# Optimal Reservoir Operation Planning of Tekeze Cascade Hydropower Development

A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of Masters of Science in Hydraulics and Hydropower Engineering of Arbaminch University

By Abera Ejigu Akelate

Arbaminch

September 2011

## Certification

The undersigned certify that he has read the Thesis entitled: **Optimal Reservoir Operational Planning Of Tekeze Cascade Hydropower Development** and hereby recommend for acceptance by the Arba-Minch University in partial fulfillment of the requirements for the degree of Master of Science **in Hydraulics and Hydropower Engineering.**

**Dr. Ing. Nigusie Tekle**

(Supervisor)

Date 30/09/11

# APPROVAL PAGE

This thesis entitled with ***"Optimal Reservoir Operational Planning of Tekeze Cascade Hydropower Development"*** has been approved by the following examiners for partial fulfillment of the requirements for the degree of Master of Science in Hydraulics and Hydropower Engineering.

Date of Defense: **October 25, 2011**

Advisor Name

1. Dr. Ing. Nigussie Tekle — Signature — 02/11/2011 Date

Principal Advisor

Members of the Examining board:

1. Dr. Assie Kemal — Signature — 26/10/2011 Date
   External Examiner
2. Prof, Sharma K. — Signature — 26/10/2011 Date
   Internal Examiner
3. Ato Hailay Z. — Signature — 26/10/2011 Date
   Chairperson

Ato Youhannes Hagos — Signature — 04/11/2011 Date

Department Head

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I, Abera Ejigu Akelate, declare that this thesis is my own original work that has not been presented and will not be presented to any other University for similar or any other degree award.

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# ACKNOWELEDGEMENT

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# DEDICATION

*This work is dedicated to*

*My brother Woldie Ejigu*

*And*

*My Sister Yordanos G/Hiewot*

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# ABBREVIATIONS

| | |
|---|---|
| DEM | Digital elevation Model |
| EEPCO | Ethiopian electric Power Corporation |
| $ET_O$ | Potential Evapo-transpiration |
| Fig. | Figure |
| GIS | Geographic information system |
| ENEC-CESEN | Ethopian National Energy Commitee and Centro Studio Energia |
| HEC | Hydraulic engineering center |
| HEC-ResSim | Hydraulic Engineering Center Reservoir Simulation |
| HEC-DSS | Hydraulic Engineering Center Data Storage Service |
| GWh/yr | Giga Watt Hours per year |
| ha | Hectare |
| Km | Kilometer |
| $Km^2$ | kilometer square |
| MoWE | Ministry of water and energy |
| MWR | Ministry of Water Resource |
| Max | Maximum |
| Min | Minimum |
| NEDCO | Netherlands Engineering Consultants |
| CFRD | Concret Face Rockfill Dam |
| MOL | Minimum operating Level |
| Rss | Result Storage System |
| DSS | Data Storage System |

| | |
|---|---|
| Res. | Reservoir |
| a.m.s.l | Above Mean Sea Level |
| mm | Millimeter |
| Mm3 | Million Cubic Meters |
| MW | Mega Watt |
| MWh | Mega Watt Hour |
| ICS | Inter Connected Systems |
| SCS | Self Contained Systems |
| KVAC | Kilo Volt Alternate Cuffent |
| KW | Kilo Watt |
| Cums | Cubic Meter per Second |
| Mcum | Million Cubic Metres |
| USBR | United States Bureau of Reclamation |
| WAPCOS | Water and Power Consultancy Service |
| GMT | Greenwich Mean Time |
| GUI | Graphical User Interface |
| TK_5 | Tekeze Dam at Site 5 |
| TK_7 | Tekeze Dam at Site 7 |
| ITCZ | Inter Tropical Convergency Zone |
| WMO | World Meteorological Organization |
| ELC | Electro Consult Milano |
| EELPA | Ethiopian Electric Light and Power Autority |

# 1 Introduction

## 1.1 Background

Management of water resources has become a major challenge in recent years. Reservoir operation is designed based on the interrelated hydrological, physical, and operational parameters that have direct and indirect relation on the water resource activity to the downstream of the reservoir.

In the next 30 years, water use will increase by 50% in the world. By 2025, about 4 billion people will live under conditions of severe water stress (Gourbesvivelli, 2008). Therefore, development of priority water infrastructures and improvements of water management have essential and complementary roles in contributing to sustainable growth and poverty reduction in developing countries like Ethiopia. One way of improving water management is through increasing efficiency of dam reservoirs. Increasing the efficiency reservoir by using optimal reservoir operation is among the solutions for improvement of hydropower generation.

Reservoir operation is a complex problem that involves many decision variables, multiple objectives as well as considerable risk and uncertainty (Oliveira, 1997). In addition, the conflicting objectives lead to significant challenges for operators when making operational decisions. The application of systems analysis techniques for reservoir management and operations has been a major focus of research in water resources engineering storage capacity and establishing release policy, both at the project planning stage and for real-time operations.

Traditionally, reservoir operation is based on heuristic procedures, embracing rule curves and subjective judgments by the operator. This provides general operation strategies for reservoir releases according to the current reservoir level, hydrological conditions, water demands and the time of the year. Established rule curves, however, do not allow a fine-tuning (and hence optimization) of the operations in response to changes in the prevailing conditions (Ngo, 2006).

An operating plan or release policy is a set of guidelines for determining the quantities of water to be stored and to release or withdraw from a reservoir or system of several reservoirs under various conditions. Operating decisions involve allocation of storage capacity and water releases between multiple reservoirs, between project purposes, between water users, and between timeperiods. Typically, a regulation plan includes a set of quantitative criteria within which significant flexibility exists for qualitative judgment. Operating plans provide guidance to reservoir management personnel. In modeling and analysis of a reservoir system, some mechanism for representing operating rules and/or decision criteria must be incorporated in the model. Reservoir system analysis models contain various mechanisms for making period-by-period release decisions within the framework of user-specified operating rules and/or criteria functions (Wurbs, 2006).

## *1.2 Statement of the problem*

Electricity is a critical economic infrastructure. If not delivered where and when needed, serious damage ensues for the economy. Considerable potential output has been lost due to power cuts in the past few years. Potential losses from power disruption will increase in the future as the economy grows and the relative contributions of the industry and service sectors increase in the economy.

Power supply must increase as rapidly as demand to avoid such losses and to ensure sustained growth. Since the major source of electricity in Ethiopia is hydropower, increasing the power production needs to construct more hydropower dams like the millennium grant dam and improving water management system. One way of improving water management system is increasing the efficiency of utilization of dam reservoirs. Optimal reservoir operation increases the power generation with in the given flow condition. Even small improvement in reservoir operation can lead to large benefits. However, there is no universal Solution for reservoir operation problems (Gebresenbet, 2010). Hence, it is necessary to study the system and determine optimal reservoir operation guides for each scheme.

The river Tekeze is undeveloped until the near past years, although several studies have considered previously its potential as a source of hydropower. The first potential sites for hydropower development were identified in the 1971 Electro-consult study and further considered in the Water Development Master Plan carried out by WAPCOS in 1990.

In addition to the functional hydropower developed at site 5 of Tekeze River (TK_5), Tekeze dam is proposed to build at site 7(TK_7). However, the two dams were selected in different master plan studies. It implies that they are designed as standalone reservoirs. On the other hand, the research efforts to evaluation the developed master plans under updated models and as a system of reservoir are almost none before.

Due to inadequate inflow, head, or any other cause, Tekeze hydroelectric plant (at dam site 5) functions under its capacity even if it has an installed capacity of 300MW. Therefore, it is sensible to see the cascaded operational planning analysis.

## 1.3 Objectives of the Study

### 1.3.1 General Objectives

The main objective carried out in this study is:

To develop the optimal reservoir operational planning of existing and planned hydropower plants at Tekeze River Basin using HEC-ResSim model.

### 1.3.2 Specific objectives

- To establish water release guide rules of Tekeze hydropower schemes.
- To undertake reservoir joint operation that helps in evaluating the best way to utilize the reservoir storage with maximum power production and minimum spill.
- To assess the dam height selection of the proposed (TK-7) dam, among the three design options in the feasibility study.

## 1.4 Location and topographic characteristic

### 1.4.1 Tekeze -basin

Tekeze River Basin is bordered by the Mereb river basin and by Eritrea in the north, the Atbara River plains in Sudan in the west, Abay River in the south, and Danakil basin to the east. Area of the entire Tekeze river basin is about 86,510 $km^2$; a relatively small part of the basin (4,160 $km^2$) is situated in Eritrea. The basin of Tekeze in side Ethiopia has an average elevation of 1,850m a.m.s.l and a catchments area of 59,306 $km^2$. The length of the Tekeze River from its source at springs near Lalibela down to Sudanese border is more than 600km (Ministry of water, May, 1998)

Tekeze River a major tributary of the river Atbara that in turn flows into the Nile downstream of the confluence of the Blue and White Niles at Khartoum. Tekeze Basin is situated in the north of Ethiopia between latitudes 11°40'and 15°12' north and longitudes 36°30' and 39°50' east (Figure 1.1), With a catchments area of 46500 km² at Embamdre and an annual discharge of 4.4 billion m³/year. The topography of the basin is flat and relatively low close to the Sudanese border in the west, and mountainous in the east, where the elevation raises to 4600m in the Simien highlands. The climate is dry with the average annual rainfall of 700 - 1200 mm concentrated in the months June - August. About 90% of the population is occupied in agriculture, mostly subsistence farming (DONKIN, December 1997).

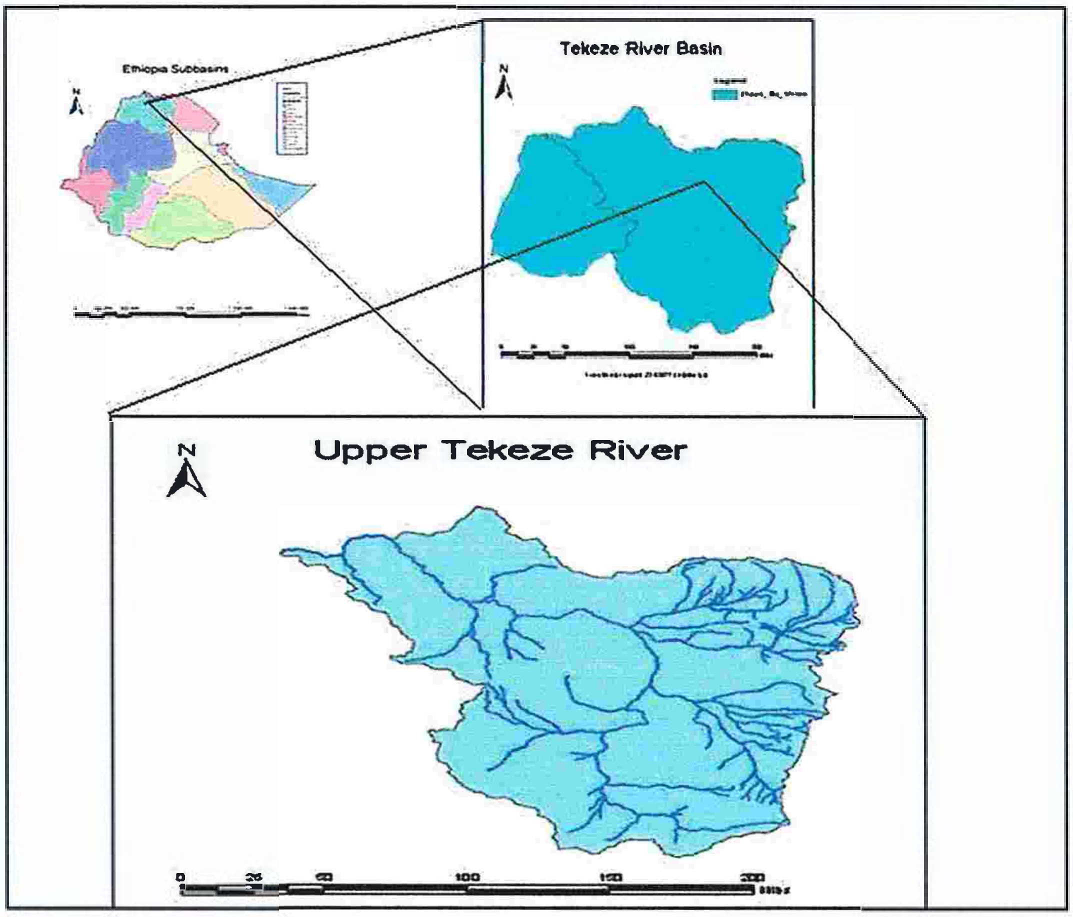


**Figure 1-0-1** Location map of upper Tekeze river sub basin

## 1.5 GEOLOGY

### 1.5.1 Regional Geology of Tekeze basin

The dam sites are located in the north of Ethiopia, on the Ethiopian plateau. The basement of the plateau consists of Precambrian rocks, with various levels of metamorphism. These basement rocks composed mainly of limestone, slates, dolomites and schist, have been folded, stretched and foliated during the Pan African Orogeny (about 500-600 millions years ago).Mesozoic sediments then deposited on the Precambrian rocks before the uplift of the Afro-Arabian dome led to outpouring of flood lavas, know as the Trap series. Following the volcanic activity, during the Oligocene period, started the rifting phase, which is still active (DONKIN, December 1997).

### 1.5.2 Tekeze Dam at Site 5 (TK_5) Geology

The rocks in the dam site area are from the upper member of the Precambrian basement composed of limestone and slates that have been subject to severe tectonic deformation. The dam site itself consists of a steep-sided gorge approximately 350 m deep extending for a distance of some 1.5 km and composed of sub-vertical thinly bedded limestone. The total thickness of the anticline stratigraphic column observed within the gorge exceeds 600 m. The dam axis is located just upstream from the heart of the antic line. The rock quality of the massive to laminated limestone forming the foundation of the dam can be stated as good, in terms of shear strength and elastic module. In addition, no significant and penetrative weathering has been observed so far. The foundations are expected to be adequately strong to support a high arch dam and underground excavations for the waterways and the powerhouse (DONKIN, December 1997).

### 1.5.3 TK_5 Reservoir Geology

Owing to the nature of the rocks constituting the future reservoir (slates and marls) and to the deep seating of the river below the plateau, it is considered that the water tightness of the reservoir is effective and that the potential leakage has to be controlled in the close vicinity of the dam. The presence of karsts, though limited, in the limestone forming the entrance of the gorge, is a matter of consideration, which will be carefully monitored through the investigations (DONKIN, December 1997).

### 1.5.4 Tekeze Dam at Site 7 (TK_7) Geology

The lower recourse of Tekeze River with site TK_7 features a wide valley with gentle slopes representing potential for embankment dam. The geotechnical conditions favor a rock fill dam of maximum 100m height with a crest length 670m and abase width of about 150m with medium slopes ($30^0 - 45^0$) at both abutments. Of concern could be the fact the alternation of basalt tuff of the site is ultra basic Meta bolcanites. However, the bedrock seem to be stable .river sediments are available in big quantity for aggregates.

## *1.6 Climate Season of Tekeze Basin*

Two season types dominate the region, which is west of the Simien Mountains, wet and dry. The wet season in this region has about four months from June to September. The region, which is east of the Simien Mountains, is characterized in three seasons as follow.

**Bega;** this is generally the dry season that covers the period from October to January. However, there is occasionally untimely rain.

**Belg;** refers to a small rainy season that covers the period from mid-February to mid-May. However, the rainfall is highly characterized by inter-annual and inter-seasonal variations.

**Kiremt;** this refers to main rainy season that covers the period from June to September. The dates mentioned above are only relative.

# 2 Literature review

## *2.1 Hydropower development, potential and status in Ethiopia*

### 2.1.1 Hydropower development

Even though there is no recorded history, the use of waterpower in Ethiopia in its non-electrical form is estimated to exist since long period. It has been used in water mills and such practice still exists in some rural areas of the country. The use of water for power generation came to existent since 1930's, when Aba-Samuel hydropower scheme is commissioned in 1932, (Sileshi, 2004). By the time, (2010) The Inter-Connected Systems (ICS) consist of 11 hydro, one geo-thermal, and 15-diesel power and the Self-Contained Systems (SCS) consists of three small hydro and many isolated diesel plants, which are located all over the country.

The number of electrified towns and villages which are highly increased for the last five years of the strategic plan period and have reached to a total number of 5163. Even though it is below the planed, it has brought the electric energy access to 41% (Fig. 2-1).

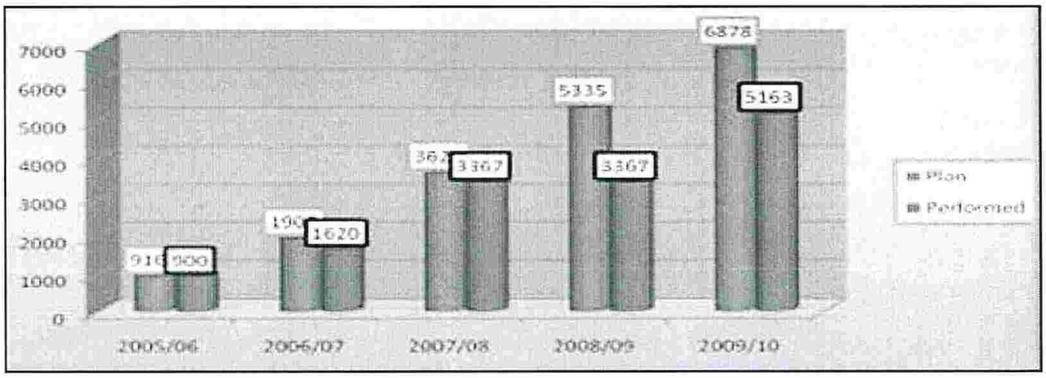


Figure 2-1 Planed and performed number of electrified towns &villages source (EEP-CO)

The Number of customers is those who are connected to get electric energy. The total number of connected customers at present has reached 1,896,265, which are higher than the current billed customers are. The number of customers who are connected in the ICS and SCS of EEPCo is depicted as Fig.2-2.

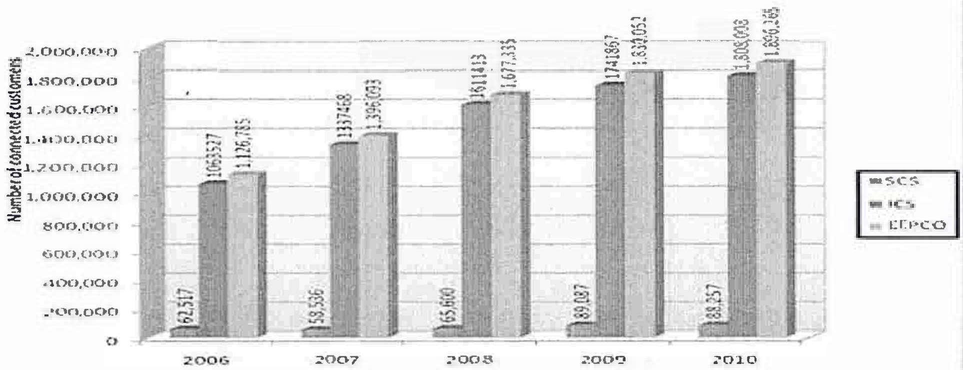


Figure 2-2 Connected customers of EEPCO by system (source EEPCO)

### 2.1.2 Hydropower potential and status

Ethiopia has the potential to become one of the largest power exporters in Africa. The long-term marginal cost of developing this generating capacity is around US$0.04 per kilowatt-hour, significantly below that of neighboring countries, which gives Ethiopia comparative competitive advantage in this area. If there were no barriers to developing and trading Ethiopia's hydropower, the country would have the potential to export more than 26 Tera watt-hours of electricity per year. This would be second only to the Democratic Republic of Congo, which has obtained from exports; this would generate annual net revenue of US$263 million for Ethiopia, or around two percent of existing GDP (Afri ca Infrastructure CountryDiagnostic (AICD), 2010).

The country is endowed with vast riches of water resources, including 12 major river basins and 12 natural and artificial lakes. The total annual surface runoff, regardless of its distribution, is estimated to be about 122BCM3, of which 75% drains to neighboring countries. 2.50 BCM3 of usable ground water is estimated not yet exploited much.

Ethiopia has a significant hydropower potential. According to recent studies, the hydropower potential is estimated to be 159,300 GWh/year (Appendix-B, Table B-1). This is estimated to be 97.5 times more than current production (ENEC-CESEN, 1986), (WAPCOS, 1990) (MWR, 1997_2008). In 2009/10, the energy production of the country was about 3,981.07 GWh, of which hydropower comprised 92.26 percent.

At the end of the Ethiopian fiscal year (July, 2009/2010) the ICS consists of 11 hydro, one geothermal and 15 diesel power plants with a total capacity of 1842.6 MW, 7.3 MW and 172.3 MW respectively. Among these, 60 MW diesel capacities are rented to cover the shortage of energy deficit for the fiscal year. The SCS consists of three small hydro and many isolated diesel plants that are located all over the country with a capacity of 6.15 MW and 31.34 MW respectively (Appendix-B, Table B-1 & Table B-2).

### 2.1.3 Present and Committed Generating Capacity

Existing and planned energy projects were drawn from the Ministry of Water Resources' Water Sector Development Plan (WSDP) and basin master plans and the Ethiopian Electric Power Corporation long-term development plans. The vast majority of these represent hydropower sources, with some alternatives (wind and geothermal) considered. Figure 2.1 illustrates the approximate spatial location of hydropower projects (Bloc, January 27, 2010).

Two development plans are considered: the first is based on published reports and targets 13 Giga Watts (GW) installed by 2030 and 17 GW by 2050. The second plan, newly proclaimed, is much more ambitious, aiming for installations of 20 GW by 2030 and 30 GW by 2050. Table B-4 in Appendix-B outlines the first development plan, including anticipated power, year of commissioning, and project costs adjusted to 2010 US dollars (Bloc, January 27, 2010). Table B-5 in Appendix-B outlines the second, more ambitious development plan. Alternatives of wind and energy are also explicitly included, although the timing of their installation has been assumed (Bloc, January 27, 2010).

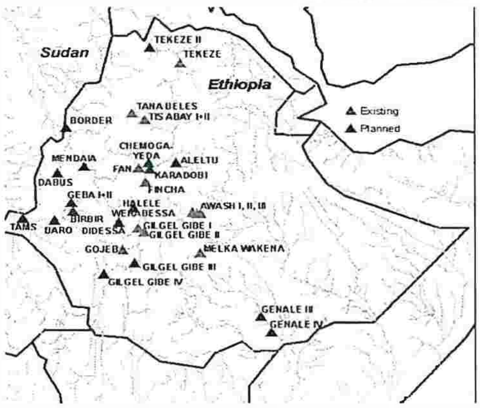


Figure 2-3 Existing and planned hydropower projects considered

## 2.2 *Previous Studies in the Basin*

### 2.2.1 Study by ELECTRO CONSULT (1971)

The National Water Resources Commission engaged Electro-consult to carry out an Evaluation Study of the water resources potential in the northern river basins, including that of Tekeze. The report was submitted in 1971. The scope of the study was to consider climate and hydrology, of previous projects and studies future projects in the context of both the physical and social environment and that of the prevailing regional economy.

### 2.2.2 Study by Hunting's (1974)

This study was carried out by Hunting in 1974. The study covered all aspects of the Tigrean rural economy including agriculture, forestry, and livestock and recommended several rural development projects. The study collects and analyses the climate and hydrometrical data available at that time and outlines several irrigation and rural water supply schemes.

### 2.2.3 Study by WAPCOS (1990)

Water and Power Consultancy Services (WAPCOS), (India) Ltd, undertakes the Preliminary Water Resources Development Master Plan for Ethiopia. WAPCOS submitted their report in 10 volumes in June 1990.

The Master Plan covered all aspects of water resource development, including domestic, agricultural and industrial use, hydropower, navigation, flood control, environmental aspects and fisheries, in the whole of Ethiopia,

The Master Plan identified ten potential hydropower sites on the Tekeze River with' technical potential' energy of 5588 GWh/year

### 2.2.4 Study by NEDECO (1995)

The Water Resources Development Authority commissioned NEDECO to carry out an integrated development master plan for Tekeze river basin and the reconnaissance phase report of which was submitted in October 1995. The Master Plan was intended to encompass all development sectors: agriculture, livestock, and fisheries, utilities including hydropower and water supply, transport, tourism and industry. To accomplish this wide range, an overview was to be taken of the natural resources, both physical and human, of the basin, and of the prevailing environmental and socio-economic conditions. In this study TK05, TK06 and TK07 were described in detail.

## 2.3 *TK_5 Hydropower Scheme (Functional)*

### 2.3.1 Background

A feasibility study carried out in 1997, investigated 6 potential dam sites and the one , designated TK_5, was selected, at coordinates 13° 21' North and 38° 45' East, approximately 80 km west of the town of Mekele. The dam is located in a steep, narrow gorge, which the river has carved through the surrounding plateau during the course of many millions of years. The powerhouse is located in an underground cavern, excavated in the rock on the downstream side of the dam, adjacent to the right bank of the river at an altitude of EL. 957m above mean sea level, whereas the crest of the dam is 1145m above sea level (DONKIN, December 1997).

### 2.3.2 Salient Feature

Tekeze Hydropower Project is comprised of a double curvature (logarithmic spiral) concrete arch dam. The appurtenant works consist of two river diversion tunnels, 75m high power intake structure, power waterways (headrace tunnels, vertical pressure shaft, manifold, and four steel lined penstocks and four tailrace tunnels). The powerhouse is underground and contains four 75MW Francis turbines, outlet works, a 230kV substation, and105 km long double circuit transmission line connecting to the Ethiopian national grid at Mekele (Appendix-C, Table C-1).Tekeze Arch Dam ranks as the highest dam in Africa. Tekeze dam is 188 meters high, eclipsing the previous record height for an African dam of 185 meters held by the Katse Arch Dam, in Lesotho (DONKIN, December 1997)

### 2.3.3 TK-7 hydropower scheme (proposed)

According to Tekeze river basin integrated development master plan project from 21 sites the one, designated Tk-7, was selected, at coordinates 13° 46' 00'' North and 38° 00' 00''East, near to Embama town. The storage capacity of the proposed highest dam is 9661Mm$^3$ with 5298Mm$^3$live storage. The dam height is 158m and the available head is 153m. The second maximum possible dam TK_7B with a gross storage capacity of 6027Mm$^3$,width to height ratio of 6.5 and the presence of a saddle offering an excellent location for a separate spillway (Appendix-C, Table C-2). A CFRD type was chosen because no evidence of sufficient core material was found so far (Ministry of water, May,1998).

## 2.4 Reservoir operation

Reservoir operation is a complex task involving numerous hydrological, technical, economical, environmental, institutional, and political considerations. It is difficult to find general algorithm that covers all type of reservoir operation problems. The choice for techniques usually depends on the reservoir specific system characteristics, data availability, the objectives specified and the constraints imposed (Bosona, 2004).It is important to utilize the existing reservoirs efficiently by re-evaluating and improving the reservoir management. However, there is no universal solution for reservoir operation problems. Therefore, it is important to study the problems and determine optimal reservoir operation guides for each scheme.

A number of studies have been found simulation to be one of the most practical and effective problem analyzing and solving techniques. A simulation can be defined as hypostatical operation of a system under certain conditions (Estuti and Lipovszki, 1997). The fields of computational hydraulics and hydrology are well researched, and many models and algorithms are already implemented to solve different aspects of hydrological systems (Abbott, 1993).Use of a computer is mandatory for system simulation in most cases. Researchers can choose any of several ways to solve a mathematical model by a computer. It is also possible to use the application programs, which have been written for such specific fields as HEC-ResSim (Klipsch, 2003) for reservoir simulation. These programs are useful for those who intend to work in the specific field that the program can handle.

## 2.5 Reservoir system analysis models

Systems analysis models are commonly categorized as being either descriptive or prescriptive. Descriptive models demonstrate what will happen if specified decisions are made. Prescriptive models determine what decisions should be made to achieve a specified objective. Simulation models are descriptive. Optimization techniques are prescriptive. However, a descriptive reservoir system simulation model may incorporate an optimization algorithm. The academic research community in particular and many practitioners as well, have been extremely enthusiastic about optimization, in the sense of mathematical programming techniques, applied to reservoir operation problems. The characteristics of certain reservoir operation problems are ideally suited for applying linear and dynamic programming and various other nonlinear programming algorithms. Research results, case studies, and limited experience in application of optimization models in actual planning and real-time operation decisions appear to indicate a high potential for improving reservoir operations through their use. However, optimization techniques have played a relatively minor role compared to simulation models concerning to influence decisions made in the planning and operation of actual projects (Ralph.W, January 1991).

### 2.5.1 Simulation model

Simulation model is a representation of a system used to predict the behavior of the system under a given set of conditions. Simulation is the process of experimenting with a simulation model to analyze the performance of the system under varying conditions. Models for simulating reservoir operations are basic analysis tools regardless of whether the application involves sizing storage capacities and establishing operating policies for proposed new reservoir projects, supporting real-time operating decisions, or analyzing proposed modifications to the operation of existing reservoirs. A reservoir system simulation model reproduces the hydrologic and, in some cases, economic performance of a reservoir system for given inflows and operating procedures. A simulation model is based on a mass-balance accounting procedure for tracking the movement of water through a reservoir-stream system. The model typically computes reservoir storage levels, releases, and discharges at pertinent stream locations for specified sequences of hydrologic inputs (stream flow and reservoir evaporation rates), demands for releases or withdrawals for beneficial purposes, and operating rules. Constraints such as storage capacities, outlet and conveyance capacities, and requirements for maintaining minimum stream flows, are also reflected in the models (Ralph.W, January 1991).

### 2.5.2 Optimization Models

Optimization (mathematical programming) algorithms systematically and automatically search through all feasible decision policies (sets of values for the decision variables) to find the decision policy which minimizes or maximizes a defined objective function. Mathematical programming methods provide useful capabilities for analyzing problems characterized by a need to consider an extremely large number of combinations of values for decision variables (Ralph.A, April 2005).

### 2.5.3 Combination of Optimization and Simulation Models

Optimization and simulation may be effectively used in combination. Jacoby and Loucks (1972) investigated several strategies for combining optimization techniques with simulation models. Preliminary screening with an optimization model may be used to develop a manageable range of alternative decision policies for further detailed analysis with a simulation model. Likewise, an optimization model may search for an optimum decision policy while activating a simulation model to compute the objective function value for any given set of decision variable values. Many complex simulation models also contain optimization algorithms to perform certain functions. HEC-ResSim contains an iterative search algorithm to determine flood control releases for each time interval during the simulation, following user specified operating rules. HEC-ResSim contain firm yield optimization options which automate the iterative search for the diversion or in stream flow requirement which just empties the storage capacity of a single reservoir or multiple reservoir system (Ralph.A, April 2005).

HEC-3 and HEC-5 are the most widely recognized and often cited of the numerous simulation and optimization models developed to analyze reservoir operations. HEC-3 and HEC-5 have probably been applied to more reservoir systems in more studies than any other single computer program (Ralph.A, April 2005).

The development ofHEC-ResSim, which can,

- Represent the physical system as *realistically* as possible.
- Reproduce the decision-making process that reservoir operators use to set releases.
- Support Multi-Purpose Operation Schemes
  - Represent both Flood Control Constraints & Conservation Goals
  - Support low flow & drought operation
  - Support environmental restoration investigation

HEC-ResSim is the successor of HEC-5 as the Corps's reservoir simulation model (Ralph.A, April 2005).

## 2.6 *Review of Reservoir/River System simulation Models*

### 2.6.1 General

The following review focuses on generalized models that have been applied by water management agencies to support actual planning and/or operations decisions. The models listed in Tables 2-1 are representative of current modeling capabilities and have a record of successful application by water management agencies in support of actual decision-making. Water management agencies and their consultants to major reservoir systems have extensively applied these models over many years to support complex decision processes. (Ralph.A, April 2005).

**Table 2-1** Reservoir/river system simulation models, descriptions model developer

| Short Name | Descriptive Name | Model Development Organization |
|---|---|---|
| HEC-5 | Simulation of Flood Control and Conservation Systems | USACE Hydrologic Engineering Center http://www.hec.usace.army.mil/ |
| HEC-PRM | Prescriptive Reservoir Model | USACE Hydrologic Engineering Center http://www.hec.usace.army.mil/ |
| ARSP | Acres Reservoir Simulation Program | Acres International, BOSS International http://civilcentral.com/html/arsp_tech_info.html |
| WEAP | Water Evaluation and Planning | Stockholm Environment Institute, http://weap21.org |
| SUPER | SWD Reservoir System Model | USACE Southwestern Division http://www.swd.usace.army.mil/ |
| HEC-ResSim | Reservoir System Simulation | USACE Hydrologic Engineering Center http://www.hec.usace.army.mil/ |

### 2.6.2 HEC-5

The *HEC-5 Simulation of Flood Control and Conservation Systems* program has been used in many Corps and non-Corps studies, including investigations of storage reallocations and other operational modifications at existing reservoirs as well as feasibility studies for proposed new projects.

HEC-5 simulates the sequential period-by-period operation of a multiple-purpose reservoir system for inputted sequences of unregulated stream flows and reservoir evaporation rates. Multiple reservoirs can be located in essentially any stream tributary configuration. The program uses a variable time interval. For example, monthly or weekly data might be used during periods of normal or low flows in combination with daily or hourly data during flood events. The user specifies the operating rules in HEC-5 by inputting reservoir storage zones, diversion, and minimum in stream flow targets, and allowable flood flows. The model makes release decisions to empty flood control pools and to meet user-specified diversion and in stream flow targets based on computed reservoir storage levels and stream flows at downstream locations (Ralph.A, April 2005).

### 2.6.3 HEC-PRM Prescriptive Reservoir Model

The HEC Prescriptive Reservoir Model (HEC-PRM) is a network flow-programming model designed for prescriptively oriented applications. Improved network flow computational algorithms have been developed in conjunction with the model.

HEC-PRM applications to date have used a monthly time interval with historic period-of-record stream flows. Unlike most of the other simulation models discussed in this review, HEC-PRM performs the computations simultaneously for all the time intervals. Thus, model results show a set of reservoir storages and releases which would minimize cost (as defined by the user-inputted penalty functions) for the given inflow sequences assuming all future flows are known as release decisions are made during each period. Since in the real-world, future stream flows are not actually known when a release decision is made, the model provides an upper limit or best possible scenario on what can be achieved (Ralph.A, April 2005).

### 2.6.4 Acres Reservoir Simulation Program ARSP

The ARSP network flow programming based model simulates multi-purpose, multi-reservoir systems. Operating policies are defined by prioritizing water demands. Monthly, weekly, daily, or hourly time steps may be used. The software assigns upper and lower bounds and cost functions to the network flow paths for the network flow programming formulation based on the input provided by the user. ARSP has been extensively applied over many years by Acres International and others for both long-term planning and operations studies of reservoir/river systems throughout the world (Ralph.A, April 2005)..

### 2.6.5 Water Evaluation and Planning (WEAP) Modeling System

The USACE Hydrologic Engineering Center has funded enhancements to the model. WEAP has been used in studies throughout the world conducted by United Nations agencies, the U.S. Agency for International Development, and other organizations. WEAP is a reservoir/river/use system water balance accounting model that allocates water from surface and groundwater sources to different types of demands. The modeling system is designed as a tool for maintaining water balance databases, generating water management scenarios, and performing policy analyses (Ralph.A, April 2005)..

### 2.6.6 SWD SUPER Modeling System

The South Western Division (SWD) of the U.S. Army Corps of Engineers (USACE) developed SUPER model. SUPER is a system of computer programs designed to simulate the daily sequential regulation of a multipurpose system of reservoirs and the corresponding hydrologic and economic impacts (Hula 1981; USACE Office of the Chief of Engineers 1985)? A simulation reflects a specified regulation plan, economic parameters, and long sequences of daily flows and net reservoir evaporation rates. Multiple simulations are performed to compare alternative variations in regulation plans. Simulation results include stage or discharge hydrographs for each reservoir and river control point, which may also be integrated with economic benefit functions (Ralph.A, April 2005)...

### 2.6.7 HEC-ResSim Modeling System

Development of the Hydrologic Engineering Center (HEC) Reservoir System Simulation (ResSim) Model was initiated in 1996 in conjunction with the Hydrologic Engineering Center's Next Generation Software Development Project. HEC-ResSim will eventually replace the *HEC-5 Simulation, Flood Control, and Conservation Systems* model, which has been extensively applied for over 20 years.

ResSim is comprised of a graphical user interface, a computational program to simulate reservoir operation, data management capabilities, and graphics and reporting features. Multipurpose multi reservoir systems are simulated using ad hoc algorithms coded specifically for the model rather than formal mathematical programming methods. The user selects the time-step, which may vary from 15 minutes to one day. Various routing options are provided. Features provide flexibility for detailed representation of reservoir system operating rules. Meeting the needs of USACE reservoir control personnel for real-time decision support has been a governing objective in developing HEC-ResSim. The model is also applicable in planning studies. The full spectrum of multiple-purpose reservoir operations is modeled (Ralph.A, April 2005).

## 2.7 *Reservoir Operation Procedures*

### 2.7.1 General

Optimizing reservoir operations which essentially mean designing operating rules, which best fulfill specified objectives and making real-time release decisions within the framework of the operating rules. A regulation procedure or release policy is a set of rules for determining the quantities of water to be stored, released, or withdrawn from a reservoir or system of several reservoirs under various conditions. Operating decisions involve allocation of storage capacity and water releases between reservoirs, between uses, and between periods. Operation procedures are needed to provide guidance to reservoir operation personnel. In modeling and analysis of a reservoir system, a set of operating decision rules must be incorporated into the model. Typically, an Operation plan involves a framework of quantitative rules within which significant flexibility exists for qualitative judgment. Day-to-day operating decisions may be influenced by a complex array of factors and often are based largely on judgment and experience. Regulation procedures may change over time with experience and changing conditions (Wurbs, January 1991).

### 2.7.2 Reservoir Pools

Reservoir operating policies are based on dividing the total storage capacity into designated pools or vertical zones. A typical reservoir consists of one or more of the zones, or pools, illustrated by Figure 2-4.

Water releases or withdrawals are normally not made from the inactive pool, except through the natural processes of evaporation and seepage. The top of inactive pool elevation may be fixed by the invert of the lowest outlet or, in the case of hydroelectric power, by conditions of operating efficiency for the turbines. An inactive pool may also be contractually set to facilitate withdrawals from outlet structures, which are significantly higher than the invert of the lowest outlet structure at the project.

Conservation purposes, such as municipal and industrial water supply, irrigation, navigation, hydroelectric power, and in stream flow maintenance, involve storing water during periods of high stream flow and/or low demand for later beneficial use as needed. The reservoir water surface is maintained at or as near the designated top of conservation pool elevation as stream flows and water demands allow. Drawdowns are made as required meeting the various needs for water.

The flood control zone remains empty except during and immediately following a flood event. The crest of an uncontrolled emergency spillway often sets the top of flood control pool elevation, with releases being made through other outlet structures (Wurbs, January 1991).

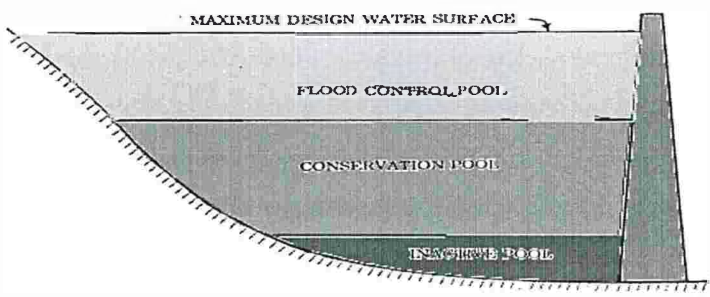


Figure 2-4 Different pool zones

### 2.7.3 Operation Rule (Guide) Curve

The term rule curve (guide curve) is used to refer to elevations which define ideal (desirable or target) storage volumes and provide a mechanism for release rules to be specified as a function of storage content. Rule curves are typically expressed as water surface elevation or storage capacity 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.

The top of conservation pool is varied seasonally at many reservoirs, particularly in regions with distinct flood seasons. The seasonal rule curve illustrated by Figure 2-5 reflects a location in which the summer months are characterized by high stream flows.

The top of conservation pool could conceivably be varied as a function of watershed conditions, forecasted inflows, and storage in other system reservoirs as well as season of the year. A seasonally or otherwise varying top of conservation pool elevation defines a joint use pool, which is treated as part of the flood control pool at certain times, and part of the conservation pool at other times (Wurbs, January 1991).

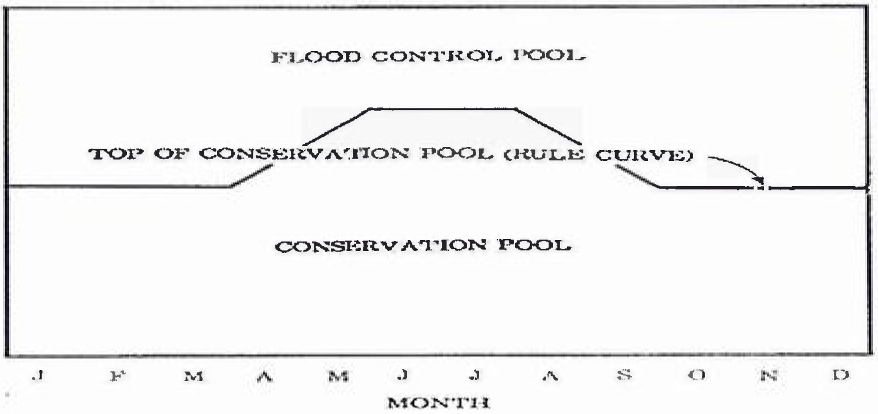


**Figure 2-5** Seasonal top of conservation pool

## 2.8 *HEC-ResSim Environment for Model Building*

### 2.8.1 General

HEC-ResSim is the successor to the "HEC-5, Simulation of Flood Control, and Conservation Systems" program (HEC, 1998). It is comprised of a graphical user interface (GUI), a computational program to simulate reservoir operation, data storage and management capabilities, and graphics and reporting facilities. The Data Storage System, HEC-DSS (HEC, 1995 and HEC, 2006b) is used for storage and retrieval of input and output time-series data.

ResSim has three sets of functions called modules that provide access to specific types of data within a watershed. These modules are watershed setup, reservoir network, and simulation (Figure 2-6). Each module has a specific purpose and an associated set of functions accessible through menus, toolbars, and schematic elements. The purpose of the *watershed setup module* is to provide a common framework for watershed creation and definition among different modeling applications. Several HEC models share this module. The *reservoir network module* allows the user to construct a river schematic, describe the physical and operational elements of the reservoir system, and develop alternatives to be analyzed. The *simulation module* is used to configure and perform a simulation and review the results. The graphical user interface allows construction of a reservoir/river system schematic by point-and-click selecting and connecting of icons. Watershed, reservoir network, and simulation data are represented visually in a georeference context with interactions with associated data.

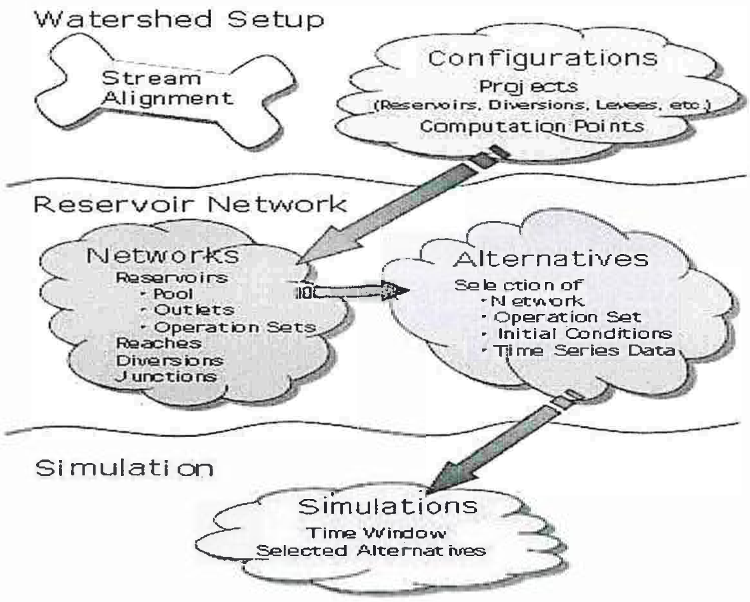


Figure 2-6 Basic modeling features available in each module ofHEC-ResSim

### 2.8.2 Concept of HEC-ResSim in reservoir System

When a tandem or parallel reservoir system is defined, the model determines the priority and the amount of release to make from each reservoir in order to operate towards a storage balance. For every decision interval, an end-of-period storage is first estimated for each reservoir based on the sum of beginning-of-period storage and period average inflow volume, minus all potential outflow volumes. The estimated end- of-period storage for each reservoir is compared 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 storages are recomputed. Depending on other constraints or higher priority rules, system operation strives for a storage balance such that either the reservoirs have reached their

Guide Curves or they are operating at the desired storage (percent of the active storage zone).

### 2.8.3 Tandem Operation Rule

A Tandem Operation rule establishes a tandem system operation where an upstream reservoir operates for a downstream reservoir to achieve a storage balance. Unlike the Downstream Control rule (which is the only other rule type used for system operation and must be included in the operation sets of all reservoirs in the system), the Tandem Operation rule is created and included in the operation set at the upstream reservoir only. The Tandem Operation rule simply identifies the downstream reservoir that is the object of tandem operation. An implicit (default) storage balance scheme is invoked by the Tandem Operation rule, and an optional explicit (user-defined) storage balance scheme can be defined and used instead of the default.

### 2.8.4 The implicit system storage balance

The default method in ResSim for determining the desired storage balance in a reservoir system is referred to as the implicit method. This method applies to both tandem and parallel system operations. The implicit method is automatically used when a reservoir system is established by using a common Downstream Control rule either in two or more parallel reservoirs, or by adding a Tandem Operation rule to an upstream reservoir, which operates for adown reservoir.

The implicit system storage balance takes into account the System Storage (the total storage from the reservoirs in the system). Additionally, this default scheme considers only one System Zone, the System Guide Curve (Sys G.C.) storage, which amounts to the sum of both reservoirs' conservation storages. The desired storage for each reservoir is determined through an implicit "balance line.“ The balance line is simply a linear relationship between storage at each reservoir and the system storage. For each reservoir, the balance line hinges on the intersection of the reservoir's Guide Curve (G.C.) storage and the System Guide Curve (Sys G.C.) storage. For system storage less than the System Guide Curve storage, the balance line has a lower limit that corresponds to empty storage at the reservoir versus empty system storage, and the upper limit corresponds to Guide Curve storage at the reservoir versus System Guide Curve storage. For system storage greater than the System Guide Curve storage, the lower limit of the balance line corres-

ponds to Guide Curve storage at the reservoir versus System Guide Curve storage and the upper limit corresponds to full storage at the reservoir versus full system storage.
In the implicit system operation, a release decision made for a particular time may not necessarily balance. The reservoirs in the system are considered "in balance when both reservoirs have reached their Guide Curves, or they operating at equivalent storage levels in terms of percentage of their counterpart system storage zones.

At the end of each decision interval (i.e., end-of-period), the desired storage for a reservoir corresponds to a point on the balance line that coincides with the sum of the estimated storages for both reservoirs. When the total estimated storage from both reservoirs is less than the System Guide Curve storage, the corresponding desired storages represent an equal percentage of the storage below the Guide Curve at each reservoir. When the total estimated storage from both reservoirs is greater than the System Guide Curve storage, the corresponding desired storages represent an equal percentage of the storage above the Guide Curve at each reservoir. If one of the reservoirs is below its desired storage and the other is above, unless other constraints in the operation set rules restrict releases and have higher priority than the system operation rule, the reservoir above its desired storage would increase its releases in order to drop its pool to the desired storage. Moreover, the reservoir below its desired storage would stop releasing from its outlets according to the restriction in operation set rules.

### 2.8.5 Explicit System Storage Balance Method

The user-defined method in ResSim for determining the desired storage balance in a reservoir system is referred to as the explicit method. This method can be used for an established reservoir system whether tandem or parallel. The implicit scheme by default develops balance line at each reservoir and (System Guide Curve).A customized desired storage balance can be made by introducing inflection points to the balance lines within each system zone. Inflection points would transform the implicit balance line into an explicit curve. The inflection points allow the slope of the line, or the relationship between individual reservoir storage and system storage, to vary. An unlimited number of balance line inflection points could be add within each system zone to further refine and shape the desired balance distribution. Like the implicit system, Reservoir, which is above its desired storage, receives the priority to release for this period in order to reduce its storage. Unless other constraints restrict releases and have higher priority than the system operation rule. On the other hand, reservoir, which is below its desired storage, is forced to cut back its releases for this particular period so that its storage can rise, as close as possible, to the desired level. If there were no higher priority rules that require a release, the Reservoir below its desired storage would not make a release from its outlet(s).

The reservoirs are considered " in balance " when both reservoirs have reached their Guide Curves or are operating at the desired storages levels along their balance line curves as prescribed in the explicit storage balance scheme. Similar to the implicit system operation, the explicit system operation is carried out each period when system rules are in effect. The process of determining desired storages is repeated every decision interval in order to assign the priority for release to the reservoir that is farthest above the desired storage.

# 3 METHODOLOGY AND DATA ANALYSIS

## *3.1 Methodology*

### 3.1.1 General

It should be recognized early in the analysis that for the simulation to be representative of the real system, considerable data will be necessary. The availability of this data will directly influence both how well a particular model will be able to represent the real system. Three types of information are necessary: data characterizing the physical components; data describing the hydrology& meteorology; and data delineating the operating criteria and system requirements (Decade, June 1977).

It was indicated in the first chapter that, the main objective of the study is to develop the optimal reservoir operational planning to improve the hydro power plant systems in Tekeze River using HEC-ResSim simulation model. The methods used include desk study and data collection from Tekeze river basin integrated development master plan project report and *Tekeze medium hydropower project feasibility report final version.* Data is collected from institutions such as Ministry of water resource, national meteorological agency, and Ethiopian electric power corporation. After collecting the necessary data for the research filling of missed data, quality checking and open water evaporation loss analysis have been made.

### 3.1.2 Flow chart

Flow chart is a skeleton of any work. To achieve objective of the study different type of data have been collected from respective organizations and master plan prepared for the study area. Data obtained from these sources are analyzed and made ready as model set up input in the model configuration. After data configuration and model set up data have been inserted, simulation was performed and results are discussed. Based on the results and objectives of the study different conclusions and recommendations are set. The flow chart is designed to show all these steps clearly (Figure 3.1).

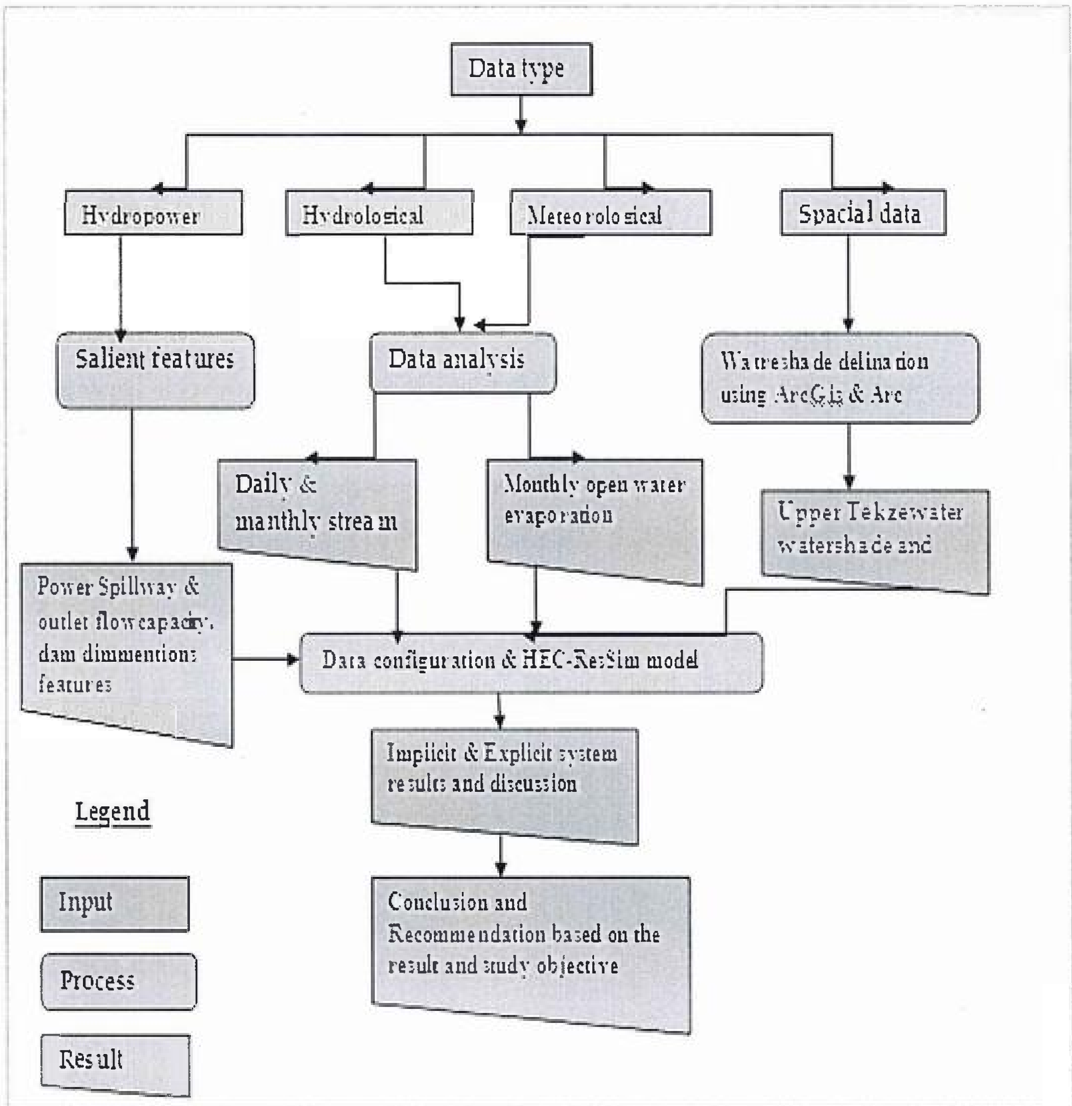


**Figure 3-1** Flow chart of the study

### 3.1.3 Material Used

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

## 3.2 Data collection and analysis

### 3.2.1 General

The initial step in data collection involves determining the time and recording interval for which data are available, the form of the data, the availability, continuity, and locations in the system. The next step is filling the missed data, checking homogeneity of the stations and putting the necessary data in the form required for simulation. This sub topic identifies and discusses the types and source of data required for the study, and their analysis.

### 3.2.2 Hydrological Data Analysis

The most important data required for this research is the long-term daily stream flow record. The hydrological data made available comes from ministry of water and energy (MoWE), Tigray regional state water, and energy bureau and from different reports, which have been done their projects on Tekeze river basin.

Due to the civil war and improper working of the hydrometric stations, there are records with missed data for longer than 27 years and months in a given year. There are about 18 hydrometric stations in the Upper Tekeze river sub basin. However, most of the stations are not working properly. Out of 18 stations, only the record of three stations was available with a maximum of 10 years continuous daily record from MoWE and Tigray regional state water and energy bureau. The hydrometric stations obtained are summarized (Table 3.1)

**Table 3-1** Hydrological stations list, location (recording length and available data)

| Station Number | River | Near by town | Location | | Area ($km^2$) | Total Records (years) | Number records with missing (years) |
|---|---|---|---|---|---|---|---|
| | | | Latitude | Longitude | | | |
| 121006 | Tekeze | Nr. Embamadre | 13d44'n | 38d12'e | 45694 | 42 | 24 (1978-1991&2004-2011) |
| 121004 | Gheba | Nr. Mekele | 13d36'n | 39d23'e | 2449 | 44 | 24 (1978-1991&2003-2011) |
| 121022 | Tekeze | Nr. Yechila | 13d21'n | 38d45'e | 28,152 | 17 | 7 (2004-2011) |

#### *3.2.2.1 Filling of missed stream flow records*

Whenever data missing and insufficiency exists, some information transfer techniques that can be appropriate for filling the missed observations and extending records, such as area ratio, average value, and regression methods, are used. In this study at least ten years flow data are intended to undertake the planned optimal reservoir operational planning. However, there is no suitable long-term record available in Tekeze catchments for correlation with Embamedre and Yachila. Filling of daily missed flow data of above 5 days were conducted by developing correlation between Yachila and Embamdre them selves, for common data period.

The missed data up to 5 days gap was filled by arithmetic mean method. The correlation was taken by dividing the year in to high flow and low flow months (Fig.D-1 to D-4 in Appendix- D). Some times, due to small-scale irrigation and some unknown reasons in the area the observed flows at Embamdre are less than the observed flows at Yachila during November to May. The relations used to fill are summarized as Table 3.2 below. Results after filling missed data are shown in Appendix-A Table A-1 and Table A-2.

**Table 3-2** Regression Equation used for filling missed data

| S.no | Station to be filled ($Q_1$) | Friend station ($Q_2$) | Regression Equation developed | Correlation coefficient | Remark |
|---|---|---|---|---|---|
| 1 | 121006(Embamadre) | Yechila | $Q1= 7.03*Q_2^{0.682}$<br>$Q1= 5.73*Q_2^{0.9}$ | 0.892<br>0.6 | June to Octo-<br>Nov. to May |
| 2 | 121022(Yechila) | Embamadre | $Q1= 0.14*Q_2^{1.308}$<br>$Q1= 0.61*Q_2^{0.9}$ | 0.892<br>0.6 | June to October<br>Nov. to May |

#### *3.2.2.2 Transposition of data to TK_5 and TK_7 dam site*

Direct stream flow observations are not available at most of sites for which discharge time relationship are required. Therefore, technique is needed for transferring flow characteristic from gauged site to not gauged site (Admasu.G, 2000).

To determine the discharge at the inlet of each reservoir, stream flow data was transferred to the site of interest using area ratio methods (eq.3-1 and eq.3-2).

$$Q_{TK\_5} = [A_{TK-5} / A_{Yachila}]^n * Q_{Ychila} \quad \text{.............................. 3-1}$$

$$Q_{TK\_7} = [A_{TK-7} / A_{Embamedre}]^n * Q_{Embamedre} \quad \text{......3-2}$$

Where:

| | |
|---|---|
| $Q_{TK\_5}$ | Discharge at TK_5 reservoir inlet |
| $Q_{TK\_7}$ | Discharge at TK_7 reservoir in let |
| $Q_{Ychila}$ | Discharge at Yachila gauging station |
| $Q_{Embamedre}$ | Discharge at Embamedre gauging station |
| $A_{Embamedre}$ | Drainage area at Embamedre gauging station |
| $A_{Yachila}$ | Drainage area at Yachila gauging station |
| $A_{TK-5}$ | Drainage area at the TK_5 reservoir inlet |
| $A_{TK-7}$ | Drainage area at the TK_5 reservoir inlet |
| n | Varies between 0.6-1.2 |

If the area ratio is within 20% i.e. (0.8< $A_{TK-5}/ A_{Yachila}$ >1.2) then n= one to be used. The same is true for TK_7. The estimated discharge at the site will be within 10% of actual discharge (S.B.Awlabachew, 2000).

The area ratio between Yachila station and TK_5 in let is 1.08 and that of Embamdre and TK_7inlet is 1.04. By using the above relation ship, monthly discharges at TK_5 and TK_7 in let points are determined from Yachila and Embamedre gauging stations respectively. The transposed values are shown in Appendix-A Table A-3 and Table A-4.

### 3.2.3 Meteorology Data Analysis

#### *3.2.3.1 General*

The meteorological analysis is based on relevant data supplied by the Meteorological Institute and existing information from previous studies. The data processing has been limited to monthly open water evaporation and rainfall to assess the reservoir net evaporation.

#### *3.2.3.2 Rainfall*

Monthly rainfall data of 11 stations have been collected from the National Meteorological Agency of Ethiopia. Mekele airport and Sheri Endeselasie are, among the class one with better continues data, stations located near TK_5 and TK_7 dams respectively. The average monthly point rainfall data obtained from these stations are used for the reservoir net open evaporation calculation (i.e. open water evaporation - rainfall on the reservoir). The rest stations have been used to fill the missing data and to check the consistency of the two stations

#### *3.2.3.3 Estimating missing rainfall data*

Measured precipitation data are important to many problems in hydrologic analysis and design. Because of the cost associated with data collection, it is very important to have complete records at every station. Obviously, conditions sometimes prevent this. For gages that require periodic observation, the failure of the observer to make the necessary visit to the gage may result in missing data. Vandalism of recording gages is another problem that results in incomplete data records, and instrument failure because of mechanical or electrical malfunctioning can result in missing data. Any such causes of instrument failure reduce the length and information content of the precipitation record. (McCuen, 1989)

Like the stream, flow data it is difficult to find continues data. From the data, collected only years 1992 to 2008 are continuous and used for analysis. A number of methods have been proposed for estimating missing rainfall data. The normal-ratio method is used for this study. The normal-ratio method is preferable when the average annual catches differ by more than 10%.

The general normal-ratio formula for computing is

$$PX = \frac{Nx}{n}\left(\frac{P1}{N1} + \frac{P2}{N2} + \ldots\ldots\ldots + \frac{Pn}{Nn}\right) \ldots\ldots\ldots 3\text{-}3$$

Where,

*PX* Missing value of precipitation to be computed

*Nx* Average annual value of rainfall for the station in question for recording period

*N*1 Average annual value of rainfall for the neighboring station for recording period

*P*1...*Pn* Rainfall of neighboring station during missing period

$n$ = Number of stations used in the computation

The monthly average rainfall graph of Mekele airport observa and Sheri Endeselasie is as Figure 3-4 and 3-5 respectively. The values are attached in Appendix-A, Table A-5, and A-6.

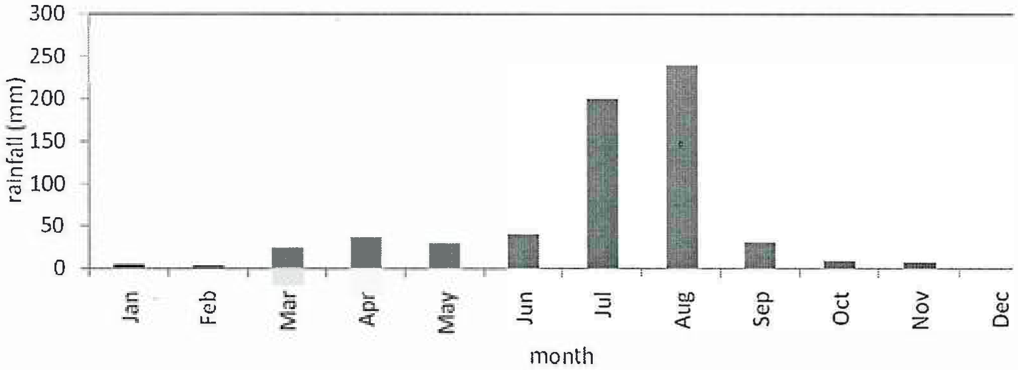


Figure 3-2Mean Monthly Rainfalls at Mekele Airport Observa Station

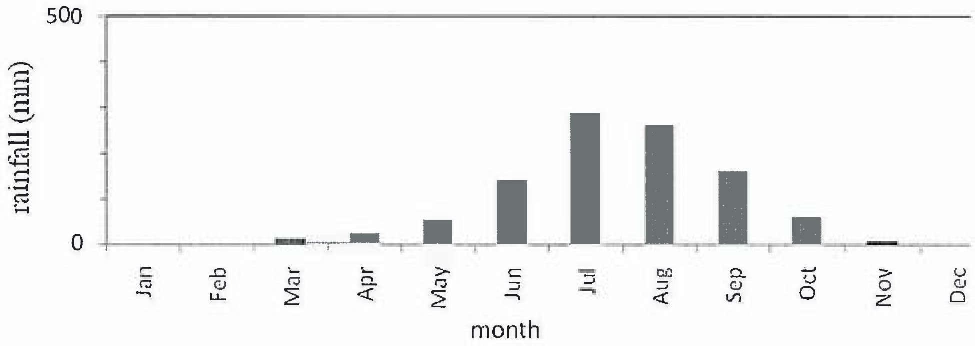


Figure 3-3Mean Monthly Rainfalls at Shire Endeselasie Station

#### *3.2.3.4 Checking Consistency and Homogeneity*

Estimating missing data is one problem that hydrologists need to address. A second problem occurs when the catch at rain gages is inconsistent over a period and adjustment of the measured data is necessary to provide a consistent record. A consistent record is one where the characteristics of the record have not changed with time. An inconsistent record may result from any one of a number of events; specifically, adjustment may be necessary due to changes in observation procedures, changes in exposure of the gage, changes in land use that make it impractical to maintain the gage at the old location, and where vandalism frequently occurs (McCuen, 1998).

**Double mass curve**

Double-mass-curve is drawn using annual cumulative catch at the rain gage interest versus the annual cumulative catch of three gages in TK_7 and four gages in TK_5 region that have been considered as they are subjected to similar meteorological occurrences. The accumulated totals of the gauge in question are compared with the corresponding totals. If significant change in the regime of the curve is observed, it should be corrected using equation 3.4.

$$P_x' = P_x \frac{M'}{M} \quad \text{3-4}$$

Where

Px' corrected precipitation at station x

Px original recorded precipitation at station x

M' corrected slope of the double mass curve

M original slope of the double mass curve

The values indicate that there is no significant change of slope relative to the original slope, so that no correction was made to the original data. For illustration the double mass curve, selected station is presented in Figure 3-6 and the other is attached to Appendix- D, Fig.D-5.

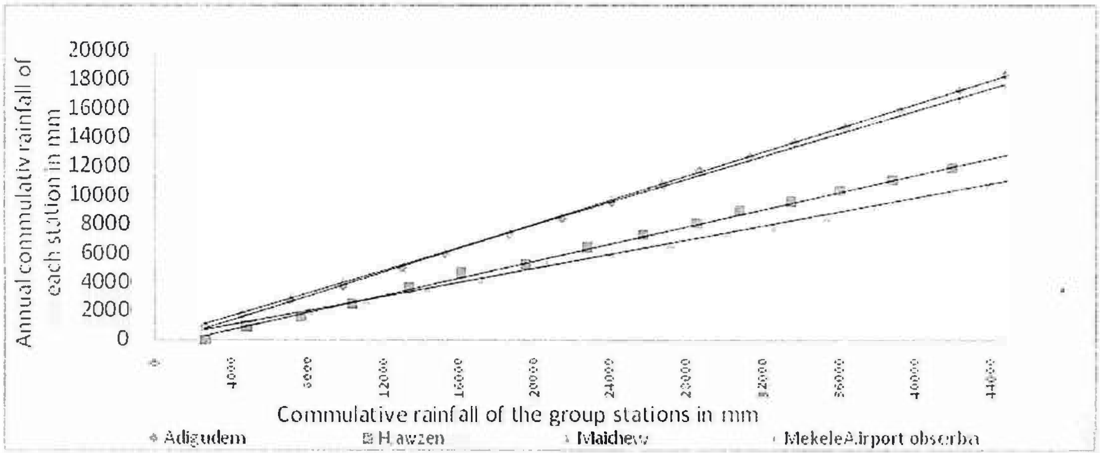


**Figure 3-4** Consistency test of Hawzen, Adigudem, Maichew, Maikentel and Mekele airport observa stations.

**Homogeneity Checking**

Checking homogeneity of group stations is essential. The homogeneity of the selected nine gauging stations average monthly rainfall records were made to be non-dimensional using equation

$$Pi = 100\% * [\frac{Pi}{Pj}] \qquad \text{.3-5}$$

Where - $P_i$ = non - dimensional value of rainfall for month i.

$P_i$ = Over years - averaged monthly rainfall at the station i.

$P_j$ = the over year - averaged yearly rainfall of the station

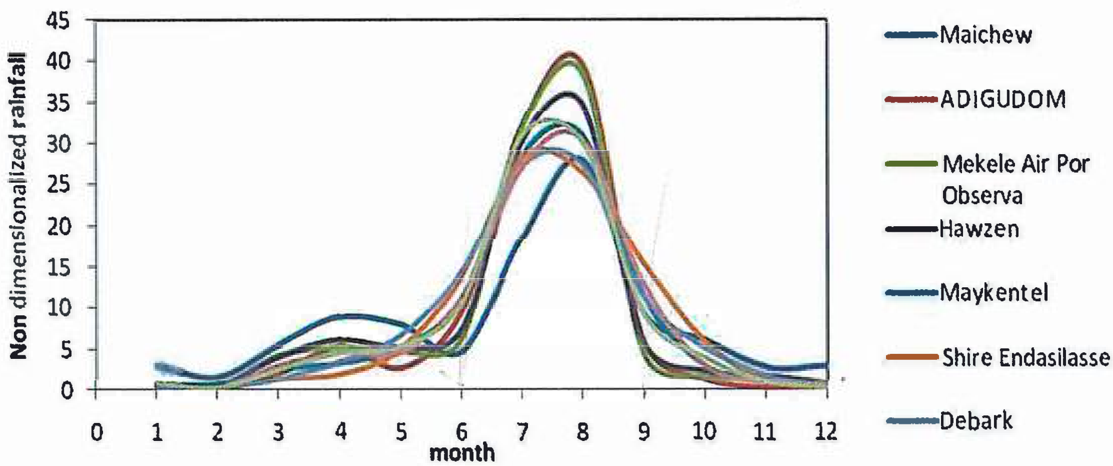


Figure 3-5 Homogeneity test of selected stations in Tekeze river basin

As shown in the above figure, one can see the homogeneous nature of the stations in study region because they have one distinct climatic and rainfall pattern and in almost all stations, the maximum rainfall falls between Junes to September.

## 3.2.4 Reservoir Evaporation

### 3.2.4.1 General

Evaporation is the process by which the phase of water is changed from a liquid to a vapor. Evaporation losses may contribute significantly to lower the water surface elevation in large reservoirs .Monthly, seasonal, or annual evaporation losses may have to be considered in the design of the reservoir. A number of studies have been made to evaluate the sensitivity of evaporation rates to causative factors. The factors believed to be most important are tbe temperature, the humidity or vapor pressure deficit, radiation rates, and the wind speed. Although other variables may be used in equations for predicting evaporation rates, these four factors are the most common (McCuen, 1998).

There are three major approaches to calculate the evaporation from open water ($ET_0$). The mass transfer method, the energy balance approach and a combination of the two (Laat, 1982).The accuracy of a model depends on a number of factors, including the input requirements and the degree to which the structure of the model approximates the underlying physical processes. As the complexity increases, one usually assumes the accuracy increases; however, as the complexity increases, the input requirements, and the effort required to make estimates also increases. Therefore, to have a manageable model one attempts to develop a model using as much theory as possible and to reduce the complexity by making simplifying assumptions but only to the point where further simplifications would adversely affect the accuracy of estimates. Penman (1948, 1956) uses this philosophy to develop an equation from the mass transfer and the energy balance equation for estimating evaporation of open water surfaces.

### 3.2.4.2 THE PENMAN EQUATION

In this study 'due to the unavailability of required data and the complexity of other methods, penman method is used.

$$E_o = \frac{[\Delta R_n + \gamma E_a]}{[\Delta + \gamma]} \quad \text{-----------------------------------------------------3-6}$$

Where

$E_0$ Daily evapo-transpiration in [mm $day^{-1}$],

$\Delta$ Slope of the saturation vapor pressure versus temperature curve in [KPa °$C^{-1}$],

$R_n$ Net radiation in [mm $day^{-1}$],

$\gamma$ Psychometric constant in [KPa °$C^{-1}$]

$E_a$ Parameter including wind velocity and saturation deficit in [mm $day^{-1}$],

- ✓ *Net radiation ($R_n$)*

The net radiation ($R_n$) is the difference between the incoming net shortwave radiations ($R_{ns}$) and the outgoing net long wave radiation ($R_{nl}$):

$$R_n = R_{ns} - R_{nl} \quad \text{------------------------------------------------------------------- 3-7}$$

- ✓ *Net solar or net shortwave radiation ($R_{ns}$)*

The net shortwave radiation, $R_{ns}$ resulting from the balance between incoming and reflected solar radiation is given by:

$$R_{ns} = (1 - \gamma)R_s \text{ ------------------------------------------ } 3\text{-}8$$

Where

$R_{ns}$ Net solar or shortwave radiation [MJ $m^{-2}$ $day^{-1}$],

$\gamma$ Reflection coefficient or albedo and it has a value of 0.23 for land surface and 0.08 for water surface [dimensionless],

$R_s$ The incoming shortwave solar radiation [MJ $m^{-2}$ $day^{-1}$],

$$R_s = R_a \left(0.25 + 0.5 \frac{n}{N}\right) \text{ ------------------------- } 3\text{-}9$$

n actual duration of sunshine [hour],

N maximum possible duration of sunshine or daylight hours as Appendix-A, Table A-

$\frac{n}{N}$ Relative sunshine duration [-]

Ra extra terrestrial radiation [MJ $m^{-2}$ $day^{-1}$], as Appendix-A, Table A-

✓ *Net long wave radiation (Rnl)*

$$R_{nl} = \sigma(T + 273.2)^4 \left(0.1 + 0.9 \times \frac{n}{N}\right)\left(\frac{0.34 - 0.14\sqrt{e_d}}{\lambda}\right) \text{ -------------------- } 3\text{-}10$$

Where

$R_{nl}$ net outgoing long wave radiation [mm $day^{-1}$],

$\sigma$ Stefan-Boltzmann constant [4.903 $10^{-9}$ MJ $K^{-4}$ $m^{-2}$ $day^{-1}$],

T air temperature [°C],

$e_d$ vapor pressure at dew point [KPa],

$\lambda$ Latent heat of vaporization, 2.45 [MJ $kg^{-1}$]

✓ *Vapor pressure at dew point*

$$e_d = e_s \times \frac{R_H}{100}$$

Where

$e_d$ In [KPa],

$e_s$ Mean saturation vapor pressure [KPa], as Appendix-A, Table A-

$R_H$ relative humidity in percentage

✓ *Mean saturation vapor pressure for a month (es)*

$$e_s = \frac{e^o(T_{max}) + e^o(T_{min})}{2} \quad \text{-----3-11}$$

Where

$e_s$ saturation vapor pressure [KPa],

$e^o(T_{max})$ saturation vapor pressure at the mean maximum air temperature [KPa],

$e^o(T_{min})$ saturation vapor pressure at the minimum air temperature [KPa].

✓ *Saturation vapor pressure as a function of air temperature ($e^o(T)$)*

$$e^o(T) = 0.6108\, exp^{\left[\frac{17.27T}{T+237.3}\right]} \quad \text{-----3-12}$$

Where

$e^o$ Saturation vapor pressure at air temperature of T [KPa],

✓ *Slope of saturation vapor pressure curve (Δ)*

For the calculation of the evapo-transpiration, the slope of between saturation vapor pressure and temperatureΔ is required. The slope of the curve at a given temperature is given by:

$$\Delta = \frac{4098\left[0.6108 exp\left[\frac{17.27T}{T+237.3}\right]\right]}{(T+237.3)^2} \quad \text{-----3-13}$$

Where

Δ Slope of saturation vapor pressure curve at air temperature [KPa $^0C^{-1}$]

✓ *Psychometric constant (γ)*

The psychometric constant,γ is given by:

$$\gamma = \frac{C_pP}{\varepsilon\lambda} = 0.665 * 10^{-3}P \quad \text{-----3-14}$$

Where

γ . psychometric constant [KPa $^\circ C^{-1}$],

P atmospheric pressure [KPa],

λ . Latent heat of vaporization, 2.45 [MJ $kg^{-1}$],

$c_p$ specific heat at constant pressure, 1.013 $10^{-3}$ [MJ $kg^{-1}$ $^\circ C^{-1}$],

ε Ratio molecular weight of water vapor/dry air= 0.622.

$$P = 101.3\left[\frac{293-0.0065Z}{293}\right]^{5.26}$$ ------------------------------------------------------------3-15

Where

P in [KPa]

Z altitude of the place [m] at a.m.s.l

✓ *Actual vapor pressure ($e_a$) derived from relative humidity data*

The actual vapor pressure can also be calculated from the relative humidity. Depending on the availability of the humidity data For $RH_{mean}$ (Smith, 1992):

$$e_a = \frac{RH_{mean}\left[\frac{e^o(T_{max})+e^o(T_{min})}{2}\right]}{100}$$ ------------------------------------------------------3-16

Where

$RH_{mean}$ Mean relative humidity in[%]

$E_a = 6.43 \cdot (a + 0.536u_2) \cdot D_{vp}$ ---------------------------------------------3-17

Where

$E_a = [mmday^{-1}]$

a constant and assumed to be 0.5 for open water

$u_2$ wind speed at 2m height in [m $s^{-1}$]

$D_{vp}$ Vapor pressure deficit in [KPa]

$$D_{vp} = \left[\frac{e_s(T_{max})+e_s(T_{min})}{2}\right]\left[1-\frac{RH}{100}\right]$$

In which $e_{s\,(Tmax)}$ and $e_{s\,(Tmin)}$ equation are computed from equation above for $T=T_{max}$ and $T=T_{min}$ respectively.

The calculated evaporation values according to the above procedures are summarized in Appendix-A (Table A-7 and A-8) and transferred directly to TK_5 and TK_7 reservoirs respectively.

# 4 HEC-ResSim Model Setup and Data configuration for the Study Area

## *4.1 Watershed Setup*

Tekeze_Reservoirs_Watershed_Setup was created by specifying the directory location, giving it a name and description, and establishing the Units of Measure as SI and Time Zone as GMT+3. Once it has been created the new watershed, ResSim generates a new directory hierarchy in the "base" working directory. The new watershed becomes active in the main window and the tools needed to create the watershed data become available. The background image that describes the Geo-referenced area of the watershed was imported from Arc View GIS.

In Tekeze_Reservoirs_Watershed_Setup the Cascade reservoirs, stream alignments and the computational points were defined (Fig.4.1). The computational point set contains the inlet and out let of the reservoirs where time-series information to be computed.

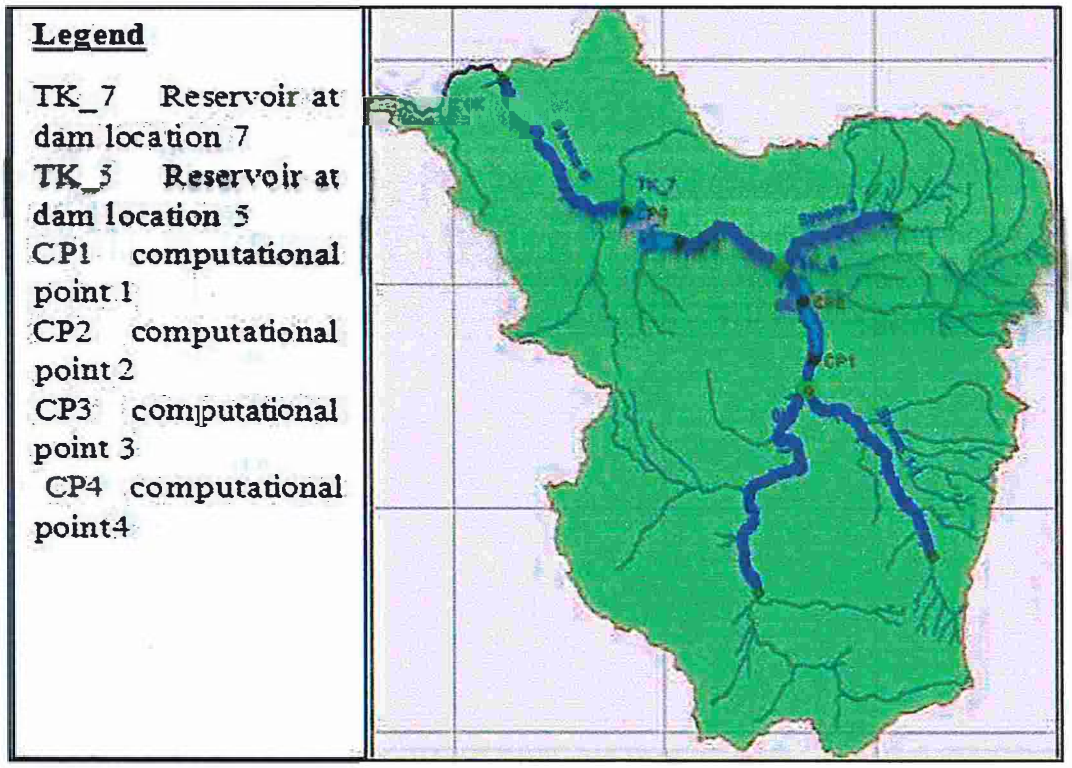

**Figure 4-1** Tekeze Watershed Setup

## *4.2 Reservoir Network Setup*

The purpose of the Reservoir Network Module is to isolate the development of the reservoir model from the output analysis (Hurst, April 2007). The river system schematic, describing the physical and operational elements of the reservoir model, and developing the alternatives to be analyzed were the main objectives In the Reservoir Network building.

Using configurations that were created in Tekeze_Reservoirs_Watershed_Setup module as a template, the basis of Tekeze reservoirs network was created. Then after CP2 to CP3 routing reaches and other network elements to complete the connectivity of the netw ork schematic have been added (Fig.4-2). Once the schematic have bee completed, physical and operational data for each network element were defined and tkres.alt alternatives were created to specify the reservoir network, operation set(s), initial conditions, and assignment of DSS pathnames (time-series mapping).

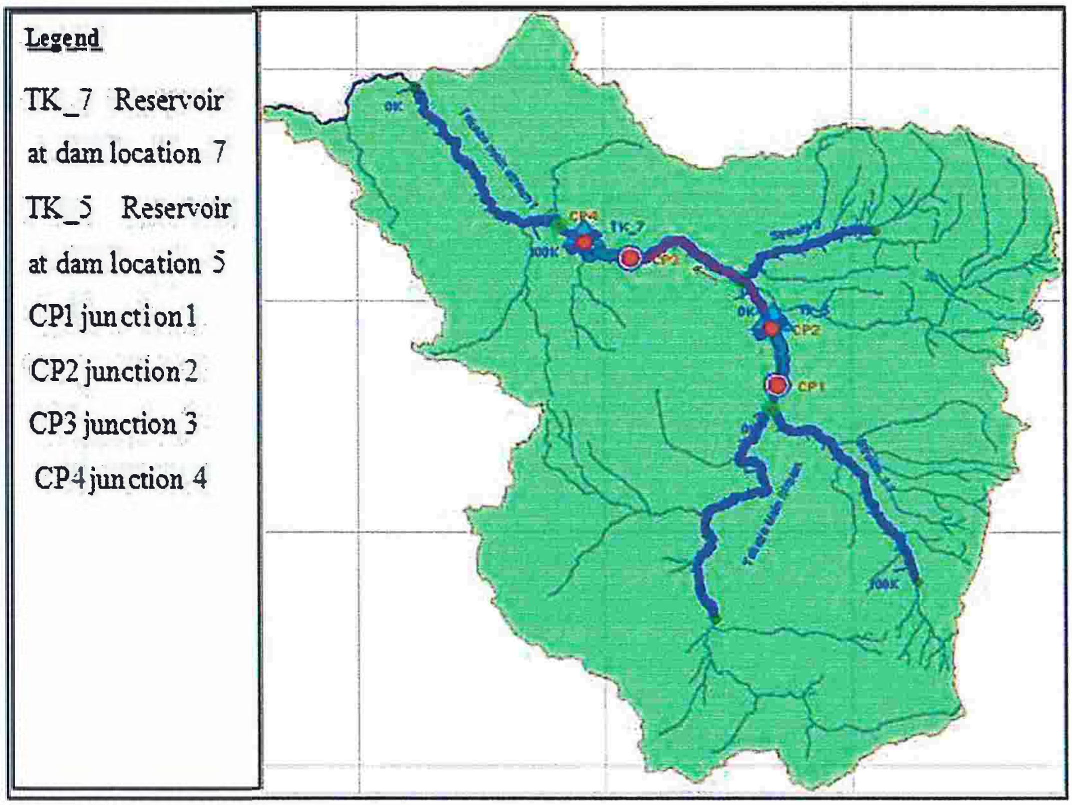


**Figure 4-2** Tekeze Reservoir Network Setup

## 4.3 Simulation Setup

Tekeze reservoirs network schematic was a template for simulation computations that was developed within the reservoir network module based on a configuration created in Tekeze_Reservoirs_Watershed_Setup module. The graphical elements allow to access data editors and specify properties of reservoir network components.

Once the reservoir model has been completed and the alternatives have been defined, the Simulation module was used to configure the simulation. The computations were performed and results are viewed within the Simulation module. During the creation of good simulation model (Fig 4.3), specifying simulation time window, computation interval and the alternatives to be analyzed were the main steps performed. Then ResSim creates a directory structure within the rss folder of the watershed that represents good simulation. Within this simulation tree will be a copy of the watershed, including only those files needed by the selected alternatives. A DSS file named good.dss has been created in the simulation, which will ultimately contain all the DSS records that represent the input and output for the selected alternatives.

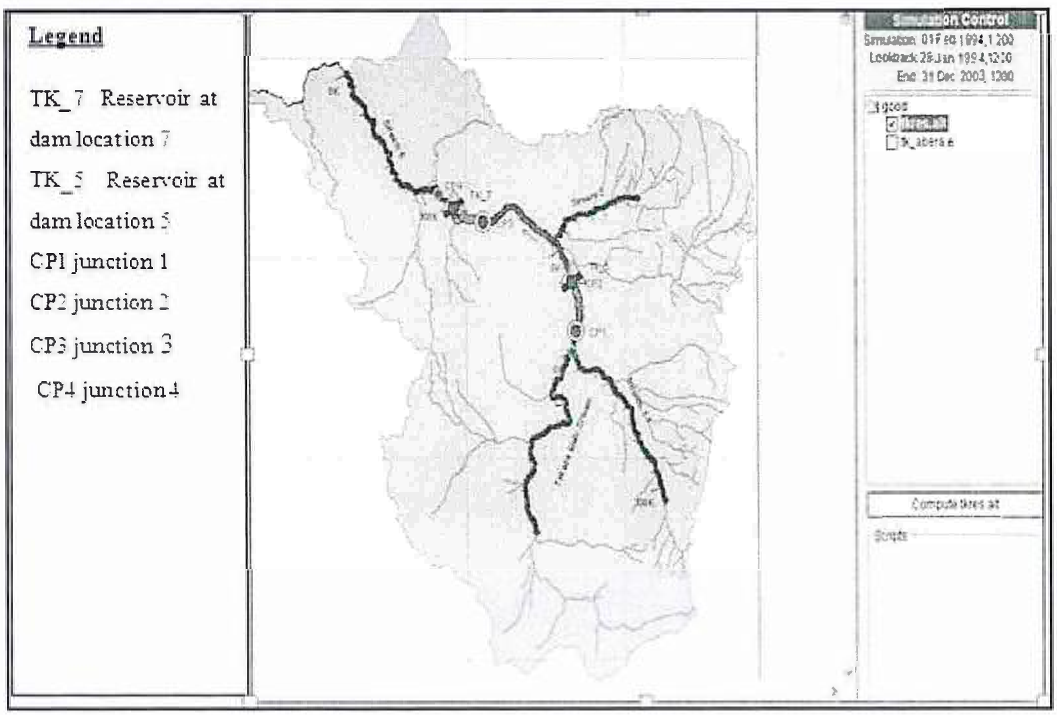


**Figure 4-3** Tekeze Reservoir Network Setup

## 4.4 Input data configuration

### 4.4.1 Reservoir Elevation Vs Storage and Area Curves

The data that defines an individual reservoir element within the reservoir network consists of two conceptual types: Physical and Operational. The physical components of a reservoir include Pool, Dam, (and Outlets on it). ResSim represents these components using a "tree structure" see fig F-1 and F-2 in Appendix-F.

Elevation-Storage-Area relationship is inserted to HEC-ResSim Reservoir editor of TK_5 (Table 4-1, Fig. 4.4) and TK_7 (Table 4-2, Fig. 4.5). For these data, copy and paste procedure was utilized to transfer from Excel Spreadsheets in to the reservoir editor. The data was obtained from Tekeze Medium Hydropower Project Feasibility Report Final Version December 1997 for TK_5 and from Federal Democratic Republic of Ethiopia Ministry of Water Resources, Tekeze River Basin Integrated Development Master Plan Project Volume 10 may, 1998 for TK_7.

**Table 4-1** Elevation vs. Storage capacity and Area relation for TK_5 pool

| Elevation(m) | Volume($m^3$) | Area(ha) |
|---|---|---|
| **975** | 1000000 | 39 |
| **1000** | 69000000 | 503.4 |
| **1010** | 134000000 | 807.4 |
| **1020** | 245000000 | 1401.5 |
| **1030** | 423000000 | 2156.1 |
| **1040** | 678000000 | 2946.3 |
| **1050** | 1023000000 | 3960.1 |
| **1060** | 1474000000 | 5055.1 |
| **1070** | 2036000000 | 6179.8 |
| **1080** | 2707000000 | 7256 |
| **1090** | 3480000000 | 8193.4 |
| **1100** | 4354000000 | 9285.1 |
| **1110** | 5388686159 | 10692.2 |
| **1120** | 6564546188 | 12242 |
| **1130** | 7871403885 | 13970.2 |
| **1140** | 9309259249 | 15687.6 |
| **1150** | 10878112282 | 17612.6 |

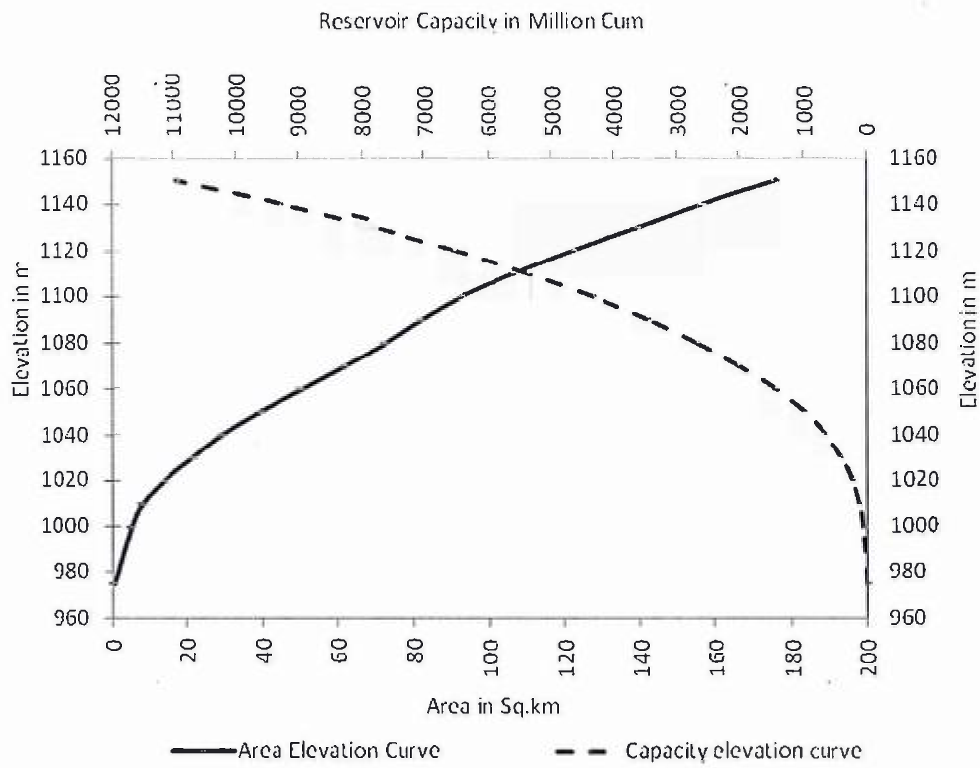


**Figure 4-4** Elevation vs. Storage capacity and Area curve of TK_5 pool

**Table 4-2** Elevation vs. Storage capacity and Area relation for TK_7 pool

| Elevation(m) | Volume($m^3$) | Area(ha) |
|---|---|---|
| **840** | 0 | 649 |
| **880** | 964400000 | 417300 |
| **920** | 2999800000 | 600300 |
| **960** | 6026800000 | 913300 |
| **1000** | 10562800000 | 1354700 |

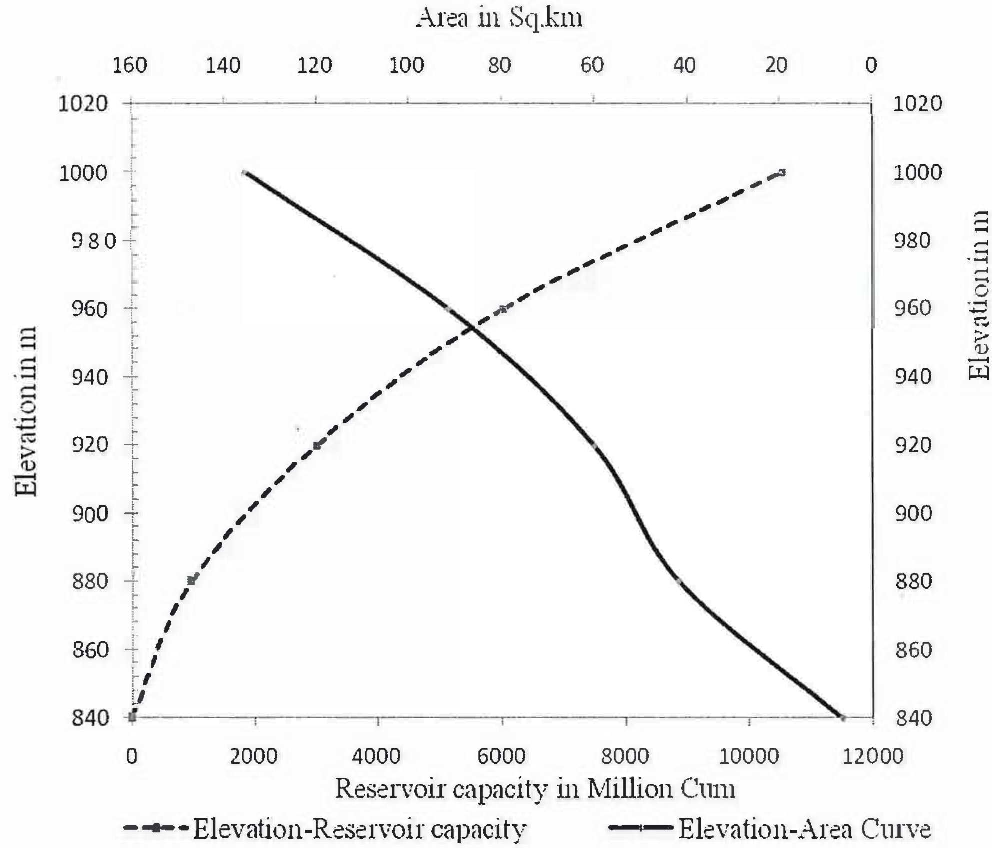


**Figure 4-5** Elevation vs. Storage capacity and Area curve ofTK_7

Plots of elevation vs. reservoir capacity and area curve of TK_5 generated by reservoir editor of reservoir network model is as Figure F-3 in Appendix-F.

### 4.4.2 Net Reservoir evaporation loss

Evaporation losses are considered in the design of large water storage reservoirs. The evaporation data series has been determined using Penman formula on 17 years monthly mean basis of Mekele AirPort Observa and SherieEndeselasie meteorological stations. Since there is no station around the reservoir with the required data to calculate evaporati on, the monthly $ET_O$ at Mekele Airport Observa and SherieEndeselasie have been transferred to estimate the net monthly evaporation at TK_5 and TK_7 dam sites respectively (Table 4-3).

**Table 4-3** Summery of monthly net evaporation at TK_5 and TK_7 reservoirs

| Month | TK_5(Mekele Airport Observa) | | | TK_7(Sheri Endeselasie) | | |
|---|---|---|---|---|---|---|
| | $E_o$ mm/month | Rainfall mm/month | Net $E_o$ mm/month | $E_o$ mm/month | Rainfall mm/month | Net $E_o$ mm/month |
| Jan | 142.8 | 5.9 | 137.0 | 126.5 | 2.6 | 123.9 |
| Feb | 181.4 | 3.3 | 178.2 | 168.0 | 1.4 | 166.7 |
| Mar | 209.8 | 24.1 | 185.7 | 208.3 | 13.5 | 194.8 |
| Apr | 233.3 | 35.9 | 197.4 | 223.2 | 21.1 | 202.1 |
| May | 263.4 | 29.4 | 233.9 | 219.5 | 54.0 | 165.5 |
| Jun | 211.7 | 41.2 | 170.5 | 140.4 | 141.3 | -0.9 |
| Jul | 142.8 | 199.8 | -56.9 | 119.0 | 289.0 | -170.0 |
| Aug | 129.5 | 239.6 | -110.1 | 104.2 | 263.9 | -159.7 |
| Sep | 164.2 | 31.1 | 133.1 | 122.4 | 161.6 | -39.2 |
| Oct | 187.5 | 9.1 | 178.3 | 145.1 | 61.3 | 83.8 |
| Nov | 159.8 | 7.7 | 152.2 | 133.2 | 10.1 | 123.1 |
| Dec | 151.8 | 1.1 | 150.7 | 122.8 | 2.2 | 120.5 |

The monthly net evaporation value is inserted to TK_7 pool tree as evaporation on the Physical tab of the Reservoir Editor (Fig F-.4 of Appendix-F)

### 4.4.3 Channel Reach Input

Flow routing is a mathematical procedure for predicting the changing magnitude, speed, and shape of a flood wave as a function of time (i.e., the flow hydrograph) at one or more points along a watercourse (waterway or channel). Flow routing is classified as either lumped or distributed. In lumped flow routing or hydrologic routing, the flow is computed as a function of time at one location along the watercourse; however, in distributed flow routing or hydraulic routing, the flow is computed as a function of time simultaneously at several cross sections along the watercourse (Fread, 1989).

The Muskingum method is a commonly used lumped routing method for handling a variable discharge-storage relationship. This method models the storage volume of flooding in a river channel by a combination of wedge and prism storages.

$T_c = 0.0078 L^{0.77} \cdot S^{-0.385}$ **(Ven Te Chow, 1988)] ............4-1**

Where:

$T_c$ Time of concentration (minutes)

L length of Channel/ditch from headwater to the outlet (ft)

S Average water shade slope (ft/ft)

In this study Lumped flow routing was assumed since the model has no distributed flow routing method. The reaches length (L) and average slope (S) obtained directly by measuring from the water shade using Arc-GIS software. The computed $T_c$ (K) in hr, X and the number sub-reaches length value have inserted as an inputs to the reach editor of the model. The value of *X* depends on the shape of the modeled wedge storage. It *ranges* from 0 for reservoir-type storage to 0.5 for a full wedge. When $X = 0$, there is no wedge and hence no backwater. In natural streams, *X* is between 0 and 0.3 with a mean value near 0.2. Great accuracy in determining *X* may not be necessary because the results of the method are relatively insensitive to the value of this parameter (Ven Te Chow, 1988). The parameter *K (i.e.34)* is the time of travel of the flood wave through the channel reach. Number of steps was approximated by dividing the travel time by the computation interval (i.e. 1). The computed (K) in hr, X and the number sub-reaches value have been entered as an inputs to the reach editor of the reservoir network model.

### 4.4.4 Spillways, controlled out lets and power plant Data input

Dam outlet works consist of spillways and bottom (high-head) outlets. Spillways are dam appurtenances ensuring a safe passage of floods from the reservoir into the downstream river reach. Spillways are normally uncontrolled, i.e. they function automatically as the water level rises above NWL, but gates may control them. In some instances, a fuse plug i.e. a credible subsidiary bank provides additional emergency spillway capacity. A bottom discharge facility is provided in most dams to provide an additional measure of drawdown control and, where reasonable, to allow emptying of the reservoir (P. Novak, 2007).

#### *4.4.4.1 Spillway Discharge Formula*

The spillways at TK_7 dam are radial gate, auxiliary fuse plug, and bottom out lets. Discharge through a partially open radial gate on a spillway crest was estimated using the basic orifice equation:

$$Q_g = C_g * A * \sqrt{2gH} \quad \text{......4-2}$$

Where

$Q_g$ =Discharge passing through one spillway span

$C_g$ =Coefficient of discharge

A =Area of orifice opening= $G_0$ *B

B =Span width

$G_o$ =Gate opening

H = Head to the center of the orifice

The coefficient of discharge Cg is primarily dependent on the characteristics of the flow lines approaching and leaving the orifice, which in turn, are dependent on the shape of the crest, radius of the gate, and location of the pivot. The coefficient $C_g$ varies from 0.67 to 0.73 (Khatsuria, 2005). In this study the average value (i.e. 0.7) was taken as the value of Cg. The values were calculated using Excel spread sheet and directly copied to physical tab of the reservoir editor. Figure 4-6 shows the main spillway discharge for different gate openings.

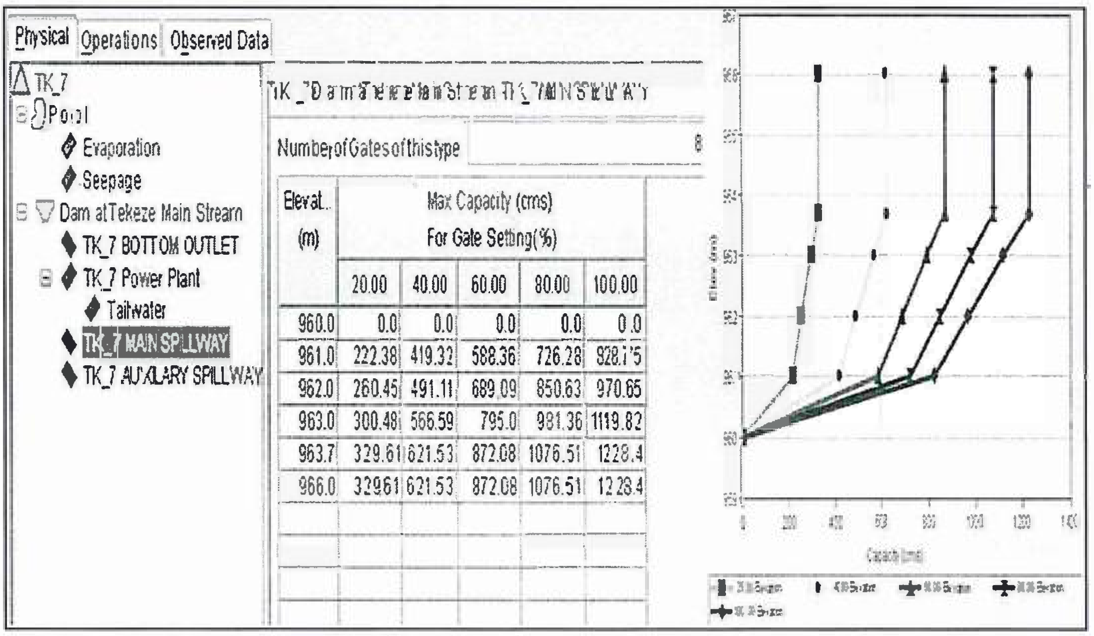


**Figure 4-6** Elevation vs. discharge capacity of TK_7 main spillway for different gate openings

Fuse plug, or a breaching section, is an erodible predetermined separate section of an earth dam designed to wash out when the inflow is in excess of the spillway capacity and the reservoir behind it reaches a specified level 962.5m.a.s.l in this case. The broad crested weir flow depends on the depth of flow above the crest ($H_0$) and the length of the crest (L). In the range $0.08 < H_0/L < 0.5$, the flow over a horizontal broad crested weir governed by

$Q = C.L.H_0^{1.5}$ .................................................................. 4-3

Based on model studies conducted by USBR, the recommended values of coefficient of discharge C After washout is complete =1.44 (Khatsuria, 2005). The procedure to calculate and put as input for the reservoir editor is the same as to the main spillway.

#### *4.4.4.2 Controlled out lets discharge formula*

The elevation versus maximum capacity for the Controlled out lets was carried out using the orifice formula.

$Q = C * A * \sqrt{2gH}$ .............................................................4-4

Where:

Q = Discharge through Controlled out lets

A and g are the cross-sectional area of conduit and acceleration due to gravity respectively, and C is contraction coefficient due to the effect of inertia and viscosity of the water, it ranges from 0.6 to 0.68 (Andrew L.Simon, 1997). TK-5 and TK_7 controlled out lets discharge was computed using eq.4.4 by taking C equal to 0.60

#### *4.4.4.3 Power Plant discharge formula*

The discharge calculation of the power plants was carried out using permissible velocity (V) in penstock and the area of inlet (A) to the penstock.

$Q = A * V$ ........................................................................4-5

$V = 0.125\sqrt{2gH}\frac{m}{s}$ ......................... 4-6 P.J. Bier formula (USBR)

Where

H pool level above center of power in take

g acceleration due to gravity

## *4.5 Defining Reservoir Operation Data*

The amount of water to be release at each time step of a simulation run has been determined for reservoirs in Tekeze reservoir network. To make this possible, an operation plan (Operation Set) was described, upon which it can base its decisions. The operation set consists of Zones, Rules, and the identification of the Guide Curve. Zones are operational subdivisions of reservoir pool. Each zone is defined by a curve describing the top of the zone. These zones are *Flood Control, Conservation, minimum release zone, and Inactive.* Fig. 4-7 and 4-8 shows zones and rules applied to Tekeze reservoir net work model.

### 4.5.1 Reservoir Operation Zone

Operation plan of this study reservoir was described by constant target pool elevation. The conservation guide curve was 1140m a.m.s.l for TK_5 and 960m a.m.s.l for TK_7. T he storage of the reservoir above this target elevation up to 1145m a.m.s.l for TK_5 and 963m a.m.s.l for TK_7 was referred to as the flood control pool. The storage between the guide curve and inactive zone, 1076.5m a.m.s.l for TK_5 and 888m a.m.s.ll for TK_7, is called the Conservation pool. The minimum release zone, 1096m a.m.s.l for TK_5 and 898m a.m.s.l for TK_7, determines the minimum level on which power generation is to-lerable (Fig 4-7 and 4-8).

The guidelines for determining the release from the reservoir are based on where the current pool elevation is in relation to the guide curve. Under basic operation, if the pool is below the guide curve, then the basic objective of the operation is to reduce releases in order to refill the pool if, the pool is above the guide curve, then the operator wants to increase releases to draw down the pool. Additional goals and constraints were applied to temper such a rigid operation plan.

### 4.5.2 Reservoir Operation Rules

Operation Rules represent the flow goals and constraints upon the releases for each zone of the operation set. Each zone can contain a different set of rules depending on the flow limits and requirements of that zone within the regulation plan. Rules were 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 guide curve concept is used as the basis for the release decision process in ResSim. Basic guide curve operation means "get the reservoir pool elevation to the current guide curve elevation as fast as possible, within the physical and operational constraints of the outlets."

Tandem operation rule was created and included in the operation set at TK_5 reservoir only. Then it identifies TK_7 reservoir that is the object of tandem operation. the Tandem Operation rule was assigned only to the reservoir (pool), not to a specific outlet or outlet group, because only the reservoir can account for all releases from the reservoir ' s outlets that could influence the flow into the downstream reservoir. At TK_7, reservoir release operation rule was created. Minimum and maximum power generation and other rules are included in each zone as a constraint (Fig 4-7 and 4-8).

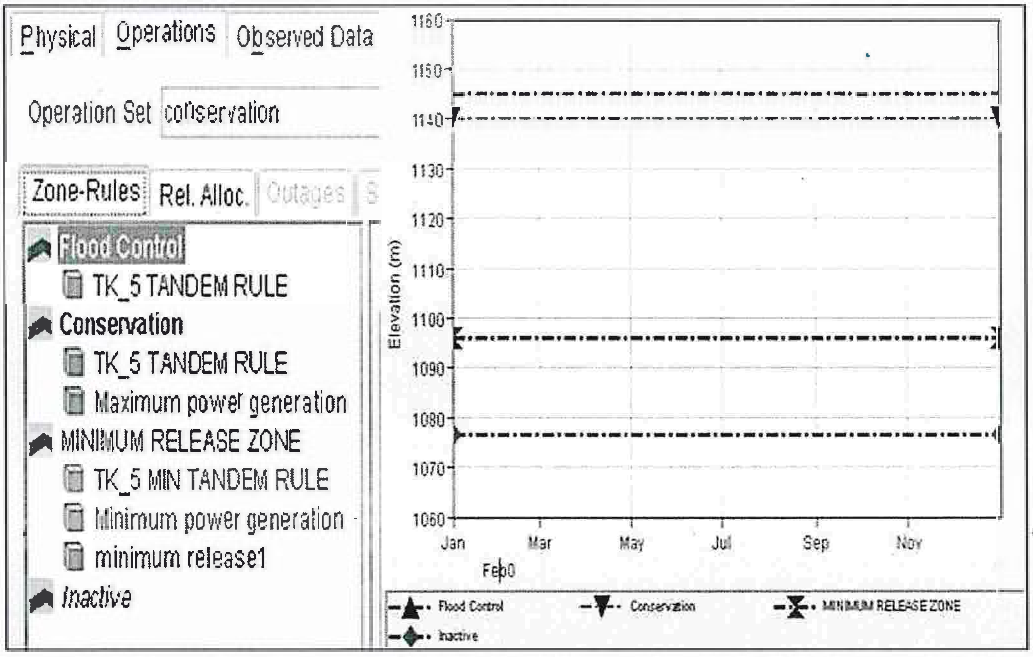


**Figure 4-7** Operation zones and rules of TK_5 in operations tab of the Reservoir editor

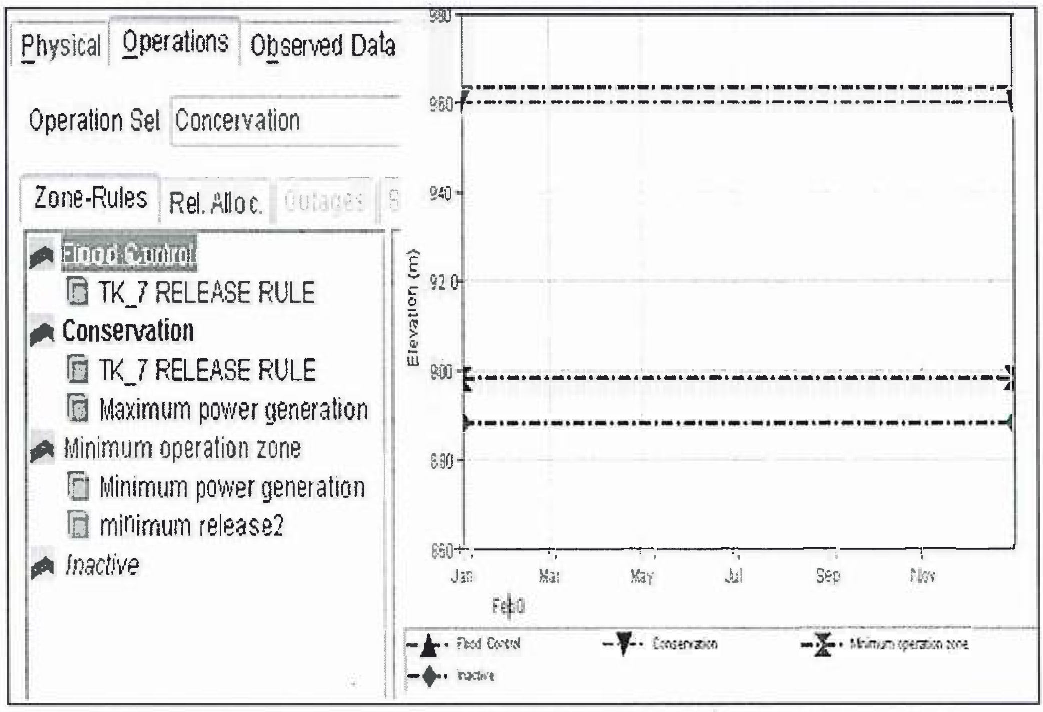


**Figure 4-8** Operation zones and rules of TK_7 in operations tab the Reservoir editor

outlets that could influence the flow into the downstream reservoir. At TK_7, reservoir release operation rule was created. Minimum and maximum power generation and other rules are included in each zone as a constraint (Fig 4-7 and 4-8).

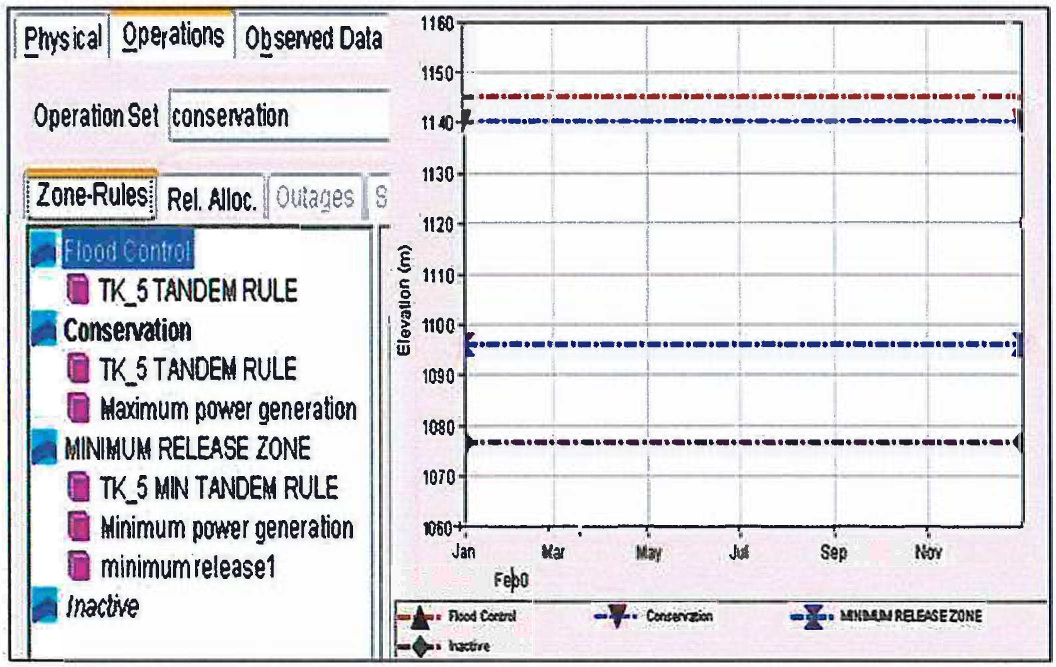


**Figure** 4-7 Operation zones and rules of TK_5 in operations tab of the Reservoir editor

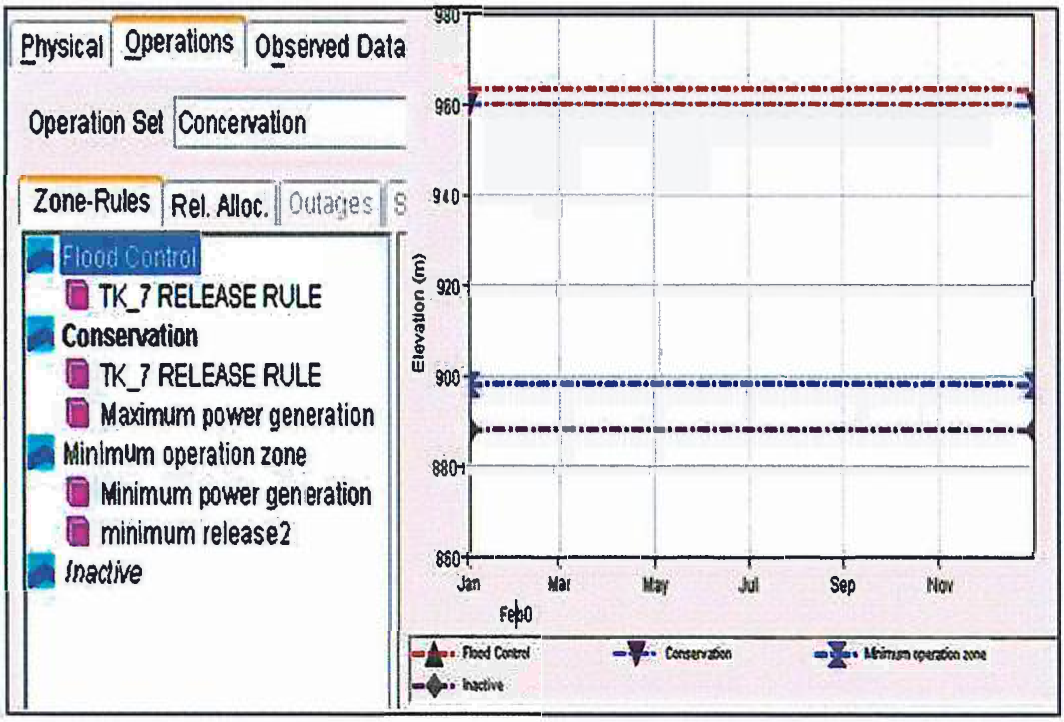


**Figure 4-8** Operation zones and rules of TK_7 in operations tab the Reservoir editor

### 4.5.3 System Operation Preparation

Tekeze reservoir system was created by defining tandem operation rule for TK_5 reservoirs to manage the storage distribution between TK_5 and TK_7 reservoirs.

When a tandem reservoir system is defined, the model determines the priority and the amount of release to make from each reservoir in order to operate towards a storage balance. For every decision interval, an end-of-period storage is first estimated for each reservoir based on the sum of beginning-of-period storage and period average inflow volume, minus all potential outflow volumes. The estimated end-of-period storage for each reservoir is compared 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 storages are recomputed. Depending on other constraints or higher priority rules, system operation strives for a storage balance such that either the reservoirs have reached their Guide Curves or they are operating at the desired storage (percent of the active storage zone). (Hurst, 2007)

#### *4.5.3.1 Implicit system storage balance method*

The implicit system storage balance scheme takes into account the System Storage (the total storage from TK_5 and TK_7 reservoirs in the system). The system storage ranges from empty (0 Mm3) to full (16,432Mm3). Additionally, this default scheme considers only one System Zone, the System Guide Curve (Sys G.C.) storage, which amounts to the sum of both reservoirs conservation storage (15,337$Mm^3$). The desired storage for each reservoir is determined through an implicit "balance line." For system storage less than the System Guide Curve storage, the balance line has a lower limit that corresponds to empty storage at the reservoir versus empty system storage, and the upper limit corresponds to Guide Curve storage at the reservoirs (9,310 Mm3 at TK_5 and 6,207 Mm3at TK_7) versus System Guide Curve storage (15,337$Mm^3$). For system storage greater than the System Guide Curve storage, the lower limit of the balance line corresponds to Guide Curve storage at the reservoirs (9,310 Mm3 at TK_5 and 6,207 Mm3at TK_7) versus System Guide Curve storage (15,337$Mm^3$). In addition, the upper limit corresponds to full storage at the reservoirs (10,077Mm3 at TK_5 and 6,355 $Mm^{3at}$ TK_7) versus full System Guide Curve storage (16,432 Mm3) (Figure 4-10).

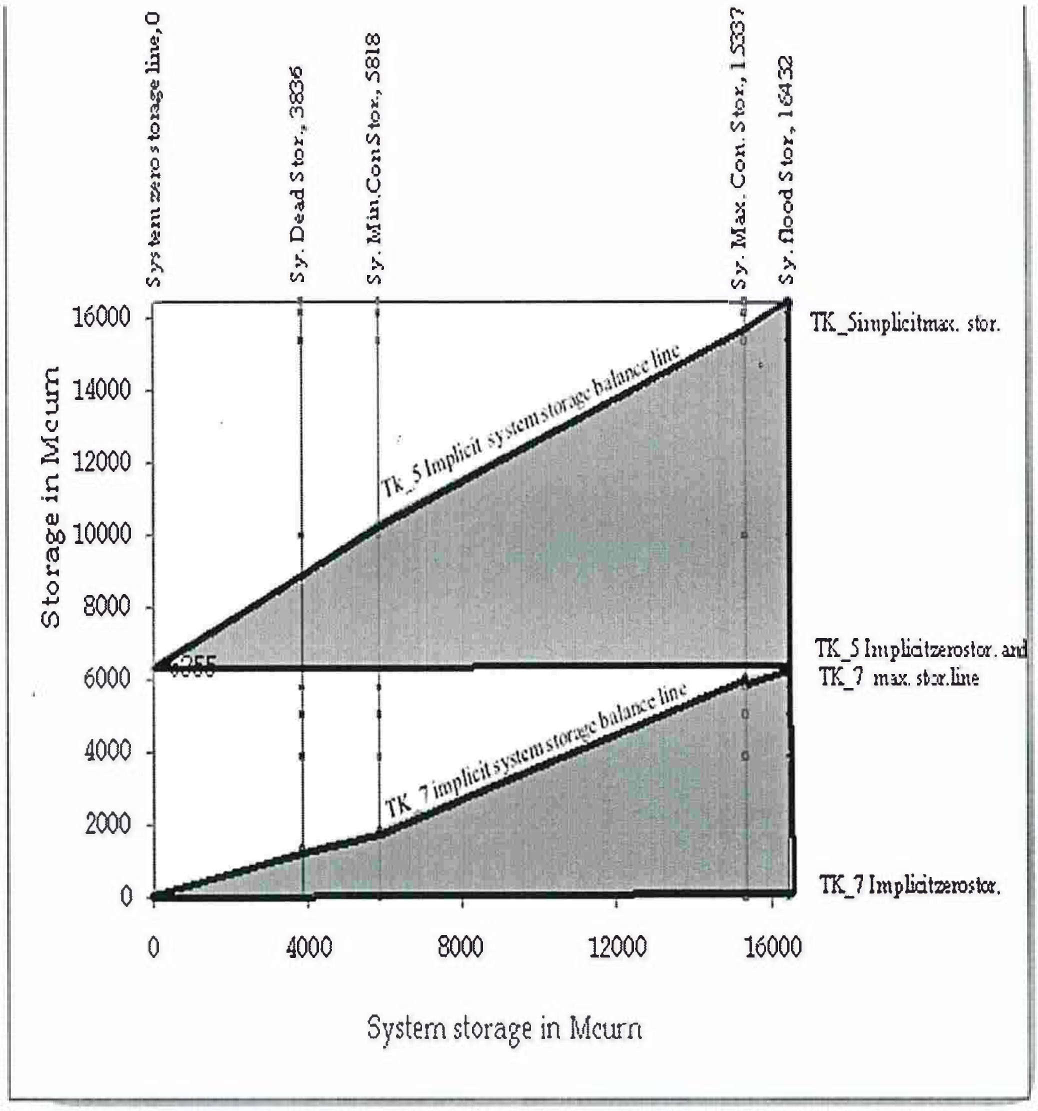


**Figure 4-9** Implicit system storage balance line

*4.5.3.2 Explicit System Storage Balance Method*

The implicit scheme by default develops balance line, using a single system storage zone (System Guide Curve) to define a linear relationship between storage at each reservoir and the total system storage. The user can further modify these balance lines explicitly to characterize the desired storage distributions using one or more system zones and placing inflection points along the balance line. (Hurst, 2007)

Since the main purpose of the reservoirs in this study is for hydropower generation, the inflection points with in the conservation zones have been given attention. The first inflection point is between the inactive and the minimum operation level. The second is between the minimum operation and the conservation level while the third is between the conservation and maximum flood level (Figure 5-12). It needs a trial and error iteration to find the inflection points, which give maximum power and minimum water loss due to spill and evaporation in the operation system. Detail of the iteration and selection of the optimal coordination is left to the next result and discussion portion. The first trial alternative was taken in such a way that TK_5 fills 60% of its operation storage in the time TK_7 fills up only 40% its operation storage (Table 4-4).

**Table** 4-4 Explicit system storage of Tekeze cascade reservoirs

| zone | Storage(TK_5,TK_7) in $Mm^3$ | Elevation (TK_5,TK_7) | System storage |
|---|---|---|---|
| Maximum Flood zone | (10077, 6355) | (1145 , 963) | 16,432 |
| Conservation zone | (9310 , 6027) | (1140, 960) | 15,337 |
| Inflection point for conservation zone balance line (60,40)% | (7173 ,3 521) | | 10,694 |
| Minimum-operation zone | (3967, 1851) | (1096, 898) | 5,818 |
| Inflection point for minimum operation storage zone balance line (60,40)% | (3389 , 1529) | | 4,917.8 |
| Inactive storage | (2522, 1314) | (1076.5 , 888) | 3,836 |

Percentage of the inflection points is inserted in the reservoir system editor for the respective system zones (Fig.F-5 in Appendix-F). The explicit system operation is carried out each time when system rules are in effect. The process of determining desired storages is repeated every decision interval in order to assign the priority for release to the reservoir that is farthest above the desired storage. A release decision made for a particular time 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 storages levels along their explicit balance line curves as prescribed in the explicit storage balance scheme.

## *4.6 Defining Alternatives*

The alternative(tkres.alt) consists of Tekeze reservoir network operation set of the two reservoirs in the network, a storage balance operation set for Tekeze reservoir system, a definition of initial (look back) conditions, and mapping of all time-series records to identified local inflows(Fig.F-6 in Appendix-F). The alternative was developed in the alternative editor of the reservoir network model. For the explicit storage balance created in the reservoir system editor, an entry appeared in the alternative editor's operations tab that identifies the reservoir system along with a field to select system storage balance operation for the reservoirs to follow.

## *4.7 Using HEC-DSSVue*

HEC-DSSVue Is a tool that allows the user to store the data in HEC-DSS database and to access data stored in HEC-DSS database files. Daily and monthly stream flows were the required time series data in this study. These data were inserted to HEC- DSSVue from Microsoft Excel sheet using manually data entry functions in utility tab (Fig.4-10).

The main step used to transfer a time series data from the Microsoft Excel in to the DSS format is the creation of DSS catalog in side 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 Pathnames are separated into six parts (delimited by slashes"/") label as in the following format.

A/B/C/D/E/F

A Project name (TK_5 &TK_7 inlet)

B Location or gage identifier (CP1&CP3)

C Data variable (FLOW)

D Starting date in the format (01JAN1994)

E Time interval (MONTHLY, DAILY)

F Additional user-defined descriptive information (OBS)

In this study The Stream flow data is transferred as, described under section 3.6, from Embamdre and Yachila gauging stations to TK_7 and TK_5 reservoir inlets as inflows.

These inflows are inserted as time series and observed data values in alternative editor from Hec-DssVue after the required data have been saved in HEC-DSS database. Figure F-7 in Appendix-F shows the steps how the daily average inflows inserted in to TK_7 and TK_5 reservoir inlets.

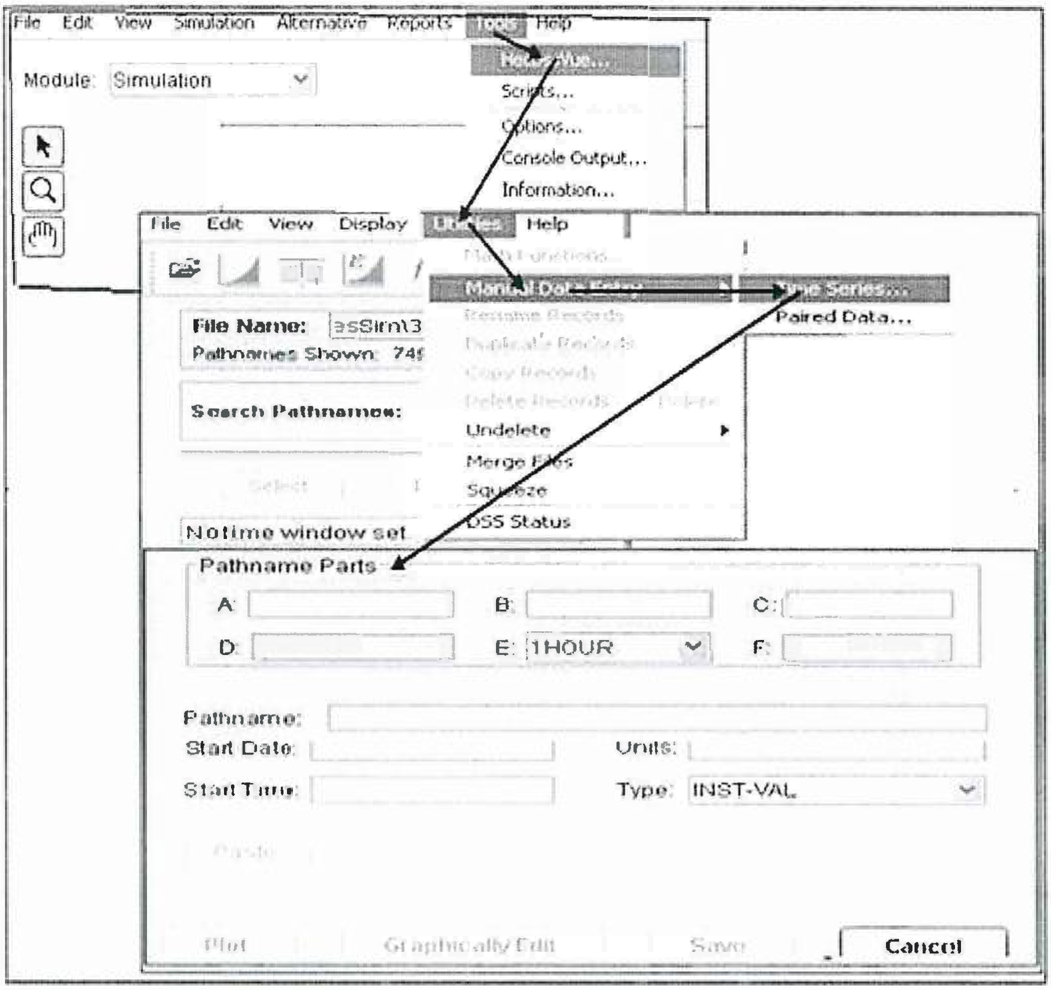


**Figure 4-10** HEC-DSSVue Manual Time Series Data Entry

## *4.8 Simulation data set up*

After all the required data have been entered and the alternative has been created, the next step was to perform simulation. Tekeze reservoir (good) simulation was created in the simulation editor of a simulation module then the look back, simulation, and end of date have been set.

## *4.9 Reservoir Operation Assumption*

To simplify the complexity of the actual operation system a number of assumptions were made. Some of the basic assumptions are:

1. Constant reservoir effective storage i.e. no reduction due to sedimentation

2. Seepage through the reservoir and the body of the dam is assumed zero at TK_7 and a constant $0.5m^3/s$. at TK_5.

3. Seepage and evaporation through the reach are negligible and assumed to be zero

4. Only free water surface evaporation losses is considered

5. Multiple gates opening for TK_7 main spillway gates depend up on the water level in the reservoir and percentage of gate opening. The rest out lets are single gate setting alternative i.e. maximum at the time of opening and zero otherwise.

6. The future down stream water development plan is based on the resulted optimal release.

# 5 RESULT AND DISCUSSION

## 5.1 General

Three classes of energy are of interest in hydroelectric power operations: average, firm, and secondary. Average energy is the mean annual amount of energy that could be generated assuming a repetition of historical hydrology. Firm energy, also called primary energy, is estimated as the maximum constant annual energy that could be generated continuously during a repetition of historical hydrology. Secondary energy is energy generated in excess of firm energy. Secondary energy, expressed on an average annual basis, is the difference between average annual energy and firm energy.

In this study, maximizing the firm and average annual energy was considered as the objective function. The explicit storage balance system trial was based on the following objectives:

- ✓ *Increasing firm energy*
- ✓ *Maximizing average annual energy,* by decreasing the total loss from the system i.e. spill loss from TK_7 and evaporation loss from both reservoirs.

## 5.2 Calibrating the Model

After the first Simulation computation, the model needs adjestment. Subjective assessement, which is based on a visual comparison of the simulation and observed local flow to TK_7 reservoir inlet, was taken to check the quality of calibration of the model. As, can be seen in Figure 5-1 there is good agreement between the simulated and observed values. It also needs to make adjustments of override values next to reservoir Simulation model calibration. At the override tab of ResSim editor of the simulation module, the values of release below the minimum operation level have been taken either zero or the minimum power plant requirement.

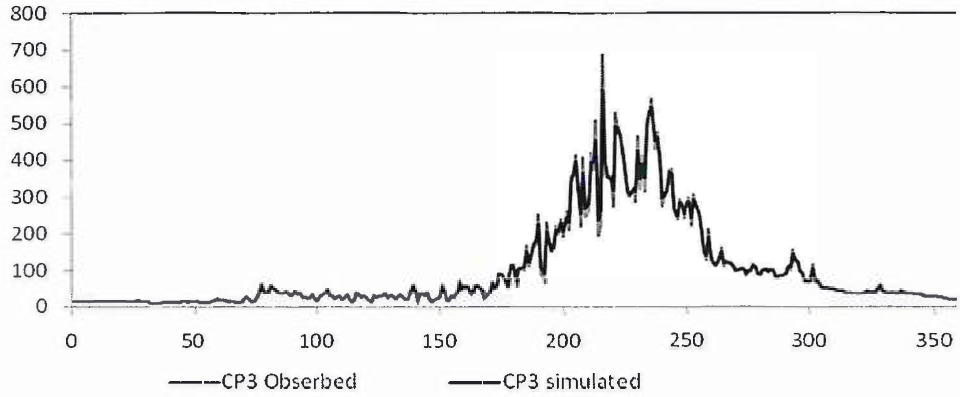


**Figure 5-1** Observed and simulated values at TK_7 inlet point (CP3)

## *5.3 Implicit system storage balance result*

The purpose of simulating using implicit system in this study is as a comparison, to show how much effective to optimize the explicit system is. The simulation was done by setting 100% inflection point in each system zone and selecting none from the reservoir system balance. The average, power that can be generated in the system is the summation of the average power in each reservoir.

### 5.3.1 Firm Power and Energy

Firm power and energy are the power and energy, which could be supplied by the station with a high (97%) degree of reliability on a continuous basis, independent of hydrological conditions in any particular year or month. The 97% reliability condition equates to partial or total failure to produce firm energy in 3% of all months, on average. Figure 5.2 and 5.3 in the upper plot region shows the HEC-ResSim implicit system power result in the analysis period. The lower region is the computed pool inflow, power plant, and total outflow of the reservoir.

The firm power was computed from the power duration curve which has been done in Excel spread sheet using the values obtained from HEC-ResSim (Figure 5.4 and 5.5).The firm power and energy that could be generated in TK-5 were 95.63 MW and 837.72 GWh/yr respectively. The firm energy obtained in the implicit system simulation is less than the value estimated by Tekeze Medium Hydropower Project Feasibility Report Final Version December 1997, which is 981 GWh/yr

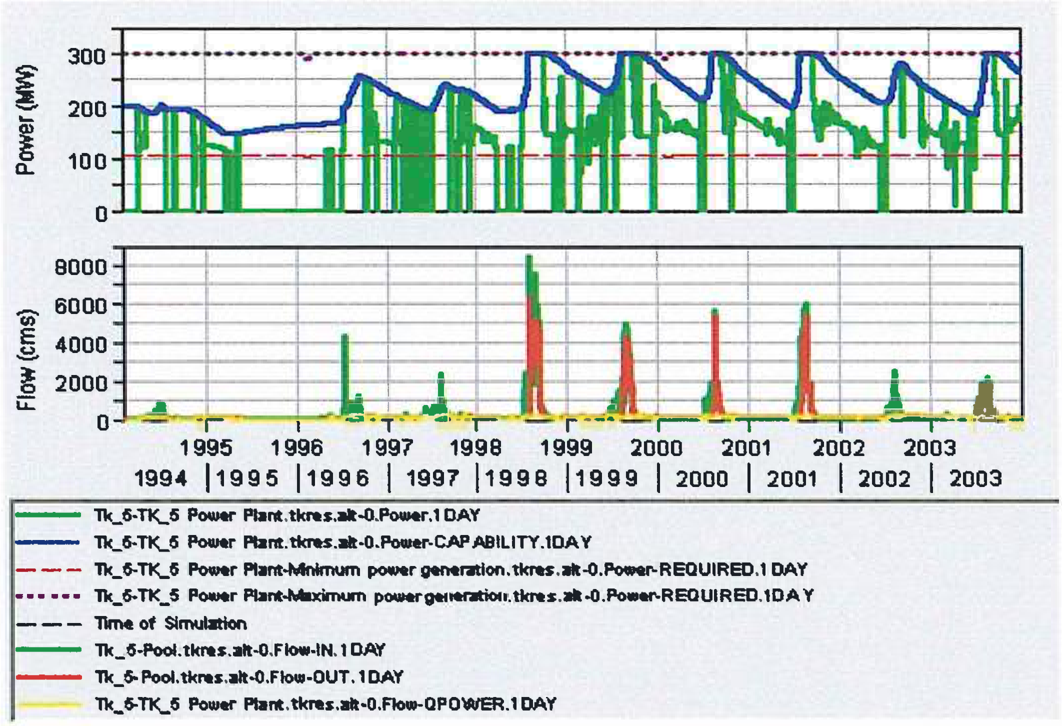


**Figure5-2** TK_5 power generated, inflow and outflow in the implicit system operation

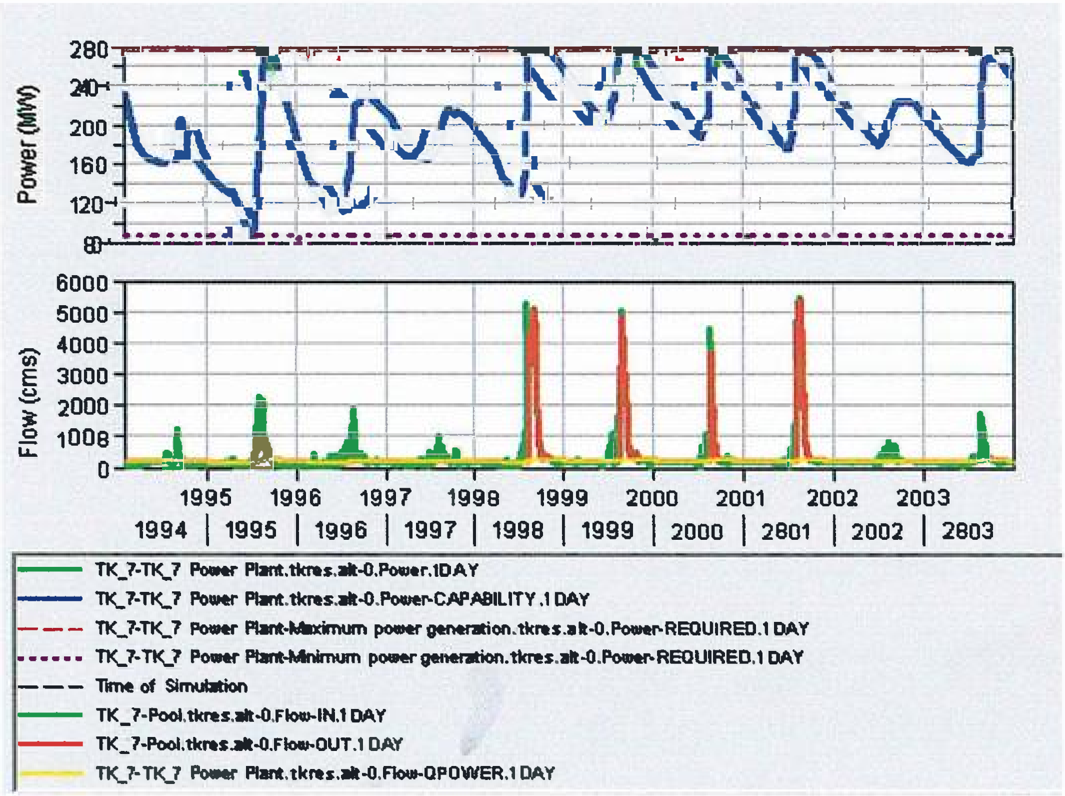


**Figure 5-3** TK_7 power generated, inflow and outflow in the implicit system

Even though there is no firm power and energy data for TK_7, the result obtained in this study indicates that 162.7 MW and 1425.25 GWh/yr power and energy respectively could be generated in the plant. The total system firm power and energy, which are the summation of the two plants, are 258.33MW and 2262.97GWh/yr respectively.

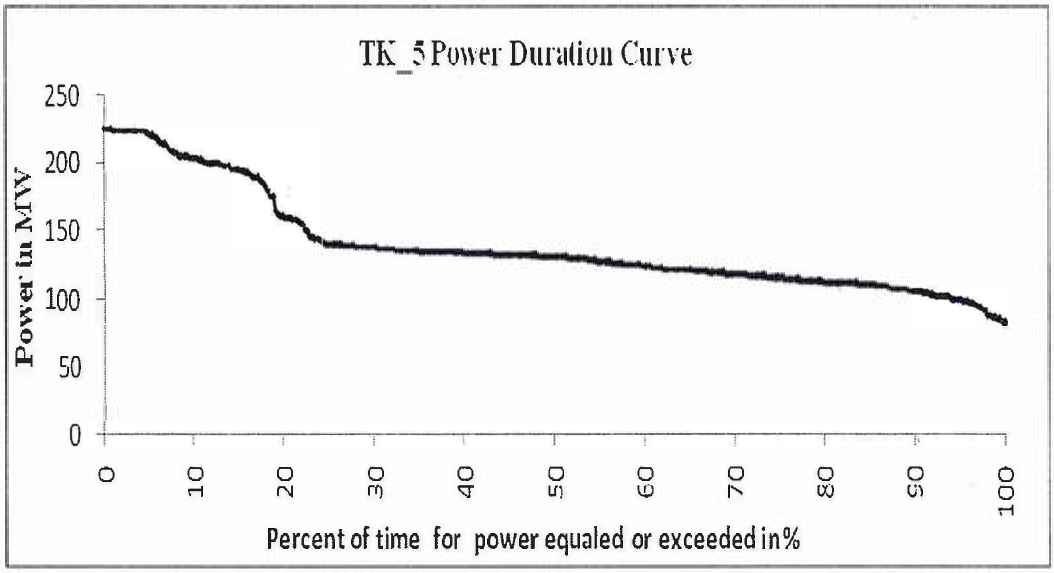


**Figure 5-4** TK_5 Power Duration Curve

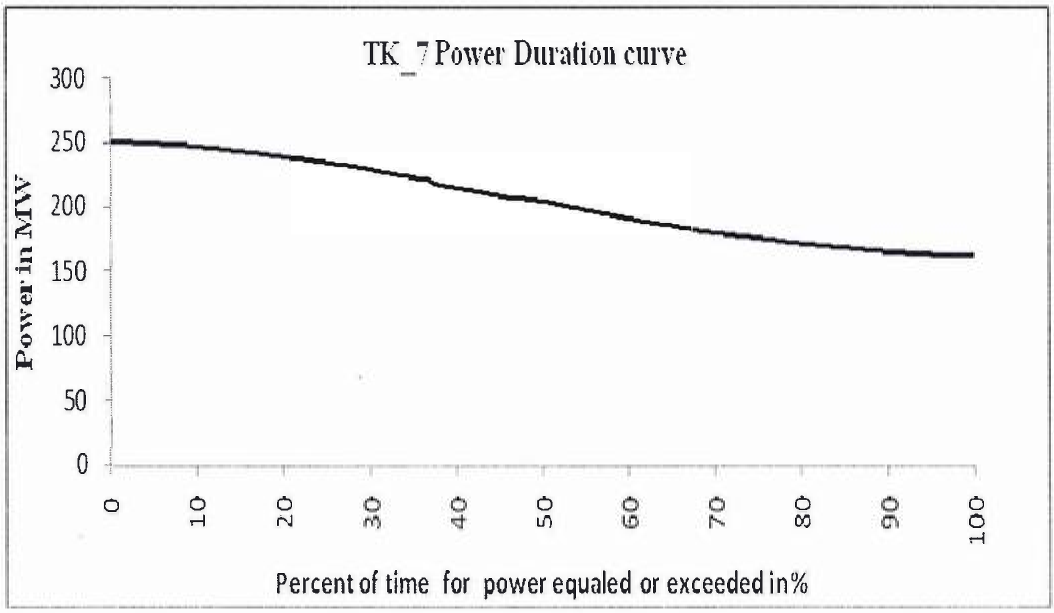


**Figure 5-5** TK_7 Power Duration Curve

### 5.3.2 Average and Secondary Power and Energy

Average power and energy are the, analysis period, average power and energy production, being the sum of firm and secondary. Secondary power and energy are productions in excess of firm power and energy respectively. This varies in amount from month to month and year to year, depending on the hydrological conditions. Plant factor of TK_5 obtained from the implicit system is 0.5, which is less than the value in the final feasibility study (i.e. 0.6). Here average, firm, and secondary power and energy of each plant and the system are summarized (Table 5-1).

**Table 5-1** Summery of implicit average, firm and secondary; power and energy

| Location/Parameter | Average | Firm | Secondary |
|---|---|---|---|
| TK_7 Energy Generated per Year (GWh/yr) | 1794.92 | 1425.25 | 369.67 |
| TK_7 Power Generated (MW) | 204.9 | 162.7 | 42.2 |
| TK_5 Energy Generated per Year (GWh/yr) | 1227.28 | 837.72 | 389.56 |
| TK_5 Power Generated (MW) | 140.1 | 95.63 | 44.47 |
| System Energy Generated per Year (GWh/yr) | 3022.20 | 2262.97 | 759.23 |
| System Power Generated (MW) | 345 | 258.33 | 86.67 |

### 5.3.3 Implicit System Storage Balance Operation Guide Curve

Setting appropriate guide curve is the core target to achieve optimal reservoir operation. Figure 5.6 and 5.7 shows the output plot of HEC-ResSim model for TK_5 and TK_7. The upper plot region is the computed reservoir pool elevation and the lower region shows the computed pool inflow and outflow. The monthly maximum, minimum and average (guide) curve of TK-5 and TK_7 are plotted in Excel spreadsheet using the result obtained from HEC-ResSim (Figure 5.8 and 5.9).

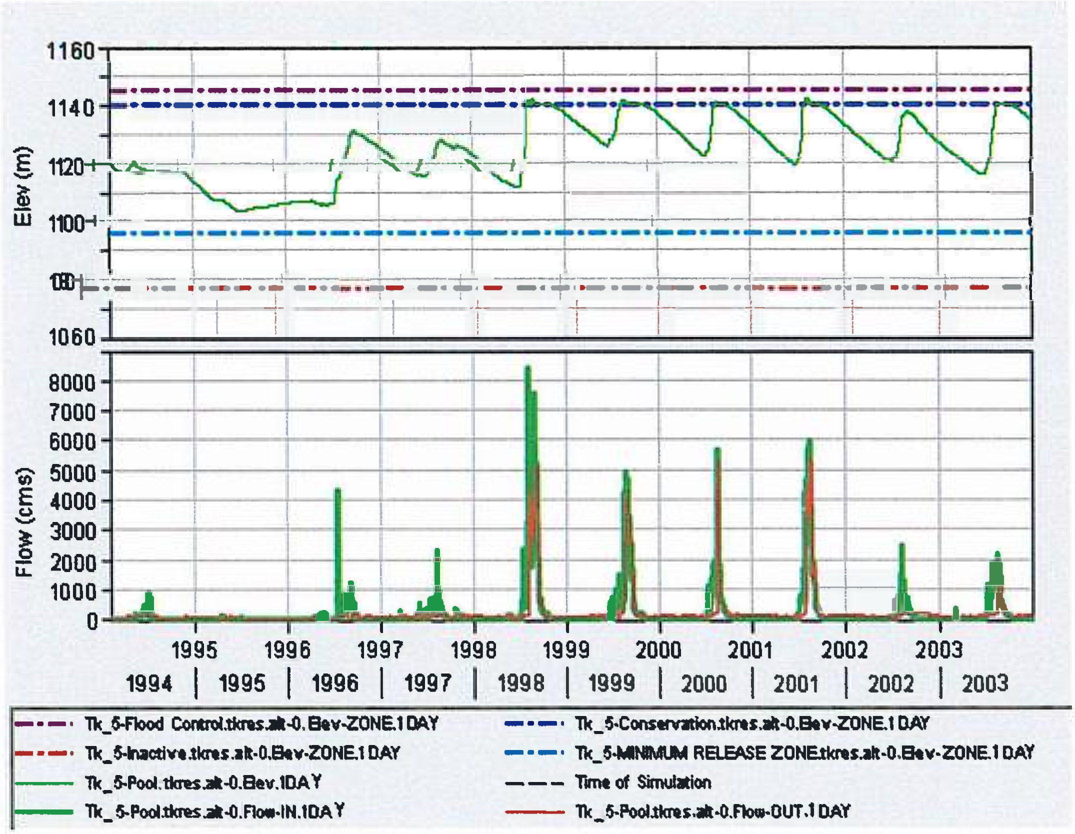


Figure 5-6 TK_5 Pool Level, Inflow and Outflow in the implicit System Storage

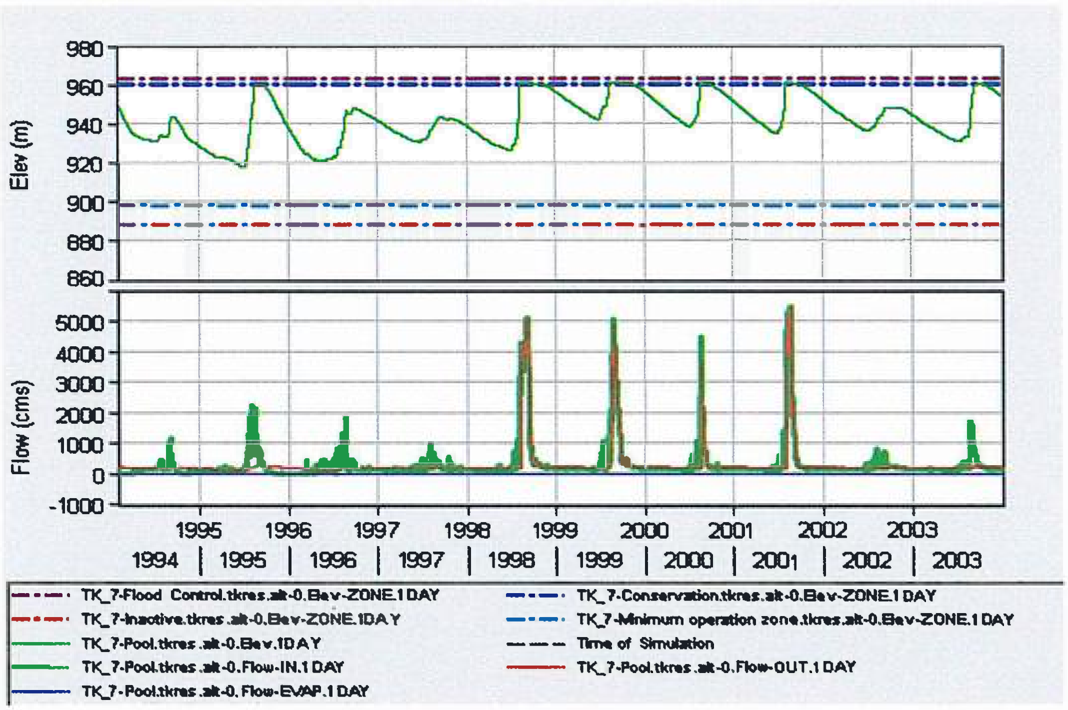


**Figure 5-7** TK_7 Pool Level, Inflow and Outflow in the implicit System Storage

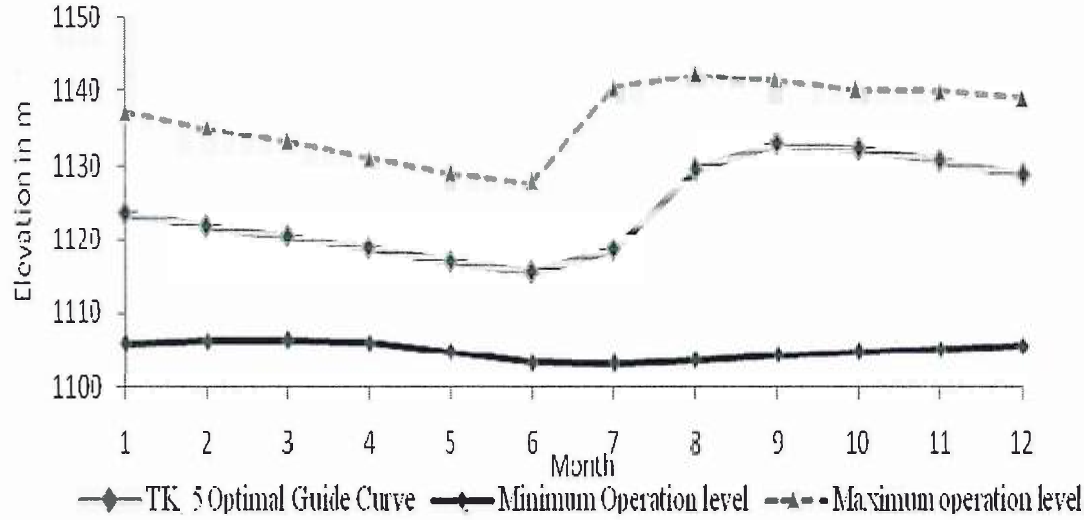


**Figure 5-8** TK_5 implicit Guide curve, minimum and maximum operation level

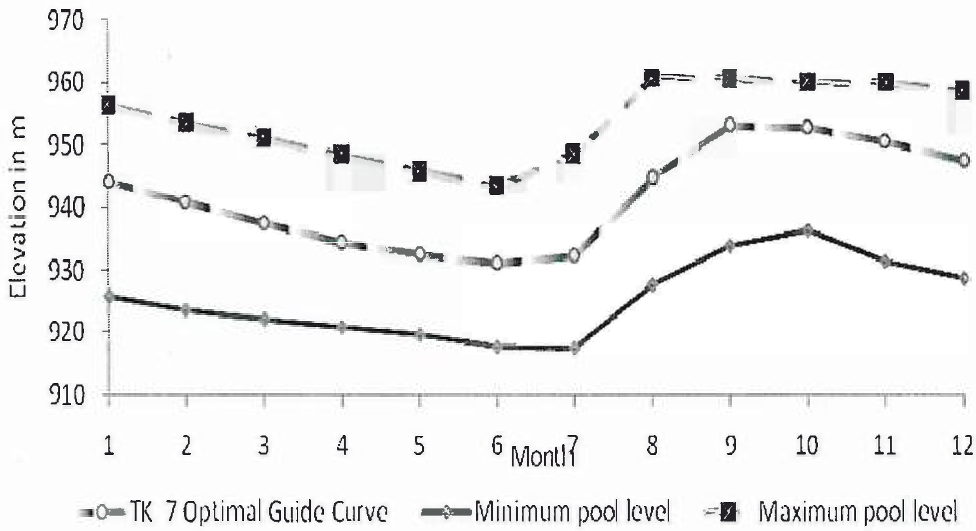


**Figure 5-9** TK_7 implicit Guide curve, minimum and maximum pool level

In addition to the above plots, the guide curve chart of the two reservoirs was prepared (Figure 5.10 and 5.11). Values in the chart notify the monthly maximum, minimum and guide curve (maximum, minimum), which are, 1142.20, 1103.2, 1132.9 and 1115.6 m a.m.s.l at TK_5 and 960.66, 917.8, 953.1and 917.8 m a.m.s.l at TK_7 respectively.

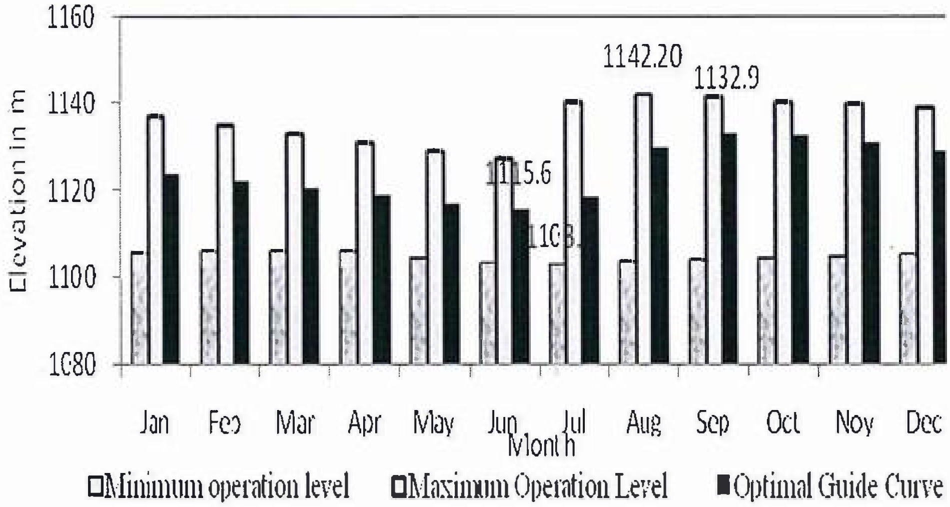


**Figure 5-10** TK_5 implicit monthly maximum, minimum and average guide curve chart

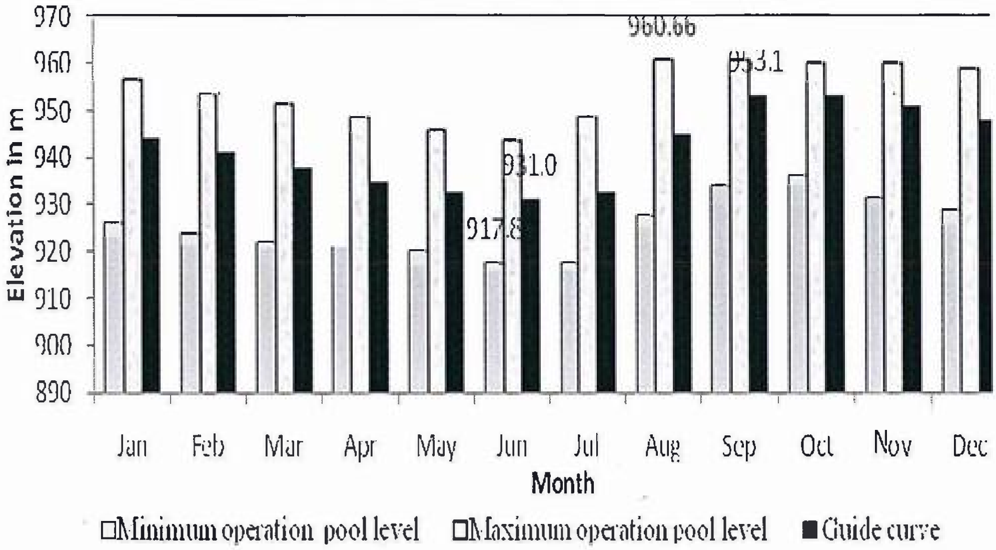


**Figure 5-11** TK_7 implicit monthly maximum, minimum and average (guide) curve chart

## 5.4 Explicit system storage balance result

In the explicit system storage, balance operation different inflection points have been taken and the optimal system storage balance line was selected at the point where minimum spill and maximum firm power and/or total energy observed. System storage, average power, and average energy generated from the system and amount of flow to power plant at TK_7 were prepared for each trial percentage of inflection points (Table 5.2). Too many inflection points have been taken and the optimal inflection point was selected (Figure 5-12). The tabulated trials are two samples and the one, which is taken as the optimal co-ordination. Generally, the optimal inflection point tends emptying TK_5 reservoir and filling TK_7 reservoir in the conservation zone. Detail discussion of the selected explicit system operation is as in the subsequent sections.

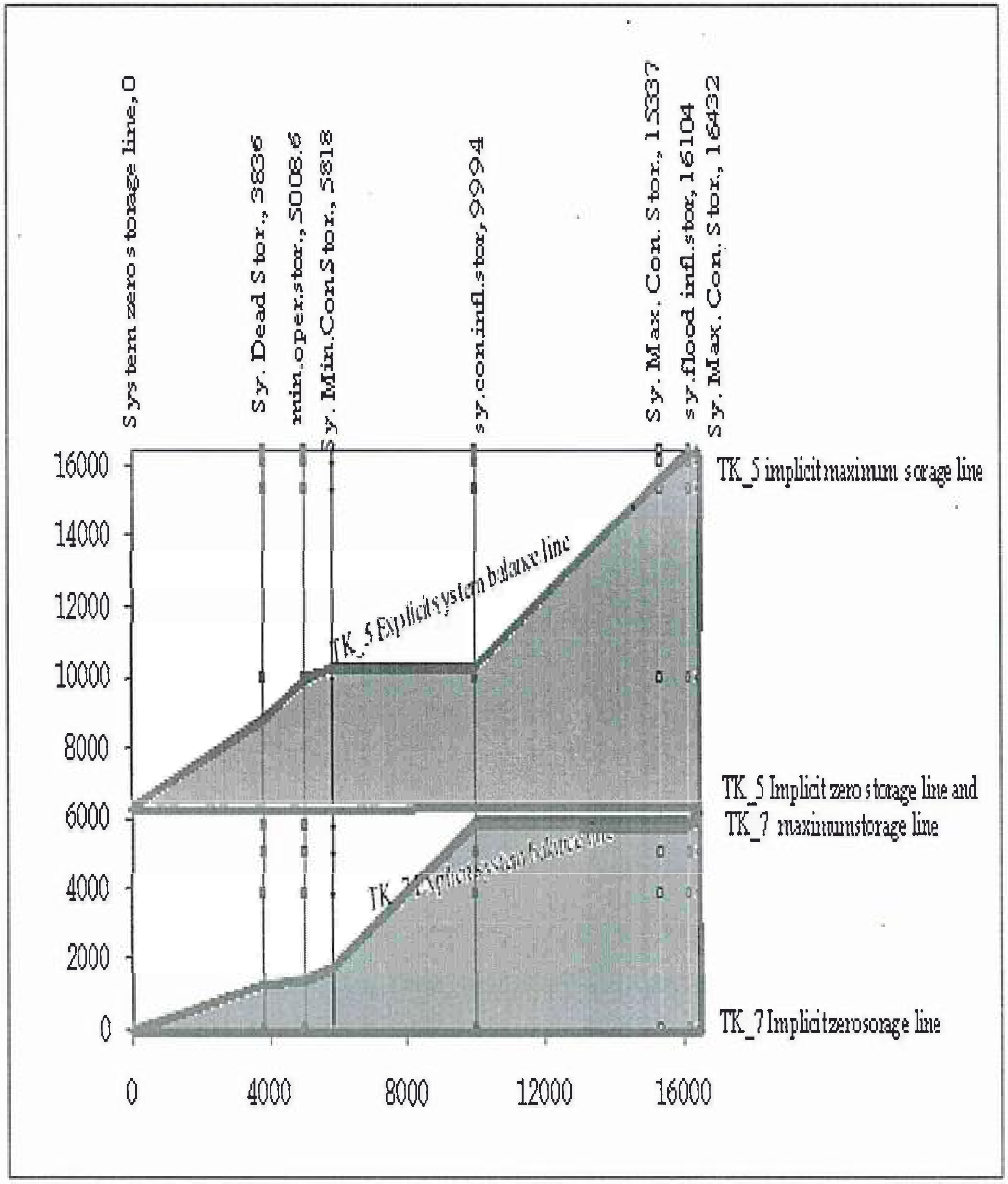


**Figure 5-12** Explicit system storage balance line

### 5.4.1 Explicit System Storage Balance Optimal reservoir operation

Trial three in Table 5.2 is the selected optimal explicit balance line inflection point. The conservation inflection point, (0,100) % TK_5, TK_7, respectively indicates up stream reservoir (TK_5) should empty the stored water and down stream reservoir (TK_7) should keep filling its conservation zone. Flow from up stream power plant can generate additional power at down stream plant and natural inflow at TK-5 is much higher than that of TK_7, then it helps to store much water during high flood occurrence. These are among the benefits of this operation. The reverse is true in flood operating zone (100, 0) percentage at TK_5 and TK_7 respectively. The upstream reservoir stores much of the flood flow to minimize spillage from down stream reservoir and then from the system. For the minimum operating zone, the inflection point is at (70, 30) percentage at TK_5 and TK_7 respectively, priority is given to the amount of energy that could be generated in the system. Even if the average Plant factor of TK_5 obtained from the explicit system is 0.5 which is less than the value in the final feasibility study (i.e. 0.6) the average energy and firm power obtained is higher than the value estimated by the feasibility study. The Plant factor of TK_7 is 0.8, which is higher than the value assumed from the feasibility study (i.e. 0.6). HEC-ResSim plots for selected optimal power plant operation including power at the upper plot position, inflow, and outflow to the power plants in the lower portion are presented in Figures 5.13 and 5.14.

The total water loss from the system in the implicit system storage balance is 118.44 $m^3/s$ (3735.07 M cum/yr). Out of this 8.3m, $^3/s$ is from evaporation, 0.5 $m^3/s$ from seepage at TK_5 reservoir and 109.64$m^3/s$ by spillage from TK_7 reservoir. While the total loss in the explicit system storage balance is 107.7$m^3/s$ (3396.52 M cum/yr). The losses are due to evaporation 7.85 $m^3/s$, by seepage 0.5 $m^3/s$ at TK_5 reservoir and by spillage 99.36$m^3/s$ from TK_7 reservoir (Fig. E-3, E-4, and E-5 in Appendix-E)

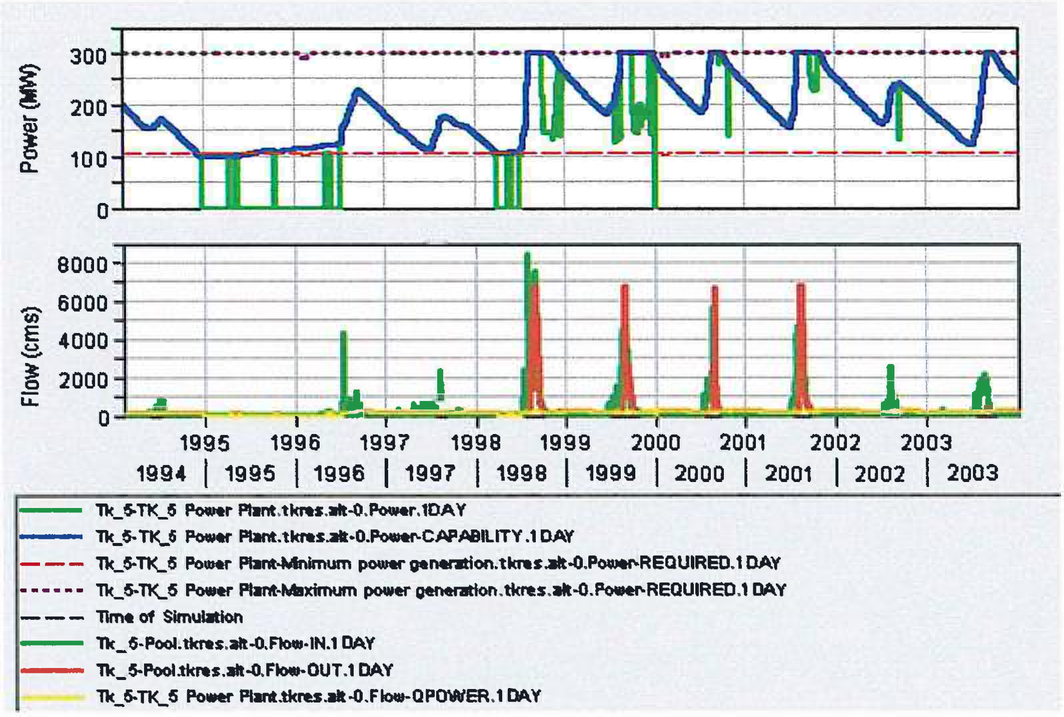


**Figure 5-13** TK_5 Power generation, Inflow and Outflow in the explicit System

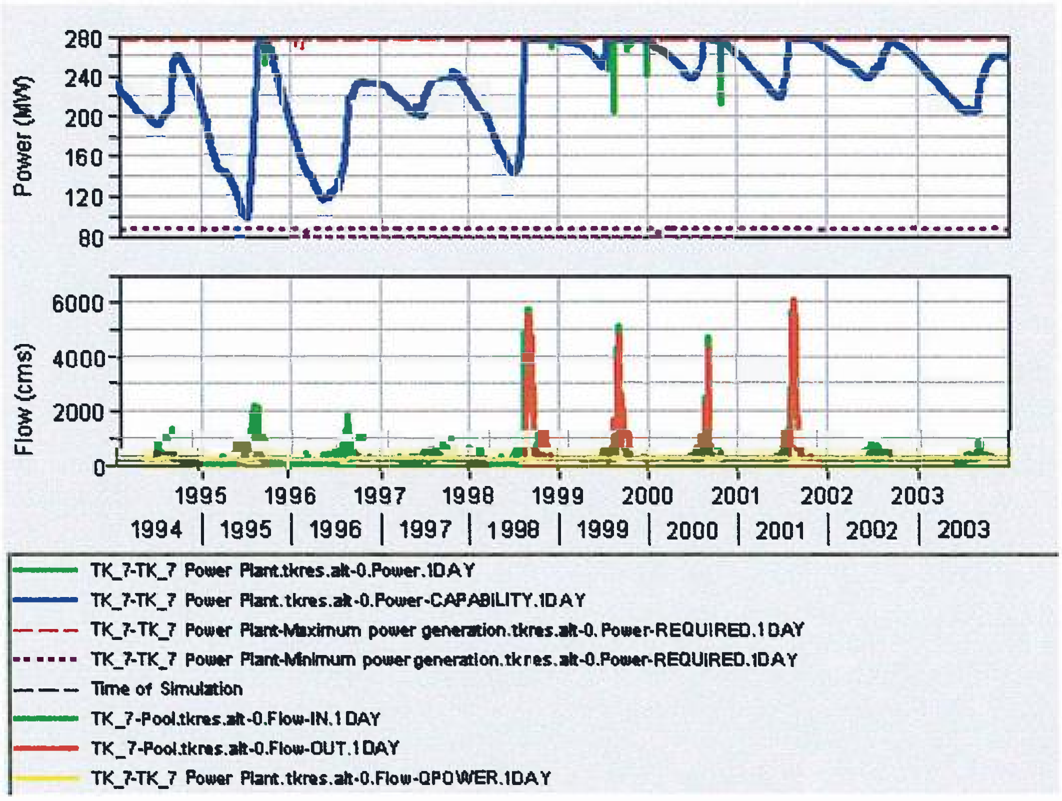


**Figure 5-14** TK_7 Power generation, Inflow and Outflow in the explicit System

**Table 5-2** Explicit system balance line optimal inflection point selection

| Zone (TK_5%, TK_7%) | Storage (TK_5,TK_7) in $Mm^3$ | Elevation (TK_5,TK_7) in m a.m.s.l | System storage $Mm^3$ | TK_5 average annual power MW | TK_7 average annual power MW | System average annual power MW | System average annual energy per yearMWh/yr | Tk_7 Power plant flow $m^3/s$ |
|---|---|---|---|---|---|---|---|---|
| Trial 1 | | | | | | | | |
| Flood control | (10077 , 6355) | (1145 , 963) | 16,432 | | | | | |
| conservation | (9310 , 6027) | (1140 , 960) | 15,337 | | | | | |
| conservation Inflection (60,40)% | (7173 ,3 521) | | 10,694 | | | | | |
| Minimum operation | (3967 , 1851) | (1096 , 898) | 5,818 | | | | | |
| minimum operation Inflection (60,40)% | (3389 , 1529) | | 4,917.8 | | | | | |
| inactive | (2522 , 1314) | (1076.5 , 888) | 3,836 | 117.4 | 176.9 | 294.3 | 2578.07 | 183.7 |
| Trial 2 | | | | | | | | |
| Flood control | (10077 , 6355) | (1145 , 963) | 16,432 | | | | | |
| conservation | (9310 , 6027) | (1140 , 960) | 15,337 | | | | | |
| conservation Inflection (20,80)% | (5035.6,5191.8) | | 10227.4 | | | | | |
| Minimum operation | (3967 , 1851) | (1096 , 898) | 5,818 | | | | | |
| of minimum operation Inflection (20,80)% | (2811,1743.6) | | 4554.6 | | | | | |
| inactive | (2522 , 1314) | (1076.5 , 888) | 3,836 | 147.6 | 202.8 | 350.4 | 3069.5 | 198.2 |
| Trial 3 | | | | | | | | |
| Flood control | (10077 , 6355) | (1145 , 963) | 16,432 | | | | | |
| Flood inflection(100,0)% | (10077,6027) | | 16,104 | | | | | |
| conservation | (9310 , 6027) | (1140 , 960) | 15,337 | | | | | |
| conservation Inflection (0,100)% | (9310, 1851) | | 11,161 | | | | | |
| Minimum operation | (3967 , 1851) | (1096 , 898) | 5,818 | | | | | |
| minimum operation Inflection (70,30)% | (3533.5 ,1475.1) | | 5008.6 | | | | | |
| inactive | (2522 , 1314) | (1076.5 , 888) | 3,836 | 163.2 | 229.1 | 392.3 | 3436.55 | 217.4 |

### 5.4.2 Explicit System Storage Balance Optimal Firm Power and Energy

HEC-ResSim in the explicit system storage balance line (i.e. at the optimal inflection point) can generate 2698.87 GWh/year, 308.09 MW firm energy and power respectively with 97% exceedency. The firm energy and power obtained in TK_5 enhanced by 30.43 GWh/yr and 3.46 MW respectively with value estimated in the final feasibility study report. The firm power and energy that could be generated in TK_7 power plant are 192.62 MW and 1687.44GWh/yr respectively. It proves that there is a clear increment of generation capacity for a given inflow than the implicit system. Figure 5.15 and 5.16 shows the optimized power duration curve of each power plant. Explicit average, firm, and secondary power and energy of each plant and the system are summarized in Table 5.3. Daily average power and inflow to power plants are prepared in Excel spreadsheet by using the values obtained from HEC-ResSim (Fig. E-6 to E-9 in Appendix-E).

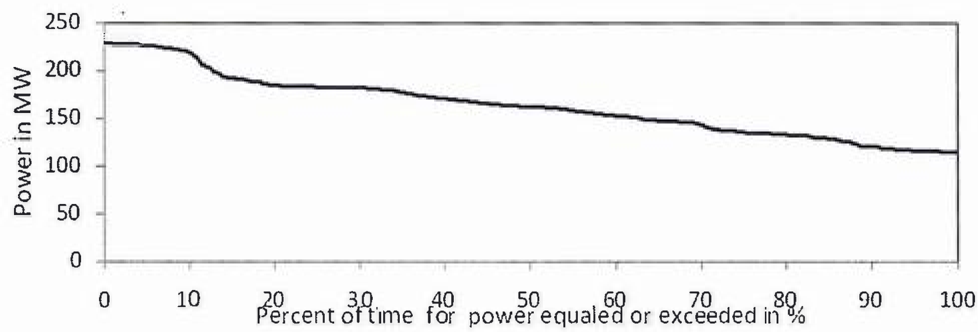


**Figure 5-15** TK_5 E explicit Power Duration Curve

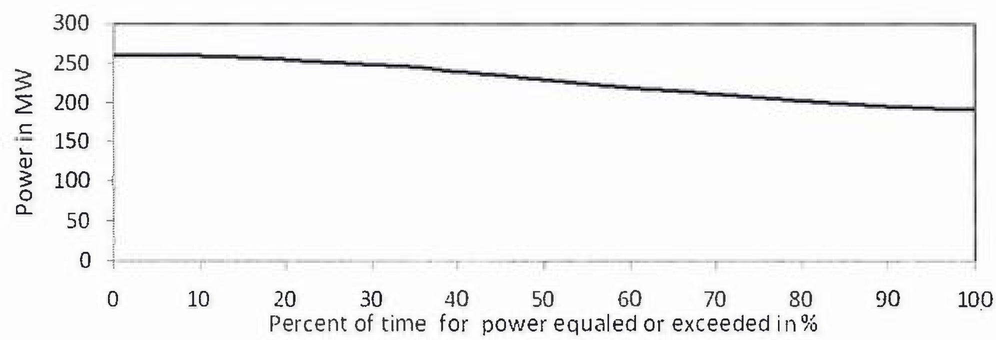


**Figure 5-16** TK_7 Explicit Power Duration Curve

### 5.4.3 Explicit Optimal Average and Secondary Power and Energy

Average power and energy are among the objective functions to select the optimal explicit system storage balance inflection point. As previously, defined Secondary power and energy are generations in excess of firm power and energy respectively. In the optim ized explicit balance line, the system can generate an annual average of 3436.55GWh/yr and 392.3MW energy and power respectively. The average energy and power obtained at TK_5 in the explicit system is 1429.63GWh/yr and 163.2MW respectively. Even though the average plant factor is less in TK_5 (i.e. 0.5) than estimated in the final feasibility (i.e. 0.6), the average energy that could be generated exceeds the average energy estim ated by the final feasibility report (i.e. 1065GWh/yr). It indicates that the energy with 0% exceedency in the explicit system (i.e. 2005.25 GWh/yr) is higher than the value esti mated in the final feasibility report. In the explicit system, TK_7 power plant generates 229.1 MW and 2006.92GWh/yr power and energy respectively. Generally, the explicit system balance line can give better result than the implicit. Table 5.3 shows summery of the optimized system average, firm and secondary power and energy.

**Table 5-3** Summery of explicit average, firm and secondary power and energy

| Location/Parameter | Average | Firm | Secondary |
|---|---|---|---|
| TK_7 Energy Generated per Year (GWh/yr) | 2006.92 | 1687.44 | 319.48 |
| TK_7 Power Generated (MW) | 229.1 | 192.62 | 36.47 |
| TK_5 Energy Generated per Year (GWh/yr) | 1429.63 | 1011.43 | 418.2 |
| TK_5 Power Generated (MW) | 163.2 | 115.46 | 47.74 |
| System Energy Generated per Year (GWh/yr) | 3436.55 | 2698.87 | 737.68 |
| System Power Generated (MW) | 392.3 | 308.09 | 84.21 |

### 5.4.4 Explicit System Storage Balance Operation Guide Curve

The reservoir average pool level obtained from the selected explicit system balance line is the optimal operation guide curve. Figure 5.17 and 5.18 shows the output plot of HEC-ResSim for TK_5 and TK_7 respectively. The upper plot region is the computed reservoir pool elevation and the lower region shows the computed pool inflow and outflow.

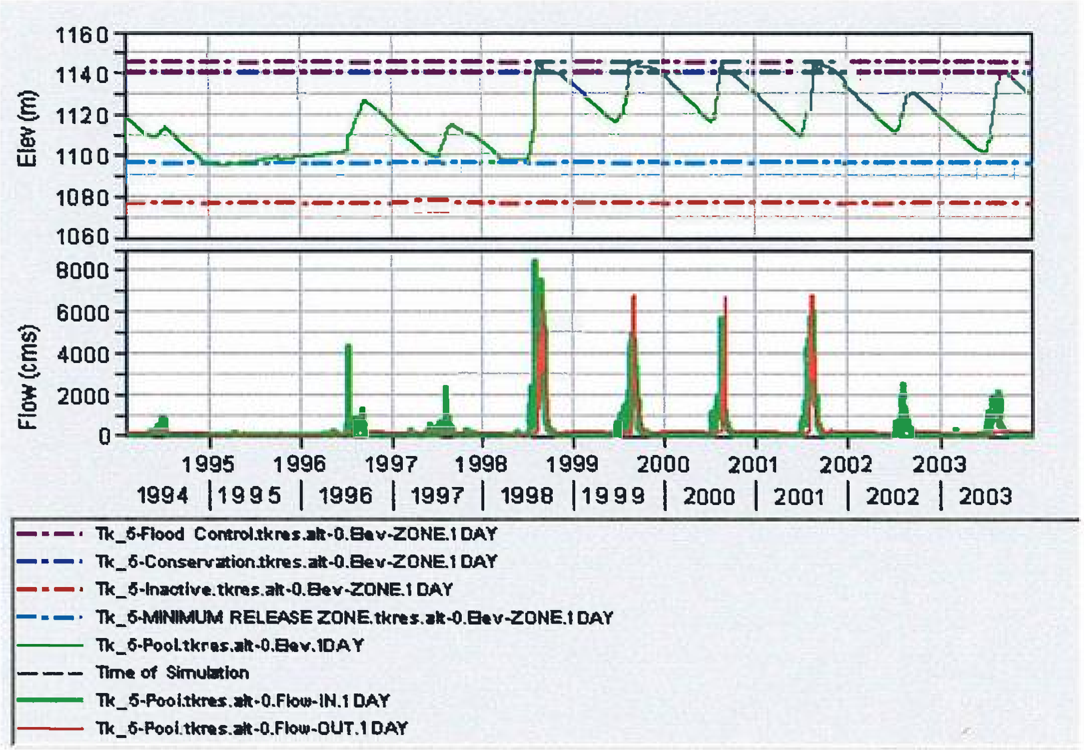


**Figure 5-17** TK_5 Pool Level, Inflow and Outflow in the explicit System

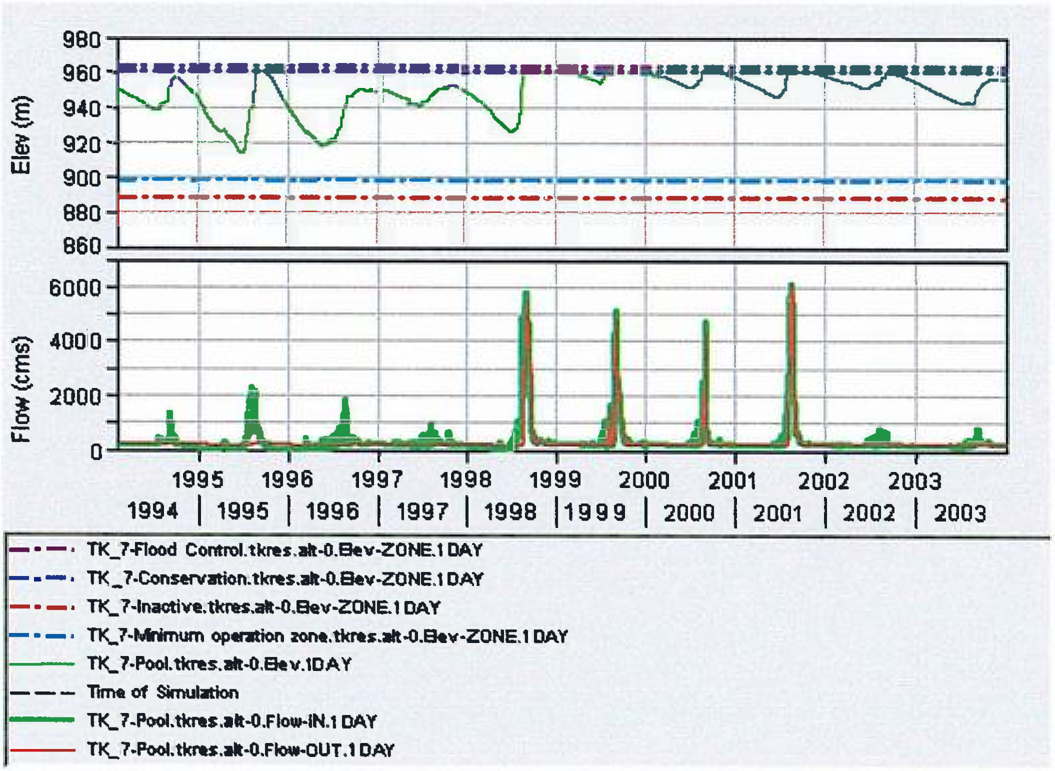


**Figure 5-18** TK_7 Pool Level, Inflow and Outflow in the explicit System

Figure 5.19 and 5.20 shows the monthly maximum, minimum and average (guide) curve of TK-5 and TK_7 respectively. The plot is prepared in Excel spreadsheet using the result obtained from HEC-ResSim.

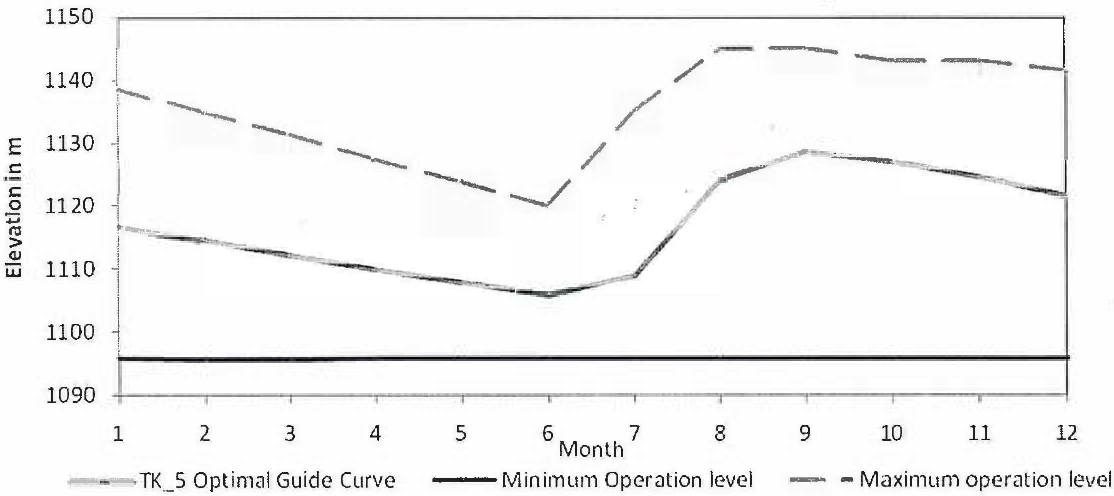


**Figure 5-19** TK_5 Explicit Guide curve, minimum and maximum pool level

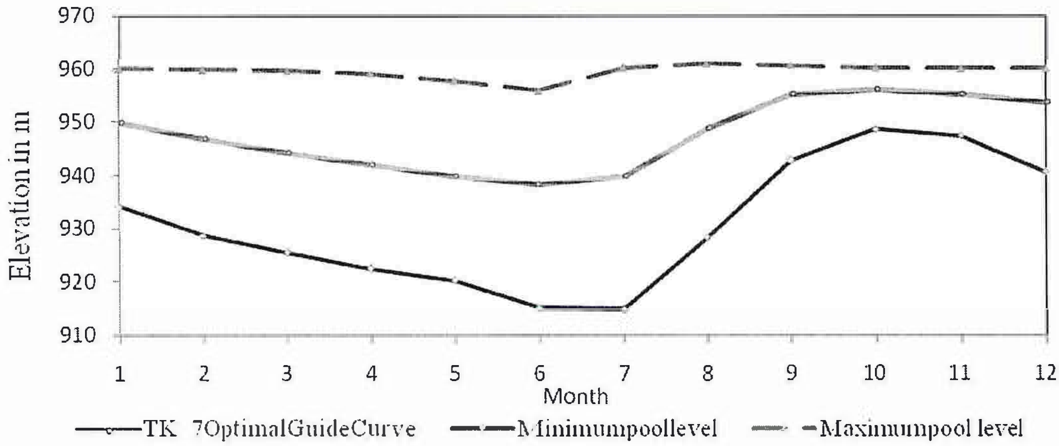


**Figure 5-20** TK_7 Explicit Guide curve, minimum and maximum pool level

Figure 5.21 and 5.22 shows the optimal guide curve chart of the two reservoirs. Values in the chart tell the optimal monthly maximum, minimum and guide curve (maximum, minimum) 1145, 1095.7, 1128.7, and 1106.2m a.m.s.l at TK_5 and 960.80, 915.0, 956.0, and 938.3 m a.m.s.l TK_7 respectively.

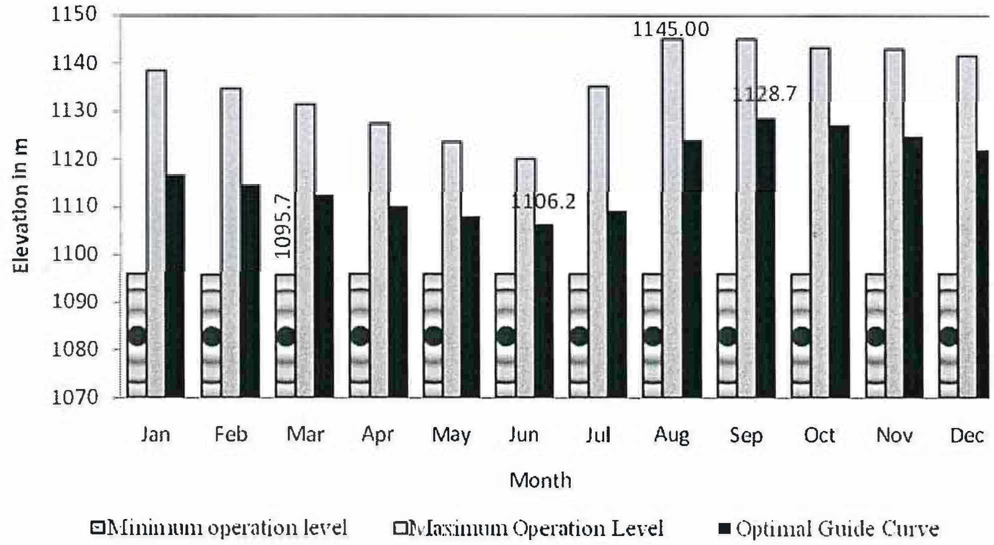


**Figure 5-21** TK_5 Explicit monthly maximum, minimum and average (guide curve) chart

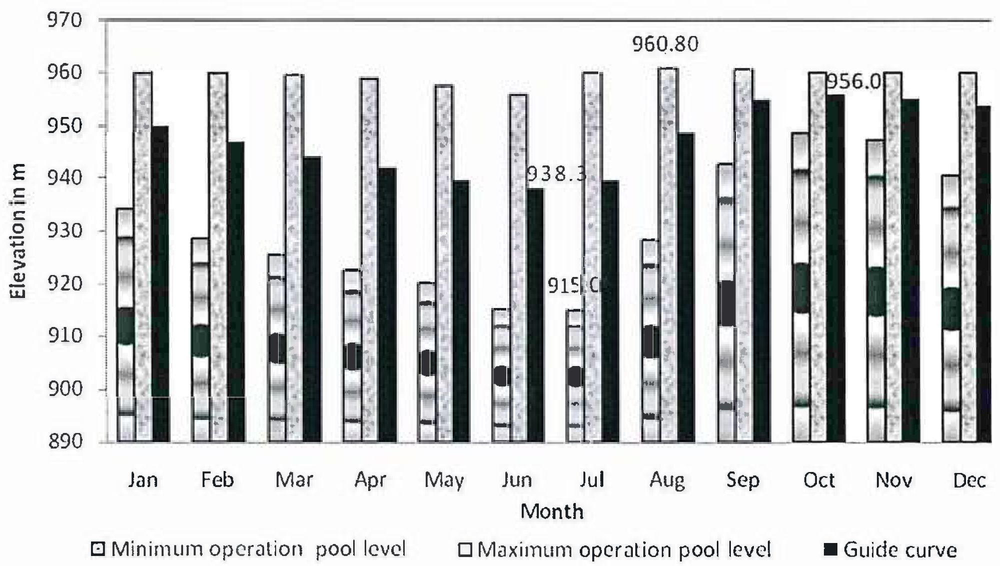


**Figure 5-22** TK_7 Explicit monthly maximum, minimum and average (guide curve) chart

# 6 Conclusion and Recommendation

## 6.1 Conclusion

This research work has attempted to carry out optimal reservoir operation planning for the maximum reservoir performance of Tekeze cascade hydropower development using HEC-ResSim 3.0 model. In this study, reservoir operation has been carried out with Implicit and Explicit system storage balance. The reservoirs have been operated under a regulation that guides the release according to the upstream reservoir level, the water level at a downstream reservoir and the maximum, minimum release capacity.

The study hydropower reservoirs are in cascade and ResSim was configured for tandem oper ation with daily requirement of the power plant. A number of inflection point trials had been made to meet the target of optimal reservoir operation. These setups had been made in reservoir system editor of reservoir network module. The results of implementing the inflection points under different alternative strategies demonstrate that, the explicit system balance can be used efficiently to optimize operation in single purpose reservoirs. Since results obtained from optimal explicit system are the main targets of the study conclusions are set based on it.

### *Power and Energy*

The average annual energy generated in explicit system storage balance was 3436.55 GWh/year. In this method TK_5 power plant was observed to produce an additional 364.63 GWh/yr average energy above the estimated in the feasibility study (i.e.1065 GWh/yr). The average plant factor of TK_7 power plant have been found 0.8, which is higher than the value estimated in the feasibility study (i.e. 0.6). Average energy of TK_7 was estimated 2006.92 GWh/yr which is surplus even compared to the plant can generate with its maximum capacity in the given plant factor (i.e. 1445.4 GWh/yr).

The simulation results in the optimal explicit system balance indicate that the quantity and uniformity of energy production were improved. Concerning the uniformity of energy production, the gap between maximum and minimum energy production of the system was reduced from 5.56GWh (implicit) to 4.41GWh (explicit). In the explicit system storage scheme , average, and firm annual energy productions show an increament of 414.35GWh and 435.9 GWh respectively.

### Guide curve

Results of optimal average pool level (guide curve) at TK_5 for each month in the explicit system storage balance shows a decrement relative to the values obtained from the implicit system storage balance of respective month. It signifies that there is a tendency in the optimal explicit system storage balance to leave more water in TK_5 reservoir and make the storage ready to hold more water during high flood season. The other thing is that the water that left from TK_5 power plant can generate additional power at TK_7. The reverse is true for operation at TK_7 (Figure E-12 and E-13 in Appendix-E). It helps to balance the system live storage and give guaranty if there is unexpected flow reduction in the coming season.

The optimum operational pool level (guide curve) fluctuates from 956 to 938.3m a.m.s.l and from 1128.7 to 1106.2m a.m.s.l at TK_5 and TK_7 respectively (Fig. 5-22 and 5-21). Fluctuation of maximum pool level at TK_7 within the maximum conservation level (i.e. 960 m a.m.s.l) and the maximum average pool level (i.e. 956 m a.m.s.l) indicates the availability of inflow for the proposed dam with crest elevation 968m a.m.s.l. The other dams proposed in the feasibility study are 940 and 998m.a.s.l high at dam crest. The dam with crest level 998m a.m.s.l is rejected due to the minimum tail water level at TK_5 (i.e. 970) and dam with crest level 940m.a.s.l is not advised to built because of excess water loss in spillage and minimizing average power generation in the system.

### Release

System Releases are releases from power plant (useful) and releases from spillways, outlets, seepage at TK_5 and evaporation from both reservoir water surfaces (loss). The average power release from the explicit system storage balance is 217.4m3/s and 135.4m3/s at TK_7 and TK_5 power plants respectively. While the average total loss from the system was 107.7$m^3$/s. It implies that there is a reducton of annual average total loss with 338.55 M cum relative to implicit system storage balance. The contribution of reduction of loss by evaporation is 20.1Mcum/yr. Daily power plant flow for the selected guide curve of each reservoir was prepared in Excel spreadsheet as Fig.E-7 and E-8 in Appendix-E.

## 6.2 Recommendation

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

In order to keep reservoir pool level at optimal guide curve and to minimize spillage from the system, it is recommended to release more water (generate more power) at TK_7 and filling the flood level of TK_5 during high flow season. On the other hand, when the system storage is with in the conservation zone, it is recommended to release more water to TK_5 power plant to generate more power and minimizing releases from TK_7 reservoir to keep the conservation pool level at TK_7 and hence the system storage.

The work conducted in this study was by employing HEC-ResSim 3.0, which still does not have ability to simulate the rainfall runoff process in the catchments, as a result outputs for reservoir, and power plant simulation was dependent on the discharge inflow into the reservoirs. Hence, it is recommendable to use a stochastically generated time series of rainfall and stream flow instead of the observed hydrological data.

The average and firm energy increases when the initial storage (look back) is increased, there fore it is recommended to start operation at the point where satisfactory storage is reached.

This study considered the stream flow data at Yachila and Embamdre during the period 1994-2003.which is exaggerated relative to the flow used during the feasibility study. Therefore, the flow-rating curve at Embamdre should be carefully examined.

This study did not consider downstream water development activities. So it should be considered for further study in the area.

Continuous and accurate monitoring at all gauging station especially key station like Embamdre is strongly recommended.

Since the dead storage capacity ofTK_5 reservoir is fixed based on the sediment value obtained from the flow in the feasibility study, it should be revised again according to the appropriate inflow to the reservoir and attention should be given to soil conservation activities over the watershed.

Since the dead storage capacity of TK_7 reservoir is estimated with out considering the construction of TK_5 dam, which reduces Sediment load in to TK_7 reservoir, it should be revised.

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## APPENDIX-A Filled Data and Result

**Table A-1** Monthly flow at Embamdre hydrometric station [m^3/s]

| year | month | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Jan | Feb. | Mar | Apr. | may | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
| 1994 | 3.9 | 3.0 | 3.2 | 4.1 | 19.6 | 38.6 | 99.1 | 145.6 | 473.0 | 28.1 | 5.6 | 1.9 |
| 1995 | 0.4 | 0.7 | 48.7 | 133.4 | 34.8 | 44.0 | 566.3 | 1077.9 | 394.0 | 85.7 | 30.5 | 26.1 |
| 1996 | 20.4 | 20.9 | 94.1 | 79.3 | 101.5 | 202.0 | 511.4 | 1044.1 | 371.5 | 123.2 | 69.1 | 55.4 |
| 1997 | 27.1 | 15.9 | 54.4 | 31.1 | 64.8 | 149.4 | 480.0 | 577.0 | 163.4 | 197.2 | 114.4 | 43.8 |
| 1998 | 15.8 | 6.3 | 7.6 | 27.3 | 81.1 | 87.3 | 1376.7 | 3129.7 | 1197.9 | 291.6 | 160.7 | 81.1 |
| 1999 | 80.0 | 49.7 | 50.1 | 47.3 | 45.2 | 99.5 | 663.6 | 2103.8 | 816.8 | 320.2 | 156.9 | 87.8 |
| 2000 | 8.7 | 21.1 | 17.0 | 8.4 | 8.1 | 19.1 | 441.4 | 1684.7 | 314.0 | 101.6 | 31.0 | 15.5 |
| 2001 | 10.0 | 4.3 | 8.2 | 4.2 | 7.3 | 70.3 | 1294.4 | 3040.0 | 411.4 | 105.1 | 26.0 | 14.2 |
| 2002 | 20.8 | 15.8 | 34.9 | 31.6 | 25.4 | 86.1 | 342.2 | 872.5 | 271.6 | 52.3 | 33.0 | 30.4 |
| 2003 | 20.8 | 20.2 | 30.6 | 40.8 | 43.1 | 88.5 | 641.7 | 1519.5 | 490.4 | 195.0 | 69.7 | 39.6 |
| average | 20.8 | 15.8 | 34.9 | 40.8 | 43.1 | 88.5 | 641.7 | 1519.5 | 490.4 | 150.0 | 69.7 | 39.6 |

**Table A-2** Monthly flow at Yachila hydrometric station [m^3/s]

| year | month | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Jan | Feb. | mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
| 1994 | 9.1 | 6.1 | 13.8 | 12.5 | 99.1 | 270.4 | 110.6 | 2.1 | 2.1 | 2.1 | 2.1 | 2.1 |
| 1995 | 2.1 | 2.1 | 19.7 | 47.7 | 26.7 | 25.6 | 16.6 | 21.0 | 19.8 | 18.0 | 24.0 | 21.4 |
| 1996 | 15.2 | 11.3 | 13.3 | 36.6 | 60.4 | 28.2 | 496.5 | 523.3 | 361.5 | 32.6 | 26.8 | 4.6 |
| 1997 | 4.3 | 3.9 | 29.1 | 12.2 | 18.4 | 78.4 | 370.0 | 445.2 | 55.8 | 74.5 | 84.3 | 25.9 |
| 1998 | 11.5 | 6.9 | 8.8 | 14.1 | 38.8 | 26.7 | 1223.7 | 3432.1 | 1408.6 | 95.7 | 22.2 | 11.0 |
| 1999 | 10.7 | 4.2 | 2.4 | 17.6 | 30.8 | 183.0 | 529.4 | 2096.4 | 1430.7 | 155.0 | 39.7 | 19.0 |
| 2000 | 10.1 | 5.1 | 2.4 | 7.1 | 6.9 | 7.3 | 438.7 | 1683.9 | 301.1 | 69.3 | 31.2 | 13.3 |
| 2001 | 6.9 | 3.4 | 7.1 | 4.5 | 5.8 | 23.5 | 1292.1 | 3030.7 | 385.7 | 41.2 | 19.4 | 14.2 |
| 2002 | 10.3 | 6.0 | 5.4 | 9.9 | 3.2 | 11.6 | 234.0 | 798.7 | 166.0 | 29.1 | 17.6 | 14.9 |
| 2003 | 11.0 | 11.3 | 32.5 | 14.4 | 10.5 | 58.0 | 598.2 | 1340.6 | 293.9 | 58.9 | 24.0 | 16.0 |
| average | 9.1 | 6.0 | 13.4 | 17.7 | 30.1 | 71.3 | 531.0 | 1337.4 | 442.5 | 57.6 | 29.1 | 14.2 |

**Table A-3** Monthly inflow at TK_7 reservoir (CP3) [m^3/s]

| year | month | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
| 1994 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 115.2 | 491.9 | 27.2 | 3.7 | 0.0 |
| 1995 | 0.0 | 0.0 | 30.3 | 89.5 | 8.5 | 19.2 | 574.1 | 1103.9 | 390.8 | 70.7 | 6.8 | 4.9 |
| 1996 | 5.4 | 10.0 | 84.4 | 44.6 | 42.9 | 181.5 | 15.6 | 543.9 | 10.5 | 94.5 | 44.2 | 53.1 |
| 1997 | 23.8 | 12.5 | 26.4 | 19.7 | 48.5 | 74.1 | 114.8 | 137.6 | 112.3 | 128.1 | 31.5 | 18.7 |
| 1998 | 4.5 | 0.0 | 0.0 | 13.9 | 44.2 | 63.3 | 104.1 | 437.6 | 0.0 | 204.6 | 144.7 | 73.2 |
| 1999 | 72.4 | 47.5 | 49.9 | 31.0 | 15.0 | 0.0 | 140.2 | 29.5 | 0.0 | 172.6 | 122.4 | 71.9 |
| 2000 | 0.0 | 16.7 | 15.2 | 1.4 | 1.2 | 12.3 | 2.9 | 82.7 | 13.4 | 33.7 | 0.0 | 2.4 |
| 2001 | 3.2 | 0.9 | 1.1 | 0.0 | 1.5 | 48.9 | 249.5 | 510.3 | 26.9 | 66.8 | 6.9 | 0.0 |
| 2002 | 13.1 | 10.7 | 31.3 | 24.4 | 23.2 | 77.7 | 113.0 | 77.1 | 110.3 | 24.2 | 16.1 | 16.2 |
| 2003 | 10.2 | 9.3 | 0.0 | 28.8 | 34.0 | 31.8 | 0.0 | 0.0 | 204.3 | 120.5 | 47.7 | 25.6 |
| Average | 13.3 | 10.8 | 23.9 | 25.3 | 21.9 | 50.9 | 131.4 | 303.8 | 136.0 | 94.3 | 42.4 | 26.6 |

**Table A-4** Monthly inflow at TK_5 reservoir (CP1) [m^3/s]

| Year | month | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
| 1994 | 9.8 | 6.5 | 14.9 | 13.5 | 107.0 | 291.9 | 119.4 | 2.2 | 2.2 | 2.2 | 2.2 | 2.2 |
| 1995 | 2.2 | 2.2 | 21.2 | 51.5 | 28.8 | 27.7 | 17.9 | 22.7 | 21.4 | 19.5 | 25.9 | 23.1 |
| 1996 | 16.4 | 12.2 | 14.3 | 39.5 | 65.2 | 30.5 | 535.9 | 564.9 | 390.2 | 35.2 | 29.0 | 4.9 |
| 1997 | 4.7 | 4.2 | 31.4 | 13.2 | 19.9 | 84.6 | 399.4 | 480.6 | 60.2 | 80.4 | 90.9 | 28.0 |
| 1998 | 12.4 | 7.4 | 9.5 | 15.2 | 41.8 | 28.9 | 1321.0 | 3704.9 | 1520.6 | 103.3 | 24.0 | 11.9 |
| 1999 | 11.5 | 4.5 | 2.5 | 19.0 | 33.3 | 197.6 | 571.5 | 2263.0 | 1544.4 | 167.3 | 42.9 | 20.5 |
| 2000 | 10.9 | 5.5 | 2.6 | 7.6 | 7.5 | 7.9 | 473.6 | 1817.8 | 325.1 | 74.8 | 33.7 | 14.3 |
| 2001 | 7.4 | 3.7 | 7.7 | 4.9 | 6.3 | 25.4 | 1394.8 | 3271.6 | 416.4 | 44.5 | 20.9 | 15.3 |
| 2002 | 11.1 | 6.5 | 5.9 | 10.7 | 3.4 | 12.6 | 252.6 | 862.2 | 179.2 | 31.4 | 19.0 | 16.1 |
| 2003 | 11.8 | 12.2 | 35.1 | 15.5 | 11.4 | 62.6 | 645.7 | 1447.1 | 317.3 | 63.6 | 25.9 | 17.2 |
| Average | 9.8 | 6.5 | 14.5 | 19.1 | 32.5 | 77.0 | 573.2 | 1443.7 | 477.7 | 62.2 | 31.4 | 15.4 |

**Table A-5** Mean monthly point rainfall at Mekele airport obserba (TK_5 res.) [mm]

| Year | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | sum |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | month | | | | | | | |
| 1992 | 8.7 | 2.1 | 38.5 | 1.0 | 30.7 | 6.2 | 140.7 | 233.1 | 1.3 | 2.1 | 54.4 | 8.3 | 527.1 |
| 1993 | 11.7 | 7.7 | 63.9 | 135.0 | 74.7 | 69.0 | 217.2 | 106.5 | 15.2 | 20.0 | 0.0 | 0.0 | 720.9 |
| 1994 | 0.0 | 5.3 | 0.4 | 43.8 | 0.8 | 67.6 | 147.9 | 317.8 | 70.1 | 0.0 | 1.8 | 2.0 | 657.5 |
| 1995 | 0.0 | 5.9 | 31.2 | 29.2 | 27.1 | 6.8 | 268.2 | 237.7 | 51.4 | 3.0 | 0.0 | 2.7 | 663.2 |
| 1996 | 1.4 | 0.0 | 59.5 | 12.5 | 92.2 | 47.9 | 109.2 | 224.0 | 7.1 | 0.0 | 31.4 | 1.1 | 586.3 |
| 1997 | 0.0 | 0.0 | 20.4 | 32.6 | 29.8 | 32.4 | 243.1 | 100.5 | 16.3 | 59.9 | 15.7 | 0.0 | 550.7 |
| 1998 | 10.0 | 1.2 | 0.0 | 10.6 | 22.0 | 48.0 | 289.0 | 318.8 | 31.7 | 22.0 | 0.0 | 0.0 | 753.3 |
| 1999 | 22.0 | 0.3 | 10.9 | 0.0 | 0.0 | 7.4 | 293.6 | 359.2 | 22.8 | 0.9 | 0.0 | 0.0 | 717.1 |
| 2000 | 0.0 | 0.0 | 0.0 | 10.4 | 24.6 | 5.4 | 201.4 | 182.0 | 15.8 | 2.2 | 10.3 | 3.5 | 455.6 |
| 2001 | 0.0 | 0.0 | 38.1 | 18.7 | 8.7 | 65.5 | 267.9 | 226.3 | 9.2 | 2.9 | 0.0 | 0.0 | 637.3 |
| 2002 | 12.9 | 0.0 | 35.5 | 4.2 | 23.0 | 60.8 | 95.5 | 208.6 | 28.0 | 0.0 | 0.0 | 0.3 | 468.8 |
| 2003 | 0.0 | 25.9 | 18.2 | 8.4 | 35.2 | 87.5 | 125.6 | 201.8 | 23.4 | 0.7 | 0.0 | 0.1 | 526.8 |
| 2004 | 7.4 | 3.7 | 35.2 | 20.5 | 7.1 | 25.4 | 64.3 | 221.1 | 1.4 | 3.1 | 0.8 | 0.0 | 390.0 |
| 2005 | 0.0 | 1.4 | 15.6 | 48.9 | 37.1 | 18.2 | 110.5 | 314.0 | 34.2 | 0.0 | 1.3 | 0.0 | 581.2 |
| 2006 | 0.0 | 0.0 | 31.3 | 117.6 | 46.3 | 38.1 | 187.1 | 298.9 | 23.6 | 12.0 | 0.0 | 0.3 | 755.2 |
| 2007 | 1.1 | 2.3 | 11.2 | 34.5 | 22.2 | 57.1 | 272.6 | 139.7 | 78.6 | 0.0 | 0.0 | 0.0 | 619.3 |
| 2008 | 24.2 | 0.0 | 0.0 | 82.4 | 19.0 | 56.5 | 361.9 | 382.6 | 97.9 | 26.6 | 14.6 | 0.0 | 1065.7 |
| Average | 5.8 | 3.3 | 24.1 | 35.9 | 29.4 | 41.2 | 199.7 | 239.6 | 31.1 | 9.1 | 7.7 | 1.1 | 628.0 |

**Table A-6** Mean monthly point rainfall at Shire Endeselasie (TK_7 res.) [Mm]

| Year | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec | sum |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | month | | | | | | | |
| 1992 | 4.7 | 0.9 | 0.0 | 34.2 | 8.4 | 107.3 | 218.0 | 284.4 | 207.7 | 33.2 | 13.0 | 17.1 | 928.9 |
| 1993 | 0.0 | 0.0 | 2.0 | 29.4 | 68.1 | 146.5 | 233.4 | 247.4 | 132.3 | 97.3 | 0.0 | 0.0 | 956.4 |
| 1994 | 0.0 | 13.8 | 0.0 | 7.7 | 36.2 | 131.4 | 282.2 | 358.3 | 231.9 | 15.8 | 11.1 | 2.9 | 1091.3 |
| 1995 | 0.0 | 0.0 | 21.1 | 17.2 | 56.2 | 76.9 | 434.2 | 192.0 | 188.1 | 2.0 | 0.0 | 0.0 | 987.7 |
| 1996 | 0.0 | 0.0 | 28.5 | 34.5 | 177.4 | 112.8 | 190.7 | 218.2 | 111.3 | 11.0 | 23.2 | 1.9 | 909.5 |
| 1997 | 0.0 | 0.0 | 11.2 | 15.3 | 100.9 | 128.7 | 349.9 | 233.1 | 144.7 | 144.2 | 79.8 | 6.0 | 1213.8 |
| 1998 | 0.0 | 0.0 | 12.2 | 3.0 | 105.0 | 109.0 | 379.8 | 278.2 | 128.9 | 55.4 | 0.0 | 0.0 | 1071.5 |
| 1999 | 2.5 | 0.0 | 0.0 | 22.4 | 16.8 | 133.3 | 383.4 | 420.3 | 181.3 | 277.0 | 0.0 | 3.0 | 1440.0 |
| 2000 | 0.0 | 0.0 | 3.5 | 51.3 | 25.0 | 142.8 | 274.6 | 232.0 | 238.4 | 144.9 | 2.3 | 0.0 | 1114.8 |
| 2001 | 0.0 | 0.0 | 27.4 | 2.8 | 50.1 | 216.5 | 292.1 | 222.4 | 161.1 | 29.3 | 4.1 | 0.1 | 1005.9 |
| 2002 | 1.1 | 0.0 | 13.7 | 7.3 | 31.2 | 114.4 | 281.6 | 185.7 | 129.0 | 9.7 | 8.3 | 1.3 | 783.3 |
| 2003 | 0.0 | 2.0 | 5.6 | 12.6 | 6.3 | 260.0 | 238.4 | 251.8 | 169.5 | 16.9 | 0.0 | 0.0 | 963.1 |
| 2004 | 10.2 | 1.9 | 6.8 | 33.3 | 0.2 | 208.9 | 222.9 | 269.3 | 75.3 | 80.6 | 20.7 | 0.0 | 930.1 |
| 2005 | 0.0 | 0.0 | 54.6 | 12.0 | 52.1 | 123.2 | 264.1 | 194.7 | 203.7 | 5.6 | 3.4 | 0.0 | 913.4 |
| 2006 | 0.0 | 0.0 | 34.0 | 13.6 | 71.7 | 95.3 | 293.9 | 414.4 | 141.1 | 98.0 | 1.4 | 5.4 | 1168.8 |
| 2007 | 0.0 | 0.0 | 8.6 | 9.7 | 67.6 | 169.3 | 337.7 | 234.9 | 177.5 | 18.1 | 0.7 | 0.0 | 1024.1 |
| 2008 | 25.0 | 4.4 | 0.0 | 53.1 | 45.0 | 125.1 | 235.9 | 248.9 | 125.0 | 3.4 | 4.0 | 0.0 | 869.8 |
| Average | 2.6 | 1.4 | 13.5 | 21.1 | 54.0 | 141.3 | 289.0 | 263.9 | 161.6 | 61.3 | 10.1 | 2.2 | 1021.9 |

**Table A-7** Mean monthly evaporation at Mekele air port observa (TK_5 res.) [mm]

| Month | Tmax °C | Tmean °C | Tmin °C | Rh max% | Rh mean% | Rh min % | u(x) m/sec | n hour/day | ETo mm/day | ETo mm/month |
|---|---|---|---|---|---|---|---|---|---|---|
| Jan | 22.9 | 16.2 | 9.4 | 83.8 | 41.8 | 61.2 | 3.6 | 9.5 | 4.6 | 142.8 |
| Feb | 24.3 | 17.3 | 10.4 | 74.6 | 36.4 | 51.5 | 4.3 | 9.8 | 6.5 | 181.4 |
| Mar | 25.2 | 18.5 | 11.9 | 79.7 | 37.7 | 53.8 | 4.1 | 8.8 | 6.8 | 209.8 |
| Apr | 25.6 | 19.5 | 13.3 | 75.7 | 37.6 | 47.0 | 4.0 | 9.2 | 7.8 | 233.3 |
| May | 26.9 | 20.4 | 13.9 | 67.4 | 33.9 | 36.9 | 3.0 | 9.9 | 8.5 | 263.4 |
| Jun | 26.8 | 20.1 | 13.4 | 72.2 | 38.0 | 42.3 | 2.3 | 7.2 | 7.1 | 211.7 |
| Jul | 23.1 | 18.2 | 13.2 | 92.7 | 66.9 | 71.2 | 2.0 | 5.0 | 4.6 | 142.8 |
| Aug | 22.3 | 17.6 | 13.0 | 94.7 | 72.2 | 78.5 | 1.7 | 5.1 | 4.2 | 129.5 |
| Sep | 24.3 | 18.0 | 11.7 | 86.5 | 47.6 | 51.7 | 1.8 | 7.6 | 5.5 | 164.2 |
| Oct | 23.5 | 17.3 | 11.1 | 80.2 | 40.8 | 47.5 | 3.0 | 9.5 | 6.0 | 187.5 |
| Nov | 22.3 | 16.3 | 10.4 | 78.9 | 42.2 | 50.6 | 3.5 | 10.0 | 5.3 | 159.8 |
| Dec | 22.2 | 15.9 | 9.6 | 81.1 | 40.1 | 55.8 | 3.8 | 10.0 | 4.9 | 151.8 |

**Table A-8** Mean monthly evaporation at Shire Endeselasie (TK_7 res.) [mm]

| Month | Tmax °C | Tmean °C | Tmin °C | Rh max% | Rh mean% | Rh min% | u(x) m/sec | n hour/day | ETo mm/day | ETo mm/month |
|---|---|---|---|---|---|---|---|---|---|---|
| Jan | 23.1 | 16.3 | 9.4 | 40.9 | 28.9 | 27.5 | 1.6 | 9.6 | 4.1 | 126.5 |
| Feb | 29.3 | 19.8 | 10.4 | 38.4 | 28.0 | 26.2 | 1.9 | 10.1 | 6.0 | 168.0 |
| Mar | 30.2 | 21.1 | 11.9 | 37.3 | 28.6 | 27.5 | 2.1 | 8.9 | 6.7 | 208.3 |
| Apr | 30.7 | 22.0 | 13.3 | 40.6 | 32.0 | 30.6 | 2.3 | 9.0 | 7.4 | 223.2 |
| May | 30.4 | 22.2 | 13.9 | 45.4 | 36.6 | 39.0 | 2.2 | 8.8 | 7.1 | 219.5 |
| Jun | 27.5 | 20.4 | 13.4 | 59.4 | 48.3 | 88.1 | 2.1 | 7.3 | 4.7 | 140.4 |
| Jul | 23.6 | 18.4 | 13.2 | 76.8 | 68.0 | 75.6 | 1.5 | 4.6 | 3.8 | 119.0 |
| Aug | 23.0 | 18.0 | 13.0 | 81.3 | 72.2 | 81.4 | 1.4 | 4.2 | 3.4 | 104.2 |
| Sep | 25.5 | 18.6 | 11.7 | 69.0 | 55.1 | 70.9 | 1.4 | 6.8 | 4.1 | 122.4 |
| Oct | 27.1 | 19.1 | 11.1 | 52.1 | 40.2 | 47.9 | 1.5 | 8.9 | 4.7 | 145.1 |
| Nov | 27.4 | 18.9 | 10.4 | 46.1 | 35.0 | 39.9 | 1.5 | 9.7 | 4.4 | 133.2 |
| Dec | 27.3 | 18.4 | 9.6 | 79.8 | 31.4 | 33.2 | 1.5 | 10.0 | 4.0 | 122.8 |

**Table A-9** Daily max. duration of bright sunshine hours N for different months and latitudes

| Northern Hemisphere | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Jan. | Feb. | Mar. | Apr. | May | Jun | July | Aug. | Sep. | Oct. | Nov. | Dec. | Lat. |
| 8.5 | 10.1 | 11.8 | 13.8 | 15.4 | 16.3 | 15.9 | 14.5 | 12.7 | 10.8 | 9.1 | 8.1 | 50° |
| 8.8 | 10.2 | 11.8 | 13.6 | 15.2 | 16.0 | 15.6 | 14.3 | 12.6 | 10.9 | 9.3 | 8.3 | 48° |
| 9.1 | 10.4 | 11.9 | 13.5 | 14.9 | 15.7 | 15.4 | 14.2 | 12.6 | 10.9 | 9.5 | 8.7 | 46° |
| 9.3 | 10.5 | 11.9 | 13.4 | 14.7 | 15.4 | 15.2 | 14.0 | 12.6 | 11.0 | 9.7 | 8.9 | 44° |
| 9.4 | 10.6 | 11.9 | 13.4 | 14.6 | 15.2 | 14.9 | 13.9 | 12.9 | 11.1 | 9.8 | 9.1 | 42° |
| 9.6 | 10.7 | 11.9 | 13.3 | 14.4 | 15.0 | 14.7 | 13.7 | 12.5 | 11.2 | 10.0 | 9.3 | 40° |
| 10.1 | 11.0 | 11.9 | 13.1 | 14.0 | 14.5 | 14.3 | 13.5 | 12.4 | 11.3 | 10.3 | 9.8 | 35° |
| 10.4 | 11.1 | 12.0 | 12.9 | 13.6 | 14.0 | 13.9 | 13.2 | 12.4 | 11.5 | 10.6 | 10.2 | 30° |
| 10.7 | 11.3 | 12.0 | 12.7 | 13.3 | 13.7 | 13.5 | 13.0 | 12.3 | 11.6 | 10.9 | 10.6 | 25° |
| 11.0 | 11.5 | 12.0 | 12.6 | 13.1 | 13.3 | 13.2 | 12.8 | 12.3 | 11.7 | 11.2 | 10.9 | 20° |
| 11.3 | 11.6 | 12.0 | 12.5 | 12.8 | 13.0 | 12.9 | 12.6 | 12.2 | 11.8 | 11.4 | 11.2 | 15° |
| 11.6 | 11.8 | 12.0 | 12.3 | 12.6 | 12.7 | 12.6 | 12.4 | 12.1 | 11.8 | 11.6 | 11.5 | 10° |
| 11.8 | 11.9 | 12.0 | 12.2 | 12.3 | 12.4 | 12.3 | 12.3 | 12.1 | 12.0 | 11.9 | 11.8 | 5° |

**Table A-9** Angot's Values of Short-Wave Radiation Flux Ra in gram- calories / cm2 / day

| Latitude° | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sept. | Oct. | No'. | Dec. | Year |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| N90 | 0 | 0 | 55 | 518 | 903 | 1077 | 944 | 605 | 136 | 0 | 0 | 0 | 3540 |
| 80 | 0 | 3 | 143 | 518 | 875 | 1060 | 930 | 600 | 219 | 17 | 0 | 0 | 3660 |
| 60 | 86 | 234 | 424 | 687 | 866 | 983 | 892 | 714 | 494 | 258 | 113 | 55 | 4850 |
| 40 | 358 | 538 | 663 | 847 | 930 | 1001 | 941 | 843 | 719 | 528 | 397 | 318 | 6750 |
| 20 | 631 | 795 | 821 | 914 | 912 | 947 | 912 | 887 | 856 | 740 | 666 | 599 | 8070 |

Note: The SI unit for RA is joules/m2/day. The conversion is 1 g-callcm2 = 41.9 kJ/m2.

**Table A-10** Saturation Vapor Pressure $e_s$ in mm Hg as a Function of Temperature t in °C

| t | 0.0 | 0.1 | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 | t |
|---|---|---|---|---|---|---|---|---|---|---|---|
| -10 | 2.15 | | | | | | | | | | -10 |
| -9 | 2.32 | 2.30 | 2.29 | 2.27 | 2.26 | 2.24 | 2.22 | 2.21 | 2.19 | 2.17 | -9 |
| -8 | 2.51 | 2.49 | 2.47 | 2.45 | 2.43 | 2.41 | 2.40 | 2.38 | 2.36 | 2.34 | -8 |
| -7 | 2.71 | 2.69 | 2.67 | 2.65 | 2.63 | 2.61 | 2.59 | 2.57 | 2.55 | 2.53 | -7 |
| -6 | 2.93 | 2.91 | 2.89 | 2.86 | 2.84 | 2.82 | 2.80 | 2.77 | 2.75 | 2.73 | -6 |
| -5 | 3.16 | 3.14 | 3.11 | 3.09 | 3.06 | 3.04 | 3.01 | 2.99 | 2.97 | 2.95 | -5 |
| -4 | 3.41 | 3.39 | 3.37 | 3.34 | 3.32 | 3.29 | 3.27 | 3.24 | 3.21 | 3.18 | -4 |
| -3 | 3,67 | 3.64 | 3.62 | 3.59 | 3.57 | 3.54 | 3.52 | 3.49 | 3.46 | 3.44 | -3 |
| -2 | 3.97 | 3.94 | 3.91 | 3.88 | 3.85 | 3,82 | 3.79 | 3.76 | 3.73 | 3.70 | -2 |
| -1 | 4.26 | 4.23 | 4.20 | 4.17 | 4.14 | 4.11 | 4.08 | 4.05 | 4.03 | 4.00 | -1 |
| -0 | 4.58 | 4,55 | 4.52 | 4.49 | 4.46 | 4.43 | 4.40 | 4.36 | 4.33 | 4.29 | -0 |
| 0 | 4.58 | 4.62 | 4.65 | 4.69 | 4.71 | 4.75 | 4.78 | 4.82 | 4.86 | 4.89 | 0 |
| 1 | 4.92 | 4.96 | 5.00 | 5.03 | 5.07 | 5.11 | 5.14 | 5.18 | 5.21 | 5.25 | 1 |
| 2 | 5.29 | 5.33 | 5.37 | 5.40 | 5.44 | 5.48 | 5.53 | 5.57 | 5.60 | 5.64 | 2 |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 3 | 5.68 | 5.72 | 5.76 | 5.80 | 5.84 | 5.89 | 5.93 | 5.97 | 6.01 | 6.06 | 3 |
| 4 | 6.10 | 6.14 | 6.18 | 6.23 | 6.27 | 6.31 | 6.36 | 6.40 | 6.45 | 6.49 | 4 |
| 5 | 6.54 | 6.58 | 6.63 | 6.68 | 6.72 | 6.77 | 6.82 | 6.86 | 6.91 | 6.96 | 5 |
| 6 | 7.01 | 7.06 | 7.11 | 7.16 | 7.20 | 7.25 | 7.31 | 7.36 | 7.41 | 7.46 | 6 |
| 7 | 7.51 | 7.56 | 7.61 | 7.67 | 7.72 | 7.77 | 7.82 | 7.88 | 7.93 | 7.98 | 7 |
| 8 | 8.04 | 8.10 | 8.15 | 8.21 | 8.26 | 8.32 | 8.37 | 8.43 | 8.48 | 8.54 | 8 |
| 9 | 8.61 | 8.67 | 8.73 | 8.78 | 8.84 | 8.90 | 8.96 | 9.02 | 9.08 | 9.14 | 9 |
| 10 | 9.20 | 9.26 | 9.33 | 9.39 | 9.46 | 9.52 | 9.58 | 9.65 | 9.71 | 9.77 | 10 |
| `11 | 9.84 | 9.90 | 9.97 | 10.03 | 10,10 | 10.17 | 10.24 | 10.31 | 10.38 | 10.45 | 11 |
| 12 | 10.52 | 10.58 | 10.66 | 10.72 | 10.79 | 10.86 | 10.93 | 11.00 | 11.08 | 11.15 | 12 |
| 13 | 11.23 | 11.30 | 11.38 | 11.45 | 11.53 | 11.60 | 11.68 | 11.76 | 11.83 | 11.91 | 13 |
| 14 | 11.98 | 12.06 | 12.14 | 12.22 | 12.30 | 12.38 | 12.46 | 12.54 | 12.62 | 12.70 | 14 |
| 15 | 12.78 | 12.86 | 12.95 | 13.03 | 13.11 | 13.20 | 13.28 | 13.37 | 13.45 | 13.54 | 15 |
| 16 | 13.63 | 13.71 | 13.80 | 13.90 | 13.99 | .14.08 | 14.17 | 14.26 | 14.35 | 14.44 | 16 |
| 17 | 14.53 | 14.62 | 14.71 | 14.80 | 14.90 | 14.99 | 15.09 | 15.18 | 15.27 | 15.38 | 17 |
| 18 | 15.46 | 15.56 | 15.66 | 15.76 | 15.86 | 15.96 | 16.06 | 16.16 | 16.26 | 16.36 | 18 |
| 19 | 16.46 | 16.57 | 16.68 | 16.79 | 16.90 | 17.00 | 17.10 | 17.21 | 17.32 | 17.43 | 19 |
| 20 | 17.53 | 17.64 | 17.75 | 17.86 | 17.97 | 18.08 | 18.20 | 18.31 | 18.43 | 18.54 | 20 |
| 21 | 18.65 | 18.77 | 18.88 | 19.00 | 19.11 | 19.23 | 19.35 | 19.46 | 19.58 | 19.70 | 21 |
| 22 | 19.82 | 19.94 | 20.06 | 20.19 | 20.31 | 20.43 | 20.58 | 20.69 | 20.80 | 20.93 | 22 |
| 23 | 21.05 | 21.19 | 21.32 | 21.45 | 21.58 | 21.71 | 21.84 | 21.97 | 22.10 | 22.23 | 23 |
| 24 | 22.37 | 22.50 | 22.63 | 22.76 | 22.91 | 23.05 | 23.19 | 23.31 | 23.45 | 23.60 | 24 |
| 25 | 23.75 | 23.90 | 24.05 | 24.20 | 24.35 | 24.49 | 24.64 | 24.79 | 24.94 | 25.08 | 25 |
| 26 | 25.31 | 25.45 | 25.60 | 25.74 | 25.89 | 26.03 | 26.18 | 26.32 | 26.46 | 26.60 | 26 |
| 27 | 26.75 | 26.90 | 27.05 | 27.21 | 27.37 | 27.53 | 27.69 | 27.85 | 28.00 | 28.16 | 27 |
| 28 | 28.32 | 28.49 | 28.66 | 28.83 | 29.00 | 29.17 | 29.34 | 29.51 | 29.68 | 29.85 | 28 |
| 29 | 30.03 | 30.20 | 30.38 | 30.56 | 30.74 | 30.92 | 31.10 | 31.28 | 31.46 | 31.64 | 29 |
| 30 | 31.82 | 32.00 | 32.19 | 32.38 | 32.57 | 32.76 | 32.95 | 33.14 | 33.33 | 33.52 | 30 |

## APPENDIX-B Hydropower Capacity

### Table B-1 Hydropower potential of Ethiopia

| Name of River Basin | Number of Potential Sites | | | | | |
|---|---|---|---|---|---|---|
| | Small Scale <40MW | Medium Scale 40-60 MW | Large Scale >60MW | Total % | Technical Hydropower Potential (GWh/year) | Percentage Share of the Total% |
| Abbay | 74 | 11 | 44 | 129 | 78,800 | 48.9 |
| Rift Valley Lakes | 7 | - | 1 | 8 | 800 | 0.5 |
| Awash | 33 | 2 | - | 35 | 4500 | 2.8 |
| Omo–Gibe | 4 | - | 16 | 20 | 35000 | 22.7 |
| Genale –Dawa | 18 | 4 | 9 | 31 | 9300 | 5.8 |
| WabiShebelle | 9 | 4 | 3 | 16 | 5400 | 3.4 |
| Baro Akabo | 17 | 3 | 21 | 41 | 18900 | 11.7 |
| Tekeze–Angereb | 11 | 1 | 8 | 20 | 6000 | 4.2 |
| total | 173 | 26 | 100 | 300 | 159,300 | 10,0 |

Sources: ENEC-CESEN, 1986; WAPCOS, 1990; MWR, 1997-2008.

### Table B-2 SCS Generation Plants (source EEPCO)

| | | Hydro | Diesel | Geothermal | Total | In-service Date |
|---|---|---|---|---|---|---|
| 1 | Yadot | 0.35 | - | - | - | - |
| 2 | Sor | 5.00 | - | - | - | - |
| 3 | Dembi | 0.80 | - | - | - | - |
| 4 | Isolated diesel power plants | - | 31.23 | - | - | - |
| | SCS Sub Total | 6.15 | 31.23 | - | 37.38 | - |
| | EEPCO Total | 1848.75 | 203.53 | 7.30 | 2,059.58 | - |

**Table B-3** ICS Generation Plants (source EEPCO)

| | | Capacity(MW) | | | | |
|---|---|---|---|---|---|---|
| | | Hydro | Diesel | Geothermal | Total | In-service Date |
| 1 | Koka | 43.20 | - | - | 43.20 | 1960 |
| 2 | Awash II | 32 | - | - | 32 | 1966 |
| 3 | Awash III | 32 | - | - | 32 | 1971 |
| 4 | Finacha | 134 | - | - | 134 | 1973/2003 |
| 5 | Melka Wakena | 153 | - | - | 153 | 1988 |
| 6 | Tis-Abay I | 11.40 | - | - | 11.40 | 1964 |
| 7 | Tis-Abay II | 73 | - | - | 73 | 2001 |
| 8 | Gilgel Gibe | 184.00 | - | - | 184.00 | 2004 |
| 9 | Aluto Langano | - | - | 7.30 | 7.30 | 1999 |
| 10 | Kaliti | - | 14.00 | - | 14.00 | 2004 |
| 11 | Dire Dawa | - | 38.00 | - | 38.00 | 2004 |
| 12 | Awash Sabatt killo | - | 35.00 | - | 35.00 | 2004 |
| 13 | Nazareth Diesel | - | 30.00 | - | 30.00 | 2008/09 |
| 14 | Debre Zeit Diesel | - | 30.00 | - | 30.00 | 2008/09 |
| 15 | Tekeze | 300.00 | - | - | - | 10/2009 |
| 16 | Gilgel Gibe II | 420.00 | - | - | - | 01/2010 |
| 17 | Beles | 460.00 | - | - | - | 5/2010 |
| | Sub Total | 1842.60 | 147 | 7.30 | 816.90 | |
| 1 | Alemaya | 43.20 | - | - | 43.20 | 1960 |
| 2 | Koka | - | 2.30 | - | 2.30 | 1958 |
| 3 | Dire Dawa (MU) | - | 4.50 | - | 4.50 | 1965 |
| 4 | Adigrat | - | 2.50 | - | 2.50 | 1992,93,95 |
| 5 | Axum | - | 3.20 | - | 3.20 | 1975,92 |
| 6 | Adwa | - | 3.00 | - | 3.00 | 1998 |
| 7 | Mekelle | - | 5.70 | - | 5.70 | 1984,91,93 |
| 8 | Shire | - | 0.80 | - | 0.80 | 1975,91'95 |
| 9 | Jimma | - | 1.10 | - | 1.10 | |
| 10 | Nekempt | - | 1.10 | - | 1.10 | 1984 |
| 11 | Ghimbi | - | 1.10 | - | 1.10 | 1962,84 |
| | Sub Total | 0 | 25.30 | 0 | 25.30 | |
| | ICS Sub Total | 1842.6 | 172.3 | 7.3 | 2022.2 | |

**Table B-4** Assumed baseline energy under first development plan

| Energy Project | Installed Capacity (MW) | Year of Commission | Cost ($M) |
|---|---|---|---|
| Existing | | | |
| Awash I (Koka) | 43 | 1960 | |
| Awash II | 32 | 1966 | |
| Finchaa | 134 | 1973 | |
| Awash ifi | 32 | 1974 | |
| MelkaWakena | 153 | 1988 | |
| Tis AbayI&II | 85 | (1964)2001 | |
| (liRel C+iheT | 184 | 2004 | |
| Gojeb (Independent) | 150 | 2004 | |
| Diesel&Geotheimal | 120 | 2008 | |
| Tekeze | 300 | 2008 | |
| Gilgel GibeR | 420 | 2009 | |
| Tana Beles | 460 | 2010 | |
| Amerti-Neshi | 100 | 2010 | |
| Fixed (comm!tted) | | | |
| Wind - Ashegoba | 120 | 2011 | 259 |
| Gilgel Gibe | 1,870 | 2013 | 1730 |
| Tendaho | 180 | 2013 | 305 |
| Planned | | | |
| Gilgel Gibe | 1,900 | 2014 | 2930 |
| Halele Werabesa | 450 | 2014 | 725 |
| Chemoga-Yeda | 278 | 2014 | 318 |
| GebaI&II | 366 | 2016 | 593 |
| Genaleffi | 258 | 2018 | 362 |
| OenaleIV | 257 | 2018 | 456 |
| TekezeII | 450 | 2020 | 694 |
| Karadobi | 1,600 | 2023 | 2411 |
| Border | 1,200 | 2026 | 1741 |
| Mendaia | 2,000 | 2030 | 2990 |
| Baro | 900 | 2034 | 914 |
| Aleltu | 405 | 2038 | 1444 |
| Didessa | 308 | 2038 | 523 |
| Dabus | 741 | 2042 | 1805 |
| Birbir | 467 | 2042 | 1199 |
| Tams | 1,060 | 2046 | 1805 |

**Table B-5** Assumed baseline energy development plan under the second development plan

| Energy Project | Installed | Year of | Cost ($M) |
|---|---|---|---|
| Existing | | | |
| Awash l(Koka) | 43 | 1960 | |
| Awash II | 32 | 1966 | |
| Finchaa | 134 | 1973 | |
| Awash ifi | 32 | 1974 | |
| Melka Wakena | 153 | 1988 | |
| Tis Abayl&ll | 85 | (1964) 2001 | |
| Gilgel Gibe I | 184 | 2004 | |
| Gojeb (Independent) | 150 | 2004 | |
| Diesel&Geothennal | 120 | 2008 | |
| Tekeze | 300 | 2008 | |
| GilgelGibell | 420 | 2009 | |
| TanaBeles | 460 | 2010 | |
| Amerti-Neshi (FAN) | 100 | 2011 | |
| Fixed (committed | | | |
| Wind-Ashegoba | 120 | 2013 | 259 |
| GilgelGibeffi | 1,870 | 2013 | 1730 |
| Tenclaho Geothermal | 180 | 2014 | 305 |
| Planned | | | |
| GilgelGibefV | 1,900 | 2014 | 2930 |
| Halele Werabesa | 450 | 2014 | 725 |
| Chemoga-Yeda | 278 | 2016 | 318 |
| Gebal&II | 366 | 2016 | 593 |
| Wind+Geothennal | 2,820 | 2018 | 5640 |
| Genaleffi | 258 | 2018 | 362 |
| GenalelV | 257 | 2019 | 456 |
| Wind+ Geothermal | 3,000 | 2020 | 6000 |
| Tekezdll | 450 | 2023 | 694 |
| Karadobi t Generic | 4,000 | 2026 | 6030 |
| Border±Generic | 3,000 | 2029 | 4350 |
| Wind+ Geothermal | 3,000 | 2030 | 6000 |
| Mendaia + Generic | 5,000 | 2034 | 7480 |
| Bare + Generic | 2,250 | 2038 | 2290 |
| Aleltu+Generic | 1,010 | 2038 | 3610 |
| Didessa+Generic | 770 | 2039 | 1310 |
| Wind+Geothermal | 3,000 | 2042 | 6000 |
| Dabus+ Generic | 1,850 | 2042 | 4510 |
| Birbir+ Generic | 1,170 | 2046 | 3000 |
| Tams+Generic | 2,650 | 1960 | 4510 |

**APPENDIX-C** Physical and Power Plant Characteristics

**Table C-1** Physical characteristics of TK_5 Dam (Salient features)

| **TK_ 5 dam physical characteristics** | | |
|---|---|---|
| Arch Dam - Features | Dimension/Quantity | Unit |
| Height | 188 | m |
| Crest length | 420 | m |
| Crest elevation | 1,145 | m |
| Thickness at base of crown cantilever | 27 | m |
| Thickness at crest | 5.6 | m |
| Low level outlet radial gates– 4 No. at El. 1,057 | 8.0 x 5.6 | m |
| Power Complex - Features | Dimension/Quantity | Unit |
| Intake structure height | 75 | m |
| Upper headrace tunnel, 7.25m lined diameter | 320 | m |
| Vertical shaft, 6.75m lined diameter | 120 | m |
| Lower tunnel 6.75m reducing to 4 - 4.0m steel lined | 408 | m |
| Length of Steel Liners | 45 | m |
| Powerhouse cavern (max. dimensions) | 951 x 18w x 38h | m |
| Tailrace tunnels, 4 No. x 5m diameter x 73m long | 292 | m |
| Francis Turbines | 4 | no |
| Plant Maximum Flow | 220 | m3/sec |
| Unit Design Head | 155 | m |
| Reservoir and Hydrology | Dimension/Quantity | Unit |
| Catchments Area | 30,390 | $km^2$ |
| Mean Annual Rainfall | 850 | mm |
| Mean Annual Inflow | 3,750 | $Mm^3$ |
| 10 year return peak flood inflow | 1,940 | $m^3/sec$ |
| Design flood peak flood inflow (10,000 year return) | 6,115 | $m^3/sec$ |
| Maximum Normal Operating Level | 1140 | m |
| Minimum Operating Level | 1096 | m |
| Total Storage(@ EL. 1140) | 9,310 | $Mm^3$ |
| Active Storage | 5,343 | $Mm^3$ |
| Spillway Capacity (4 LLO Radial Gates@ EL. 1140) | 4,416 | $m^3/sec$ |
| Estimated Reservoir Annual Evaporation Losses | 1,921 | mm |
| Estimated Firm Annual Energy (HCR estimate) | 981 | GWh/yr |
| Estimated Average Annual Generation (HCR esti- | 1,065 | GWh/yr |

**Table C-2** Physical characteristics ofTK_7 Dam (Salient features)

TK_7 dam physical characteristics and GPS co ordinate

| | description | Unit | Dimension/Quantity |
|---|---|---|---|
| DAM | Height | m | 128 |
| | Crest length | m | 840 |
| | Crest elevation | a.m.s.l | 968 |
| RESERVOIR | Normal storage level | a.m.s.l | 960 |
| | Dead storage level | a.m.s.l | 897.43 |
| | Gross storage | $Mm^3$ | 6027 |
| | Live storage | $Mm^3$ | 4176 |
| Service spillway | Design discharge | $m^3$/sec | 9879 |
| | Crest level | a.m.s.l | 952 |
| | No, of gates | No, | 8 |
| | Gates height/width | m/m | 16/14 |
| Auxiliary spillway(fuse plug) | Design discharge | $m^3$/sec | 7599 |
| | Crest level | a.m.s.l | 952 |
| | Width | m | 100 |
| | Maximum flood level | a.m.s.l | 963 |
| DIVERSION | No, of tunnels | No, | 2 |
| | Tunnels diameter | m | 14 |
| | Tunnels length | m | 500 |
| | Design discharge | $m/s^3$ | 7415 |
| BOTTOM OUTLET | Design discharge | $m/s^3$ | 856 |
| | No, of service gate | No. | 4 |
| | No, of revision gates | No. | 4 |
| | Total gate area | $m/s^2$ | 2*40 |
| POWER PLANT | Turbine design dis- | $m/s^3$ | 2*120* |
| | Turbine design head | m | 131 |
| | Installed capacity | MW | 275 |

*modified

**APPENDIX-D** Relation and double mass curve of the Stations

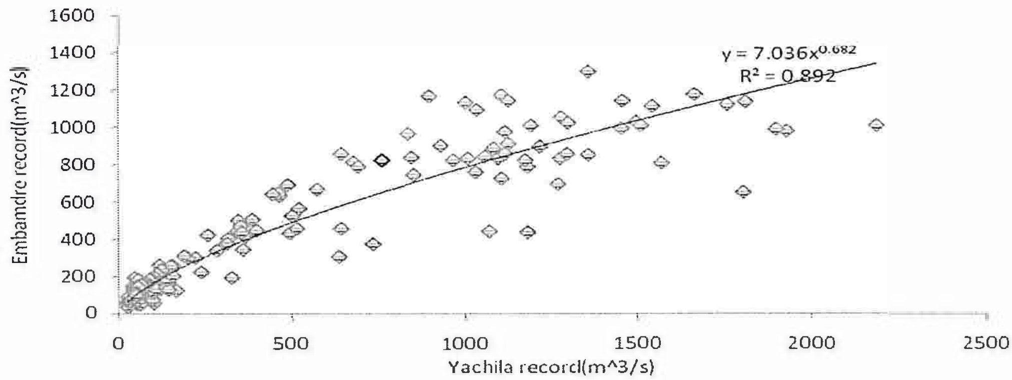



**Figure D-1** Yachila vs. Embamdre discharge relation for months June to October

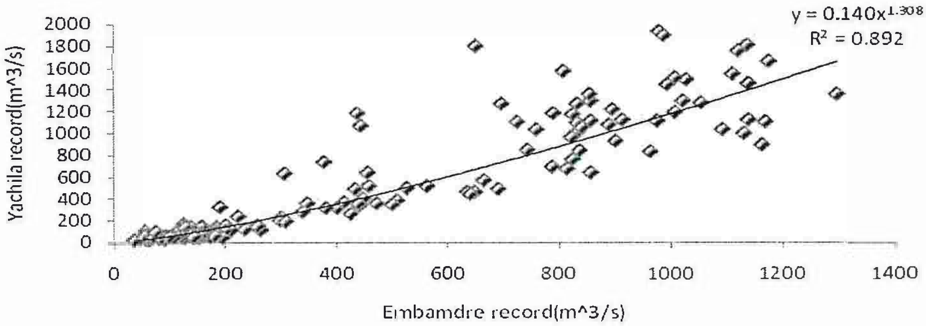



**Figure D-2** Embamdre vs. Yachila discharge relation for months June to October

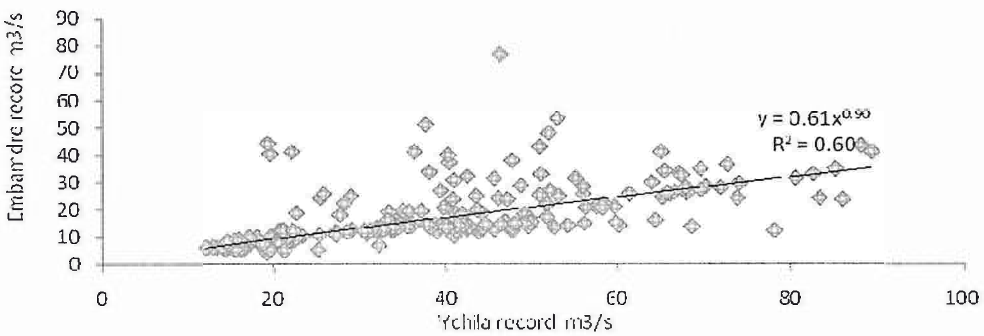



**Figure D-3** Embamdre vs. Yachila discharge relation for months Nov. to M

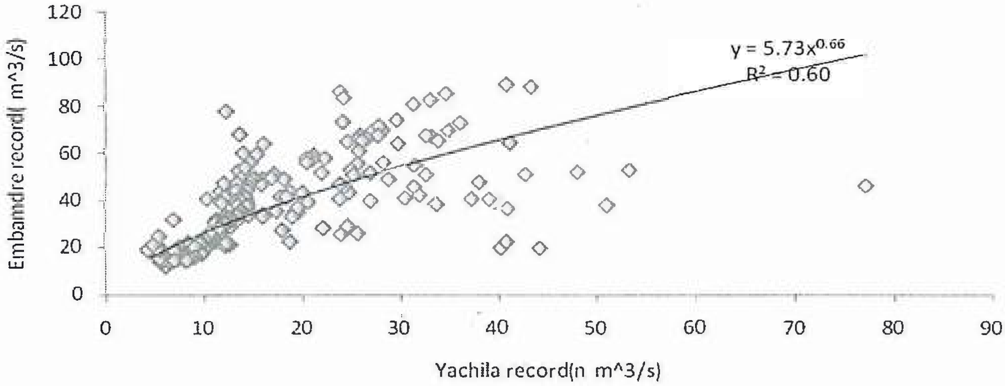



**Figure D-4** Yachila vs. Embamdre discharge relation for months Nov. to May

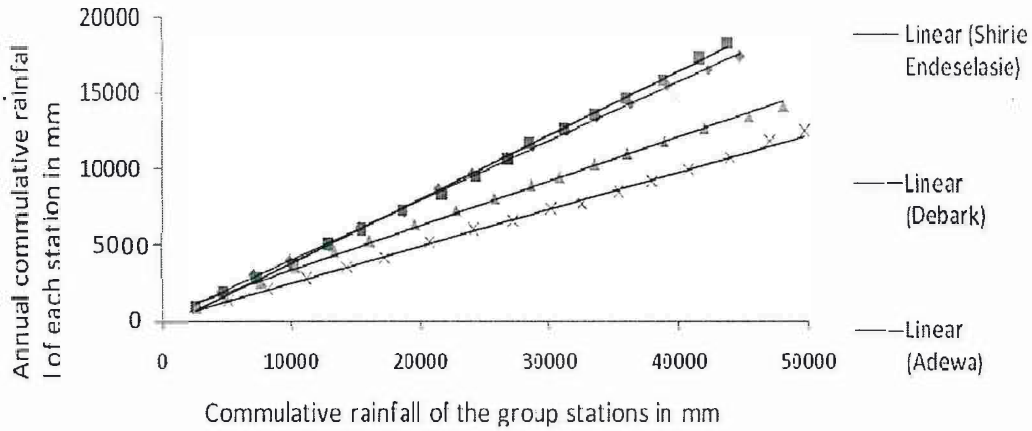



**Figure D-5** Double mass curve of Shire, Debark, Adewa, and Axume

**APPENDIX-E** HEC-ResSim and Excel Result Graphs

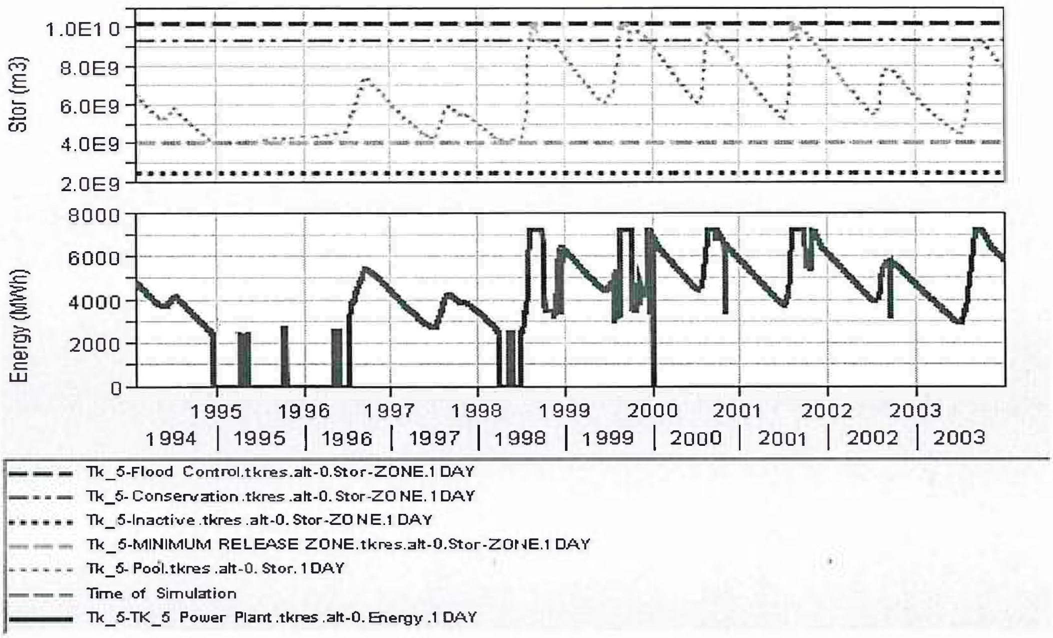



**Figure E-1** Explicit operation reservoir storage volume and energy generated at TK_5

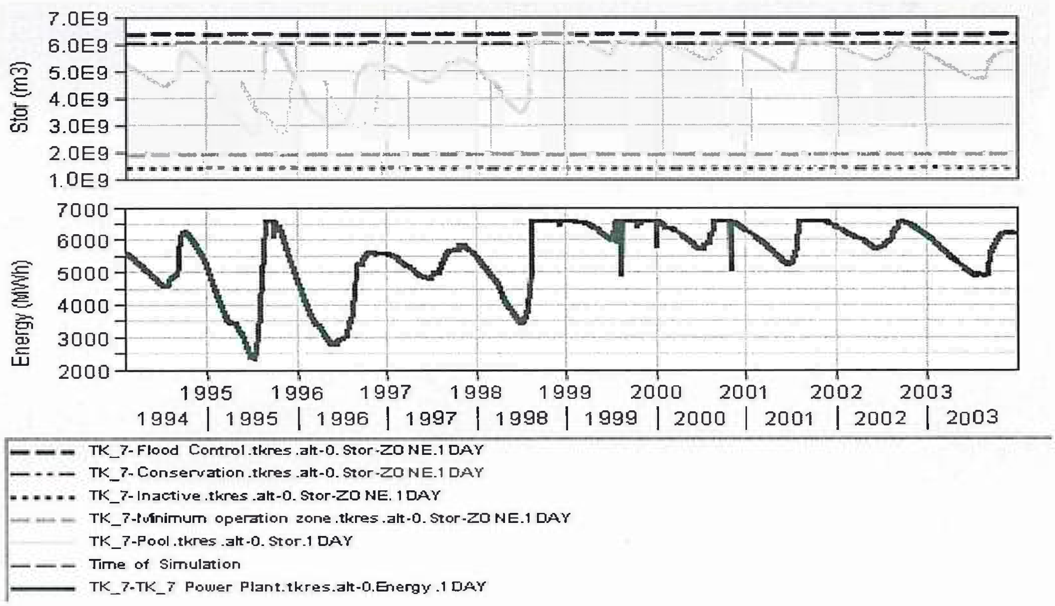



**Figure E-2** Explicit operation reservoir storage volume and energy generated at TK_7

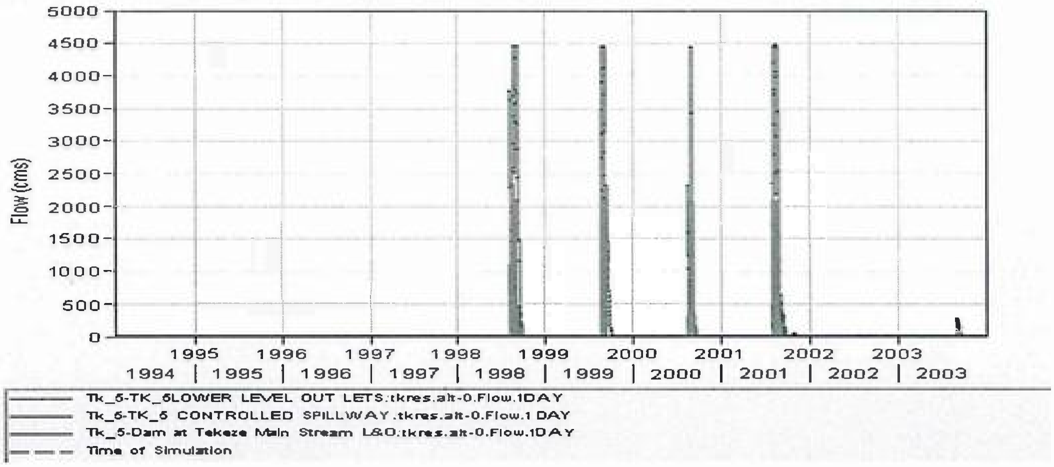



**Figure E-3** TK_5 spillway and outlet loss flows

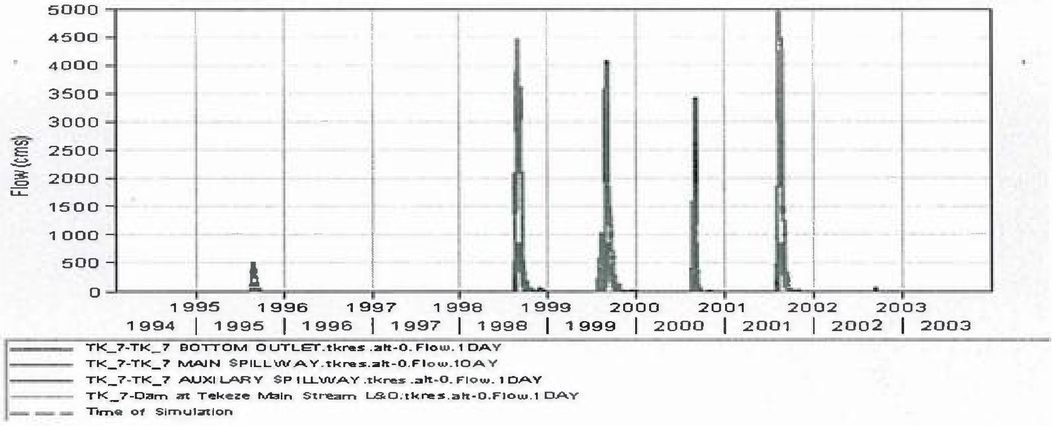



**Figure E-4** TK_7 spillway and outlet loss flows

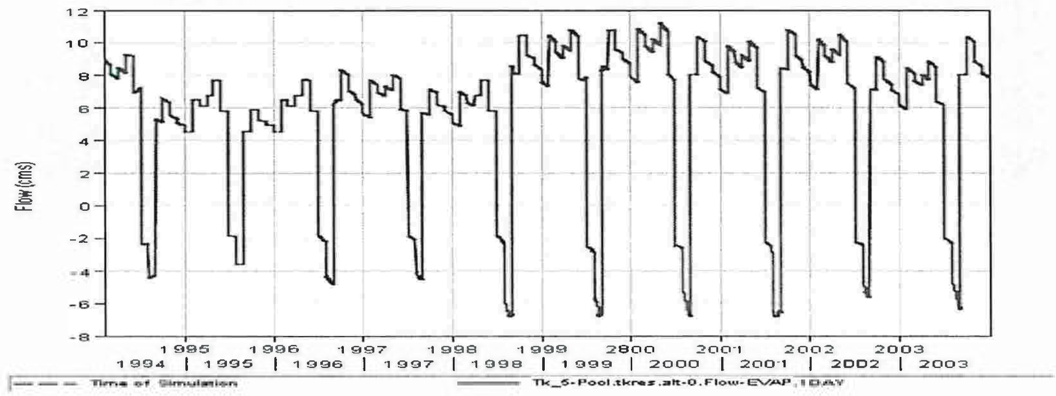



**Figure E-5** TK-5 net evaporation loss flows

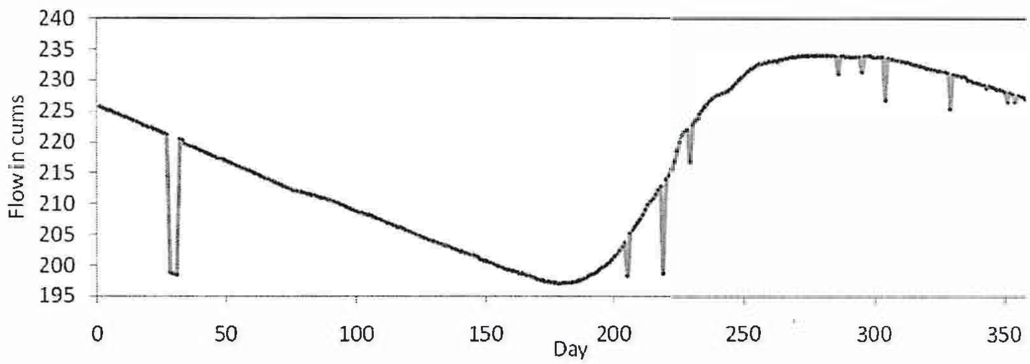



**Figure E-6** Daily optimal power plant release at TK_7 reservoir

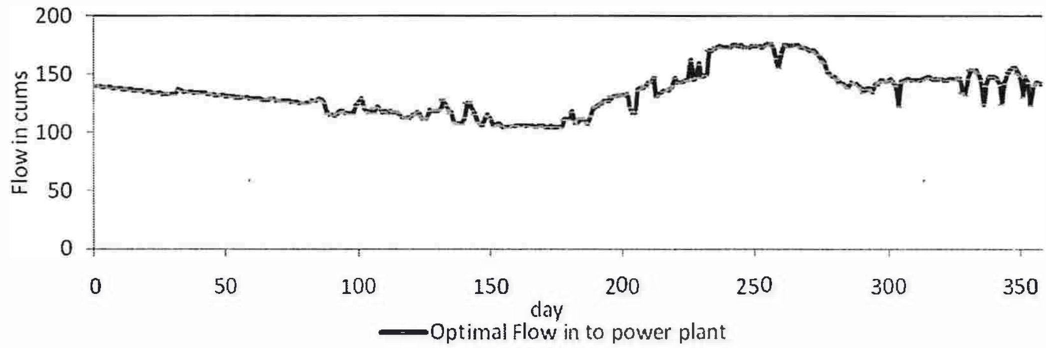



**Figure E-7** Daily optimal power plant release at TK_5 reservoir

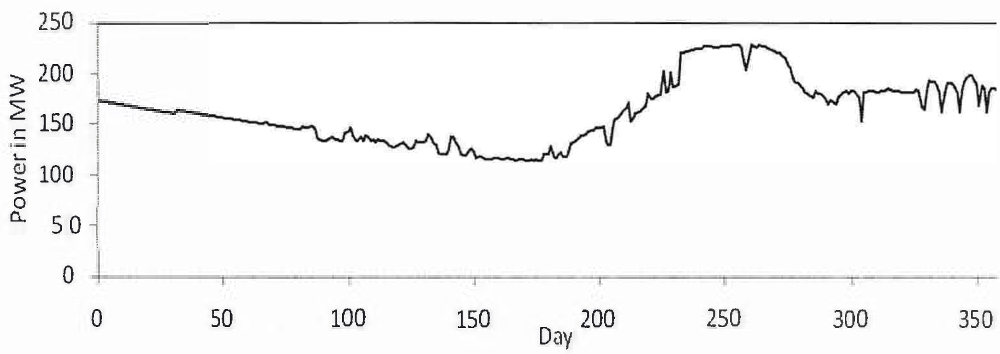



**Figure E-8** Daily optimal power generation at TK_5 power plant

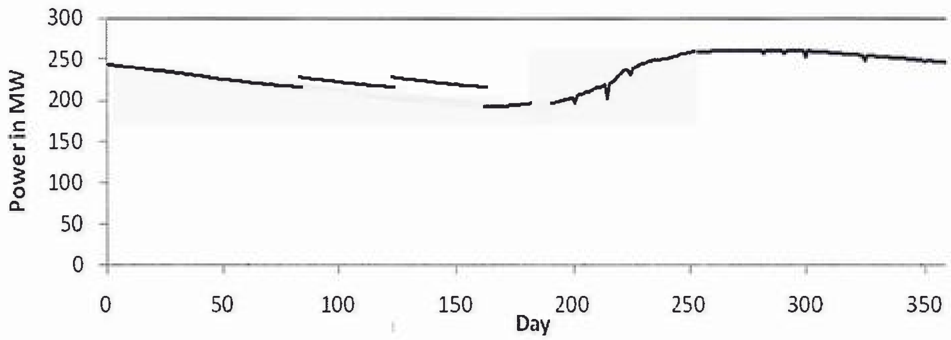



**Figure E-9** Daily optimal power generation at TK_7 power plant

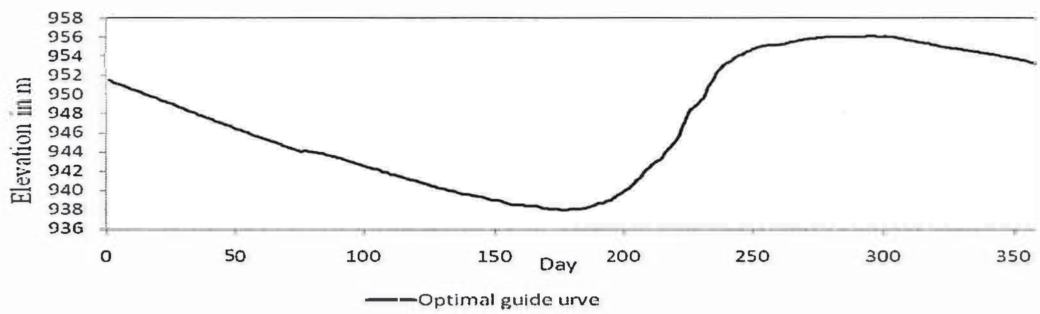



**Figure E-10** Daily optimal guide curve at TK_5 reservoir

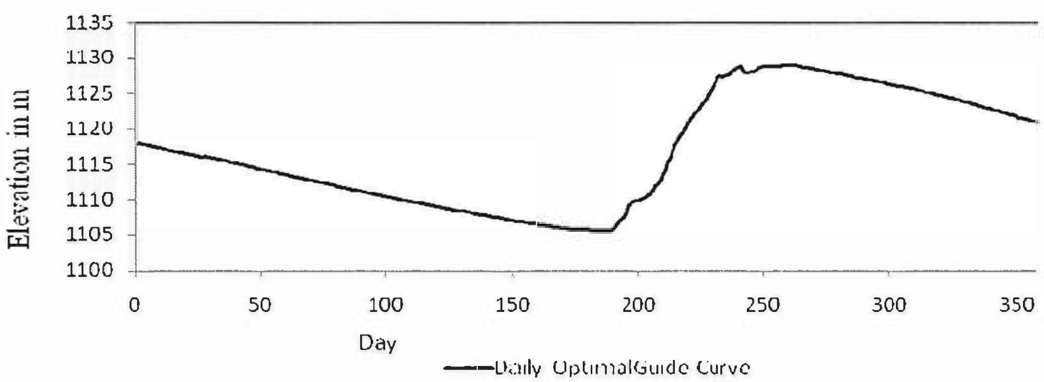



Figure E-11 Daily optimal guide curve of TK_7 reservoir

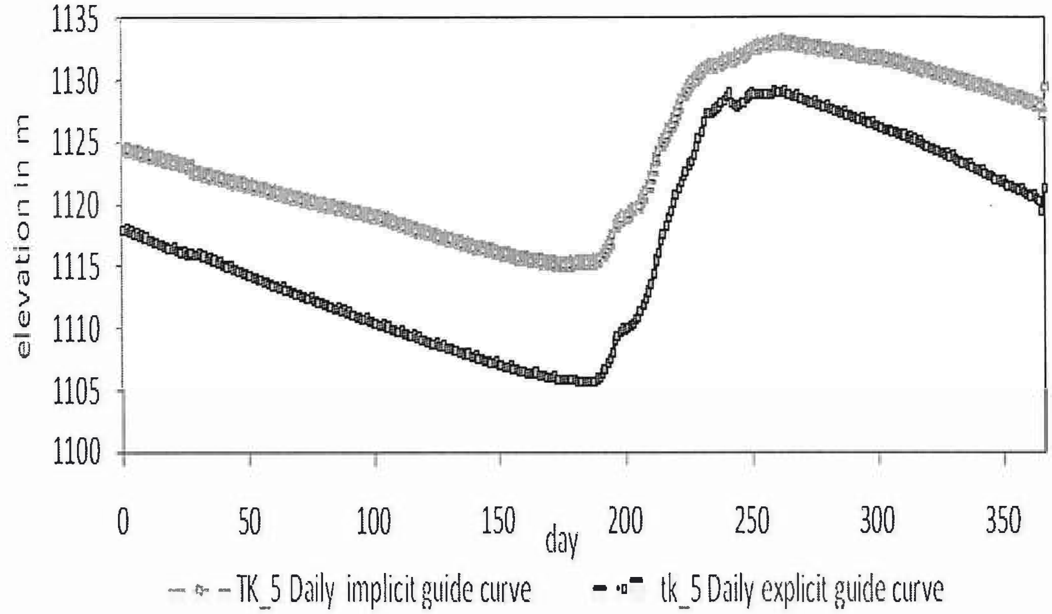



**Figure E-12** TK _5 implicit and explicit system guide curves

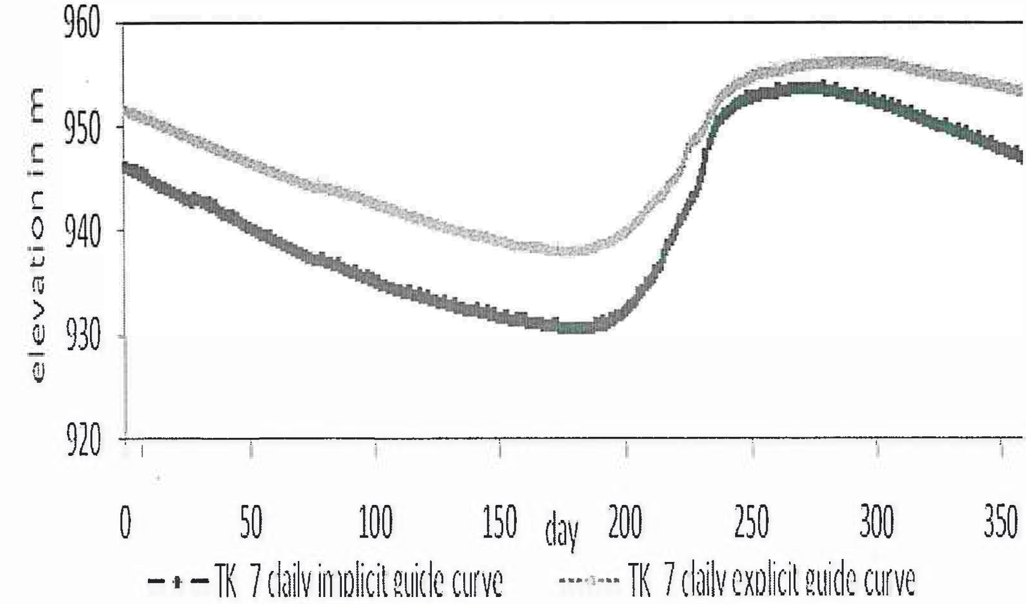
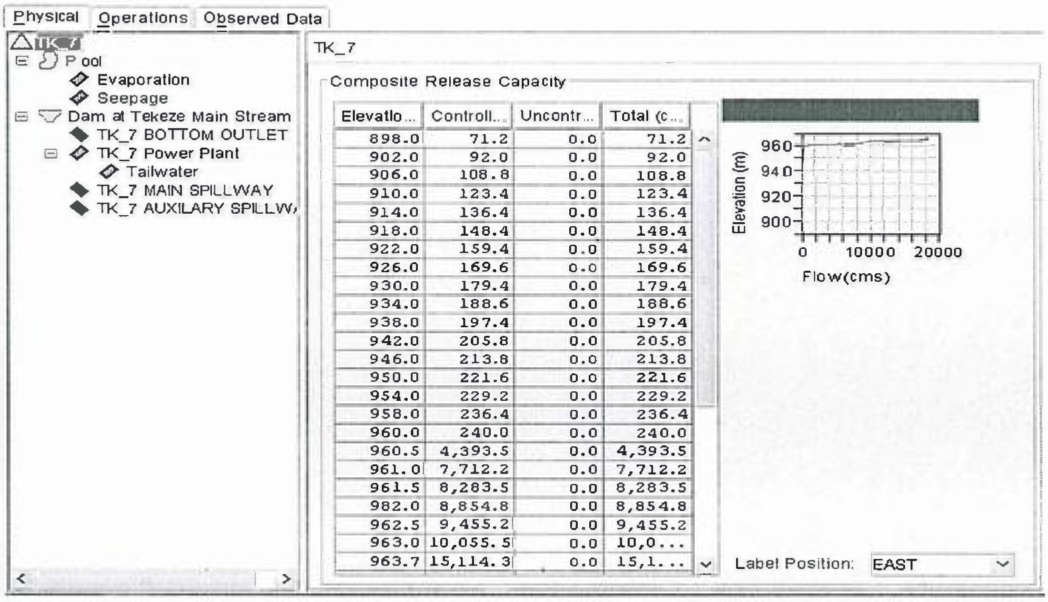


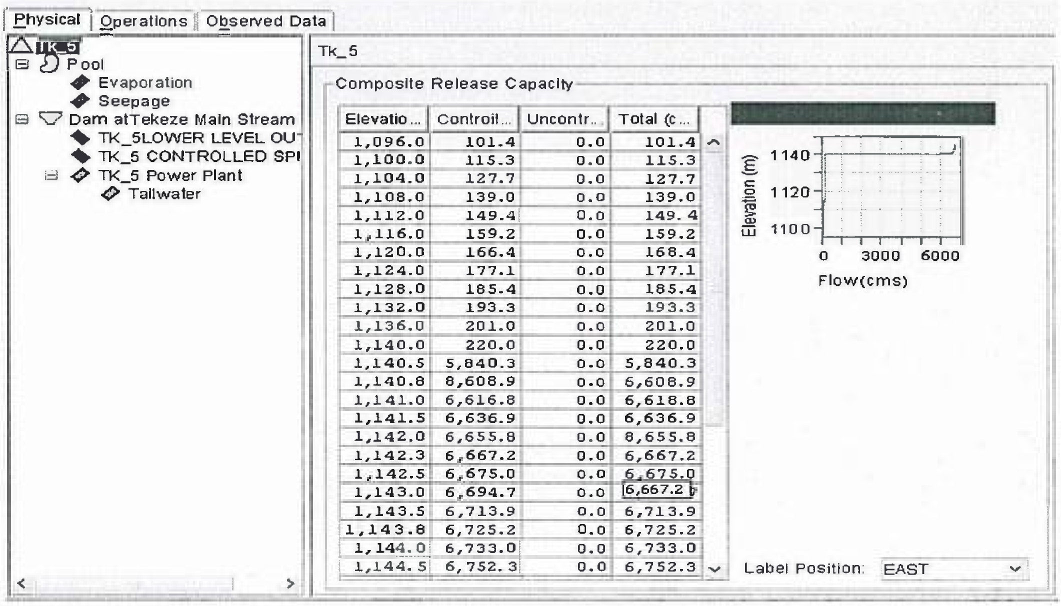

**Figure E-13** TK _7 implicit and explicit system guide curves

# APPENDIX-F HEC-ResSim Model Data Setups




| Elevatio... | Controll... | Uncontr... | Total (c... |
|---|---|---|---|
| 898.0 | 71.2 | 0.0 | 71.2 |
| 902.0 | 92.0 | 0.0 | 92.0 |
| 906.0 | 108.8 | 0.0 | 108.8 |
| 910.0 | 123.4 | 0.0 | 123.4 |
| 914.0 | 136.4 | 0.0 | 136.4 |
| 918.0 | 148.4 | 0.0 | 148.4 |
| 922.0 | 159.4 | 0.0 | 159.4 |
| 926.0 | 169.6 | 0.0 | 169.6 |
| 930.0 | 179.4 | 0.0 | 179.4 |
| 934.0 | 188.6 | 0.0 | 188.6 |
| 938.0 | 197.4 | 0.0 | 197.4 |
| 942.0 | 205.8 | 0.0 | 205.8 |
| 946.0 | 213.8 | 0.0 | 213.8 |
| 950.0 | 221.6 | 0.0 | 221.6 |
| 954.0 | 229.2 | 0.0 | 229.2 |
| 958.0 | 236.4 | 0.0 | 236.4 |
| 960.0 | 240.0 | 0.0 | 240.0 |
| 960.5 | 4,393.5 | 0.0 | 4,393.5 |
| 961.0 | 7,712.2 | 0.0 | 7,712.2 |
| 961.5 | 8,283.5 | 0.0 | 8,283.5 |
| 982.0 | 8,854.8 | 0.0 | 8,854.8 |
| 962.5 | 9,455.2 | 0.0 | 9,455.2 |
| 963.0 | 10,055.5 | 0.0 | 10,0... |
| 963.7 | 15,114.3 | 0.0 | 15,1... |

**FigureF-1** Physical components of TK_7 reservoir




| Elevatio... | Controll... | Uncontr... | Total (c... |
|---|---|---|---|
| 1,096.0 | 101.4 | 0.0 | 101.4 |
| 1,100.0 | 115.3 | 0.0 | 115.3 |
| 1,104.0 | 127.7 | 0.0 | 127.7 |
| 1,108.0 | 139.0 | 0.0 | 139.0 |
| 1,112.0 | 149.4 | 0.0 | 149.4 |
| 1,116.0 | 159.2 | 0.0 | 159.2 |
| 1,120.0 | 166.4 | 0.0 | 168.4 |
| 1,124.0 | 177.1 | 0.0 | 177.1 |
| 1,128.0 | 185.4 | 0.0 | 185.4 |
| 1,132.0 | 193.3 | 0.0 | 193.3 |
| 1,136.0 | 201.0 | 0.0 | 201.0 |
| 1,140.0 | 220.0 | 0.0 | 220.0 |
| 1,140.5 | 5,840.3 | 0.0 | 5,840.3 |
| 1,140.8 | 8,608.9 | 0.0 | 6,608.9 |
| 1,141.0 | 6,616.8 | 0.0 | 6,618.8 |
| 1,141.5 | 6,636.9 | 0.0 | 6,636.9 |
| 1,142.0 | 6,655.8 | 0.0 | 8,655.8 |
| 1,142.3 | 6,667.2 | 0.0 | 6,667.2 |
| 1,142.5 | 6,675.0 | 0.0 | 6,675.0 |
| 1,143.0 | 6,694.7 | 0.0 | 6,667.2 |
| 1,143.5 | 6,713.9 | 0.0 | 6,713.9 |
| 1,143.8 | 6,725.2 | 0.0 | 6,725.2 |
| 1,144.0 | 6,733.0 | 0.0 | 6,733.0 |
| 1,144.5 | 6,752.3 | 0.0 | 6,752.3 |

**Figure F-2** Physical components of TK_5 reservoir

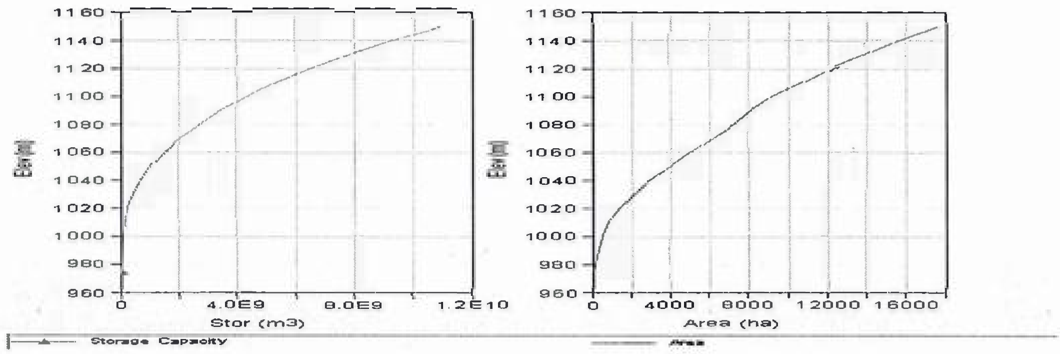



**Figure F-3** Elevation-reservoir capacity and elevation -area curve ofTK_5

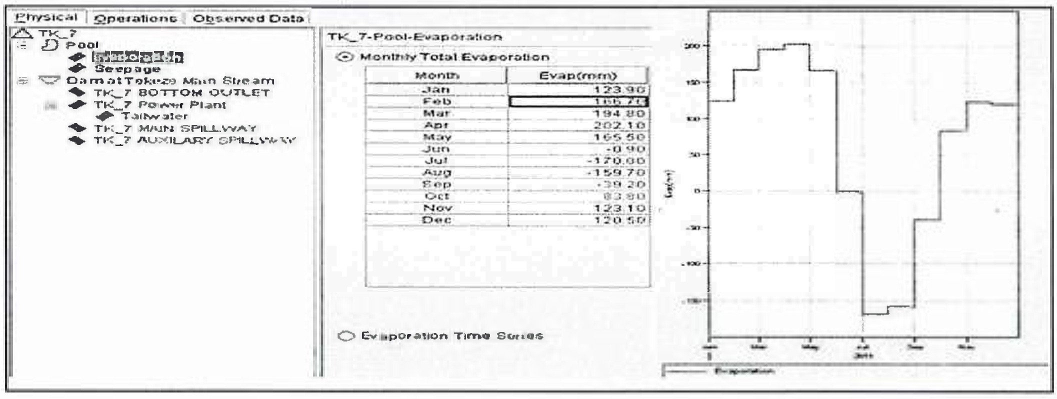



**Figure F-4** Evaporation data input set up of TK_7 reservoir pool

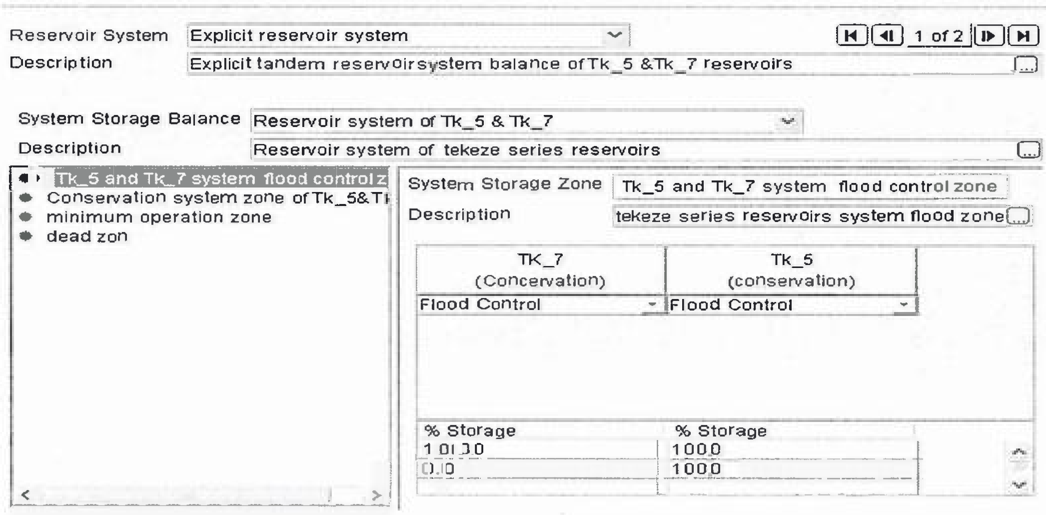



**Figure F-5** Reservoir System ofTekeze _Reservoir_Watershed setup

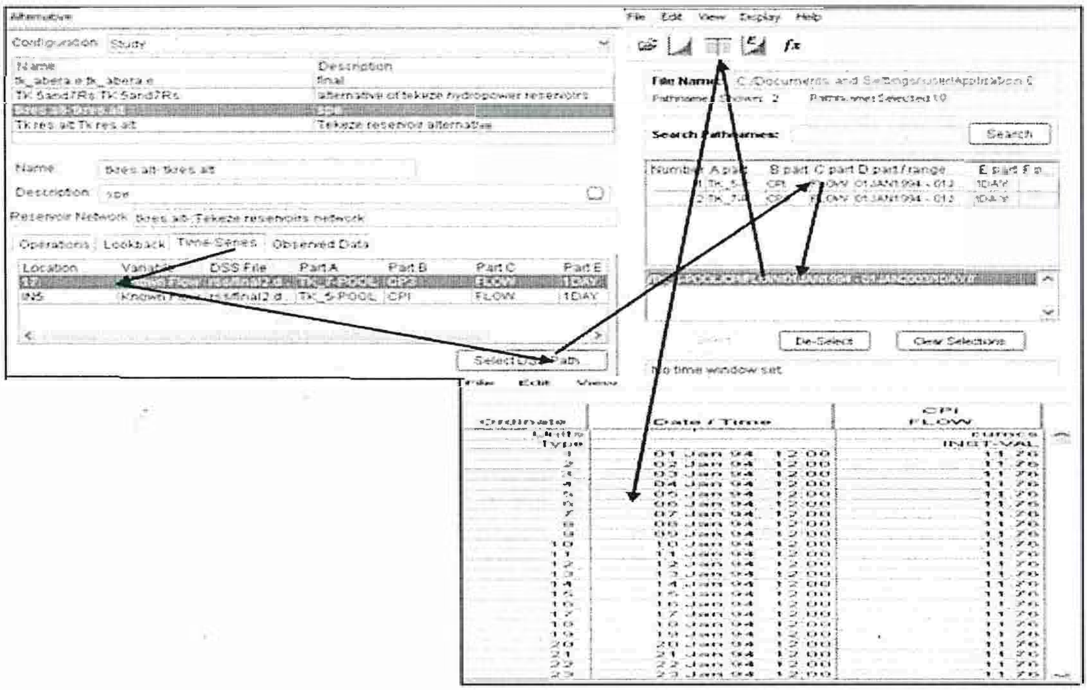


**Figure F-6** Accessing time series data files in HEC-DSS database using HEC-DSSVue

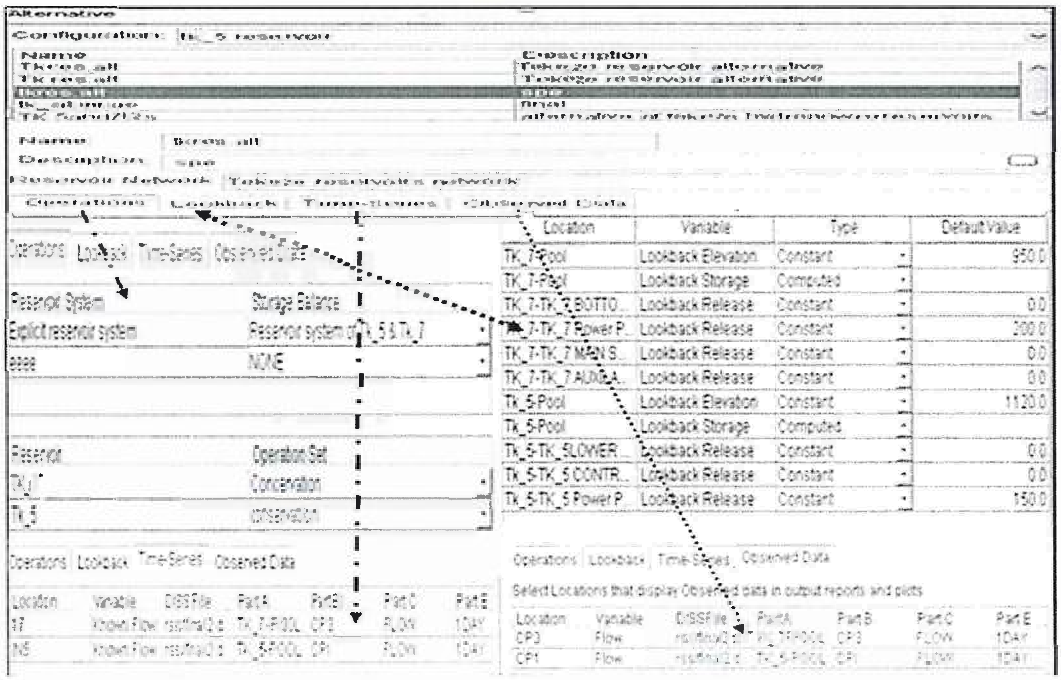


**Figure F-7** Tekeze Reservoir network alternative editor