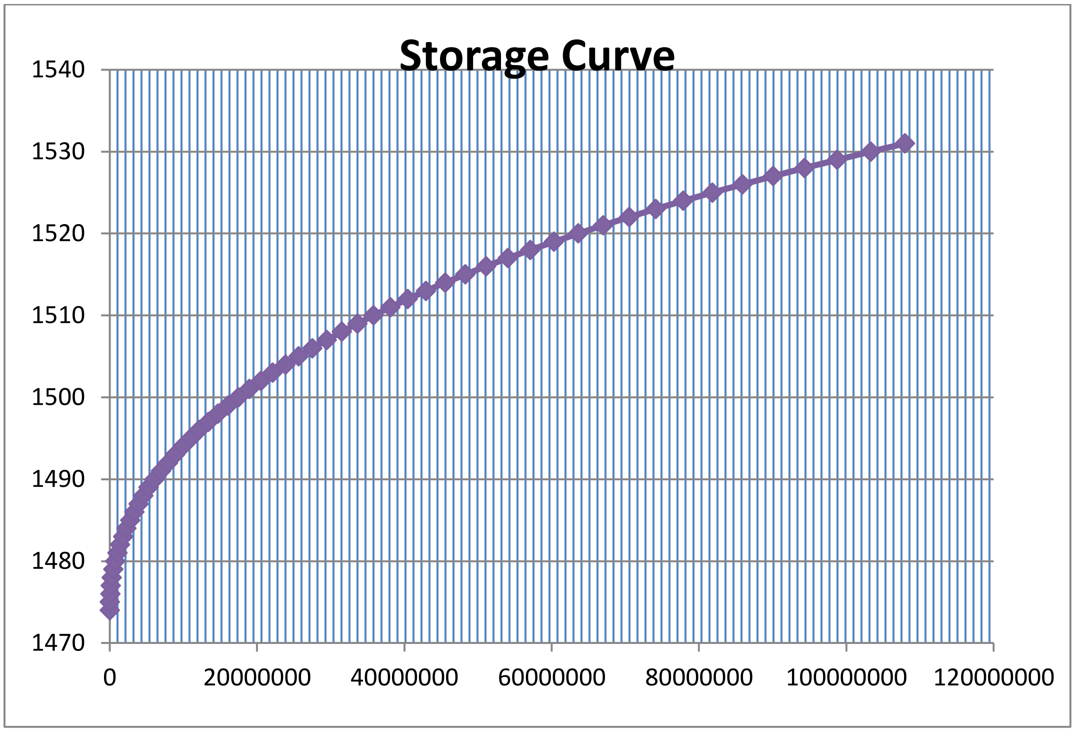


Figure B-1 Elevation-Storage curve for Melka Wakena reservoir



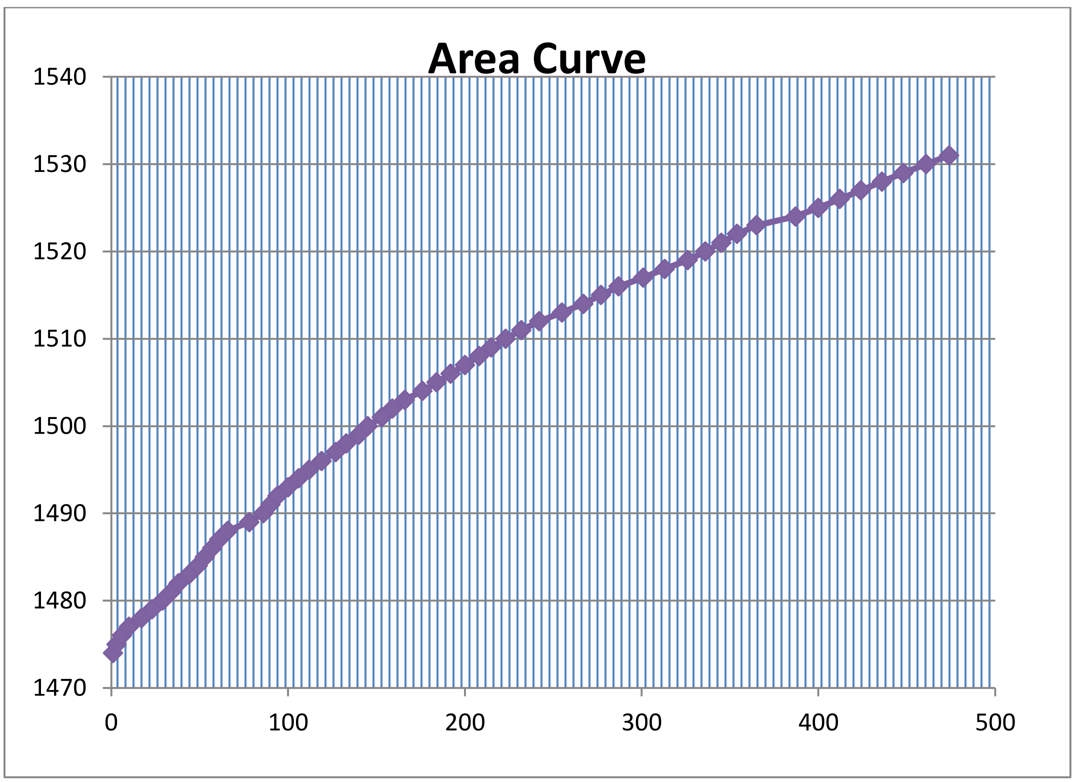


Figure B-2 Elevation-Storage curve for Gololcha reservoir

APPENDIX-C: HEC-ResSim Reservoir Inputs

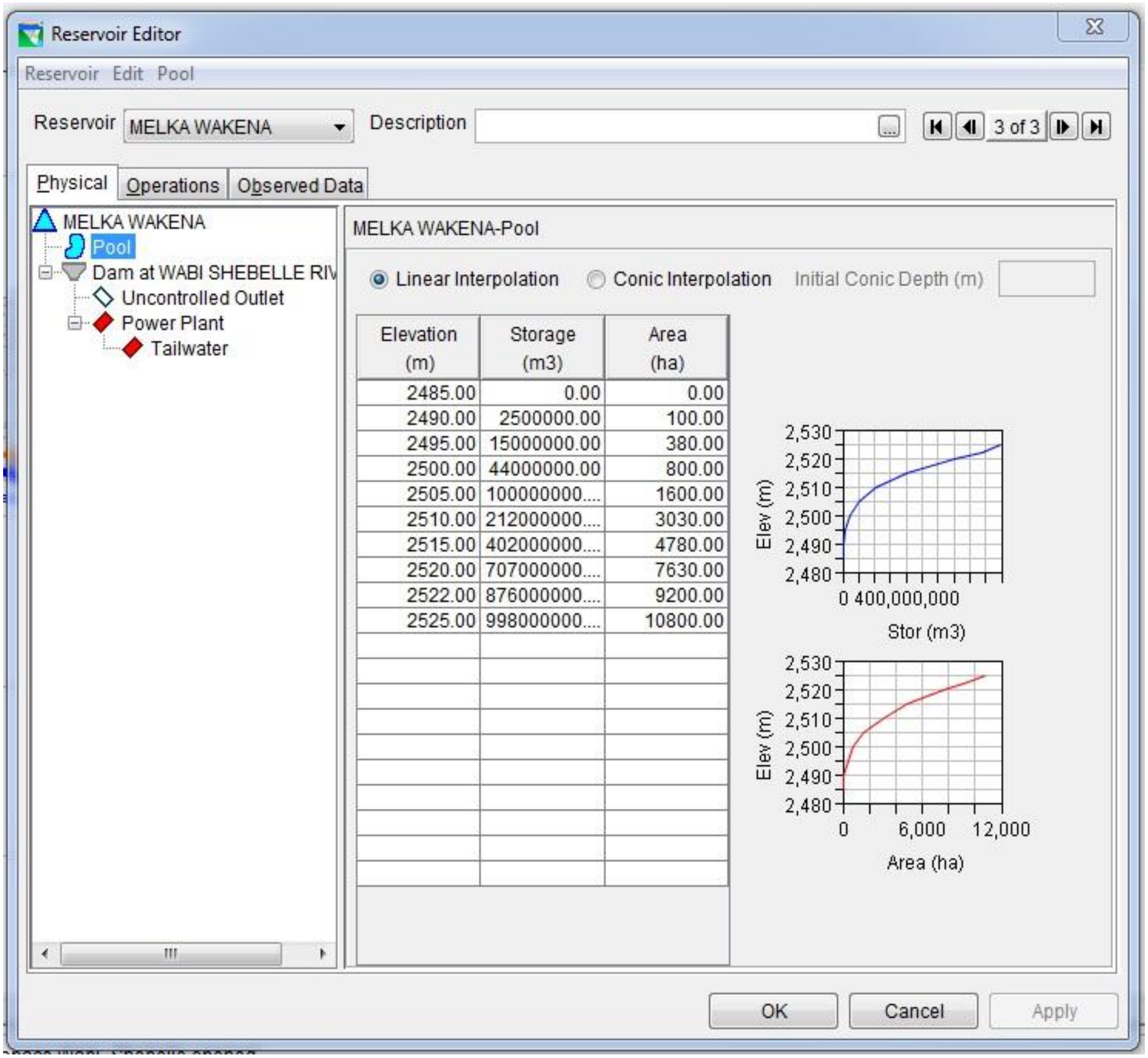
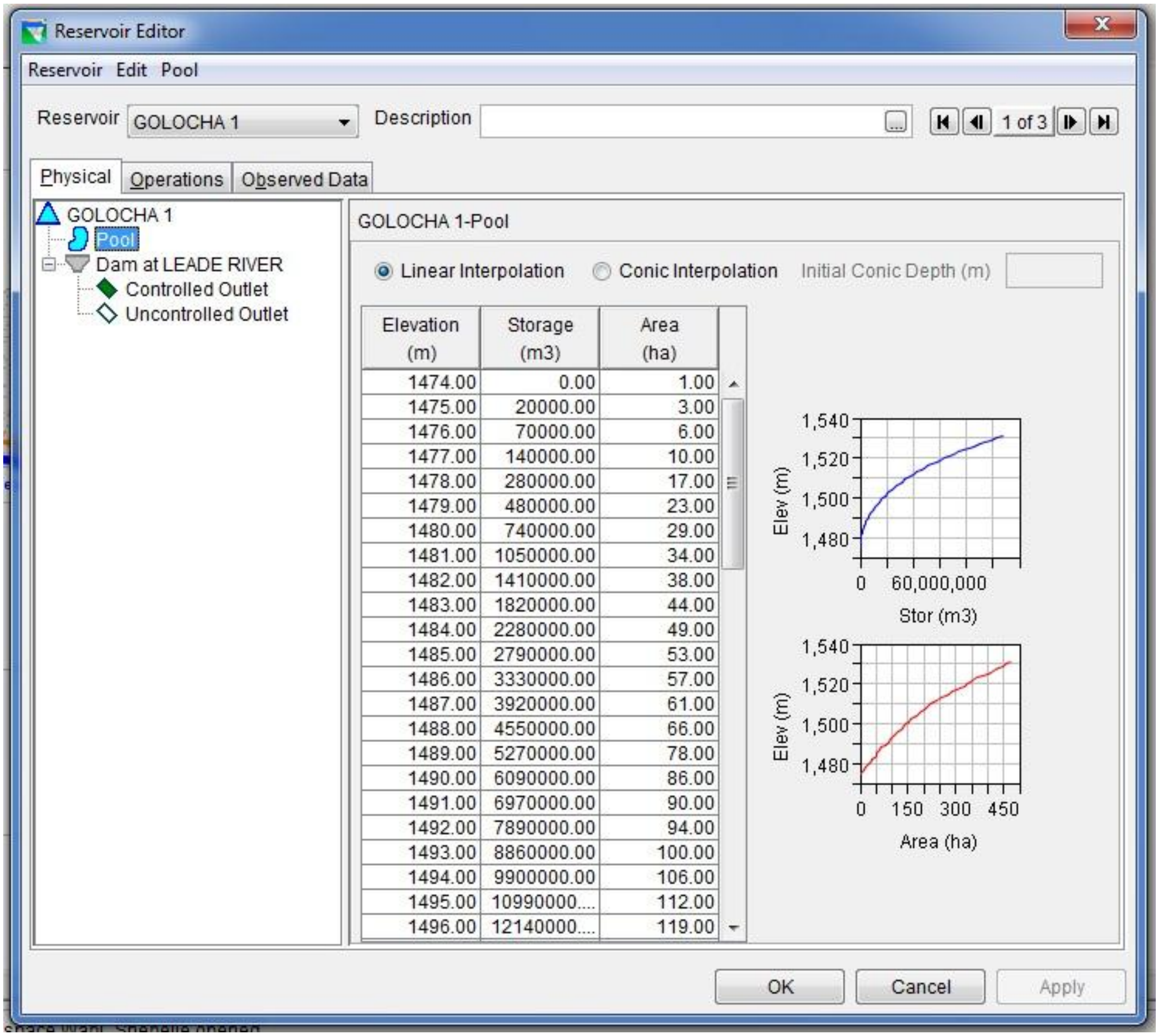


Figure C-1 Elevation –Storage – Area of Melka Wakena



Elevation (m)	Storage (m3)	Area (ha)
1474.00	0.00	1.00
1475.00	20000.00	3.00
1476.00	70000.00	6.00
1477.00	140000.00	10.00
1478.00	280000.00	17.00
1479.00	480000.00	23.00
1480.00	740000.00	29.00
1481.00	1050000.00	34.00
1482.00	1410000.00	38.00
1483.00	1820000.00	44.00
1484.00	2280000.00	49.00
1485.00	2790000.00	53.00
1486.00	3330000.00	57.00
1487.00	3920000.00	61.00
1488.00	4550000.00	66.00
1489.00	5270000.00	78.00
1490.00	6090000.00	86.00
1491.00	6970000.00	90.00
1492.00	7890000.00	94.00
1493.00	8860000.00	100.00
1494.00	9900000.00	106.00
1495.00	10990000....	112.00
1496.00	12140000....	119.00

Figure C-2 Elevation –Storage – Area of Gololcha

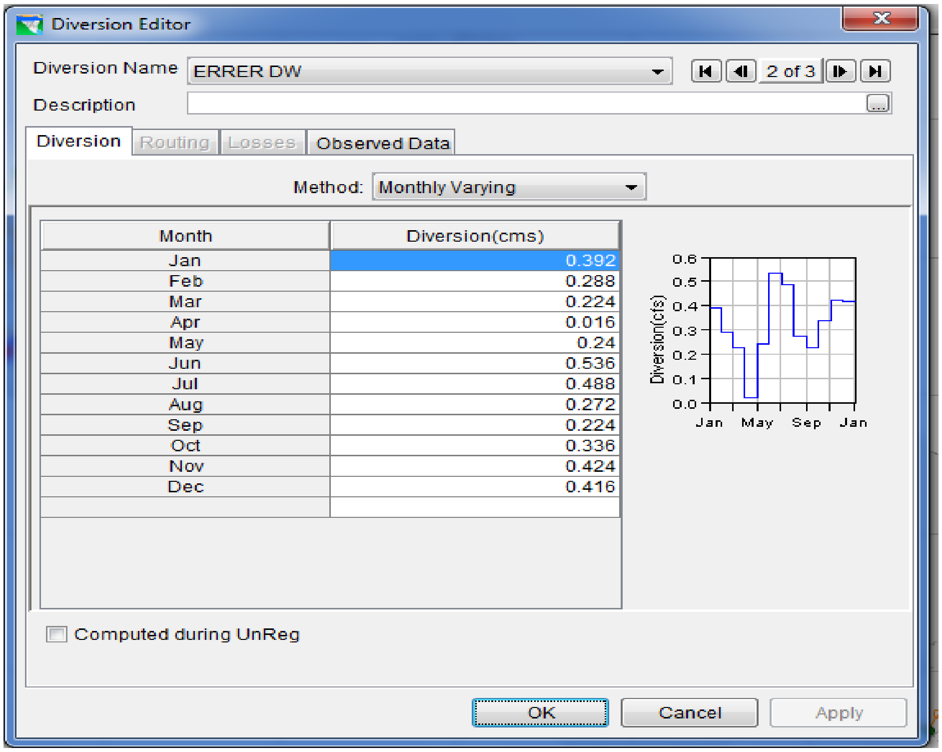


Figure C-3: Erer Irrigation Project diversion

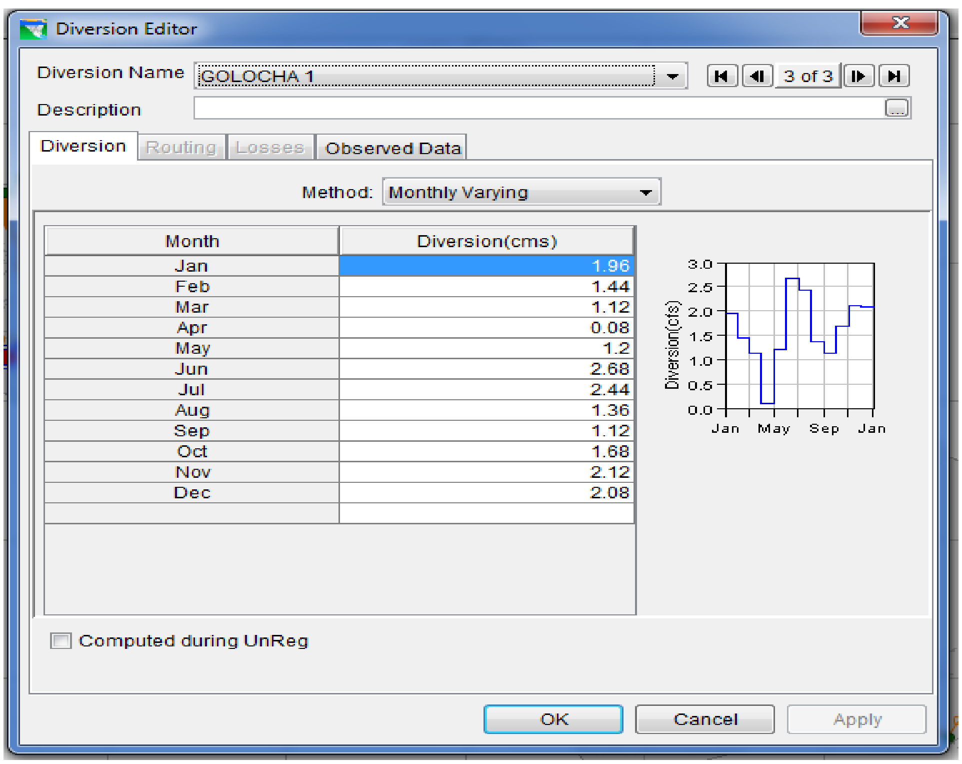


Figure C-4: Gololcha Irrigation Project diversion

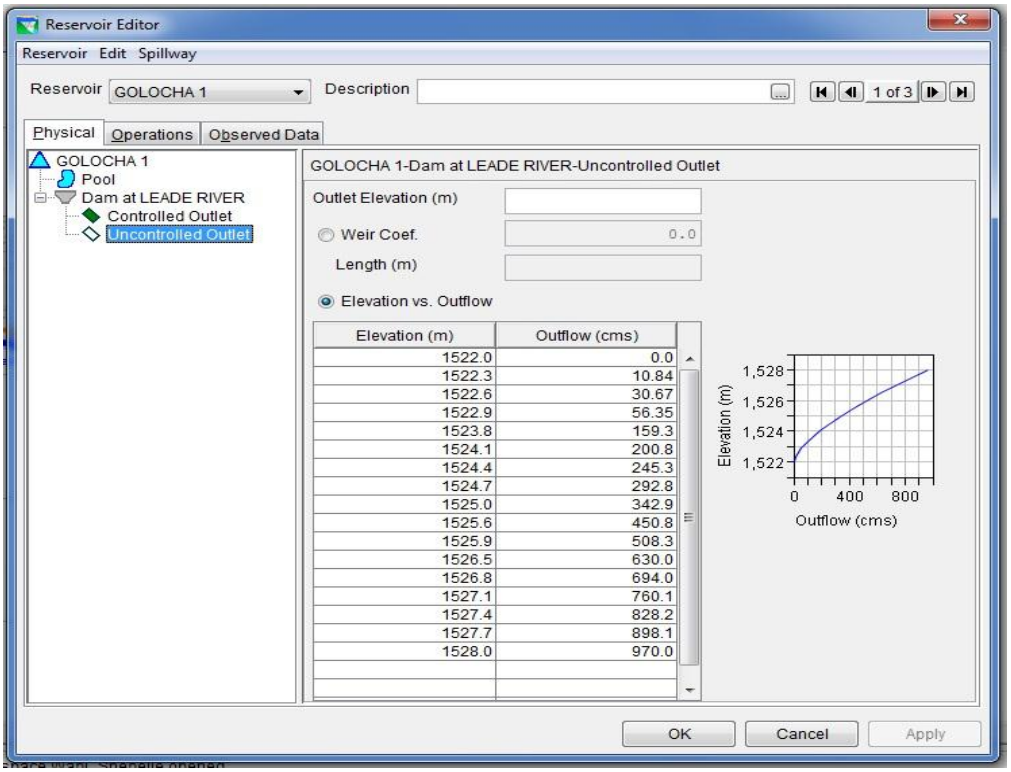


Figure C-5: Gololcha 1 Spillway Elevation –outflow Relation

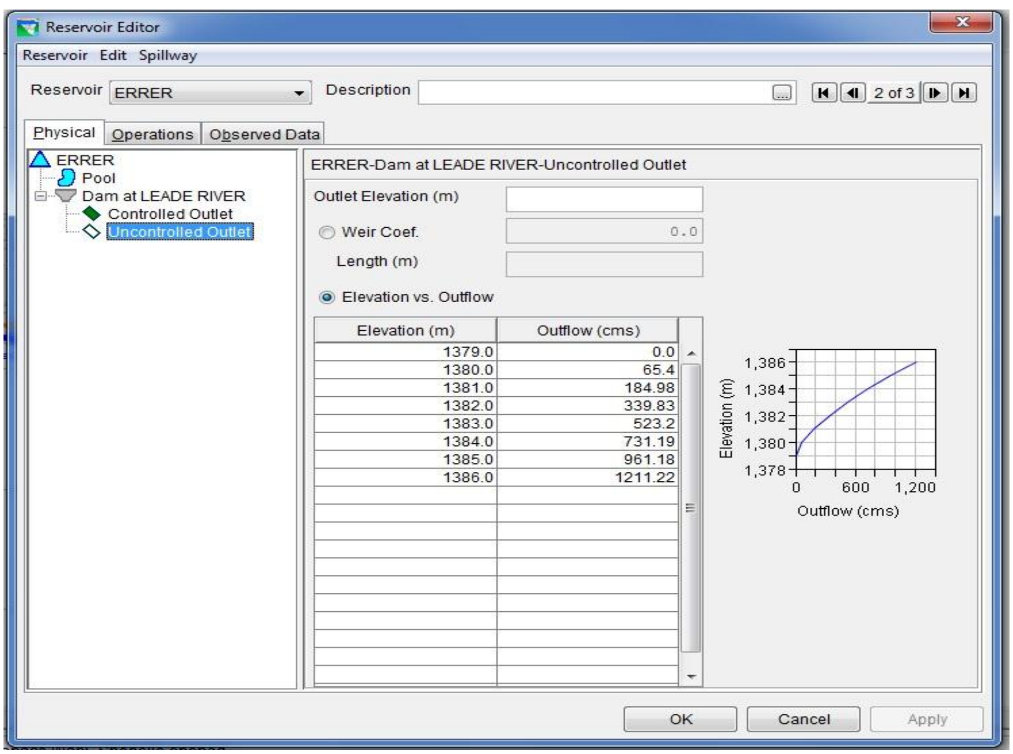


Figure C-6: Erer Spillway Elevation –outflow Relation

APPENDIX - D: Standard Graphic Output Graph from HEC-ResSim Model

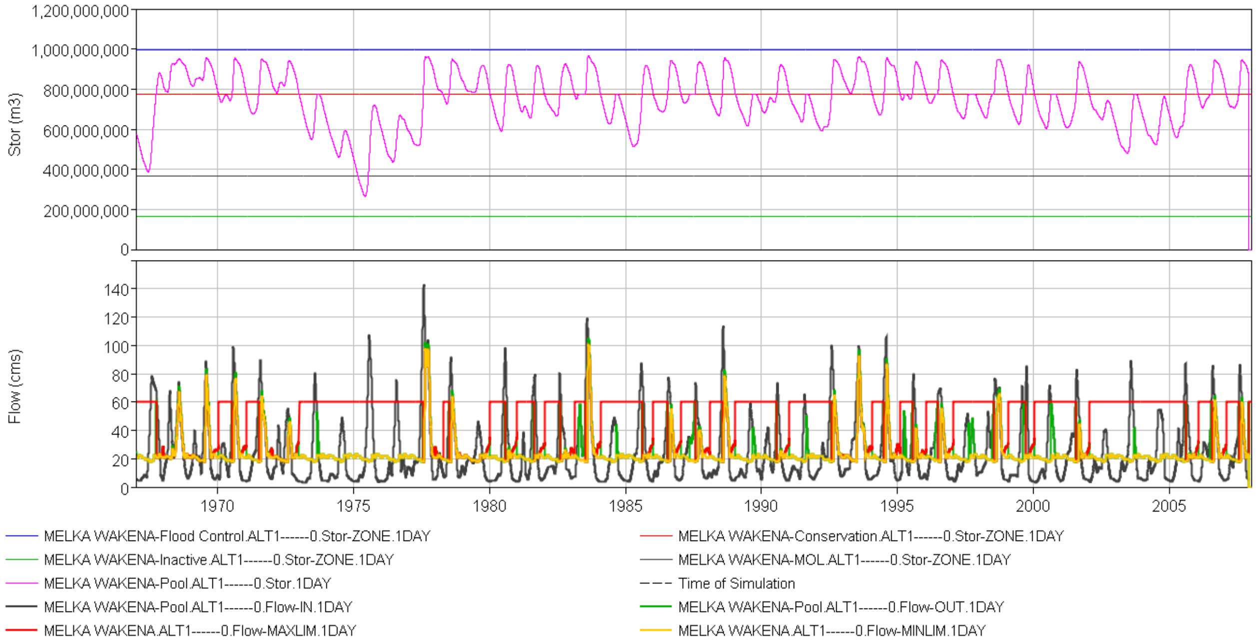


Figure D-1 Operation plot for Melka Wakena hydropower plant.

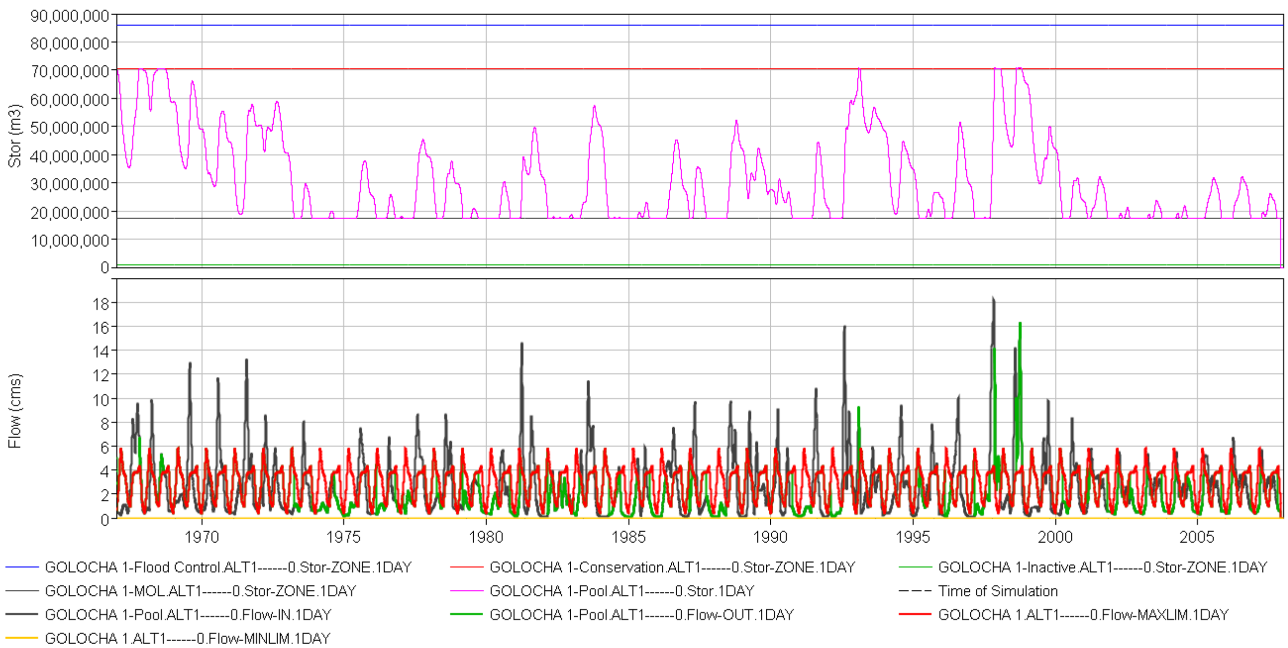


Figure D-2 Operation plot for Gololcha irrigation Project.

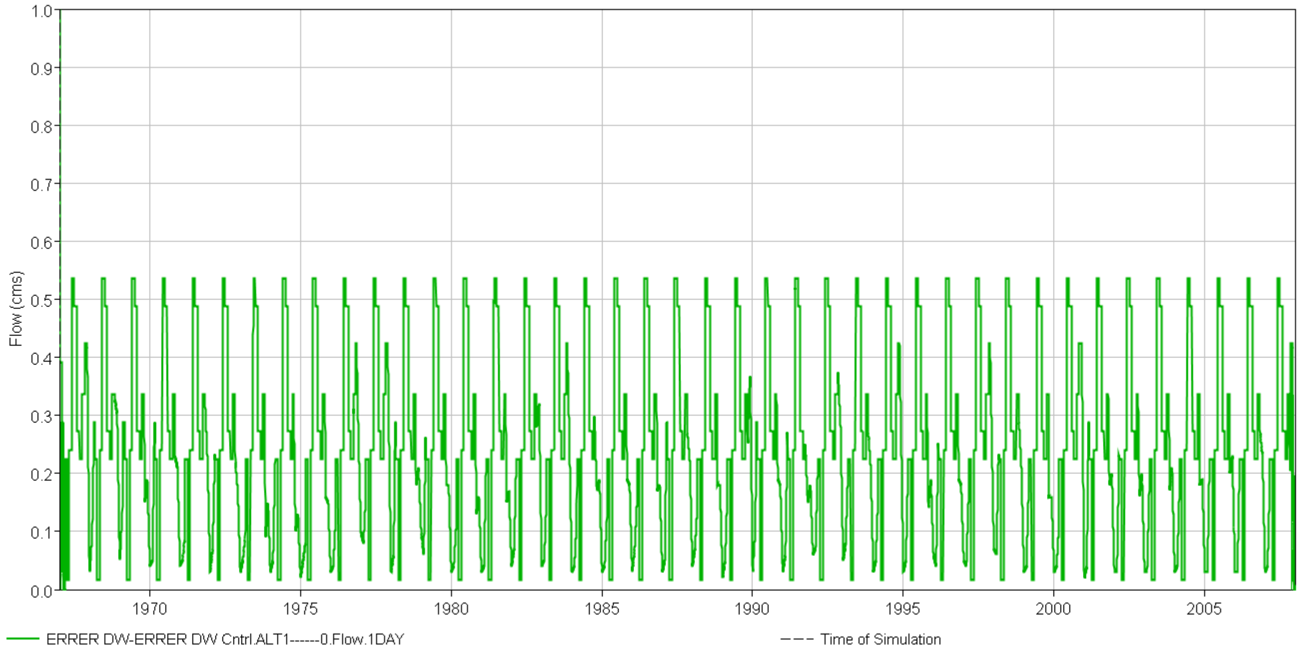


Figure D-3: Diverted water at Erer Irrigation Project by using Hydropower schedule operation Rule power plant.

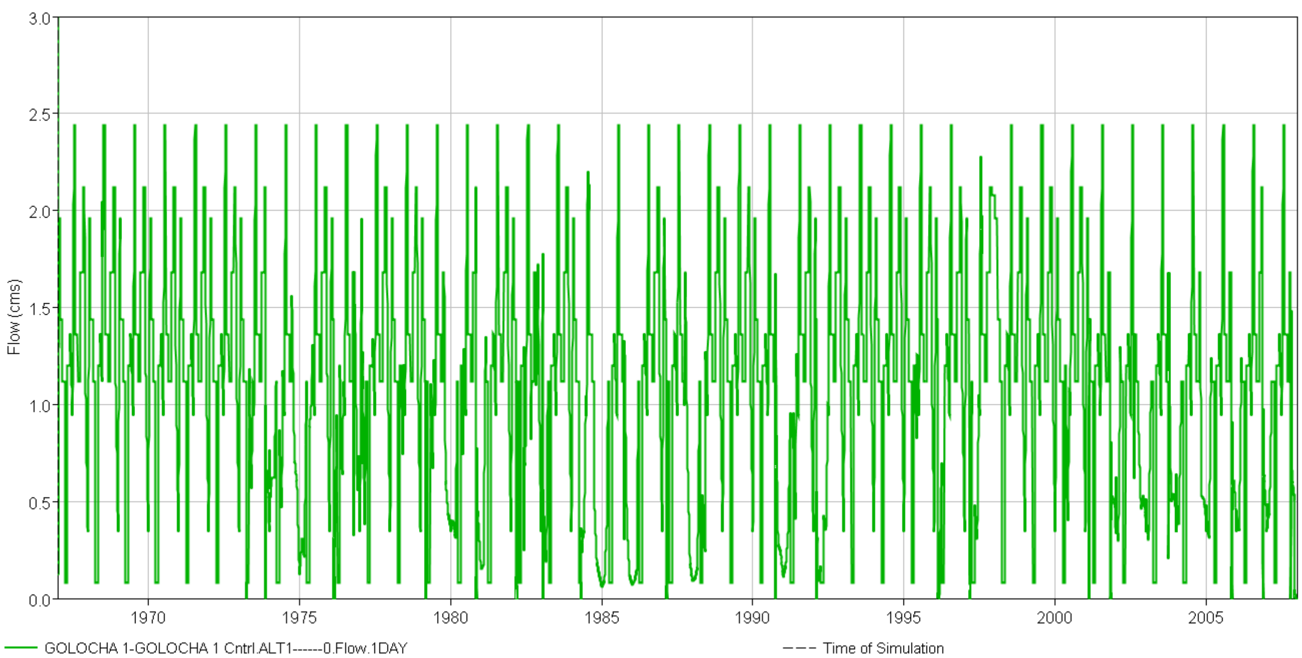


Figure D-4: Diverted water at Gololcha Irrigation Project by using Hydropower schedule operation Rule power plant.

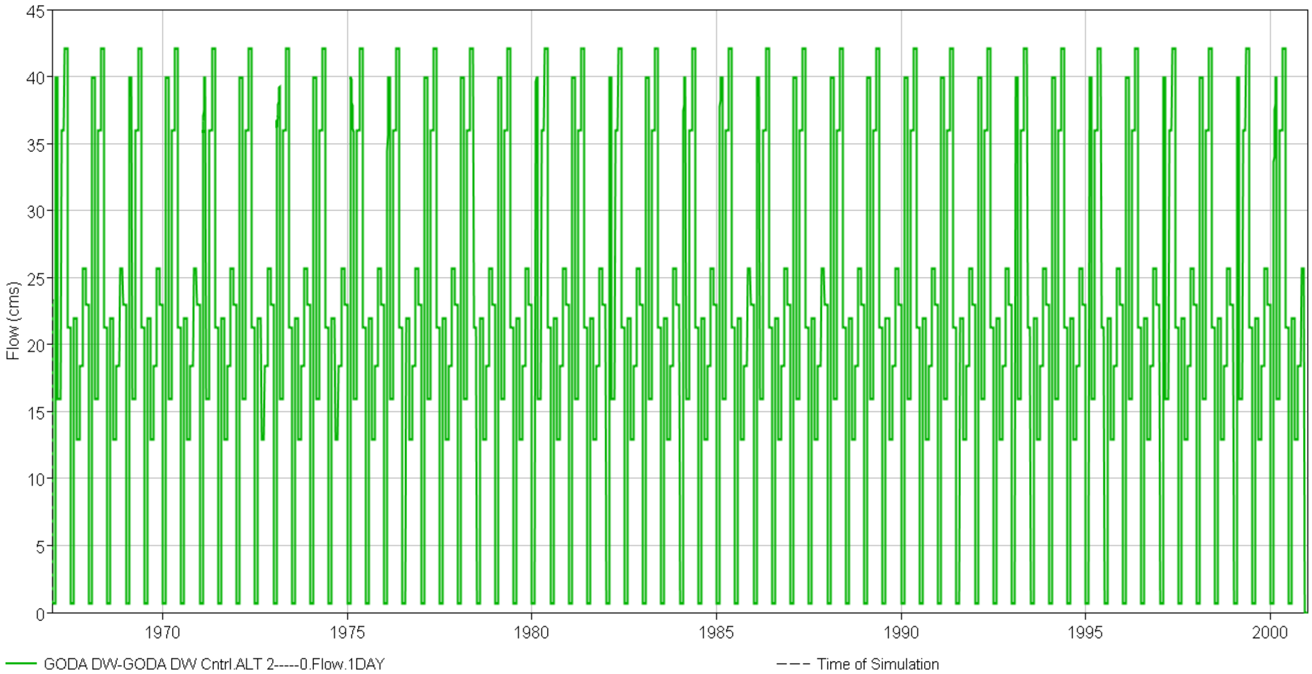


Figure D-5: Diverted water at Gode Irrigation Project by using Hydropower schedule operation Rule power plant.