DEVELOPMENT OF THE RULE CURVE
FOR ALTIPARMAK HYDROELECTRIC POWER PLANT

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
MIDDLE EAST TECHNICAL UNIVERSITY

BY

ŞERİFE ECE BOYACIOĞLU

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF MASTER OF SCIENCE
IN
CIVIL ENGINEERING

JUNE 2013

Approval of the thesis:

DEVELOPMENT OF THE RULE CURVE

FOR ALTIPARMAK HYDROELECTRIC POWER PLANT

submitted by **ŞERİFE ECE BOYACIOĞLU** in partial fulfillment of the requirements for the degree of **Master of Science in Civil Engineering Department, Middle East Technical University** by,

Prof. Dr. Canan Özgen ______________________
Dean, Graduate School of **Natural and Applied Sciences**

Prof. Dr. Ahmet Cevdet Yalçıner ______________________
Head of Department, **Civil Engineering**

Assoc. Prof. Dr. Elçin Kentel ______________________
Supervisor, **Civil Engineering Dept., METU**

Prof. Dr. A. Melih Yanmaz ______________________
Co-Supervisor, **Civil Engineering Dept., METU**

Examining Committee Members:

Assist. Prof. Dr. Şahnaz Tiğrek ______________________
Civil Engineering Dept., METU

Assoc. Prof. Dr. Elçin Kentel ______________________
Civil Engineering Dept., METU

Prof. Dr. A. Melih Yanmaz ______________________
Civil Engineering Dept., METU

Assoc. Prof. Dr. Nuri Merzi ______________________
Civil Engineering Dept., METU

Mümtaz Ak, M.Sc. ______________________
Netsu Engineering

Date: 25.06.2013

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Name, Last Name : **ŞERİFE ECE BOYACIOĞLU**

Signature :

ABSTRACT

DEVELOPMENT OF THE RULE CURVE FOR ALTIPARMAK HYDROELECTRIC POWER PLANT

Boyacıoğlu, Şerife Ece

M.Sc., Department of Civil Engineering

Supervisor : Assoc.Prof.Dr. Elçin Kentel

Co-Supervisor : Prof.Dr. A. Melih Yanmaz

June 2013, 61 Pages

Energy requirement of Turkey increases day by day and hydropower is currently the main renewable energy source of the country. Thus, planning the development of the unused hydropower potential of Turkey is critical. Available water resources have to be developed and managed in a wise manner. Reservoir operation rule curves are fundamental guidelines for long term reservoir operation. Rule curve which results in the maximum energy generation has to be developed for each hydropower plant (HEPP). The goal of this study is to develop the rule curve for Altıparmak Dam and HEPP. An optimization problem is formulated and coupled with Sequential Streamflow Routing method to determine optimum end of the month operating levels of the reservoir. Monthly operating levels form the rule curve of Altıparmak Dam and HEPP. Total energy generation obtained with the rule curve generated as a result of the optimization study is compared with results obtained from the feasibility studies of Altıparmak Dam and HEPP and it is observed that approximately 5% increase is achieved.

Keywords: Hydropower, Sequential Streamflow Routing, Rule Curve, Optimization.

ÖZ

ALTIPARMAK HİDROELEKTRİK SANTRALİ İÇİN KURAL EĞRİSİ GELİŞTİRME

Boyacıoğlu, Şerife Ece

Yüksek Lisans, İnşaat Mühendisliği Bölümü

Tez Yöneticisi : Doç.Dr. Elçin Kentel

Ortak Tez Yöneticisi : Prof.Dr. A. Melih Yanmaz

Haziran 2013, 61 Sayfa

Türkiye'nin enerji ihtiyacı her geçen gün artmakta olup, bugünlerde ülkenin başlıca yenilenebilir enerji kaynağı hidroelektrik enerjidir. Bu sebeple, Türkiye'nin kullanımda olmayan hidroelektrik enerji potansiyelinin geliştirilmesinin planlanması oldukça önem taşımaktadır. Mevcut su kaynakları, akıllı bir şekilde geliştirilmeli ve yönetilmelidir. Hazne işletme kural eğrileri uzun dönem rezervuar işletmeleri için geliştirilen temel yönlendiricilerdir. Her bir hidroelektrik santrali (HES) için, maksimum enerji üretimini sağlayan kural eğrileri geliştirilmelidir. Bu çalışmanın amacı, Altıparmak Barajı ve HES için kural eğrisi geliştirmektir. Ay sonu optimum hazne işletme seviyelerini belirlemek için, Ardışık Akım Ötelemesi yöntemi kullanılmakta ve bir optimizasyon problemi oluşturulmaktadır. Aylık işletme seviyeleri, Altıparmak Barajı ve HES'in kural eğrisini oluşturmaktadır. Bu optimizasyon çalışmasının bir sonucu olarak elde edilen kural eğrisi tarafından sağlanan toplam enerji üretimi, Altıparmak Barajı ve HES için yapılan fizibilite çalışmalarında elde edilen sonuçlarla karşılaştırılmakta ve yaklaşık %5'lik bir artış sağlandığı gözlenmektedir.

Anahtar Kelimeler: Hidroelektrik, Ardışık Akım Ötelemesi, Kural Eğrisi, Optimizasyon.

To My Family

ACKNOWLEDGEMENTS

This thesis would not have been possible without the guidance and the help of several individuals who in one way or another contributed and extended their valuable assistance in the preparation and completion of this study.

First and foremost, I would like to thank to my supervisor of this study, Assoc.Prof.Dr. Elçin Kentel for the valuable guidance, advice and patience. She inspired me greatly to work on this project. Her willingness to motivate me contributed tremendously to this study.

I also sincerely thank to my co-supervisor Prof.Dr. Melih Yanmaz for special guidance and encouragement in carrying out this project work.

Moreover, I would like to express my many thanks to M.Sc. Mümtaz Ak for sharing his experiences and suggestions with me.

A special gratitude I give to Dr. Gökhan Tunç, my boss at previous job, for providing me an opportunity to work on my thesis project going along with my job.

Also, Emre Gök, Bekir Albay, M.Sc. Mehmet Akın Çetinkaya, Berna Vural, Gülden Erkal, Erdem Korkmaz, Ozan Çoban, Onur Çuvalcı and Yurdem Merve Uludağ, thank you so much for sharing same feelings at very lovely thesis meeting evenings.

I would like to thank Water Resources Laboratory Research Assistants M.Sc. Melih Çalamak, M.Sc. Meriç Selamoğlu, M.Sc. Deniz Velioğlu and Cem Sonat for their help and lovely conversations on the laboratory.

Doubtlessly, I have to say that I would never have been able to finish my thesis without consultations, motivations and support of my chief, manager, brother M.Sc. Cem Dipçin.

My colleagues and best friends in the world, M.Sc. Mehmet Kayra Ergen, Barış Hacıkerimoğlu, M.Sc. Umut Egemen Çam, Baran Çobanoğlu, Çağatay Hanedan, Yılgün Gürcan, Ertuğrul Gören, Ufuk Çalışkan, M.Sc. Miran Dzabic, Nilay Doğulu, M.Sc. Tuğçe Neslinur Güney, Ava Bagherpoor, İlke Göçmen, Beray Yaldız, M.Sc. Oya Memlük and M.Sc. Pınar Berberoğlu, life could not be as magnificent as without your consultations in engineering, moral support, motivation and friendship. We smiled, laughed, cried, got angry, fought, missed, travelled, cooked even Mantı and briefly we made all together. Thank you so much for everything.

Besides, my special thanks go to Selin Dindaroğlu, Murat Taşer, Gökhan Kutlubay, Mehmet Ali İncücük, Cansın Yavuz, Seda Sürenkök, Tuğçe Akkoç and Mehmet Alkan for giving a meaning to my life and awesome memories in METU from beginning to end. Kilometers are not obstacle for us still to carry on our friendship.

This thesis is especially dedicated to my family members mother Hidayet Boyacıoğlu, father Sermet Boyacıoğlu, brother Celil Utkuhan Boyacıoğlu, sister Gülperi Boyacıoğlu and dear cousin, sister, friend, buddy and everything of me Miray Özpeynirci for their love and endless support spiritually throughout my life.

TABLE OF CONTENTS

LIST OF FIGURES

FIGURES

LIST OF TABLES

TABLES

CHAPTER 1

INTRODUCTION

1.1. Objective of the Study

Due to increase in population and development of industry energy requirement of Turkey increases continuously. Thus, planning the development of available energy resources of the country is critical for Turkey. Distribution of Turkey's installed capacity among various energy sources is given in Figure 1.1. According to statistical data of General Directorate of Electrical Power Resources Survey and Development Administration Turkey imports 55.7 % of total consumed energy as of 2011 (given in Figure 1.2). Thus, development of domestic and renewable energy sources of Turkey is very important in maintaining sustainable development. Main domestic and renewable energy resource of the country is hydropower. Energy Market Regulatory Authority, EPDK issued Law No: 5346 "Renewable Energy Law" in 2005 to accelerate utilization of renewable energy sources to increase contribution of domestic energy resources in the energy budget and to reduce greenhouse gas emissions. Currently, only 35% of hydroelectric potential in Turkey has been developed and 65% of the hydropower potential of Turkey is yet to be developed (EPDK, 2012).

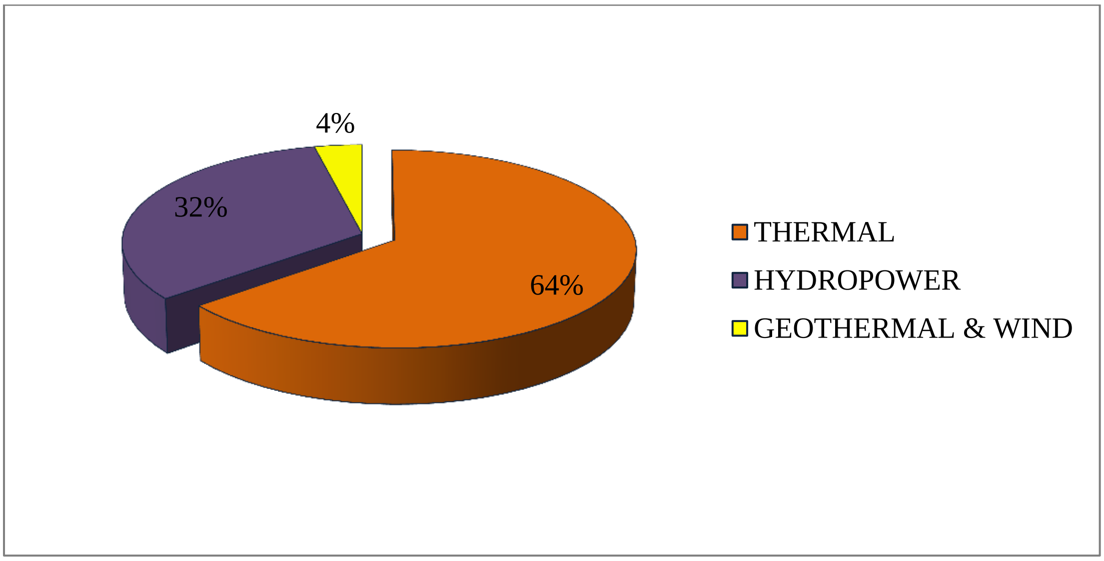

Figure 1.1 - Turkey Installed Capacity Percentages of Energy Sources (EPDK, 2012)

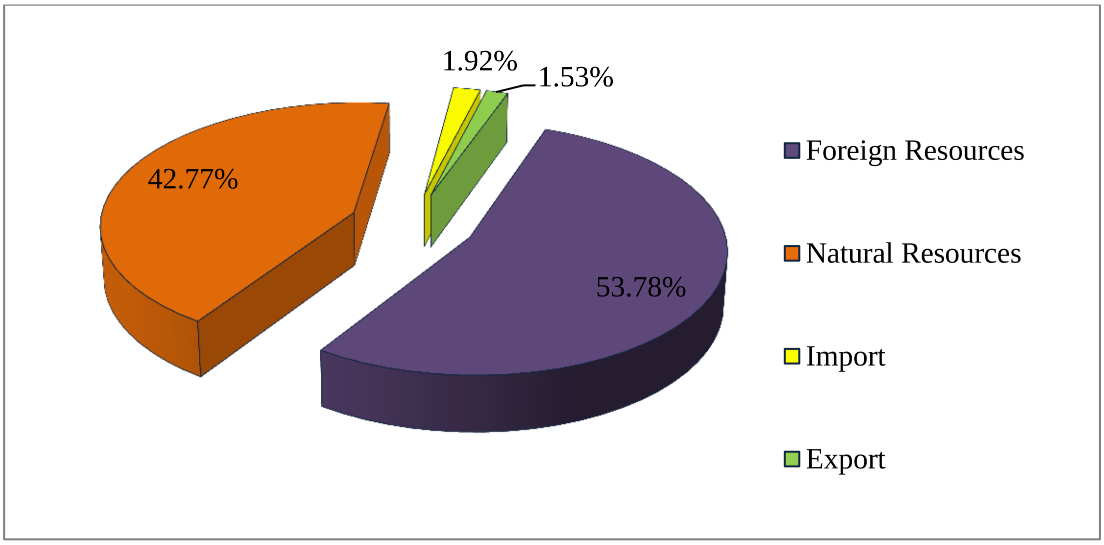

Figure 1.2 - Turkey Annual Energy Generation Percentages (EPDK, 2012)

Efficient use of hydropower energy potential of country is critical and reservoir operation studies play a significant role in increasing the efficiency. Generally, operation of hydroelectric power plant (HEPP) depends on maximization of energy generation which can be achieved by developing reservoir specific rule curves. Main goal of this study is to develop a rule curve for Altıparmak Dam and HEPP. To achieve this goal, an optimization problem is formulated and coupled with Sequential Streamflow Routing (SSR) method to determine optimum end of the month operating levels of the reservoir (i.e. the rule curve). Microsoft Excel's Solver is used to solve the optimization problem.

Using the rule curve developed as a result of the optimization study, total energy generation of Altıparmak HEPP between 1972 and 2007 is calculated as 8176.65 GWh. Ak (2011) conducted a feasibility study for Altıparmak Dam and HEPP and using a constant rule curve (i.e. keeping the reservoir at its maximum level throughout the whole year) estimated total energy generation as 7760.36 GWh. In this study, it is assumed that two parallel turbines with equal installed capacities are used and flow is distributed among these turbines equally. Thus, the rule curve developed through the optimization study results in an increase of approximately 5% in the total energy generation of Altıparmak Dam and HEPP.

A further analysis is conducted to evaluate impact of using two parallel turbines with different installed capacities and distributing flow among these turbines unequally. When these two parameters are treated as decision variables, the size of the problem increases and Excel's Solver starts experiencing convergence problems. Thus, various trial and error studies conducted and it is identified that using two equally sized (i.e. same installed capacities) turbines results in the maximum energy generation and flow should be distributed among these turbines equally.

CHAPTER 2

LITERATURE REVIEW

2.1. Reservoir Management

Jain and Singh (2003) stated that reservoir operation studies are very important as well as construction steps. Determination of water release schedule resulting in the maximum benefit for a single-purpose reservoir is the basic problem in the reservoir operation. On the other hand, the main operation complexity for multi-purpose reservoirs is to provide optimal water allocation among various purposes.

A conceptual description of the need for regulation of the flow to meet the requirements of the society is given in Figure 2.1 (Jain & Singh, 2003). The terms or situations can be expressed as follows:

- Water deficit might occur when the natural flow is lower than the demand discharge,
- Flood damage will be observed if the natural flow higher than the non-damaging flow,
- Minimum flow deficit is observed when flow is both lower than the demand discharge and the minimum required flow.

These irregularities in the flow can be handled by the regulation of the reservoir.

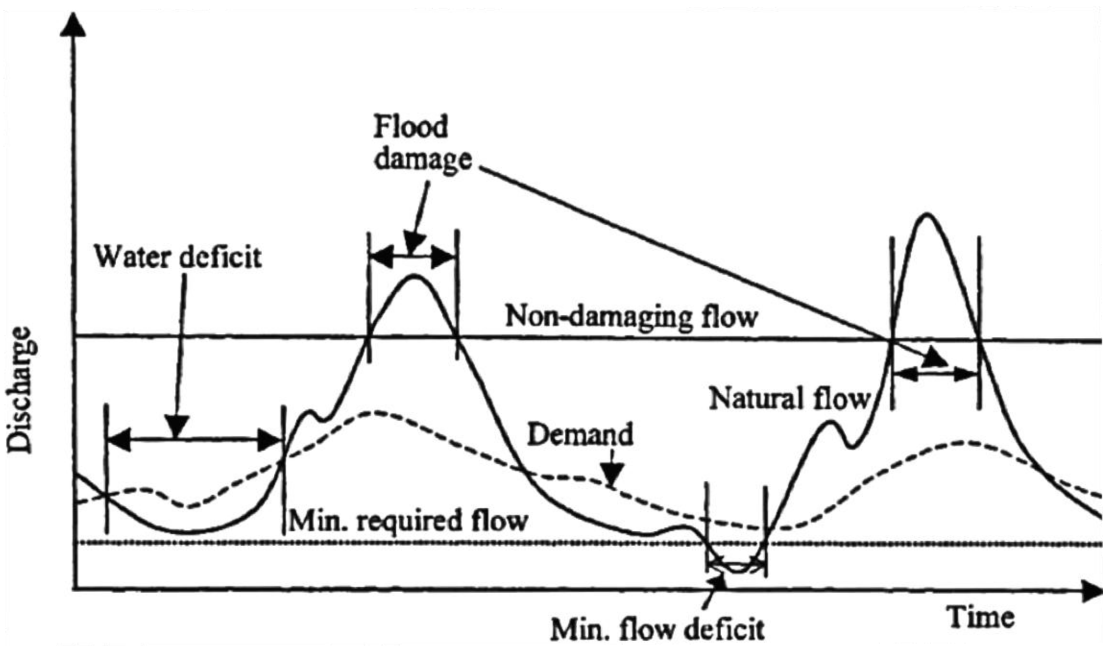

Figure 2.1 - The need of regulation to meet the requirements of the society (Jain & Singh, 2003)

Reservoir operating policies or control strategies constitute decision rules. Reservoir operation models are developed for optimization of beneficial water use, minimization of risk of flood and droughts, or supply of available water for multiple uses. After construction stage, these decision rules in a written instructions format are provided to the operator for the utilization of the rules consciously (United States Department of the Interior Bureau of Reclamation, USBR, 1987).

In the literature, there has been a debate on utilization of optimization or simulation models for identification of reservoir operation rules. Simulation models have more flexibility in a complex analysis and they are also more detailed and realistic whereas optimization models are better at identifying best solutions (Jain, Goel, & Agarwal, 1998). Both optimization and simulation models are used with historical data and are based on mass-balance equations. The performances of both models are evaluated to follow the movements of flow in a reservoir-stream system and derive an operation policy. Both simulation and optimization studies are mainly concerned with reducing frequencies of water shortages or average water shortages, or reducing frequencies of excess releases or average releases (Jain, Goel, & Agarwal, 1998). Historical developments of simulation and optimization models are briefly explained below.

Initial computer studies on reservoir simulation in the United States were performed by U.S. Army Corps of Engineers on six main reservoirs of the Missouri River in 1953 (Wurbs, 2005). Then, both U.S. Army Corps of Engineers and Bonneville Power Administration studied simulation of hydropower operation on the Columbia River. In 1955, to determine operation policies for multiple reservoirs, simulation studies of Nile River Basin in Egypt were performed considering 17 hydropower reservoirs (Wurbs, 2005). On the other hand, several researchers worked on reservoir operation optimization models. For example, Loucks et al. (1981), Mays and Tung (1992), Karamouz et al. (2003) and Jain & Singh (2003) issued water resources system books about optimization techniques of reservoir operations. Numerous researchers worked on initial simulation and optimization of computer models for reservoir system operations. These pioneer studies have been developed up to day and several literature studies have been performed during the last fifty years.

For both optimization and simulation models, the decision rules can be developed to decide how to operate the reservoir. The reservoir operating rule curves have been used as the optimal solution for long term operation (Kangrang & Lokham, 2013). Various generalized model types obtained for reservoir systems are listed in Table 2.1 (Wurbs, 2005). Nonetheless, various researchers raise concerns about the gap between theoretical development and real-world applications of reservoir operation systems (Celeste & Billib, 2009).

Table 2.1 –Reservoir System Models (Wurbs, 2005)

Name	Description	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/
SSAR	Streamflow Synthesis and Reservoir Regulation	USACE North Pacific Division http://www.nwdwc.usace.army.mil/report/ssarr.htm
WRIMS (CALSIM)	Water Resources Integrated Modeling System	California Department of Water Resources http://modeling.water.ca.gov/hydro/model/description.html
StateMOD	State of Colorado Stream Simulation Model	Colorado Water Conservation Board and Colorado Division of Water Resources, http://cdss.state.co.us/
OASIS	Operational Analysis and Simulation of Integrated Systems	HydroLogics, Inc. http://www.hydrologics.net/
ARSP	Acres Reservoir Simulation Program	Acres International, BOSS International http://civilcentral.com/html/arsp_tech_info.html
MIKE BASIN	GIS-Based Decision Support for Water Planning& Management	Danish Hydraulic Institute http://www.dhisoftware.com/mikebasin/
RIBASIM	River Basin Simulation	Delft Hydraulics, http://www.wldelft.nl
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/
RiverWare	River and Reservoir Operations	Bureau of Reclamation, TVA, CADSWES http://animas.colorado.edu/riverware/
MODSIM	Generalized River Basin Network Flow Model	Colorado State University http://modsim.engr.colostate.edu/modsim.html
WRAP	Water Rights Analysis Package	Texas Commission on Environmental Quality, USACE, TWRI, http://ceprofs.tamu.edu/rwurbs/wrap.htm

2.2. Reservoir Operation

Surface water reservoir systems are mainly grouped into conservation and flood control purposes. The determination of reservoir storage for a reservoir project is one of the basic hydrologic analyses and storage allocation zones are shown in Figure 2.2. Case studies of this thesis focus on conservation purposes of reservoir operations, especially hydroelectric energy generation. Details of reservoir operation for electricity generation are explained in the following sections. Energy potential determination methods, hydroelectric energy types, power study procedure, rule curves and excel solver application to obtain rule curves are summarized in the following sections.

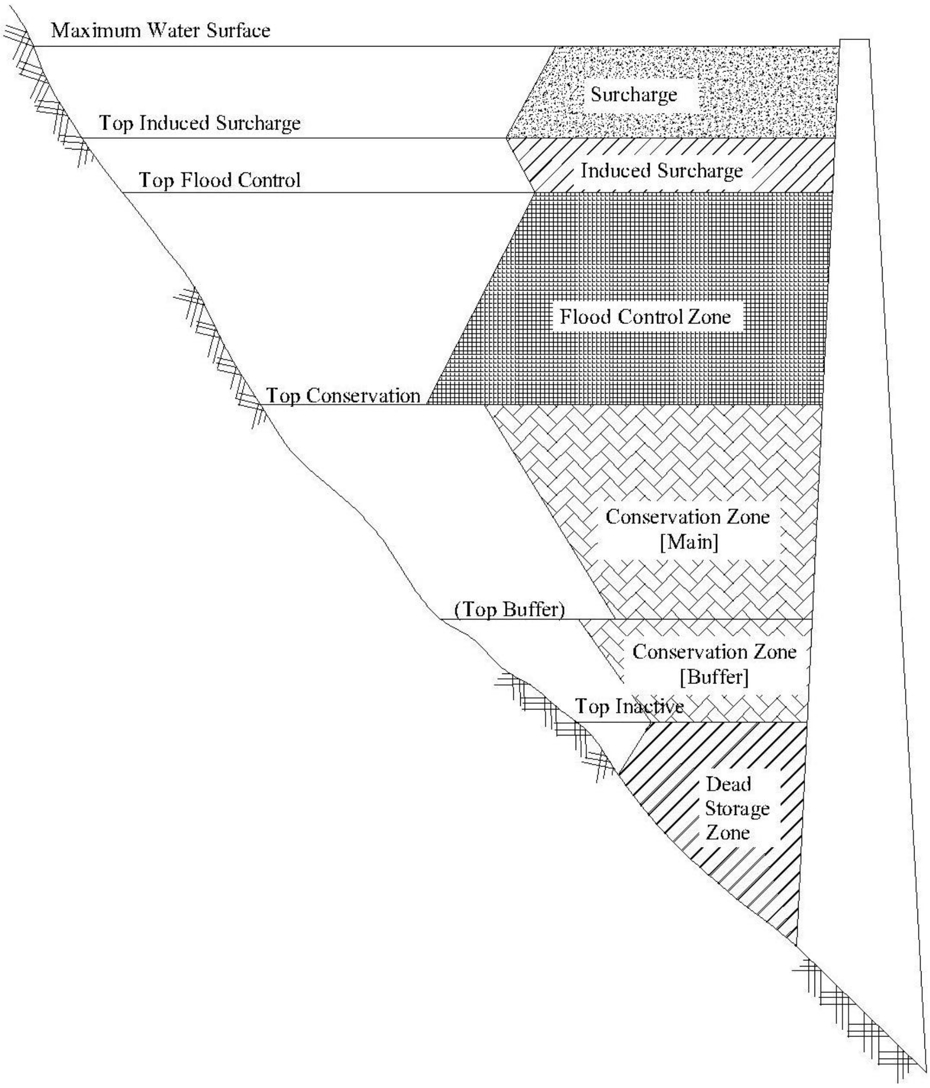

Figure 2.2 – Reservoir Storage Allocation Zones (U.S. Army Corps of Engineers, 1977)

2.2.1. Energy Potential Determination Methods

Three methods are used for determination of energy potential of a reservoir: the non-sequential (flow-duration curve) method, the sequential streamflow routing method and hybrid method (U.S. Army Corps of Engineers, 1985).

Flow-Duration Curve (FDC) Method

Flow-duration curves are obtained from historical flow data. Cumulative streamflow values are arranged in descending order, and flow-duration curve is prepared by plotting flow versus percent of time it is equaled or exceeded. An example flow-duration curve is given in Figure 2.3. The main advantage of the method is that it is relatively simpler, faster and more economic for computing energy potential compared to the other methods. Notwithstanding, the primary disadvantage is that it does not represent the flows according to chronological order. Besides, the other disadvantages that it cannot analyze the multireservoir projects and cannot be used for the projects where head varies independently of flow (U.S. Army Corps of Engineers, 1985).

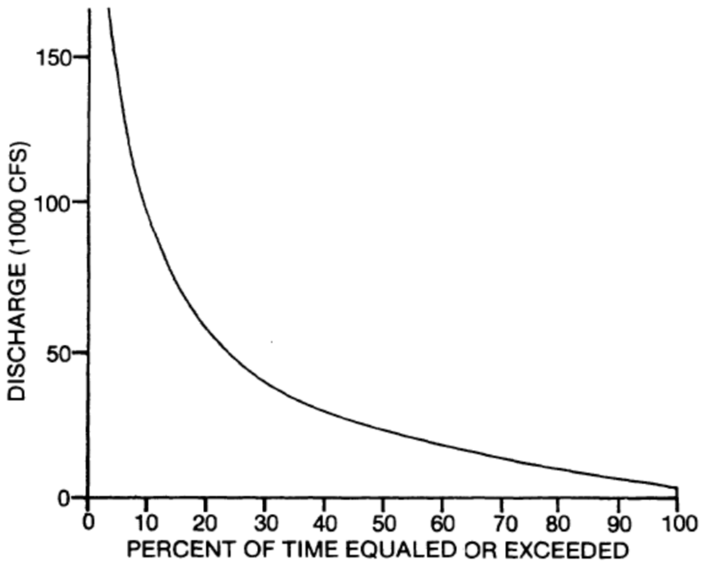

Figure 2.3 - Flow – Duration Curve (U.S. Army Corps of Engineers, 1985)

Sequential Streamflow Routing (SSR) Method

The method can be applied to almost any type of hydropower analysis, such as run-of-river projects, run-of-river projects with pondage, projects with flood control and storage only, projects with conservation storage not regulated for power, projects with storage regulated for multiple purposes included power, peaking hydropower projects and pumped-storage hydropower projects (U.S. Army Corps of Engineers, 1985). Nonetheless, the operation studies of the method are especially developed for storage projects or the systems composing of storage projects. The method is based on the continuity equation (U.S. Army Corps of Engineers, 1985):

$$\Delta \boldsymbol{S} = \boldsymbol{I} - \boldsymbol{O} - \boldsymbol{L} \tag{2.1}$$

where $\Delta \boldsymbol{S}$ is expressed as a change in the reservoir storage volume, $\boldsymbol{I}$ and $\boldsymbol{O}$ represent volumetric reservoir inflow and outflow values during a specified time interval, respectively, and $\boldsymbol{L}$ is reservoir losses such as evaporation, diversion, etc.

The basic steps for the SSR procedure are outlined as follows (U.S. Army Corps of Engineers, 1985):

Step 1 – Select plant capacity

Step 2 – Compute streamflow available for power generation

Step 3 – Determine average pond elevation

Step 4 – Compute net head

Step 5 – Estimate efficiency

Step 6 – Compute generation

Step 7 – Compute average annual energy

Contrary to FDC method, it can be applied to the projects where head varies independently of streamflow. In addition, the effects of reservoir regulation for multi-purpose projects might be included in the model. However, there are major disadvantages that the method has complexity issues and large amount of time is required for long time periods.

Hybrid Method

This method combines features of FDC and SSR methods. The main purpose of the method is to analyze an additional power requirement for an existing project and it is convenient for the flood control and non-power purposes conservation storage projects. It is usually slower than FDC method whereas it is faster than SSR method.

Types of hydroelectric energy used in energy potential determination methods (SSR, FDC or Hybrid Methods) are explained in the following sections.

2.2.2. Hydroelectric Energy Types

Hydroelectric energy is conversion of the potential energy to the electric energy through hydraulic turbine and generators. Three types of hydroelectric energy estimates are calculated in hydropower studies: average annual energy, firm energy and secondary energy. Briefly descriptions of these energy types are given below (U.S. Army Corps of Engineers, 1985):

Average Annual Energy

It is the average amount of yearly energy generation for the selected period by means of historical streamflow data. In SSR method, it is computed by taking the mean of annual generations over the historical period whereas in FDC method, it is calculated by estimating the area under the power-duration curve. Despite the requirement of firm and secondary energy evaluation separately, most of the power studies use average annual energy to evaluate energy benefits.

Firm Energy

It is the available electrical energy that is supplied on a guaranteed basis even on the most adverse period of historical streamflow values.

Secondary Energy

It is the energy generation in excess of the firm energy output and it is usually produced in the high runoff periods. Also, it can be defined as the difference between average annual energy and firm energy.

2.2.3. Power Study Procedure

Power Study procedure is composed of all steps that need to be followed for reservoir management. The procedure includes the required steps leading to the construction of the hydropower plant and steps after construction. Although these steps are not carried out in this thesis study, outputs are used to generate reservoir operation rules. Power study for Altıparmak Dam and HEPP was carried out by Ak (2011) and outputs of that study form the basis for this study. To better understand the general concept, power study procedure is briefly explained in the following section.

Although each step requires detailed technical studies, U.S. Army Corps of Engineers (1985) outlined roughly the organization of a power study checklist for an example power study project as follows:

1. Need for Power
2. Hydrologic Data Preparation
3. Preliminary Power Studies
4. Environmental/Operational Studies
5. Type of Project
6. Range of Plant Sizes
7. Detailed Power Studies

8. Cost Estimates
9. Basis for Benefits
10. Power Values
11. Power Benefits
12. Net Benefits
13. Marketability Study
14. Select Plan
15. Successive Iterations

The schematic process of a power study analysis is also illustrated as in Figure 2.4 (U.S. Army Corps of Engineers, 1985).

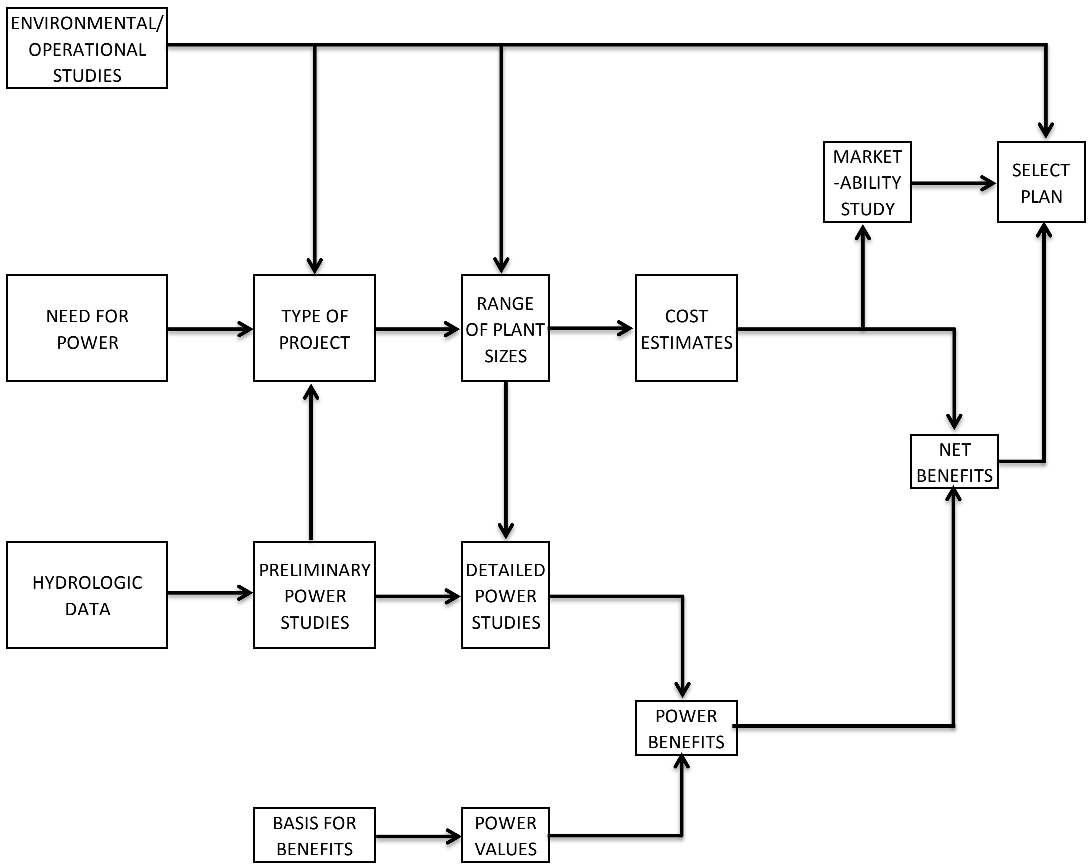

Figure 2.4 - Power Planning Flow Chart for Reservoir Management (U.S. Army Corps of Engineers, 1985)

2.2.4. Rule Curves

Reservoir operation rule curves are fundamental guidelines for long term reservoir operation (Kangrang & Lokham, 2013) and optimum rule curve reservoir levels are derived from the best reservoir operation policy (Jain, Goel, & Agarwal, 1998). Curves are developed to obtain the highest monthly time reliability with the least number of critical failure months and to provide guidance to operator (Jain, Goel, & Agarwal, 1998). Therefore, manager can easily decide one of the potential operation strategies.

Rule curves generally depend on detailed sequential analysis of critical hydrologic conditions and demands and the reservoir operation rule curve is defined as a curve or family of curves, indicating how a reservoir is to be operated under specific conditions to obtain best or predetermined results (Mays, 2010). To extract optimal reservoir rules, in the literature, different methodologies were proposed. None of these methodologies are exactly followed in this study. A combination of these methodologies is developed and is explained in Chapter 3. However, to better understand and evaluate these methodologies, they are investigated and explained in the following paragraphs.

Wei and Hsu (2009) proposed a general methodology for development of rule curve as given in Figure 2.5. Moreover, Hobbs et al. (1996) briefly outlined the procedure of an example project to obtain reservoir operation rule curves as follows:

STEP – 1: Identify the critical period,

STEP – 2: Make a preliminary estimate of the firm energy potential,

STEP – 3: Make one or more critical SSR to determine the actual firm energy capability and to define operating criteria that will guide year-by-year reservoir operation,

STEP – 4: Make an SSR routing for the total period of record to determine average annual energy,

STEP – 5: If desired, make additional period-of-record routings using alternative operating strategies to determine which one optimizes power benefits.

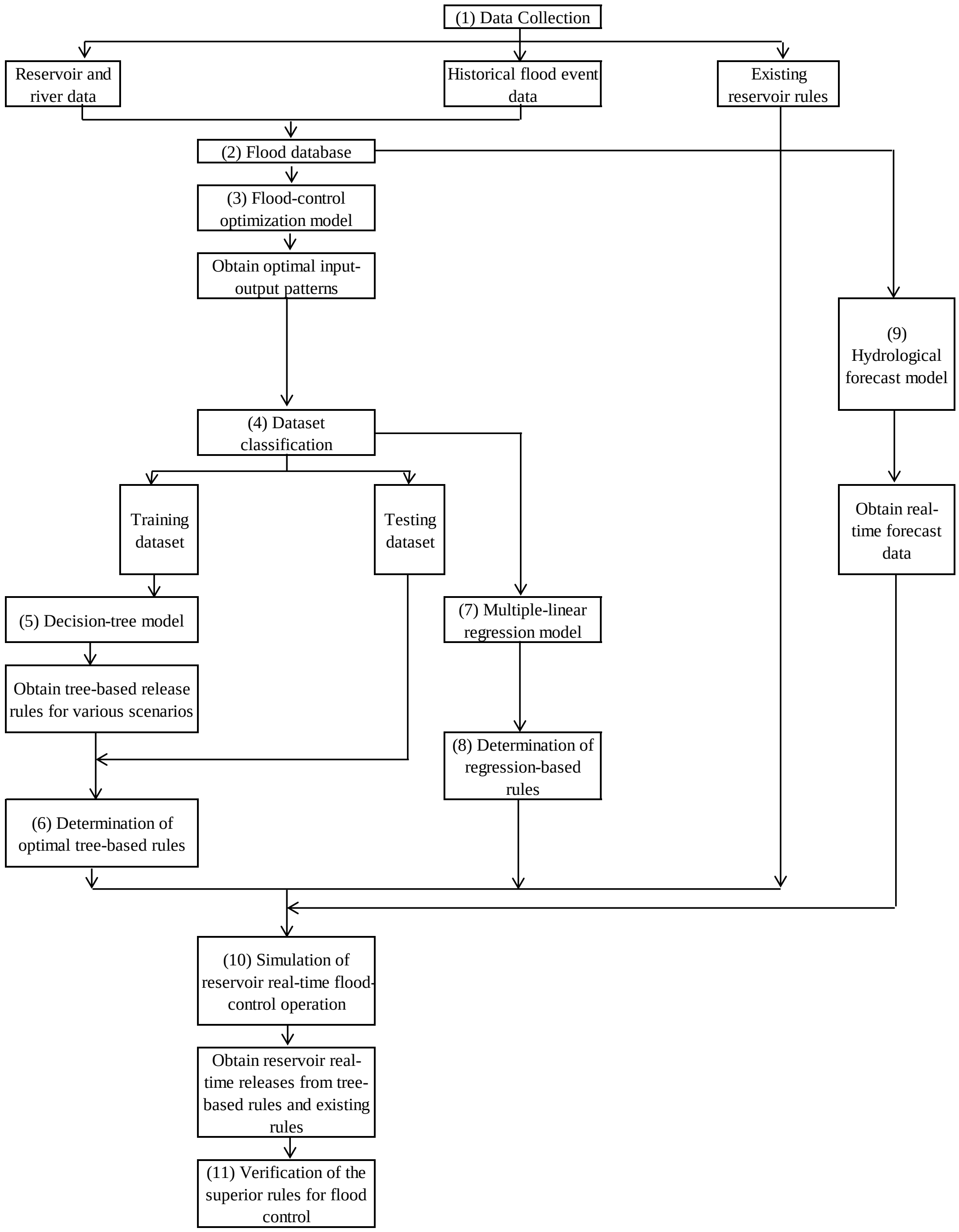

Figure 2.5 – Flowchart of Methodology for Extracting Optimal Reservoir Rules (Wei & Hsu, 2009)

Wurbs (2005) provided a comprehensive summary of different methods that are used to obtain reservoir rule curves:

- **Trial-error method:**

The enhancement of rule curve strategies in reservoir management begins with trial-error approaches. Trial-error technique is comprehensible, direct and applicable for both simple and complex systems. However, the optimal rule curves obtained by this technique do not guarantee to supply yield.

- **Dynamic Programming (DP):**

Dynamic programming (DP) method is developed to analyze the non-linear problems of water resources. Most of the DP studies use deterministic optimization models. Nevertheless, DP studies do not consider the uncertainties of future variables and do not generally represent real hydrologic conditions (Hormwichian, Kangrang, & Lamom, 2009).

- **Stochastic Dynamic Programming (SDP):**

Stochastic dynamic programming (SDP) has been developed to overcome the drawbacks of DP deterministic models (Celeste & Billib, 2009). The basic steps of the procedure to construct operating policies have been defined as shown in Figure 2.6. For instance, Liu et al. (2011) studied SDP to derive optimal reservoir operation rules for cascade hydropowers and compared the results with conventional operation rule curves. However, it has been observed that the method is limited for multi reservoir systems due to dimensionality problems.

- **DP with Principle Progressive Optimality (DP-PPO):**

Kangrang et al. (2007) derived a technique called DP with principle progressive optimality (DP-PPO) to obtain the optimal rule curves and remedy dimensionality limitations of DP and SDP. However, the most important disadvantage of the application is that it is too complicated.

- **Genetic Algorithm (GA):**

Chang et al. (2003) used genetic algorithms to search optimal rule curves of the reservoir system. Chen (2003) and Chang et al. (2005) conducted more studies about this technique. Genetic Algorithm (GA) methods are applicable to any type of function. Also, Kangrang et al. (2011) improved a simulation model based on GA and the water balance equation with the objective function of minimization of average water shortage. Notwithstanding, GA is a complicated technique due to the needs of multi-computation of reservoir operation levels.

• **Parameterization-Optimization-Simulation Approach:**

As a new solution, Celeste and Billib proposed parameterization-simulation-optimization approach to develop reservoir operation rules (2009). In this approach, optimization and simulation models are simultaneously used considering all parameters. The procedure of the approach can be explained as follows. Initial parameters are defined and a preliminary rule is obtained with these parameters. The process is continued and reservoir is operated for different combinations up to provide optimum scenario. The procedure is summarized in Figure 2.7.

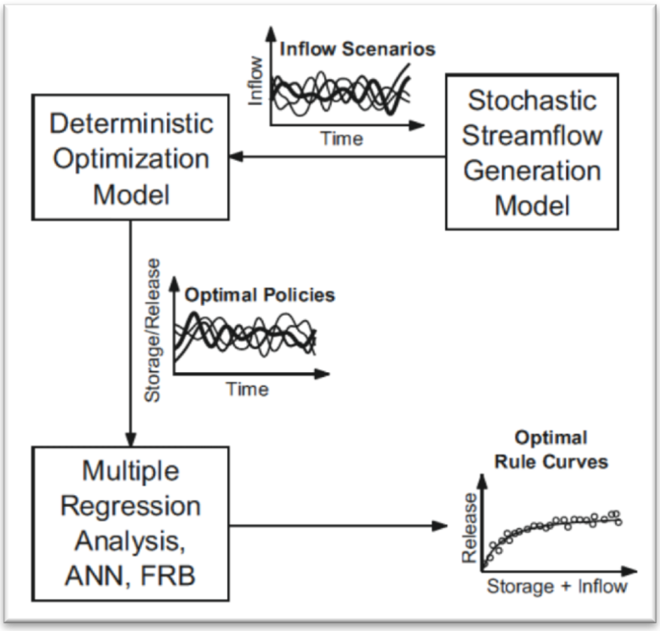

Figure 2.6 – Implicit Stochastic Optimization Procedure (Celeste & Billib, 2009)

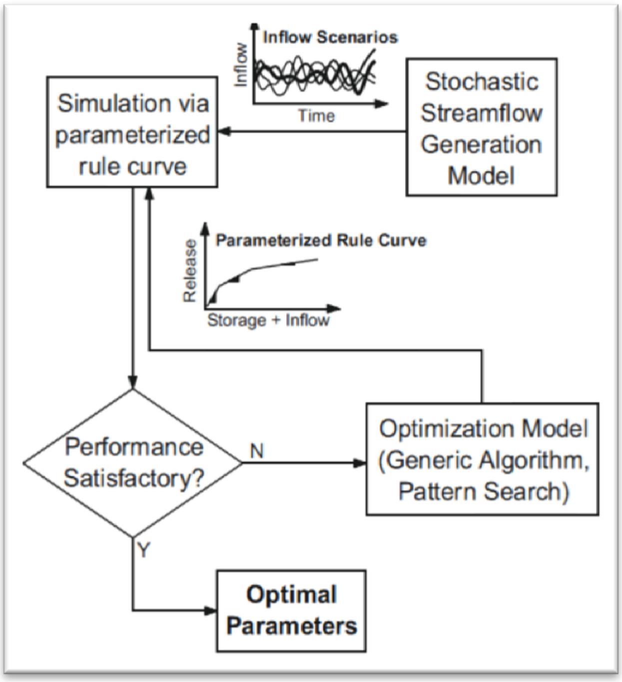

Figure 2.7 – Parameterization-Optimization-Simulation Procedure (Celeste & Billib, 2009)

In this study, a methodology similar to parameterization-optimization-simulation approach is developed and Microsoft Excel's Solver is used to solve the problem. The general usage and application of Solver application is explained in the following section.

2.2.5. Excel Solver Application

Solver engine is an add-in of Microsoft Office 2010 Excel (program code are copyright 1990, 1991, 1992, 1995 and 2008 by Frontline Systems Inc.) to find global optimum solutions for the large and complex optimization problems. The aim of the engine, developed by Frontline System Inc., is to solve operation models having uncertainty by the new methods of robust optimization, stochastic programming and simulation optimization (Frontline System Inc., 2013).

For the solution of optimization problem, **Solver Analysis** defines three solving methods to set objective functions with the consideration of changing variable and constraints. These are respectively as follows (Frontline System Inc., 2013):

Simplex LP Solving Method: Simplex Engine is used for the problems that are linear optimization problems (implemented by John Watson and Daniel Fylstra, Frontline Systems, Inc.).

Generalized Reduced Gradient (GRG) Nonlinear Solving Method: Nonlinear engine is used for solver problems that are smooth nonlinear (developed by Leon Lasdon, University of Texas at Austin, and Alan Waren, Cleveland State University, and enhanced by Frontline Systems, Inc.).

Evolutionary Solving Method: Evolutionary engine is selected for the problems that are non-smooth (implemented by several individuals at Frontline Systems, Inc.).

The solver analysis will stop when it finds an optimal solution potentially global, when it cannot produce a feasible solution or when the time limit or maximum number of iterations is reached. Optimization of the reservoir system operation is a nonlinear problem; therefore, simplex LP solving method cannot be applied for these analyses. The nonlinear functions are the functions that they cannot be written in algebraic formula (Frontline Systems Inc., 2013). The main difference between GRG and Evolutionary solving method is that function is smooth or not. If the graph of the function's derivative does not have any break, function is called as smooth; otherwise, it is defined as non-smooth. Considerations of time and cost consumption are the most significant disadvantages of evolutionary solving method with respect to GRG solving method whereas evolutionary solving method is more reliable than GRG solving method (Frontline System Inc., 2013).

The optimization problem of rule curve generation is a nonlinear function (Kangrang & Lokham, 2013). Also, it is assumed that the graph of the function's derivative does not have any break. Therefore, GRG nonlinear solving method can be used for this type of optimization problems. In **Solver Options** dialog box, the following parameters shown in Figure 2.8 are described below:

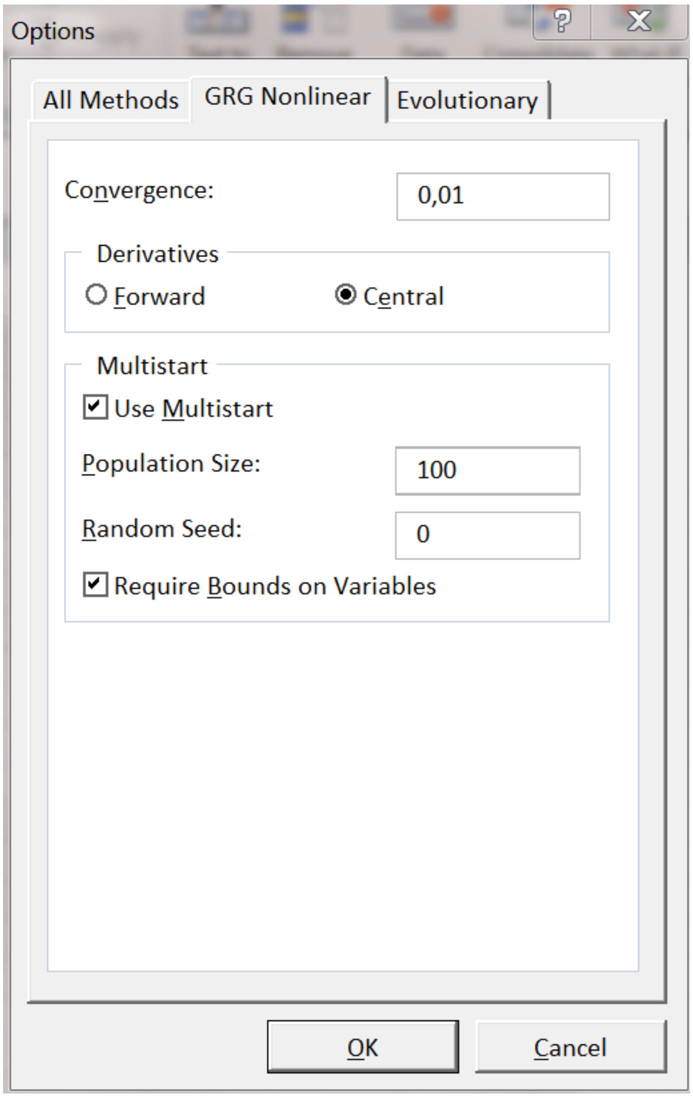

Figure 2.8 – Solver Options Dialog Box Example Snapshot

Convergence: it shows the amount of relative change for last 5 iterations before the solver is stopped. The smaller convergence amount shows the proximity to the optimal solution and more time is required to obtain the optimal solution (Frontline System Inc., 2013).

Derivatives: There are two options for the derivatives box. The main difference between forward and central options is that the accuracy of the derivatives and central derivative produces more accuracy. However; this accuracy of central requires twice as many calculations for optimal solution (Frontline System Inc., 2013).

Multistart Option: If the **Multistart** button is checked, the run will be run repeatedly for different starting values and the better results will be obtained. The only consideration of the Multistart use is that it will take more time to provide optimum solutions than a single run GRG solution. The **Population Size** box indicates the number of starting points. For instance, “20” value in Population Size box equals to population size as 20 times decision variables. The value in **Random Seed** box is used as a starting point for Multistart option and if the box is left blank, it will generate random number instead of starting with the same point. If the calculation is specified to be bounded with the decision variables in the **Subject to the Constraints** box, the Require Bound on Variables box is to be checked (Frontline System Inc., 2013).

Optimization studies in the literature of water resources management and power generation fields using the Excel Solver application are available and some of them are summarized below.

Benli and Kodal (2003) developed an optimization model for farm irrigation with adequate and limited water supplies in South-East Anatolian Project (GAP). The main goal was to evaluate the difference between the results of linear and nonlinear optimization models, and to determine an optimum water amount under adequate and limited water supply conditions. To construct the optimization model, Solver Analysis application in Excel was used. The results showed that the methodology produced by non-linear model was more reliable than linear functions and optimum irrigation amount for the region was calculated.

Howard (2006) constructed a model for optimizing hydropower operations into two stages by using Excel Solver and Frontline Systems’ Premium Solver. The first stage of the model consisted of a quadratic optimization model. The objective function was a quadratic linear function whereas the constraints were linear. At the second stage, unit efficiencies, forebay and tailwater elevation calculations were integrated into the model as nonlinear functions. After the optimization algorithm was solved an optimal operation policy.

Hidalgo et al. (2010) studied data analysis of hydroelectric plants to develop a methodology for future operation policies. The main aim was consolidation of data on hydroelectric plants, enhancement on the reliability of data use for the model of reservoir operation planning, and contribution to the production of economic and reliable operation policies. The case study was applied to a large Brazilian hydroelectric plant under operation. The model was based on water balance equation and production function. The physical data functions were composed of area-level polynomial, level-volume polynomial, level-release polynomial, maximum power function, maximum water discharge function, penstock head loss function, generator efficiency function, turbine efficiency function, and overall efficiency function. At the stage of overall efficiency function, Solver application of Excel was used. Forebay level, tailrace level, reservoir volume, water inflow, water discharge, water spill, power output, evaporation, penstock head loss and turbine-generator efficiency were dependent with the physical data and all these parameters were implemented as variable data. Consequently, the reservoir operation policy was proposed to the Brazilian hydroelectric plant under the operation and this study was presented as an example model for future studies.

Arai et al. (2011) simulated a study in Bangladesh to show the impact of power generation on economic growth by using Excel Solver application. For different power generation scenarios, six steps were followed and Excel solver was used for the nonlinear problems in the model. The following steps were tracked consequently:

Step – 1: The constants and conditions were set,

Step – 2: Price system calculation was obtained,

Step – 3: Income and final demand were calculated,

Step – 4: Production demand was calculated,

Step – 5: The equilibrium was solved (GRG solving method was used in Excel Solver application),

Step – 6: Future capital accumulation and electricity prices were calculated.

With the comparison of the results for different development models, a feasible planning and operation policy was acquired by the power generation capacities and composition.

CHAPTER 3

PROJECT SITE DESCRIPTION & REQUIRED INPUT DATA

Altıparmak Dam and HEPP is selected as a case study. Ak (2011) performed alternative feasibility studies for different formulations of Altıparmak Dam and HEPP. Detailed economic analyses were conducted to compare different formulations. As a result of his study, Ak (2011) recommended that development and reevaluation of operating strategies is necessary and development of a better rule curve for Altıparmak Dam and HEPP may result in higher energy incomes.

The purpose of Altıparmak Dam and HEPP is energy generation. Therefore, the main aim of this study is to develop an operation policy maximizing annual energy generation and supplying tailwater requirements using this storage capacity. As explained above several formulations were proposed for Altıparmak Dam. In this study, rule curve for ANC Formulation is developed. In the following sections, general information about project site, hydrological data and project specifications of ANC Formulation are provided.

3.1. Project Site Description

Altıparmak Dam and HEPP is under planning stage and is planned to be constructed on Parhal Stream (a branch of Çoruh River), Artvin (Eastern Blacksea Basin of Turkey). Location of the project in Turkey map is indicated in Figure 3.1. A detail map of the project site is given in Figure 3.2.

Figure 3.1 – Location of Altıparmak Dam and HEPP in Turkey Map (General Directorate of State Hydraulic Works, DSİ, 2013)

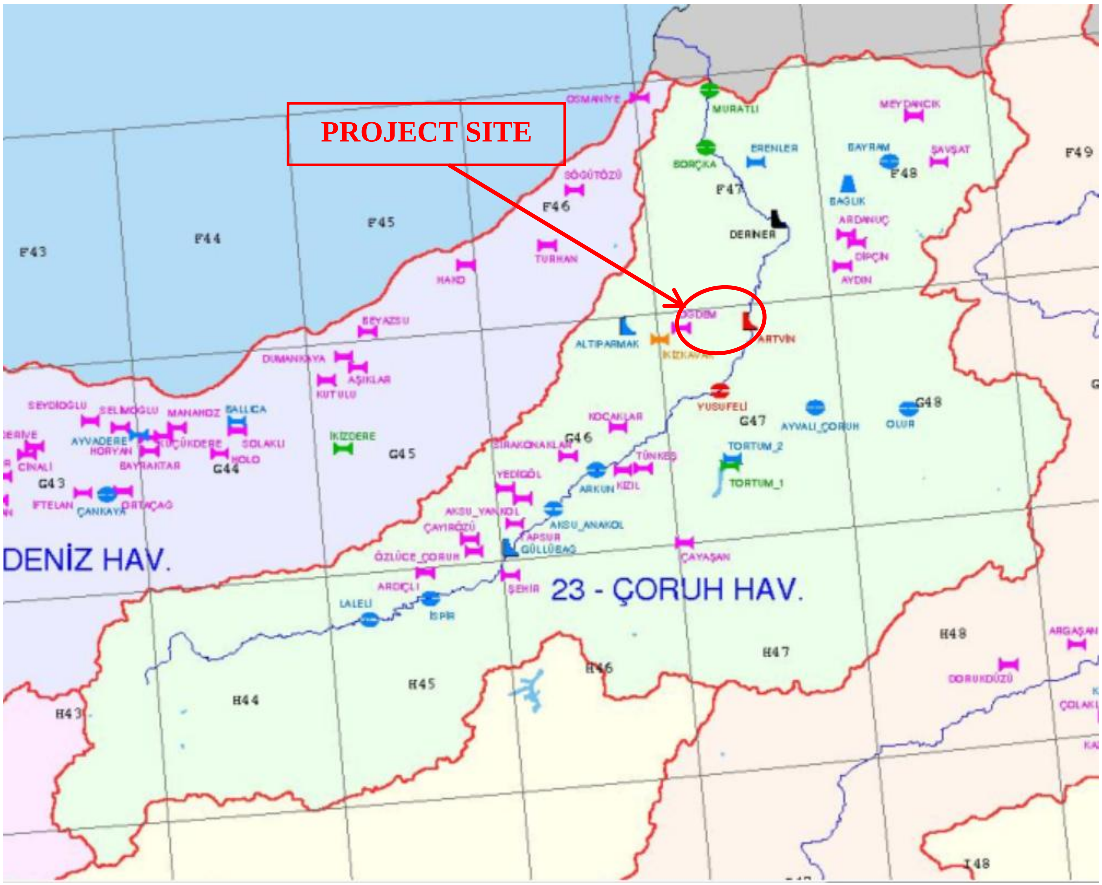

Figure 3.2 – Detail Map of the Project (General Directorate of Electrical Power Resources Survey and Development Administration, EİE, 2013)

3.2. Physical Characteristics of Altıparmak Dam

Physical characteristics of the Altıparmak Dam and HEPP for ANC Formulation are given in Table 3.1 (Ak, 2011). Most of these properties are used in developing the rule curve for Altıparmak Dam and HEPP.

Table 3.1 – Physical Characteristics of Altıparmak Dam and HEPP (Ak, 2011)

Physical Characteristics	Unit	Description
Location	-	Parhal Stream, Çoruh River
Type	-	Roller Compacted Concrete (RCC) Dam
Thalweg Elevation	(m)	1160.00
Minimum Water Elevation	(m)	1195.52
Maximum Water Elevation	(m)	1230.00
Tailwater Elevation	(m)	840.00
Drainage Basin Area	(km^2)	306.67
Maximum Reservoir Area	(km^2)	0.37
Reservoir Surface Area at Maximum Water Level	(km^2)	0.36

Table 3.1 (continued) - Physical Characteristics of Altıparmak Dam and HEPP (Ak, 2011)

Reservoir Surface Area at Minimum Water Level	(km^2)	0.15
Reservoir Volume at Maximum Water Level	(hm^3)	9.96
Reservoir Volume at Minimum Water Level	(hm^3)	1.93
Tunnel Length	(m)	8635
Tunnel Diameter	(m)	3.00
Darcy-Weisbach Epsilon Value for Tunnel (Concrete)*	(m)	0.00018
Darcy-Weisbach Minor Loss Coefficient for Tunnel (Concrete)*	-	1.50
Penstock Length	(m)	687
Penstock Diameter	(m)	2.00
Darcy-Weisbach Epsilon Value for Penstock (Steel)*	(m)	0.000025
Darcy-Weisbach Minor Loss Coefficient for Penstock (Steel)*	-	2.20
Installed Capacity	(MW)	70
Firm Energy Generation	(GWh)	37.04
Secondary Energy Generation	(GWh)	161.40
Total Energy Generation	(GWh)	198.44
Project Design Discharge	(m^3/s)	27
Residual Water Discharge	(m^3/s)	0.8431
Turbine Type	-	Francis
Number of Turbine	ea	2
Minimum Turbine Discharge Ratio*	-	0.3

* (European Small Hydropower Association, ESHA, 1998)

3.2.1. Hydrological Data

Historical streamflow records used in the hydrological analysis part are obtained from Ak (2011). The closest stream gauging station to proposed dam location is EİE 23A042. However, it has only 15 years of data between 1993 and 2007. To extend this data, another close by stream gauging station on Parhal River, EİE 23A021 having 36 years streamflow record between 1972 and 2007 years is used. Correlation study is carried out for EİE 23A042 and EİE 23A021 gauging station measurements for common years 1993 – 2007 and the results are given in Figure 3.3. According to results of the correlation study between two gauging stations, monthly streamflow estimations for EİE 23A042 are generated for 1972 – 1993 interval. Finally, drainage-area ratio method is used to transfer the resulting streamflow values to the dam axis. Streamflow gauging station locations are given in Figure 3.4.

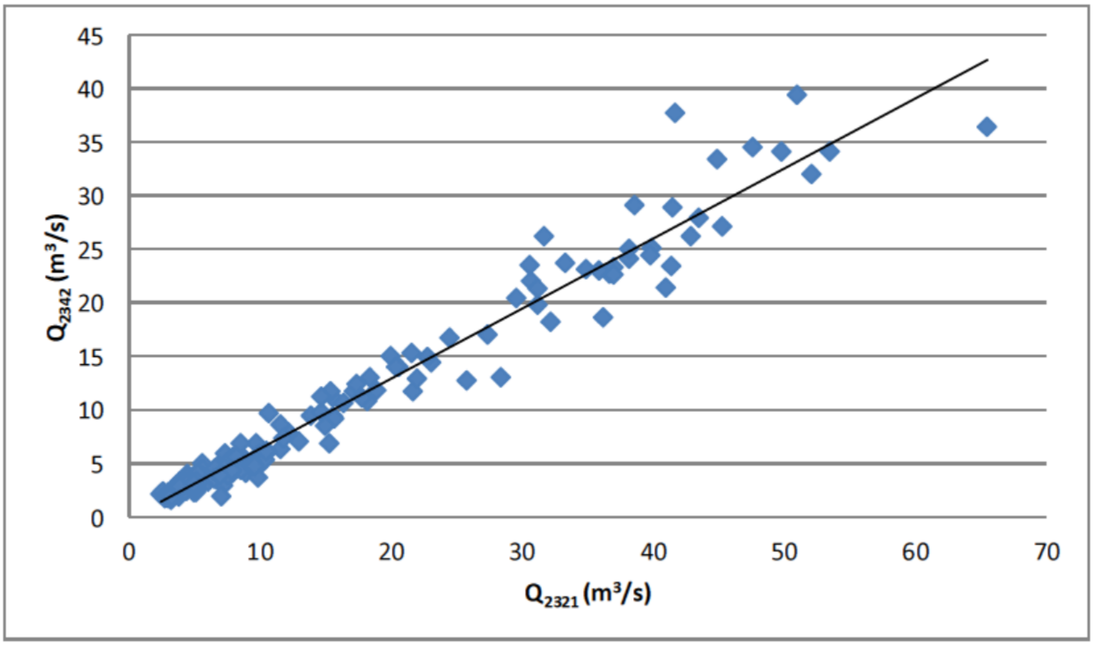

Figure 3.3 – Streamflow Correlation Study between EİE 2342 and EİE 2321 (Ak, 2011)

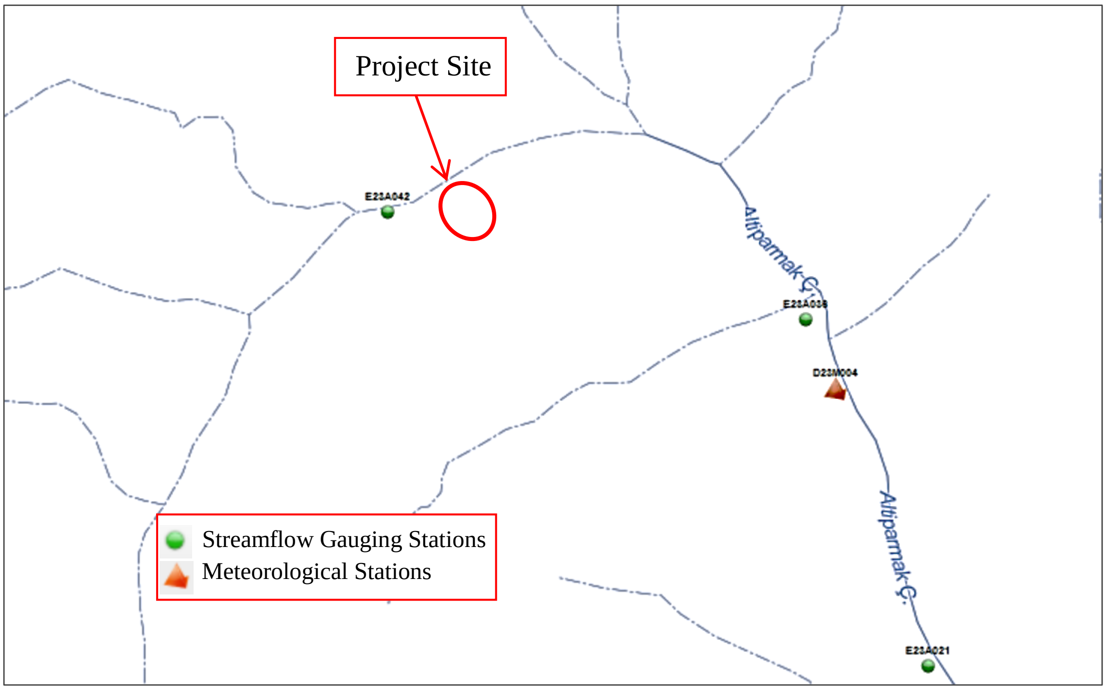

Figure 3.4 – Streamflow Gauging and Meteorological Stations in the Project Site (General Directorate of State Hydraulic Works, DSİ, 2013)

3.2.2. Meteorological Data

For the precipitation values, the closest meteorology station, Yusufeli Meteorology Station D23M004 is used. It has 22 years precipitation data and the monthly average precipitation values are shown in Table 3.2. Nevertheless, evaporation values of this station are not available and another close by meteorology station, Bayburt Meteorology Station, is used for the evaporation and temperature values. The correlation equation between temperature and evaporation values in Bayburt Meteorology Station is used to calculate evaporation values with temperature values of Yusufeli Meteorology Station. The monthly average evaporation values are given in Table 3.2 as well.

Table 3.2 – Monthly Meteorological Data for Altıparmak Dam and HEPP (Ak, 2011)

Month	Precipitation (mm)	Evaporation (mm)
January	18.6	18.6
February	16.7	26.7
March	25.7	60.28
April	33.9	122.3
May	42.4	168.7
June	43.7	203.6
July	24.3	236.6
August	15.2	236.1
September	16.9	198.6
October	20.3	136.5
November	25.1	64.31
December	24.4	25.03

3.2.3. Topographical Data

Reservoir surface area and elevation values corresponding to different operation storages are required while developing rule curves and determining operation policies. Reservoir surface area and storage values are calculated from a map (with a scale of 1/25000) using 10 m interval contour lines by Ak (2011). Storage volume and reservoir surface area values corresponding to different elevations are given in Table 3.3.. Using the method of linear interpolation with these values, volume-elevation and area-elevation curves are developed and shown in Figure 3.5. This figure is used to calculate storage volume and surface area for different operation levels.

Table 3.3 – Altıparmak Reservoir Volume-Area-Elevation

Elevation (m)	Area (km^2)	Total Volume (hm^3)
1160.00	0.000036	0.01
1170.00	0.015999	0.09
1180.00	0.049743	0.42
1190.00	0.096837	1.15
1200.00	0.184881	2.56
1210.00	0.251165	4.74
1220.00	0.313040	7.56
1230.00	0.372299	10.99

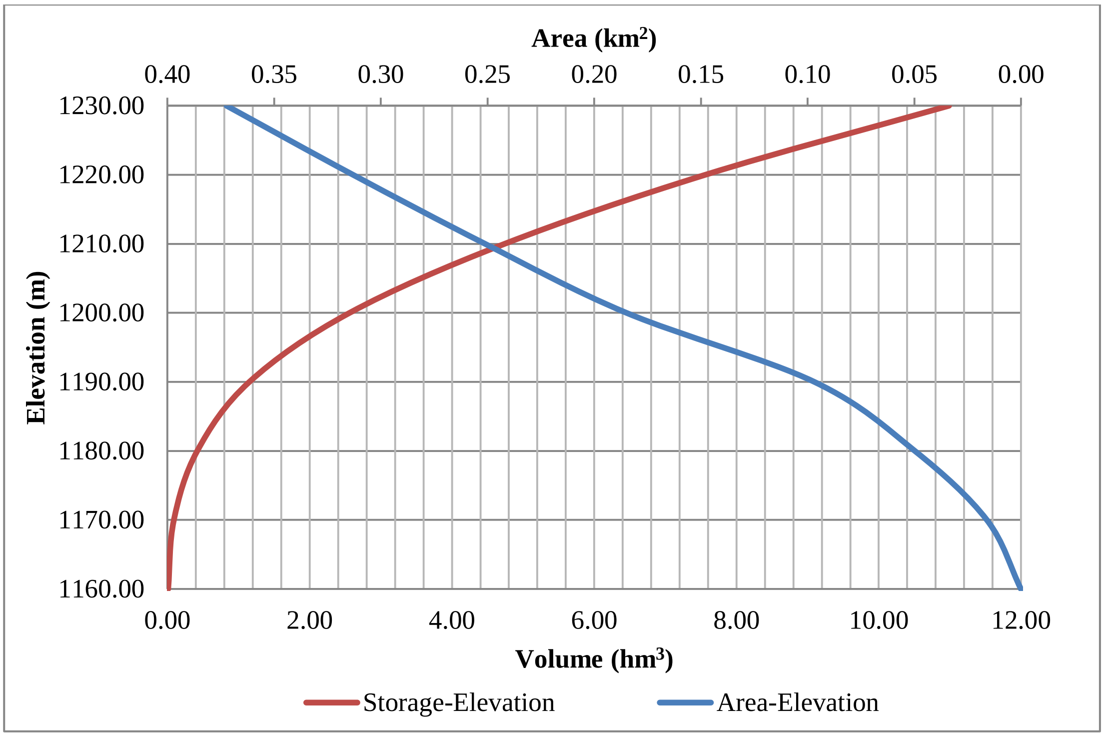

Figure 3.5 – Volume-Area-Elevation Curves

3.2.4. Residual Water Flow

The residual water flow can be explained as the minimum water, released for downstream requirements. DSİ (2009) defines residual water flow for feasibility studies as 10% of the average streamflow value in the last ten years. In Altıparmak Dam and HEPP, the average streamflow value for last ten years is 8.431 m^3/s. Therefore, 10% of this average value is used as residual water discharge. Monthly storage volumes of the residual water flow are also indicated in Table 3.4.

Table 3.4 – Residual Water Flow for Altıparmak Dam and HEPP

Month	Residual Water (hm^3)
January	2.258
February	2.040
March	2.258
April	2.185
May	2.258
June	2.185
July	2.258
August	2.258
September	2.185
October	2.258
November	2.185
December	2.258

3.2.5. Tailwater Rating Flow

HEC-RAS software is used to estimate the tailwater elevation for different flow values (Ak, 2011). Coordinates of 40 river cross-sections with 50 m interval in the streambed, taken from the map through AutoCAD Software, are given as input data to HEC-RAS. For 8 different flow values ranging from 2 m^3/s to 60 m^3/s, tailwater elevation values are estimated as shown in Table 3.5. Tailwater rating curve is obtained for these values. The rating curve is given in Figure 3.6. The rating curve is used to estimate tailwater levels corresponding to different discharge values in rule curve development.

Table 3.5 – Tailwater Elevation Values Corresponding to the Different Flow Values (Ak, 2011)

Discharge (m^3/s)	Elevation (m)
2.00	840.43
4.00	840.56
6.00	840.67
8.00	840.75
10.00	840.81
12.00	840.87
14.00	840.93
16.00	840.98
18.00	841.03
20.00	841.07
25.00	841.17
30.00	841.26
35.00	841.34
40.00	841.41
45.00	841.48
50.00	841.54
55.00	841.60
60.00	841.66

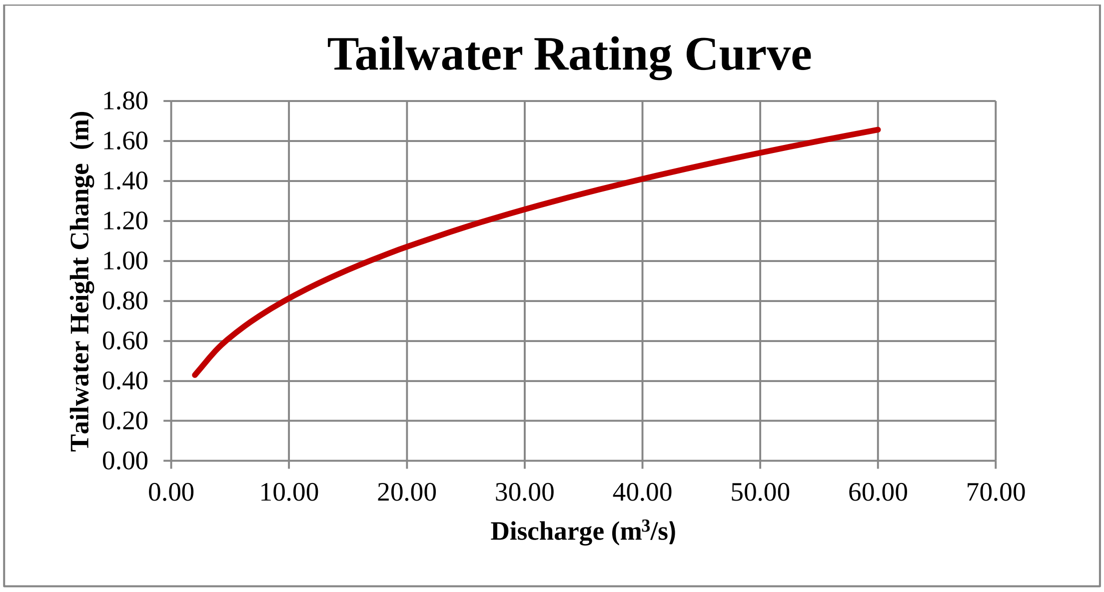

Figure 3.6 – Tailwater Rating Curve

The fitted equation to the curve in Figure 3.6 is shown below:

$$y_t = 0.326\, Q_t^{\,0.397} \tag{3.1}$$

where y_t is expressed as tailwater height change in m at the end of the period and Q_t indicates release discharge at the end of the period in m^3/s.

3.3. Characteristics of Altıparmak Dam and HEPP used in Rule Curve Development

Design Discharge: Ak (2011) conducted a reservoir operation study using Sequential Streamflow Routing method. However, to estimate percent ranges of historical streamflow for alternative design discharges, it was benefited from Flow-Duration Curve (FDC) method. Discharge equaled or exceeded between 5% and 30% of time from FDC were considered as alternative design discharges. Ak (2011) formulated a decision making problem for these alternative design discharges and design discharge was found as 27 m^3/s.

Turbine Installed Capacity Ratio: In this study, it is assumed that two turbines will be used in parallel and the design discharge is divided equally among these two turbines. Thus, the ratio is taken as 0.5.

Maximum Turbine Discharge: Maximum turbine discharge is calculated by multiplying the design discharge with turbine installed capacity ratio. Thus, maximum turbine discharge is taken as 13.5 m^3/s. It is called as turbine design discharge.

Minimum Turbine Discharge: It is assumed that Francis type of the turbines will be used at Altıparmak Dam and HEPP. For Francis type of turbines, the ratio of minimum turbine discharge to turbine design discharge is selected as 0.3 (European Small Hydropower Association, ESHA, 1998). Thus, the minimum turbine discharge is calculated by multiplying turbine design discharge with 0.3 and found as 4.05 m^3/s.

Turbine Discharge Ratio: To determine turbine discharge ratio, decision making calculation is conducted in a different spreadsheet. Energy generation for various discharge values is calculated during this decision making procedure. Discharge volume, calculated in the main analysis spreadsheet, is converted to discharge values and divided into 7 intervals from minimum turbine discharge to maximum turbine discharge. The value giving the highest total energy generation is selected as discharge. Then, to develop the rule curve, the discharge values are distributed among two turbines according to certain rules. The following rules are implemented for the distribution of flow among two turbines:

Rule – 1: If the discharge is smaller than the minimum turbine discharge, neither turbine generates energy.

Rule – 2: If the discharge is between the minimum and the maximum turbine discharges, all the flow is sent to one of the turbines for energy generation.

Rule – 3: If the discharge is greater than the turbine maximum discharge, the flow is distributed to each turbine with a ratio of 0.5. However, the distributed flow has to be between minimum and maximum turbine discharge values. This constraint is checked as well.

Turbine Efficiency: Turbine efficiency is based on the type of the turbine and discharge rate. Turbine efficiency curves for various turbines are shown in Figure 3.7. Since Francis type turbines are used in this study, efficiency curves for this type of turbine are used. An equation is fitted to the efficiency curve (Figure 3.8):

$$\boldsymbol{\varepsilon_t = -4.197y^4 + 10.897y^3 - 10.601y^2 + 4.812y + 0.004} \qquad \textbf{(3.2)}$$

where $\boldsymbol{\varepsilon_t}$ is expressed as turbine efficiency and $\boldsymbol{y}$ indicates the ratio of turbine discharge for each month to turbine design discharge.

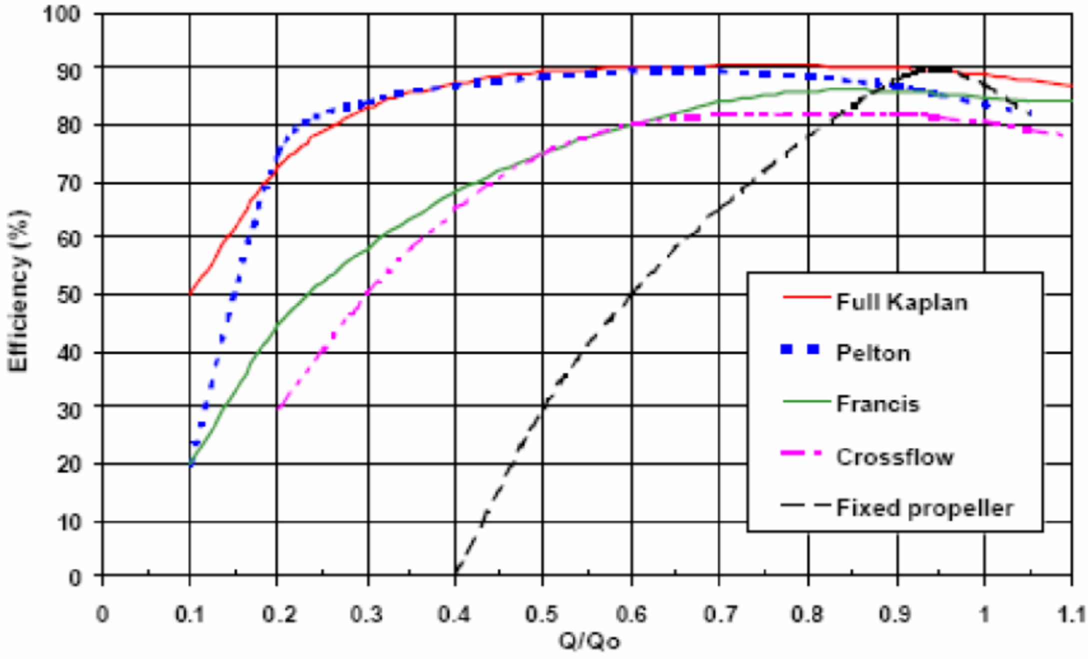

Figure 3.7 – Turbine efficiencies based on turbine type and discharge rate (University of Technology, 2013)

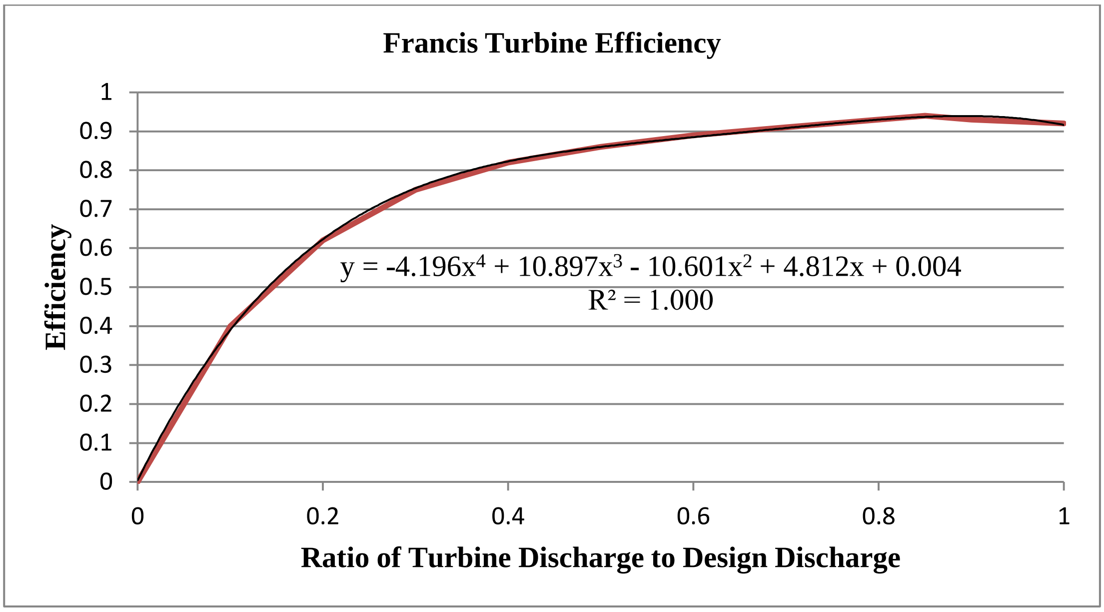

Figure 3.8 – Francis Turbine Efficiency Curve

CHAPTER 4

METHODOLOGY

The analysis performed for Altıparmak Dam and HEPP comprises of two main parts: reservoir operation study and development of the rule curve. Reservoir operation studies are generally performed for conservation and/or flood control purposes. The determination of the best reservoir operation policy depends on these studies. Since each reservoir has different limitations and requirements, there is no unique method to obtain the optimal reservoir operation policy. However, rule curves are commonly developed as guidance for real-time reservoir operation. In this study, the goal is to develop a rule curve for Altıparmak Dam and HEPP. Reservoir operation study is conducted through streamflow sequential routing (SSR) and the rule curve is developed by solving a non-linear optimization problem. SSR and development of the rule curve are explained in detail in the following sections.

4.1. Streamflow Sequential Routing (SSR) Method

SSR method is based on the continuity equation as already explained in Section 2.1.1 (U.S. Army Corps of Engineers, 1985):

$$\Delta \boldsymbol{S} = \boldsymbol{I} - \boldsymbol{O} - \boldsymbol{L} \tag{4.1}$$

where ΔS is the change in the reservoir storage volume, I and O represent reservoir inflow and outflow, respectively and L is reservoir losses such as evaporation, diversion, etc.

An Excel spreadsheet is prepared to conduct SSR in this study. The basic steps of SSR are explained below. Table 4.1 shows the SSR calculations between Column-1 and Column-8, and these columns are explained below.

Column – 1: It shows the number of months within the whole analysis. For Altıparmak Dam and HEPP it ranges from 1 to 432 (i.e. a total of 36 years).

Column – 2 and 3: They indicate year and month for the routing period of the analysis respectively. For Altıparmak Dam and HEPP, this period is between October 1972 and September 2007.

Column – 4: It shows the number of days in each month.

Column – 5: It demonstrates storage volume (hm^3) at the beginning of the period. The first value is provided by the user. For instance, it can be assumed that SSR starts with the reservoir at its full capacity. The storage volume at the end of each period (i.e. Column-30) calculated as a result of SSR is used as the storage volume at the beginning of the following period.

Column – 6: It shows the elevation (m) at the beginning of the period. It is calculated from Volume-Elevation curve corresponding to the value in Column-5.

Column – 7: It shows the surface area (km^2) at the beginning of the period. It is calculated from Area-Elevation curve corresponding to the value in Column-6.

Column – 8: It is the historical streamflow data (hm^3).

Table 4.1 – SSR Calculations between Column-1 and 8

1	2	3	4	5	6	7	8
# of months	**Routing period**		**# of days in month**	**Storage volume at the beginning of the period**	**Elevation at the beginning of the period**	**Surface area at the beginning of the period**	**Inflow**
t	**year**	**month**	**day**	S_t	h_t	A_t	I_t
-	-	-	-	(hm^3)	(m)	(km^2)	(hm^3)

Table 4.2 shows the SSR calculations between Column-9 and Column-17, and these columns are explained below.

Column – 9 and 10: Precipitation data for each month (mm) are given in Column-9 and precipitation values in hm^3 are given in Column-10 and it is calculated by multiplying the surface area (Column-7) by depth of precipitation (Column-9).

Column – 11 and 12: Evaporation data for each month (mm) are given in Column-11 and evaporation values in hm^3 are given in Column-12 and it is calculated by multiplying the surface area (Column-7) by depth of evaporation (Column-11).

Column – 13: It shows the target elevation (m) at the end of the period. Target elevation for each month forms the rule curve. Target elevations are determined from the optimization analysis which is explained in Section 4.2.

Column – 14: It indicates the target storage volume (hm^3) at the end of the period. It is calculated from Volume-Elevation curve corresponding to the value in "Column-13".

Column – 15: It shows the required release volume (hm^3) to keep the reservoir at the target level (i.e. Column-13). The following equation is used for the calculations:

$$\boldsymbol{R_t = S_t + I_t + P_t - E_t - S_{t+1}}^* \qquad \textbf{(4.2)}$$

where S_t (Column-5) is expressed as storage volume at the beginning of the period, I_t, P_t and E_t represent monthly inflow (Column-8), precipitation (Column-10) and evaporation (Column-12) values, respectively. $S_{t+1}{}^*$ (Column-14) indicates the required storage volume at the end of the period.

Column – 16: It shows the real release volume (hm^3), $\boldsymbol{R_t}^*$, at the end of the period. Target release volume calculated in Column-15 can be a negative value which is not possible in real life. To prevent negative values, if the value in Column-15 is equal or smaller than "zero", the value in Column-16 is set equal to value "zero", otherwise, the value in Column-15 remains the same in Column-16.

Column – 17: It is the real release volume in m^3/s at the end of the period.

Table 4.2 – SSR Calculations between Column-9 and 17

9	10	11	12	13	14	15	16	17
Precipitation		**Evaporation**		**Target elevation at the end of the period**	**Target storage volume at the end of the period**	**Required Release Volume at the end of the period**	**Real Release Volume at the End of the Period**	
$\boldsymbol{P_t}$		$\boldsymbol{E_t}$		$\boldsymbol{h_{t+1}}^*$	$\boldsymbol{S_{t+1}}^*$	$\boldsymbol{R_t}$	$\boldsymbol{R_t}^*$	
(mm)	(hm^3)	(mm)	(hm^3)	(m)	(hm^3)	(hm^3)	(hm^3)	(m^3/s)

Table 4.3 shows the SSR calculations between Column-18 and Column-26, and these columns are explained below.

Column – 18: It shows the residual water requirement (hm^3) which needs to be released for the downstream habitat. For Altıparmak Dam and HEPP, residual water flow is selected as 0.8431 m^3/s, which is already explained in Section 3.2.4. This value is converted to monthly residual water volume (hm^3).

Column – 19: It is the combined power discharge volume (hm^3) for turbines. It is the available water for power discharge calculated by subtracting the residual water requirement (Column-18) from release volume at the end of the period (Column-16):

$$\boldsymbol{Q_{p(T1+T2)} = R_t^* - Rs_t^*} \quad \textbf{(4.3)}$$

where $Q_{p(T1+T2)}$ is expressed as power discharge volume for both turbines, R_t^* and Rs_t^* indicate the real release volume at the end of the period and residual requirement volume respectively. When $Q_{p(T1+T2)}$ is found to be zero or less than zero, it is set to zero.

Column – 20: It is the spilled water volume (hm^3). If there is more water than the power design discharge, the difference will spill:

$$\boldsymbol{Sp_t = Q_{p(T1+T2)} - Q_{d(T1+T2)}} \quad \textbf{(4.4)}$$

where Sp_t is expressed as spilled water volume, $Q_{p(T1+T2)}$ and $Q_{d(T1+T2)}$ show the available power discharge volume, calculated considering beginning and end of the month storage volumes, and design discharge volume for power generation respectively. For Altıparmak Dam and HEPP, the design discharge was identified as 27 m^3/s. This value is converted from m^3/s to hm^3 (monthly discharge volume).

Column – 21: It is the power discharge volume (hm^3) for both turbines calculated by subtracting spilled water volume (Column-20) from power discharge volume (Column-19). The equation can be specified below:

$$\boldsymbol{Q^*_{p(T1+T2)} = Q_{p(T1+T2)} - Sp_t} \quad \textbf{(4.5)}$$

where $Q_{p(T1+T2)}{}^*$ is expressed as power discharge volume for both turbines after spilling water, $Q_{p(T1+T2)}$ and Sp_t show the available power discharge volume for both turbines and spilled water volume respectively.

Column – 22: It shows the power discharge (m^3/s) for both turbines after subtracting spilled water. However, this value is not directly obtained from conversion of hm^3 in Column-21 to discharge (m^3/s). The value is obtained from decision making calculations conducted in a separate spreadsheet. In the decision making procedure, energy generations for various discharge values are evaluated and turbine discharge corresponding to the maximum energy generation is selected. Power discharge volume in Column-21 is used for the procedure. This power discharge volume (hm^3) is converted to seven alternative turbine discharges (m^3/s) ranging from minimum turbine discharge to maximum turbine discharge. Then, the discharge is distributed among two turbines according to the rules provided in Section 3.3. Turbine discharge combination resulting in the maximum total energy generation is selected as the turbine discharges and SSR is completed with these values.

Column – 23 and 25: They show power discharges (m^3/s) for Turbine-1 and Turbine-2 respectively. These values come from decision making analysis explained in the previous paragraph.

Column – 24 and 26: They show power discharge volumes (hm^3) for Turbine-1 and Turbine-2.

Table 4.3 – SSR Calculations between Column-18 and 26

18	19	20	21	22	23	24	25	26
Residual Water Requirement	**Power Discharge Volume for Both Turbines**	**Spilled Water Volume**	**Power Discharge Volume for Both Turbines (After Spilling)**		**Power Discharge Volume for Turbine-1**		**Power Discharge Volume for Turbine-2**	
$\boldsymbol{Rs_t}^*$	$\boldsymbol{Q_{p(T1+T2)}}$	$\boldsymbol{Sp_t}$	$\boldsymbol{Q^*_{p(T1+T2)}}$		$\boldsymbol{Q^*_{p(T1)}}$		$\boldsymbol{Q^*_{p(T2)}}$	
(hm^3)	(hm^3)	(hm^3)	(hm^3)	(m^3/s)	(m^3/s)	(hm^3)	(m^3/s)	(hm^3)

Table 4.4 shows the SSR calculations between Column-27 and Column-32, and these columns are explained below.

Column – 27: It shows the duration of energy generation (hr) in a day. This value comes from the decision making analysis worksheet explained under Column-22.

Column – 28 and 29: They indicate efficiencies of Turbine-1 and Turbine-2, respectively. Turbine efficiencies are based on the type of the turbine and flow rate. The equation used for Francis type of turbine efficiency was given in Section 3.3.

Column – 30: It shows the real storage volume (hm^3) at the end of the period. It is calculated using:

$$\boldsymbol{S_{t+1} = S_t + I_t + P_t - E_t - R_t{}^*} \qquad \textbf{(4.6)}$$

where S_{t+1} indicates the real storage volume at the end of the period, S_t (Column-5) is expressed as storage volume at the beginning of the period, I_t, P_t, E_t and $R_t{}^*$ represent monthly inflow (Column-8), precipitation (Column-10), evaporation (Column-12) and real release volume at the end of the period (Column-16) values, respectively.

Column – 31: It indicates the real elevation (m) at the end of the period corresponding to the real storage volume at the end of the period in Column-30. It is calculated from Volume-Elevation curve.

Column – 32: It shows the real surface area (km^2) value at the end of the period corresponding to the real elevation at the end of the period in Column-31. It is calculated from Area-Elevation curve.

Table 4.4 – SSR Calculations between Column-27 and 32

27	28	29	30	31	32
Energy Generation Duration	**Turbine-1 Efficiency**	**Turbine-2 Efficiency**	**Real Storage Volume at the End of the Period**	**Real Elevation at the End of the Period**	**Real Surface Area at the End of the Period**
$\boldsymbol{hr}$	$\boldsymbol{\varepsilon_{t(T1)}}$	$\boldsymbol{\varepsilon_{t(T2)}}$	$\boldsymbol{S_{t+1}}$	$\boldsymbol{h_{t+1}}$	$\boldsymbol{A_{t+1}}$
(hour)	-	-	(hm^3)	(m)	(km^2)

Table 4.5 shows the SSR calculations between Column-33 and Column-40, and these columns are explained below.

Column – 33: It indicates the change in tailwater elevation (m). The tailwater level changes with respect to discharge and tailwater rating curve, which is explained in Section 3.2.5.

Column – 34: Tailwater elevation (m) at the end of the period is calculated by adding tailwater streambed elevation and tailwater stage change, which is found in Column-33.

$$\boldsymbol{h_{t(TW)} = z_{tw} + y_{t(TW)}} \tag{4.7}$$

where $h_{t(TW)}$ is expressed as tailwater elevation at the end of the period, z_{TW} and $y_{t(TW)}$ show the tailwater streambed elevation (840.00 m) and tailwater stage change, respectively.

Column – 35 and 37: They show the friction losses (m) for tunnel and penstock, respectively. Darcy-Weisbach equation is used for calculation of friction losses (Mays L. W., 2010):

$$\boldsymbol{h_f = f\left(\frac{L}{D}\right)\frac{V^2}{2g}} \tag{4.8}$$

where f is expressed as a dimensionless friction factor, L is the length of the pipe in meter (m), D is the pipe diameter in meter (m), V is the average velocity in meter per second (m/s) and g is the gravitational acceleration (9.81 m/s^2).

For the friction factor, f, Swamee and Jain developed an equation as an explicit solution, depends on relative roughness e/D (Potter et al., 2012).

$$\boldsymbol{f = 1.325\left\{ln\left[0.27\left(\frac{e}{D}\right) + 5.74\left(\frac{1}{\frac{VD}{\vartheta}}\right)^{0.9}\right]\right\}^{-2}} \quad \textbf{(4.9)}$$

where ϑ is viscosity of water and equals to approximately 10^{-6} m^2/s. Roughness height, e 0.03 mm for cast steel penstock and 0.18 mm for concrete tunnel are selected (Potter et al., 2012). The equation is valid over the ranges $10^{-8} < e/D < 0.01$, and $5000 < \boldsymbol{VD/\vartheta} < 10^{8}$.

Column – 36 and 38: They show the minor losses for tunnel and penstock (m), respectively as well. The equation is shown below (Potter et al., 2012):

$$\boldsymbol{h_f = K\frac{V^2}{2g}} \quad \textbf{(4.10)}$$

where K is expressed as a minor loss coefficient, V is the average velocity in meter per second (m/s) and g is the gravitational acceleration (9.81 m/s^2).

In practice, general minor loss coefficient value, K**,** 1.50 for concrete tunnel and 2.20 for steel penstock is used (Potter et al., 2012).

Column – 39: Average reservoir elevation (m) is calculated by taking the average of reservoir elevations at the beginning and at the end of the period.

Column – 40: Net head (m) is the remaining head after subtracting hydraulic headlosses (Column-35, 36, 37 and 38) from the difference between average reservoir elevation at the forebay (Column-39) and tailwater elevation (Column-34):

$$\boldsymbol{H_{t(n)} = \frac{(h_t + h_{t+1})}{2} - h_{t(TW)} - h_{LT(f)} - h_{LT(m)} - h_{LP(f)} - h_{LP(m)}} \quad \textbf{(4.11)}$$

where $H_{t(n)}$ is expressed as net head, $h_{LT(f)}$ and $h_{LP(f)}$ show friction headlosses for tunnel and penstock respectively, $h_{LT(m)}$ and $h_{LP(m)}$ indicates minor headlosses for tunnel and penstock respectively.

Table 4.5 – SSR Calculations between Column-33 and 40

33	34	35	36	37	38	39	40
Tailwater Height Difference at the End of the Period	**Tailwater Elevation at the End of the Period**	**Friction Headloss for Tunnel**	**Minor Headloss for Tunnel**	**Friction Headloss for Penstock**	**Minor Headloss for Penstock**	**Average Reservoir Elevation**	**Net head**
$\boldsymbol{y_{t(TW)}}$	$\boldsymbol{h_{t(TW)}}$	$\boldsymbol{h_{LT(f)}}$	$\boldsymbol{h_{LT(m)}}$	$\boldsymbol{h_{LP(f)}}$	$\boldsymbol{h_{LP(m)}}$	$\boldsymbol{\frac{(h_t+h_{t+1})}{2}}$	$\boldsymbol{H_{t(n)}}$
(m)	(m)	(m)	(m)	(m)	(m)	(m)	(m)

Table 4.6 shows the SSR calculations between Column-41 and Column-43, and these columns are explained below.

Column – 41 and 42: They show power generation (GWh) for Turbine-1 and Turbine-2 respectively. The equation is shown below:

$$\boldsymbol{E_p = \varepsilon_t \, \gamma \, Q_p^* \, H_{t(n)}} \tag{4.12}$$

where E_p is expressed as power generation, ε_t shows turbine efficiency, γ indicates the specific weight of the water (9.81 kN/m^3), $\boldsymbol{Q_p^*}$ is the power discharge for turbines, $H_{t(n)}$ is the net head.

Column – 43: It shows the total power generation (GWh) and it is the summation of power generations of Turbine-1 (Column-41) and Turbine-2 (Column-42).

$$\boldsymbol{E_{p(T1+T2)} = E_{p(T1)} + E_{p(T2)}} \tag{4.13}$$

Table 4.6 – SSR Calculations between Column-41 and 43

41	42	43
Turbine-1 Power Generation	**Turbine-2 Power Generation**	**Total Power Generation**
$\boldsymbol{E_{p(T1)}}$	$\boldsymbol{E_{p(T2)}}$	$\boldsymbol{E_{p(T1+T2)}}$
(GWh)	(GWh)	(GWh)

After preparation of SSR calculation table, optimization stage begins and details about optimization process are explained below.

4.2. Optimization to Generate Rule Curve

Excel Solver is used for the optimization problem. Reservoir elevations at the end of each period (i.e. each month in this study) are the decision variables of the optimization problem. These are the target levels. Amount of water to be released for energy generation at each month is decided according to these target levels. The optimization model depends on the mass balance equation (Mays and Tung, 1992). Optimization problem is composed of an objective function and a number of constraints such as mass balance equation and physical limitations. Optimization model formulated to develop the rule curve (i.e. reservoir elevations at the end of each month) is given below:

Objective Function:

$$\boldsymbol{Maximize\ Z = E_{p(T1+T2)} = E_{p(T1)} + E_{p(T2)} = \sum_{t=1}^{432} \varepsilon_{t(T1)}\, \gamma\, Q^{*}_{p(T1)}\, H_{t(n)} \Delta t + \varepsilon_{t(T2)}\, \gamma\, Q^{*}_{p(T2)}\, H_{t(n)} \Delta t} \qquad \textbf{(4.14)}$$

Subject to:

$$\boldsymbol{S_{t+1} - S_t = I_t + P_t - E_t - R_t^{\,*}, \qquad t = 1, 2, \dots, 432} \qquad \textbf{(4.15)}$$

$$\boldsymbol{h_{min} \le h_{T(target)} \le h_{max}, \qquad T = 1, 2, \dots, 12} \tag{4.16}$$

$$\boldsymbol{S_{min} \le S_T \le S_{max}, \qquad T = 1, 2, \dots, 12} \tag{4.17}$$

$$\boldsymbol{Q_{p(T1)min} \le Q^*_{p(T1)} \le Q_{p(T1)max}} \tag{4.18}$$

$$\boldsymbol{Q_{p(T2)min} \le Q^*_{p(T2)} \le Q_{p(T2)max}} \tag{4.19}$$

$$\boldsymbol{Q_{p(T1)min} = 0.3\, Q_{p(T1)design}} \tag{4.20}$$

$$\boldsymbol{Q_{p(T2)min} = 0.3\, Q_{p(T2)design}} \tag{4.21}$$

$$\boldsymbol{h_{mod12(t)} = h_{T(target)}, \qquad t = 1, 2, \dots, 432} \tag{4.22}$$

$$\boldsymbol{H_{t(n)} = \frac{(h_t + h_{t+1})}{2} - h_{t(TW)} - h_{LT(f)} - h_{LT(m)} - h_{LP(f)} - h_{LP(m)}} \tag{4.23}$$

where $E_{p(T1+T2)}$ is expressed as total power generation (GWh), $E_{p(T1)}$ and $E_{p(T2)}$ show turbine power generations (GWh), $\varepsilon_{t(T1)}$ and $\varepsilon_{t(T2)}$ show turbine efficiencies, γ indicates the specific weight of the water (9.81 kN/m^3), $\boldsymbol{Q^*_{p(T1)}}$ and $\boldsymbol{Q^*_{p(T2)}}$ are expressed as turbine discharges (m^3/s), $H_{t(n)}$ is the net head (m), S_{t+1} indicates the real storage volume at the end of the period (hm^3), S_t is expressed as storage volume at the beginning of the period (hm^3), I_t, P_t, E_t and R_t^* represent monthly inflow (hm^3), precipitation (hm^3), evaporation (hm^3) and real release volume values at the end of the period (hm^3), $h_{T(target)}$ is expressed as target reservoir operation level as the result of rule curve (m), h_{min} is expressed as minimum reservoir operation level (equal to 1195.52 m) and h_{max} is expressed as maximum reservoir operation level (equal to 1227.00 m), S_{min} is expressed as minimum reservoir capacity (equal to 1.93 hm^3) and S_{max} is expressed as maximum reservoir storage capacity (equal to 9.96 hm^3), $Q_{p(T1)min}$ and $Q_{p(T2)min}$ are expressed as minimum turbine discharges, $Q_{p(T1)design}$ and $Q_{p(T2)design}$ are expressed as turbine design discharges, 0.3 shows the ratio of minimum turbine discharge to turbine design discharge (European Small Hydropower Association, ESHA, 1998), h_t is expressed as reservoir operation level (m), $h_{LT(f)}$ and $h_{LP(f)}$ show friction headlosses for tunnel and penstock, $h_{LT(m)}$ and $h_{LP(m)}$ indicates minor headlosses for tunnel and penstock.

CHAPTER 5

RESULTS

To develop the rule curve for Altıparmak Dam and HEPP, SSR is conducted and the optimization problem is solved. The optimization problem is solved using different sets of initial values for decision variables. A complete run takes approximately 9 hours on a laptop with 6GB RAM and Intel Core i7-2630QM, 2.0 GHz processor. Optimum end of the month operation levels obtained from this analysis are given in Table 5.1. Monthly minimum, maximum and average inflow values are provided in Table 5.1 as well. Rule curve developed for Altıparmak Dam and HEPP together with minimum and maximum inflows are given in Figure 5.1.

Table 5.1 – Monthly Operation Levels and Minimum, Average, Maximum Inflow Values

Month	Minimum Inflow (hm^3)	Maximum Inflow (hm^3)	Average Inflow (hm^3)	Operation Level (m)
October	4.63	31.20	10.93	1227.00
November	4.74	21.95	9.89	1195.52
December	3.55	13.06	7.31	1227.00
January	3.07	8.67	5.78	1196.77
February	3.15	10.79	5.81	1227.00
March	5.02	27.44	13.02	1227.00
April	14.09	74.27	35.47	1227.00
May	38.07	99.67	65.62	1227.00
June	42.73	100.80	65.16	1227.00
July	15.25	69.27	35.98	1227.00
August	7.90	29.61	14.56	1227.00
September	5.56	19.02	9.74	1195.52

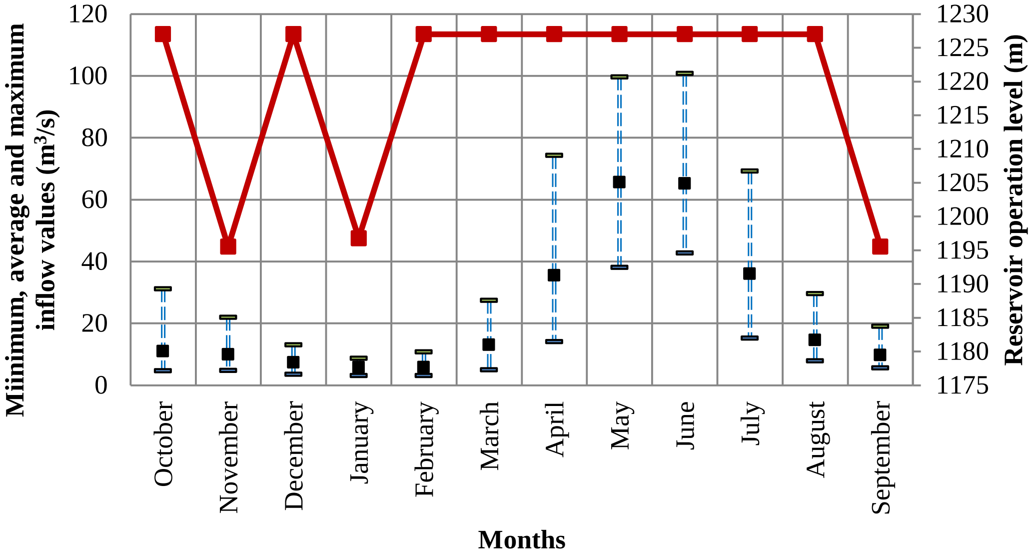

Figure 5.1 – Monthly Rule Curve Generation and Minimum, Average, Maximum Inflow Values

In order to investigate the relation between operating levels and total inflow into the reservoir, historical streamflow data are evaluated. Historical streamflow data for the period between October 1972 and September 2007 are shown in Figure 5.2. In order to investigate change in streamflow values for each month throughout the study period (i.e. 1972 to 2007) monthly streamflow values are shown separately in Figure 5.3.

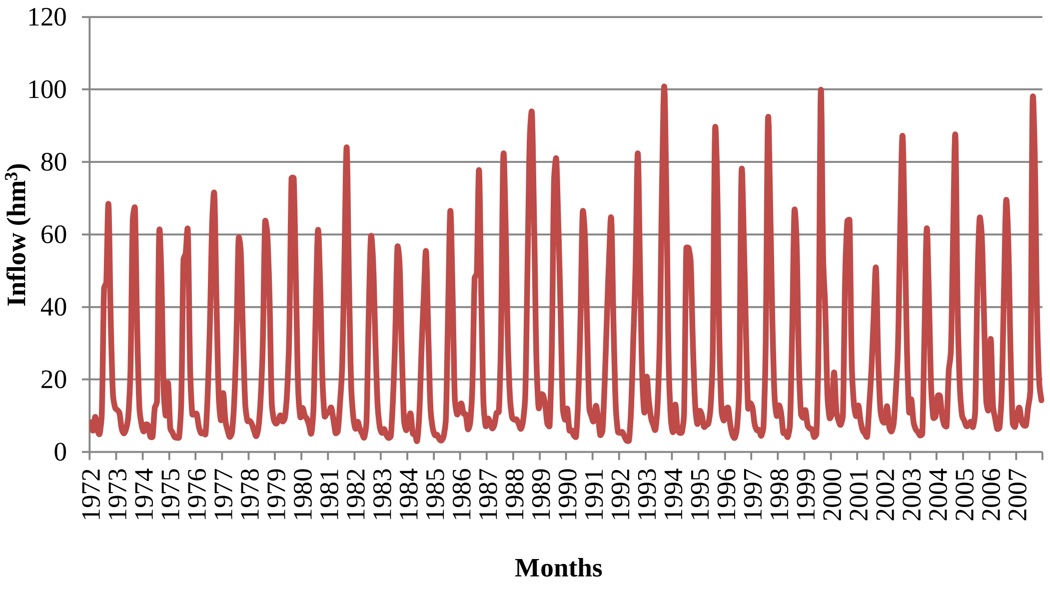

Figure 5.2 – Monthly Historical Streamflow Values

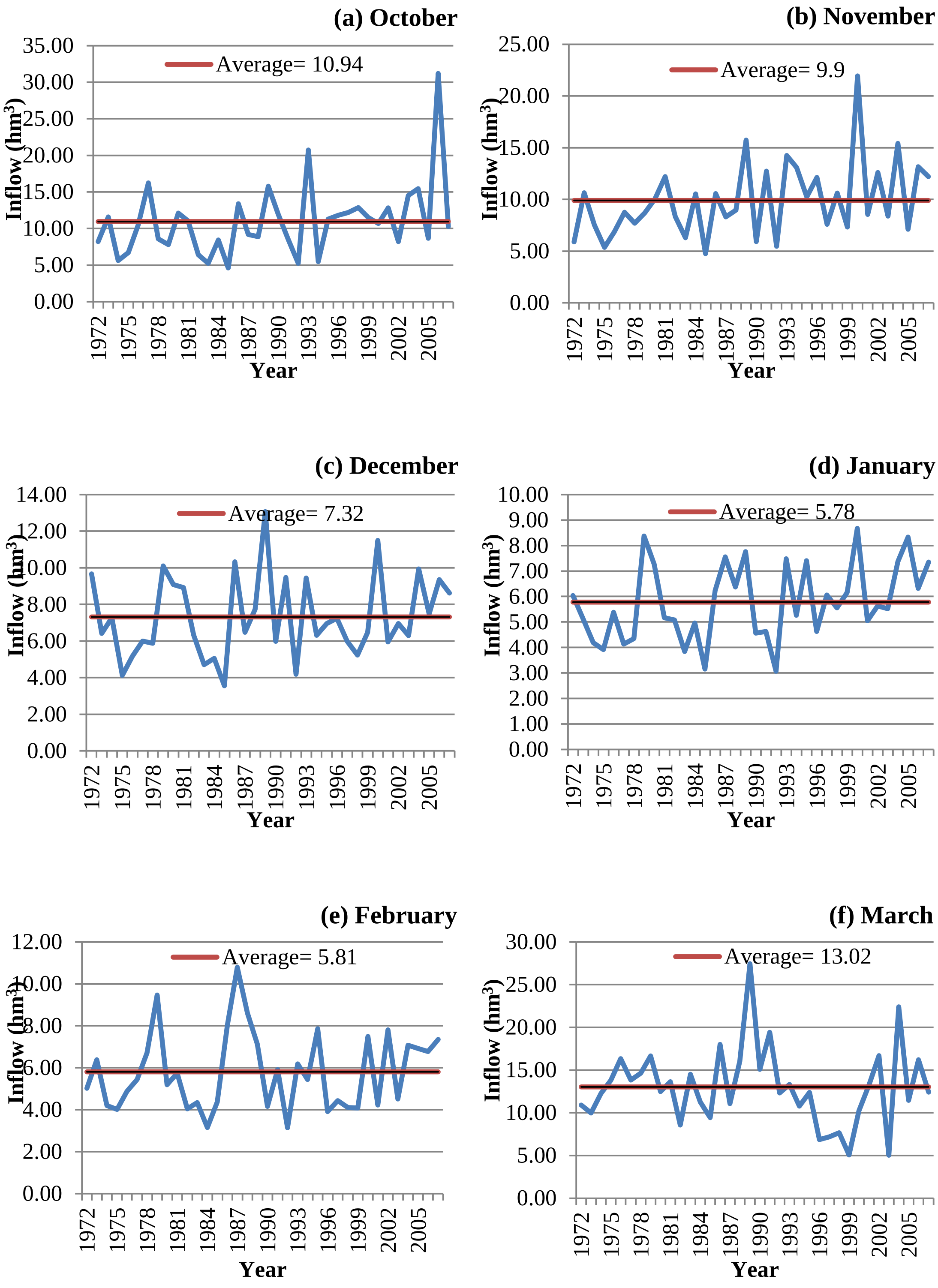

Figure 5.3 - Historical Streamflow Values (a) October, (b) November, (c) December, (d) January, (e) February, (f) March, (g) April, (h) May, (i) June, (j) July, (k) August and (l) September

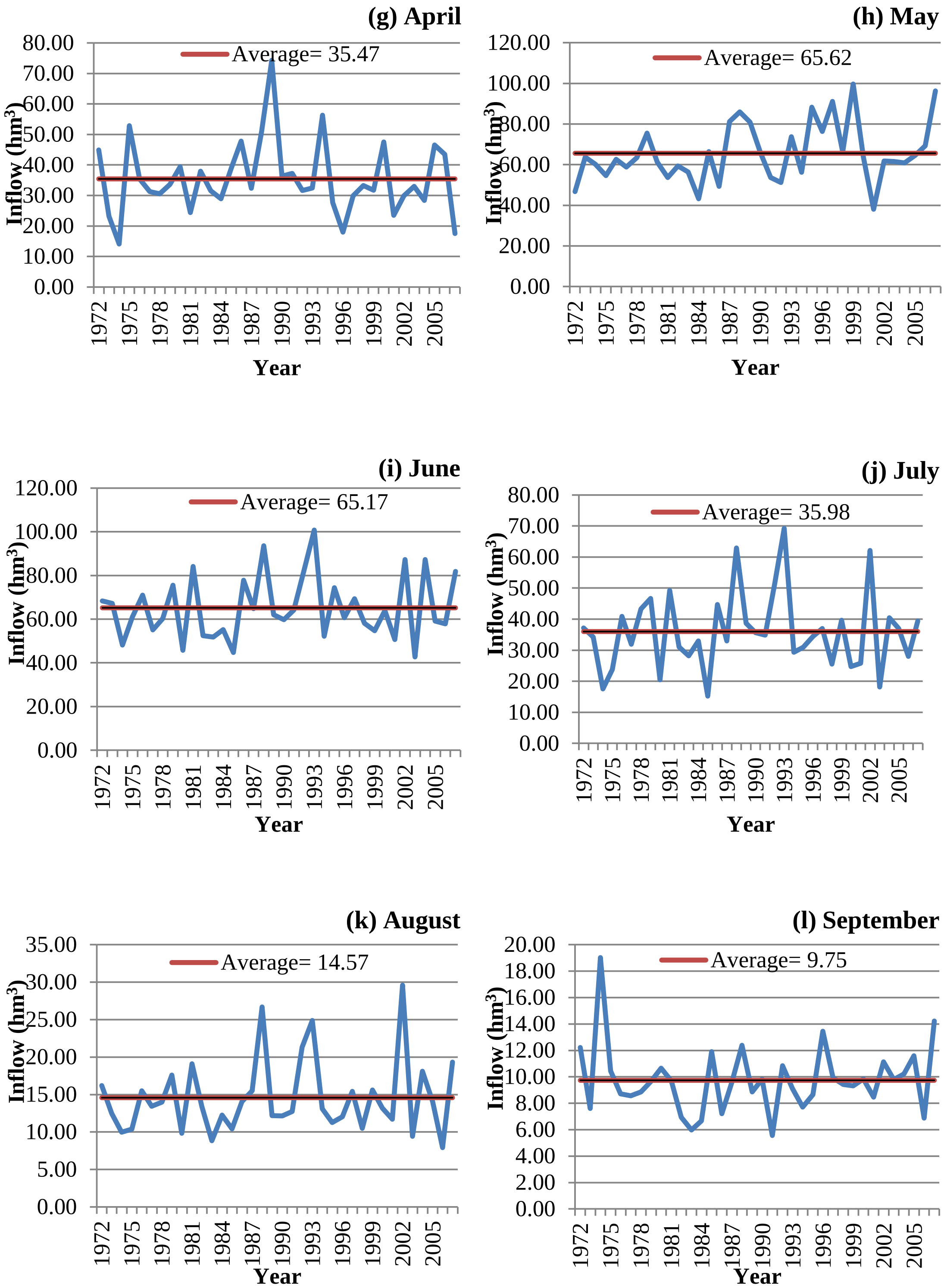

Figure 5.3 (continued) – Historical Streamflow Values (a) October, (b) November, (c) December, (d) January, (e) February, (f) March, (g) April, (h) May, (i) June, (j) July, (k) August and (l) September

Total energy generation between October 1972 and September 2007 is shown in Figure 5.4. Total energy generations for each month are given in Figure 5.5.

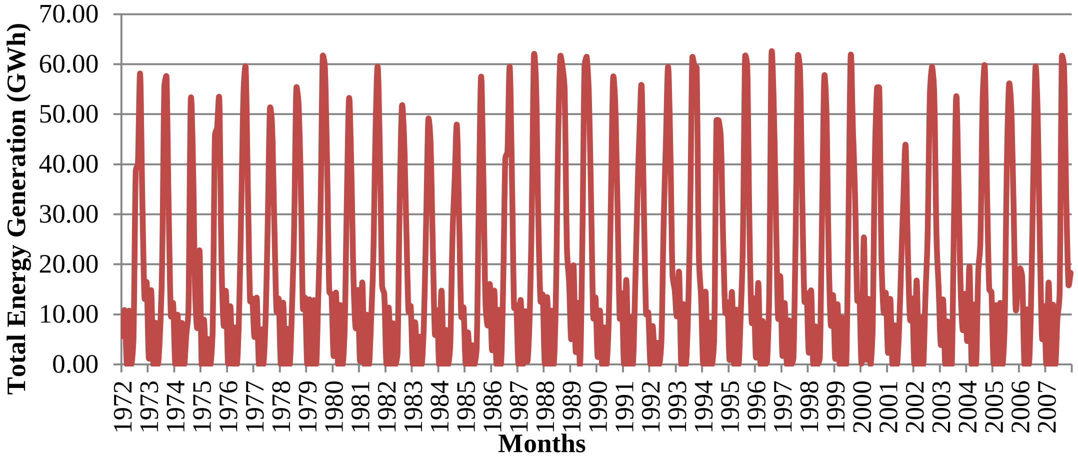

Figure 5.4 - Monthly Total Energy Generation Values

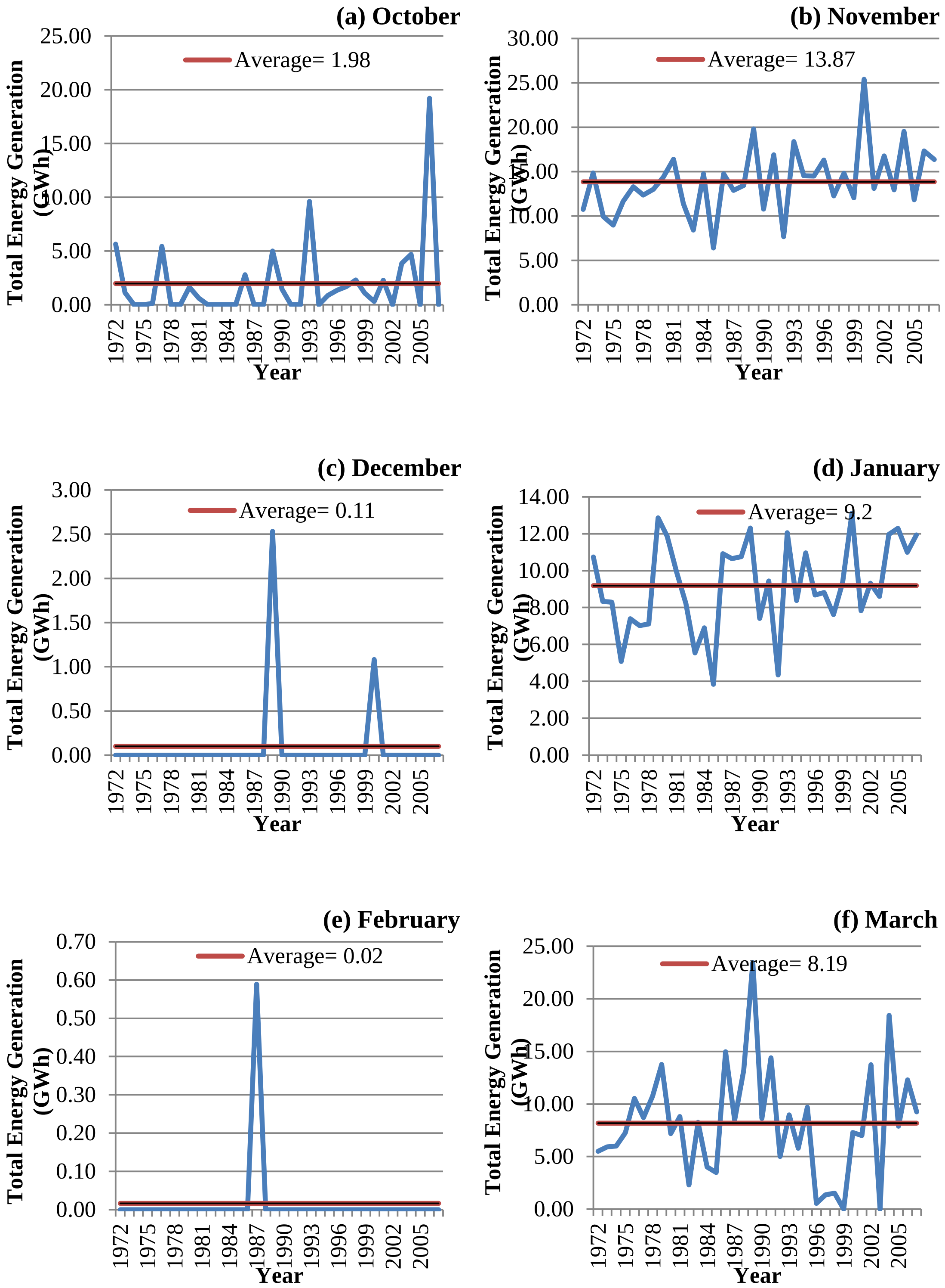

Figure 5.5 Total energy generations (a) October, (b) November, (c) December, (d) January, (e) February, (f) March, (g) April, (h) May, (i) June, (j) July, (k) August and (l) September

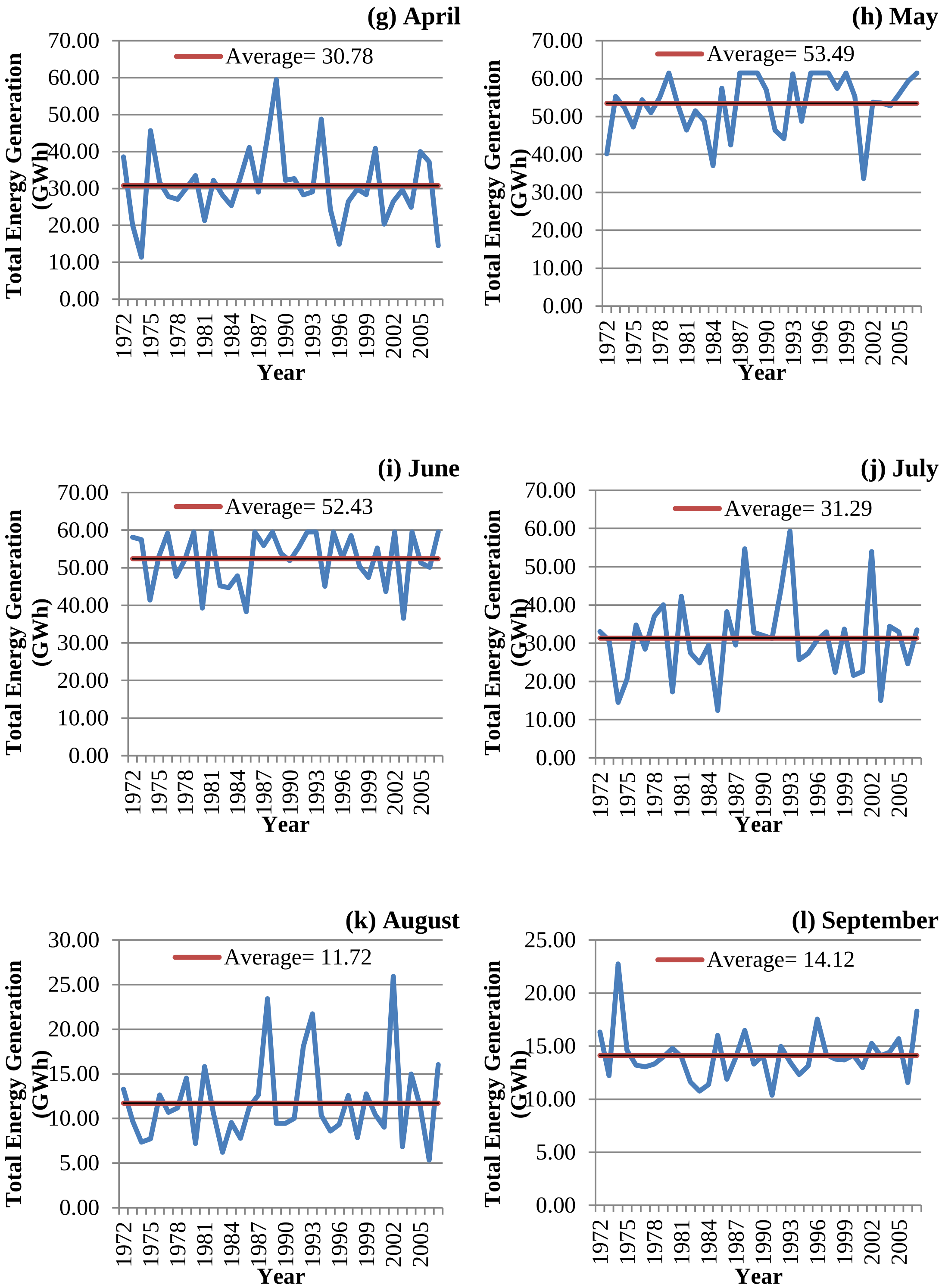

Figure 5.5 (continued) – Total energy generations (a) October, (b) November, (c) December, (d) January, (e) February, (f) March, (g) April, (h) May, (i) June, (j) July, (k) August and (l) September

As can be seen from Figure 5.1 and Figure 5.3, inflow values into the reservoir are relatively low between August and March. Thus, it is not possible to generate energy efficiently (i.e. using high head and design discharge). The optimization model forces the turbines to operate selectively throughout these low inflow months. As can be seen from Figure 5.5, total energy generations in December and February are almost zero throughout the study period. During December and February no energy is generated and inflow is stored in the reservoir. As a result of this, reservoir levels at the end of December and February reach the maximum reservoir level (i.e. 1227 m). A similar situation is observed for October as well. As can be seen from Figure 5.5 (a) average energy generation is very low (i.e. 1.98 GWh) and reservoir level at the end of October reaches to 1227 m (see Figure 5.1). On the other hand, when inflows to the reservoir are relatively high (i.e. between April and July), high amounts of energy are generated (i.e. 30.78 GWh, 53.49 GWh, 52.43 GWh and 31.29 GWh for April, May, June, and July, respectively) and reservoir levels are still kept at the maximum level (see Figure 5.1).

In the alternative feasibility study conducted by Ak (2011), target reservoir level was selected as 1227 m (maximum water elevation) throughout the whole year and with this constant rule curve total energy generation was found as 7760.36 GWh. In this study, operation levels in Table 5.1 are used and total energy generation is calculated as 8176.65 GWh. Rule curve developed as a result of this study resulted in 5.36% increase in the total energy.

While developing the rule curve (i.e. end of the month operating levels) given in Figure 5.1, it is assumed that two turbines will work in parallel and turbine installed capacity ratio is taken as 0.5. A further analysis is conducted in order to investigate the effects of turbine discharge ratio and turbine installed capacity ratio on total energy generation. This analysis is explained below.

The goal of this analysis is to evaluate simultaneous impact of turbine discharge ratio and turbine installed capacity ratio on total energy generation. For this purpose the following procedure is used:

1. In addition to the decision variables of the original optimization problem (i.e. end of the month reservoir operating levels) turbine discharge ratio and turbine installed capacity ratio are specified as decision variables.
2. The rule curve developed as a result of the original optimization problem is used as initial values of end of the month reservoir operating levels. Initial values of both the turbine installed capacity ratio and the turbine discharge ratio is selected as 0.5.
3. Excel's Solver is used to solve the new optimization problem with the same objective function (i.e. maximize total energy generation).

Due to the increase in the problem domain, Excel's Solver experienced convergence problems and optimum solutions cannot be obtained. Then it is decided to carry out the analysis for a number of turbine discharge ratio and turbine installed capacity ratio combinations. However, to limit the search space equal turbine discharge ratio and turbine installed capacity ratio values are selected. The results obtained for different combinations are given in Table 5.2. A total of six combinations are evaluated and all of these separate runs resulted in the same rule curve. However total energy generations associated with these different turbine discharge ratios and turbine installed capacity ratios varied slightly. The results are given in Figure 5.6 as well. As can be seen from Table 5.2and Figure 5.6 the maximum total energy generation is achieved when turbine discharge ratio and turbine installed capacity ratio are both selected as 0.5. Thus, as a result of this simple trial and error decision making approach utilization of two equal sized (i.e. same installed capacity) turbines and distribution of the total flow among these turbines equally is a reasonable choice.

Table 5.2 – Total Energy Generations corresponding to Different Ratio of Flow

Turbine Installed Capacity Ratio	Turbine Discharge Ratio	Total Energy Generation Amount (GWh)
0.10	0.10	8065.71
0.15	0.15	8117.97
0.20	0.20	8154.79
0.30	0.30	8158.40
0.40	0.40	8166.91
0.50	0.50	8176.65

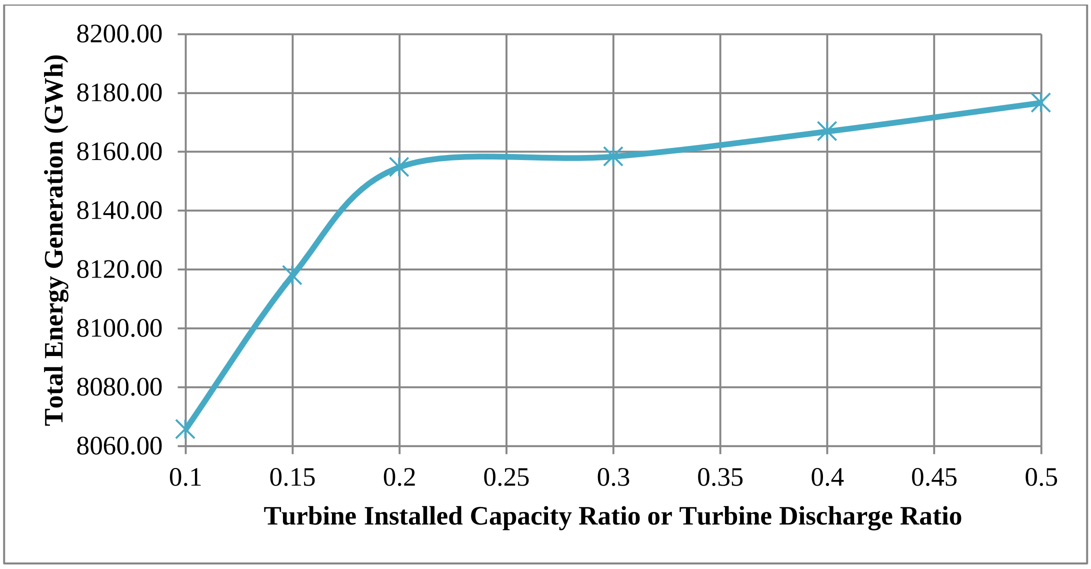

Figure 5.6 – Turbine Installed Capacity Ratio or Turbine Discharge Ratio vs Total Energy Generation Graph

CHAPTER 6

CONCLUSION AND RECOMMENDATIONS

In Turkey, private companies, which are working on the design and operation studies of hydropower plants, generally use Microsoft Excel to perform reservoir operation studies for hydroelectric power plants (HEPPs). However, to our knowledge there are no published studies related with determination of monthly reservoir operation levels (i.e. the rule curve) to guide operators of HEPPs. In this study, the rule curve for Altıparmak Dam and HEPP is developed solving an optimization problem.

Determination of the rule curve is achieved by solving an optimization problem in which reservoir operation is conducted by sequential streamflow routing. Microsoft Excel's Solver is used for solving the optimization problem in this study. The following conclusions are reached:

- Abrupt changes are observed in the rule curve. Basic reason for these major changes in reservoir levels is related with the reservoir capacity. Total reservoir capacity of Altıparmak Dam and HEPP is approximately 7 hm^3, while average monthly inflows range from 5.78 hm^3 to 65.62 hm^3. Thus, inflow to the reservoir plays more important role than reservoir storage in total energy generation. The optimization algorithm ceases energy generation during every other low inflow month and accumulates incoming flow to fill the reservoir and generates energy in the following month using maximum reservoir operating level.
- Total energy generation obtained by using the rule curve developed in this study increased 5.36% compared to total energy generation obtained by Ak (2010) using constant reservoir operation level (i.e. keeping the reservoir level at its maximum value) throughout the year. Although it is not a major improvement in terms of total energy generation for Altıparmak Dam and HEPP, if applied to many hydropower plants, development of HEPP specific rule curves may result in a significant contribution to overall energy generation of Turkey.
- The original optimization problem is formulated such that turbine discharge ratio and turbine installed capacity ratio are both taken as fixed values equal to 0.5. When end of the month reservoir levels are chosen as decision variables (i.e. a total of 12 decision variables), Excel's Solver converges to the optimum solution and the rule curve for Altıparmak Dam and HEPP is developed. However, when the turbine discharge ratio and the turbine installed capacity ratio are added as decision variables in addition to end of the month reservoir levels, problem domain increases and Excel's Solver starts experiencing convergence problems. Thus, optimum values for turbine discharge ratio and turbine installed capacity ratio cannot be identified. However, as an initial analysis, Solver's performance is acceptable.

- To investigate impact of various turbine discharge ratio and turbine installed capacity ratio combinations, a number of trial and error runs are conducted. In order to limit the search space equal turbine discharge ratio and turbine installed capacity ratio values are selected. The same rule curve is obtained for all different runs; however, total energy generations varied slightly. Equal sized turbines (i.e. turbine installed capacity = 0.5) and distribution of the total flow equally (i.e. turbine discharge ratio = 0.5) resulted in the highest total energy generation.

Excel's Solver sucessfully identified optimum end of the month operating levels for Altıparmak Dam and HEPP when turbine discharge ratio and turbine installed capacity ratio are both fixed at 0.5. When turbine discharge ratio and turbine installed capacity ratio are added as decision variables to the optimization problem Excel's Solver experienced convergence problems. Thus, it is recommended that a high-level optimization software should be used to determine rule curve together with optimum turbine discharge ratio and turbine installed capacity ratio.

Altıparmak Dam and HEPP has a single purpose (i.e. generating electricity). Thus, the optimization problem is formulated to maximize the total energy generation. However, there may be situations where the goal is maximization of the firm energy generation or achievement of multiple purposes such as flood mitigation, supplying irrigation or domestic water together with energy generation. Thus, as an extension of this study, the optimization problem may be reformulated to handle multiple purpose reservoirs.

REFERENCES

Ak, M. (2011). “Alternative Feasibility Studies for Altıparmak Dam and HEPP.” M.S. "Thesis, Middle East Technical University, Ankara.

Arai, M., Tanaka, K., Abe, R. and Mogi, G. (2011). “Time-Series Analysis in Power Supply System to Achieve a Sustainable Economic Growth in Bangladesh.” *Proc., International Conference on Mechanical Engineering (ICME) RT-015*, Dhaka, Bangladesh.

Benli, B. and Kobal, S. (2003). “A Non-Linear Model for Farm Optimization with Adequate and Limited Water Supplies Application to the South-East Anatolian Project (GAP) Region.” *Agricultural Water Management, 62,* 187-203.

Celeste, A. B. and Billib, M. (2009). “Evaluation of Stochastic Reservoir Operation Optimization Models.” *Advances in Water Resources, 32,* 1429-1443.

Chang, J. F., Chen, L. and Chang, C. L. (2005). “Optimizing the Reservoir Operating Rule Curves by Genetic Algorithms.” *Hydrological Processes, 19,* 2277-2289.

Chang, J. F., Lai, S. J. and Kao, S. L. (2003). “Optimization of Operation Rule Curves and Flushing Schedule in a Reservoir.” *Hydrological Processes, 17,* 1623-1640.

Chen, L. (2003). “Real Coded Genetic Algorithm Optimization of Long Term Reservoir Operation.” *Journal of the American Water Resources Association (JAWRA), 39,* 1157-1165.

Google Earth version 7.1.1.1580, (2013), (computer software), Google Inc.

DOKAY-ÇED Environmental Engieering Co. Ltd. (2011). “Altıparmak Barajı ve HES Projesi Çevresel Etki Değerlendirilmesi Başvuru Dosyası.” Ankara.

Energy Market Regulatory Authority (EPDK). (2005). “Yenilenebilir Enerji Kaynaklarının Elektrik Enerjisi Üretimi Amaçlı Kullanımına İlişkin Kanun No:5346.” *Official Gazette, 25819*.

Energy Market Regulatory Authority (EPDK). (2011). Türkiye Elektrik Enerjisi 10 Yıllık Üretim Kapasite Projeksiyonu (2011-2020), <http://www.epdk.gov.tr/documents/elektrik/rapor_yayin/Elk_Yayin_Uretim_Kapasite_Projeksiyonu_2011_2020.pdf> (June 9, 2013).

Energy Market Regulatory Authority (EPDK). (2012). "Elektrik Piyasası Sektör Raporu 2011." Energy Market Regulatory Authority, Ankara.

European Small Hydropower Association (ESHA). (1998). *LAYMAN's Guidebook on How to Develop a Small Hydro Site*, European Small Hydropower Association, Brussels.

European Small Hydropower Association (ESHA). (2004). *Guide on How to Develop a Small Hydropower Plant.* European Small Hydropower Association, Brussels.

Excel Solver (2010), (computer software application), Frontline System Inc.

Frontline Systems Inc. (2013). "User Guide For Use With 2003-2013 Version 12.5." *Frontline Solvers*, <http://www.solver.com/system/files/access/FrontlineSolversUserGuide.pdf> (May 21, 2013).

General Command of Mapping (HGK). (2013). "Downloadable Thematic Maps." *General Command of Mapping*, <http://www.hgk.msb.gov.tr/CografiUrunKatalogu/tematik/sayfa21.asp> (May 27, 2013).

General Directorate of Electrical Power Resources Survey and Development Administration (EİE). (2001). "Altıparmak HEPP Feasibility Report." General Directorate of Electrical Power Resources Survey and Development Administration, Ankara.

General Directorate of Electrical Power Resources Survey and Development Administration (EİE). (2012). "Elektrik Enerjisi Kaynaklara Göre Üretim." *General Directorate of Electrical Power Resources Survey and Development Administration*, <http://www.eie.gov.tr/document/elektrik_enerjisi_kaynaklara_gore_uretim.PNG> (June 9, 2013).

General Directorate of Electrical Power Resources Survey and Development Administration (EİE). (2013). “Hidroelektrik Enerjisi Potansiyel Atlası.” *General Directorate of Electrical Power Resources Survey and Development Administration*, <http://www.eie.gov.tr/HES/image.aspx?HESNO=0> (June 9, 2013).

General Directorate of Meteorology (DMİ). (2011). “Yıllık Toplam Yağış Verileri – Meteoroloji Genel Müdürlüğü.” *Veri ve Değerlendirme,* <http://www.dmi.gov.tr/veridegerlendirme/yillik-toplam-yagis-verileri.aspx> (June 1, 2011).

General Directorate of State Hdyraulic Works (DSİ). (2009). “Water and DSİ.” General Directorate of State Hdyraulic Works, Ankara.

General Directorate of State Hydraulic Works (DSİ). (2013). “Hidrometri Gözlem İstasyonları.” *General Directorate of State Hydraulic Works*, <http://rasatlar.dsi.gov.tr/#> (May , 2013).

General Directorate of State Hydraulic Works (DSİ). (2013, May). “Bölgelerimiz.” *General Directorate of State Hydraulic Works*, <http://www.dsi.gov.tr/bolgelerimiz> (May 23, 2013).

Hidalgo, I. G., Fontane, D. G., Secundino, S. F., Cicogna, M. A. and Lopes, J. E. (2010). “Data Consolidation from Hydrolectric Plants.” *Journal of Energy Engineering*, *136:3*, 87-94.

Hobbs, B. F., Mittelstadt, R. L. and Lund, J. R. (1996). “Energy and Water.” *Water Resources Handbook (edited by L. W. Mays)*, McGraw-Hill, New York.

Hormwichian, R., Kangrang, A. and Lamom, A. (2009). “Conditional Genetic Algorithm Model for Searching Optimal Reservoir Rule Curves.” *Journal of Applied Sciences, 9,* 3575-3580.

Howard, J. C. (2006). “Technical Basis for Optimizing Hydropower Operations with MS-Excel.” *Great Wall World Renewable Energy Forum and Exhibition*, Beijing-GWREF2006, China.

International Hydropower Association (IHA). (2011). “Advancing Sustainable Hydropower - 2011 Activity Report.” *International Hydropower Association,* <http://www.hydropower.org/downloads/ActivityReports/2011-12_Activity_Report-web.pdf> (June 9, 2013).

Jain, S. K. and Singh, V. P. (2003). *Water Resources Systems Planning and Management,* Elsevier Science B.V., Amsterdam.

Jain, S. K., Goel, M. K. and Agarwal, P. K. (1998). “Reservoir Operation Studies of Sabarmati System, India.” *Journal of Water Resources Planning and Management,* 31-38.

Kangrang, A. and Chleeraktrakoon, C. (2007). “Genetic Algorithms Connected Simulation with Smoothing Function for Searching Rule Curves.” *American Journal of Applied Sciences, 4,* 73-79.

Kangrang, A. and Lokham, C. (2013). “Optimal Reservoir Rule Curves Considering Conditional Ant Colony Optimization with Simulation Model.” *Journal of Applied Sciences, 13,* 154-160.

Kangrang, A., Compliew, S. and Campus, K. (2009). “Heuristic Algorithm with Simulation Model for Searching Optimal Reservoir Rule Curves.” *American Journal of Applied Sciences*, 263-267.

Kangrang, A., Lehner, A. and Mayrhofer, P. (2011). “An Improvement of Small Reservoir Rule Curves using Genetic Algorithms and Water Balance Equation.” *Australian Journal of Basic and Applied Sciences, 5(12),* 707-714.

Karamouz, M., Szidarovszky, F. and Zahraie, B. (2003). *Water Resources Systems Analysis,* CRC Press, Florida.

Liu, P., Guo, S., Xu, X. and Chen, J. (2011). “Derivation of Aggregation-Based Joint Operating Rule Curves for Cascade Hydropower Reservoirs.” *Water Resources Management, 25,* 3177-3200.

Loucks, D., Stedinger, J. and Haith, D. (1981). *Water Resource Systems Planning and Analysis,* Prentice-Hall, Englewood Cliffs, New Jersey.

Mays, L. W. (2010). *Water Resources Engineering,* John Wiley & Sons Inc., Hoboken, New Jersey.

Mays, L. and Tung, Y. (1992). *Hydrosystems Engineering and Management,* McGraw-Hill, New York.

Potter, M. C., Wiggert, D. C. and Ramadan, B. H. (2012). "Internal Flows." Mechanics of Fluids, Global Engineering, Stamford, CT, 271-344.

Stam, A., Salewicz, K. A. and Aronson, J. E. (1998). "An Interactive Reservoir Management System for Lake Kariba." *European Journal of Operational Research*, 119-136.

U.S. Army Corps of Engineers (USACE). (1977). "Reservoir System Analysis for Conservation." *Hydrologic Engineering Methods for Water Resources Development,* Davis, CA.

U.S. Army Corps of Engineers(USACE). (1985). *Engineering and Design - Hydropower,* Washington, DC.

United States Department of the Interior Bureau of Reclamation (USBR). (1987). *Design of Small Dams, A Water Resources Technical Publication,* U.S. Government Printing Office, Washington, DC.

University of Technology. (2011). *Mini-Hydropower*, Technische Universiteit Eindhoven, <http://w3.tm.tue.nl/fileadmin/tm/TDO/Indonesie/Hydro_Power.pdf> (May 31, 2013).

Wei, C. C. and Hsu, N. S. (2009). "Optimal Tree-Based Release Rules for Real-time Food Control Operations on a Multipurpose Multireservoir System." *Journal of Hydrology, 365*, 213-224.

Wurbs, R. A. (2005). *Comparative Evaluation of Generalized Reservoir/River System Models,* Texas Water Resources Institue College Station, Texas.

Yanmaz, A. M. (2006). *Applied Water Resources Engineering,* METU Press, Ankara.