

OPTIMIZATION OF COST AND ENERGY PRODUCTION AT
HYDROELECTRIC POWER PLANTS

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ABSTRACT

OPTIMIZATION OF COST AND ENERGY PRODUCTION AT HYDROELECTRIC POWER PLANTS

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As the world's demand for energy increases, it is crucial to use available energy sources effectively. Renewable energy sources, especially hydropower, play a significant role in energy generation. Therefore, there have been efforts to optimize reservoir operations for hydropower generation. In this study, different reservoir operation optimization models were developed for single storage systems, run-of-river systems, and cascade storage systems of hydropower plants. Twenty different tools were developed, with thirteen being for single storage systems, five for cascade storage systems, and two for run-of-river systems. The models aim to maximize energy generation, revenue, and profit in different operation scenarios.

The first model, Fixed Reservoir Level at the End of Operation (FRLEO), limits the reservoir level at the end of the operation duration to a user-specified value and aims to maximize energy generation or maximize revenue for the entire period. The second model, Fixed Reservoir Level at the End of Year (FRLEY), limits the reservoir level at the end of each water year to a user-specified value and aims to

maximize energy generated or maximize revenue for the whole operation duration. The third and last model, the Reservoir Level Operation Rule (RLOR), fixes the reservoir levels of every same month of the year for the entire operation period and finds twelve end-of-month reservoir levels that maximize energy generation or maximize revenue. The Generalized Reduced Gradient (GRG) Nonlinear optimization algorithm is used for all the models.

The developed models were tested with a cascade of three dams in Southeast Central Turkey and a run-of-river hydropower plant in the same region. The results show that different operation models affect the energy generation capacity of dams with a considerably large storage capacity, as well as the cascade effect. Small storage capacity dams are not significantly affected by different operation models. However, as the operation models become stricter with additional constraints on end-of-month reservoir operation levels, energy generation capacities are negatively affected, and spilled water volumes increase as expected.

Present study provides insight into optimizing reservoir operations to increase energy generation or increase revenue. The suitability and effectiveness of the operation models for single or cascade systems depend on the specific characteristics of the system under consideration. It is important to conduct trials and evaluate the results before deciding on the most appropriate option. Nevertheless, the models developed in this study can be used to determine the optimal operation rules for any single or multi-reservoir system as well as run-of-river systems.

Keywords: Hydropower, Single Reservoir Operation, Energy Optimization, Cascade Reservoir Operation, Reservoir Operation Rule

ÖZ

HİDRO-ELEKTRİK SANTRALLERDE ENERJİ ÜRETİMİ VE YATIRIM MALİYETİ OPTİMİZASYONU

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Dünyanın enerji talebi arttıkça mevcut enerji kaynaklarının etkin kullanılması büyük önem taşımaktadır. Yenilenebilir enerji kaynakları, özellikle de hidroelektrik, enerji üretiminde önemli bir rol oynamaktadır. Bu nedenle hidroelektrik enerji üretimini artırmak için rezervuar işletmesini optimize etmek üzerine çalışmalar yapılmaktadır. Bu çalışmada tekil depolamalı sistemler, nehir tipi sistemler ve kaskat depolamalı sistemlerin işletme optimizasyonu için farklı rezervuar işletme modelleri geliştirilmiştir. On üçü tekil depolamalı sistemler için, beşi kaskat depolamalı sistemler için ve ikisi nehir tipi sistemler için olmak üzere toplam yirmi farklı araç geliştirilmiştir. Modeller, farklı operasyon senaryolarında enerji üretimini, geliri ve karı en üst düzeye çıkarmayı amaçlamaktadır.

İlk model olan İşletme Sonu Sabit Rezervuar Seviyesi (FRLEO), işletme süresi sonundaki rezervuar seviyesini kullanıcı tarafından belirlenen bir değerle sınırlandırmakta ve tüm işletme dönemi için enerji üretimini veya geliri maksimuma çıkarmayı amaçlamaktadır. İkinci model olan Yıl Sonu Sabit Rezervuar Seviyesi

(FRLEY), her su yılı sonundaki rezervuar seviyesini kullanıcı tarafından belirlenen bir deęerle sınırlandırmakta ve tüm işletme dönemi için üretilen enerjiyi veya geliri maksimuma çıkarmayı amaçlamaktadır. Üçüncü ve son model olan Rezervuar Seviyesi İşletim Kuralı (RLOR), tüm işletme dönemi boyunca yılın aynı ayına ait rezervuar seviyelerini sabitler ve enerji üretimini veya geliri maksimuma çıkaran oniki ay sonu rezervuar seviyesini bulur. Tüm modeller için Genelleştirilmiş Azaltılmış Gradyan (GRG) Doğrusal Olmayan optimizasyon algoritması kullanılmıştır.

Geliştirilen modeller, Türkiye'nin Güneydoğu Anadolu Bölgesinde yer alan üç baraj içeren kaskat depolamalı bir sistem ve aynı bölgedeki nehir tipi bir hidroelektrik santral için kullanılmıştır. Sonuçlar, farklı işletme modellerinin ve kaskat etkisinin depolama kapasitesi büyük olan barajların enerji üretim kapasitesini etkilediğini göstermektedir. Küçük depolama kapasiteli barajlar, farklı işletme modellerinden önemli ölçüde etkilenmemektedir. Ancak ay sonu rezervuar işletme seviyelerine ek kısıtlamalar getirilerek işletme modelleri daha katı hale geldikçe, enerji üretim kapasiteleri olumsuz etkilenmekte ve beklendiği gibi dolusavaktan atılan su hacimleri artmaktadır.

Mevcut çalışma, enerji üretimini artırmak veya geliri artırmak için rezervuar operasyonlarının optimize edilmesine ilişkin fikir vermektedir. Tekil veya kaskat sistemler için çalışma modellerinin uygunluğu ve etkinliği, söz konusu sistemin belirli özelliklerine bağlıdır. En uygun seçeneğe karar vermeden önce denemeler yapmak ve sonuçları değerlendirmek önemlidir. Bununla birlikte, bu çalışmada geliştirilen modeller, herhangi bir tekil veya çoklu rezervuar sistemi ile nehir tipi sistemler için en uygun işletme kurallarının belirlenmesinde kullanılabilir.

Anahtar Kelimeler: Hidroelektrik, Tekil Rezervuar İşletmesi, Enerji Optimizasyonu, Kaskat Rezervuar İşletmesi, Rezervuar İşletme Kuralı



To My Family

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TABLE OF CONTENTS

ABSTRACT.....	v
ÖZ	vii
ACKNOWLEDGMENTS	x
TABLE OF CONTENTS.....	xi
LIST OF TABLES	xiv
LIST OF FIGURES	xv
LIST OF ABBREVIATIONS.....	xvii
LIST OF SYMBOLS	xxii
CHAPTERS	
1 INTRODUCTION	1
2 LITERATURE REVIEW	5
3 METHODOLOGY	19
3.1 Framework	19
3.1.1 Single Storage Systems.....	20
3.1.2 Cascade Storage Systems.....	25
3.1.3 Run-of-River Systems.....	25
3.2 Generalized Reduced Gradient (GRG) Method	27
3.3 Mathematical Model	28
3.3.1 Single Storage Systems.....	28
3.3.1.1 Maximization of Energy – FRLEO	28
3.3.1.2 Maximization of Energy – FRLEY	42
3.3.1.3 Maximization of Energy – RLOR	42

3.3.1.4	Maximization of Revenue – FRLEO	49
3.3.1.5	Maximization of Revenue – FRLEY	49
3.3.1.6	Maximization of Revenue – RLOR	50
3.3.1.7	Maximization of Profit – FRLEO	50
3.3.2	Cascade Storage Systems	60
3.3.2.1	Maximization of Energy – FRLEO	60
3.3.2.2	Maximization of Energy – FRLEY	67
3.3.2.3	Maximization of Energy – RLOR.....	68
3.3.2.4	Maximization of Revenue – FRLEO	75
3.3.2.5	Maximization of Revenue – FRLEY	76
3.3.3	Run-of-River Systems	76
3.3.3.1	Maximization of Energy	76
3.3.3.2	Maximization of Revenue	81
4	CASE STUDY FOR SINGLE AND CASCADE STORAGE SYSTEMS.....	89
4.1	Introduction.....	89
4.2	Single Operation – Maximization of Energy	91
4.3	Cascade Operation – Maximization of Energy	96
4.4	Single Operation – Maximization of Revenue	99
4.5	Cascade Operation – Maximization of Revenue	102
4.6	Single Operation – Maximization of Profit	103
4.7	Discussion of Results.....	108
5	CASE STUDY FOR RUN-OF-RIVER SYSTEMS.....	117
5.1	Introduction.....	117
5.2	Maximization of Energy	119

5.3	Maximization of Revenue	120
5.4	Discussion of Results	126
6	CONCLUSION.....	129
	REFERENCES	135
	APPENDICES	147
A.	Storage Systems Characteristic Data Input Sheet.....	147
B.	Single Storage Systems Inflow Data Input Sheet	148
C.	Electro-Mechanical Equipment Efficiency Data Input Sheet.....	149
D.	Single Storage Systems Calculation Summary Sheet.....	150
E.	Storage Systems Energy Price Data Input Sheet	151
F.	Storage Systems Cost Data Input Sheet.....	152
G.	Run-of-River Systems Characteristic Data Input Sheet.....	153
H.	Run-of-River Systems Inflow Data Input Sheet	154
I.	Run-of-River Systems Energy Price Data Input Sheet	155
	CURRICULUM VITAE	157

LIST OF TABLES

TABLES

Table 1.1 Summary of the Studies Carried out in this thesis	4
Table 4.1 Main Characteristics of the Cascade	90
Table 4.2 Dam 1 Single Operation Annual Average Energy Production.....	91
Table 4.3 Dam 2 Single Operation Annual Average Energy Production.....	92
Table 4.4 Dam 3 Single Operation Annual Average Energy Production.....	92
Table 4.5 Cascade Total Single Operation Annual Average Energy Production....	92
Table 4.6 Dam 1 Single Operation Annual Average Spilled Volume	94
Table 4.7 Dam 2 Single Operation Annual Average Spilled Volume	94
Table 4.8 Dam 3 Single Operation Annual Average Spilled Volume	94
Table 4.9 Cascade Total Annual Average Spilled Volume.....	95
Table 4.10 Cascade Operation Annual Average Energy Generation	96
Table 4.11 Cascade Operation Annual Average Spilled Water Volume	98
Table 4.12 Single Operation Annual Average Energy Generation and Revenue .	100
Table 4.13 Single Operation Annual Average Spilled Water Volume	101
Table 4.14 Cascade Operation Annual Average Energy Generation and Revenue	102
Table 4.15 Input Unit Costs and Ratios for Maximization of Profit	103
Table 4.16 Alternative Installed Capacities Derived for Maximization of Profit .	105
Table 4.17 Results for Annual Average Energy Generation of Storage Systems for Maximization of Energy (GWh)	109
Table 4.18 Results for Annual Average Energy Generation and Revenue of Storage Systems for Maximization of Revenue	110
Table 5.1 Main Characteristics of the HEPP.....	118
Table 5.2 HEPP Energy Production Results for Maximization of Energy	119
Table 5.3 Energy Prices Used for Maximization of Revenue of HEPP	121
Table 6.1 Usability of Developed Models at Different Stages of a Hydropower Investment	132

LIST OF FIGURES

FIGURES

Figure 3.1 Normalized Turbine Hill Chart of Atatürk Dam HEPP (Su Ener, 2020)	23
Figure 3.2 Generator Efficiency Curve of Kepez Dam HEPP	23
Figure 3.3 Flowchart for single reservoir operation optimization, maximization of energy – FRLEO	29
Figure 3.4 Flowchart for single reservoir operation optimization, maximization of energy – RLOR	43
Figure 3.5 Flowchart for cascade reservoir operation optimization, maximization of energy – FRLEO	61
Figure 3.6 Flowchart for cascade reservoir operation optimization, maximization of energy – RLOR	69
Figure 3.7 Flowchart for run-of-river system operation optimization for maximization of energy.	77
Figure 3.8 Flowchart for run-of-river system operation optimization for maximization of revenue	82
Figure 4.1 Location of the Cascade in Turkey	89
Figure 4.2 Schematic Profile of the Cascade	91
Figure 4.3 Results for Dam 2 Maximization of Profit Installed Capacity vs Total cost, Total Revenue and Net Profit	106
Figure 4.4 Results for Dam 2 Maximization of Profit Installed Capacity vs Net Profit	107
Figure 4.5 Reservoir Levels of Dam 2 for Maximization of Energy for Years 1968 to 1970	113
Figure 4.6 Spillway Discharges of Dam 2 for Maximization of Energy for Whole Operation Period	114
Figure 4.7 Spillway Discharges of Dam 2 for Maximization of Energy for Years 1968 to 1970	115

Figure 5.1 Location of the HEPP in Turkey.....	117
Figure 5.2 Daily Average Inflow of the HEPP (From Feasibility Report)	118
Figure 5.3 HEPP Normalized Turbine Discharges vs Inflow	120
Figure 5.4 Storage Volume and Energy Prices for the HEPP Operated for Maximization of Revenue with Daily Average Inflow of 32.29 m ³ /s.....	122
Figure 5.5 Normalized Turbine Powers and Inflow Rates for the HEPP Operated for Maximization of Revenue with Daily Average Inflow of 32.29 m ³ /s.....	122
Figure 5.6 Storage Volume and Energy Prices for the HEPP Operated for Maximization of Revenue with Daily Average Inflow of 12.08 m ³ /s.....	123
Figure 5.7 Normalized Turbine Powers and Inflow Rates for the HEPP Operated for Maximization of Revenue with Daily Average Inflow of 12.08 m ³ /s.....	123
Figure 5.8 Storage Volume and Energy Prices for the HEPP Operated for Maximization of Revenue with Daily Average Inflow of 8.10 m ³ /s.....	124
Figure 5.9 Normalized Turbine Powers and Energy Prices for the HEPP Operated for Maximization of Revenue with Daily Average Inflow of 8.10 m ³ /s.....	125

LIST OF ABBREVIATIONS

ABBREVIATIONS

APO	Artificial Physics Optimization
CLTR	Concrete Liner Thickness Ratio
CPT	Discharge Capacity of Turbines
DAI	Daily Average Inflow
DANI	Daily Average Net Inflow
DE	Differential Evolution
DVTT	Difference Between Maximum Volume That Can Be Turbined and Min Volume That Should Be Turbined
DWR	Downstream Water Rights
EP	Average Monthly Energy Price
ESO	Explicit Stochastic Optimization
EV	Evaporation from The Reservoir
FRLEO	Fixed Reservoir Level at the End of Operation
FRLEY	Fixed Reservoir Level at the End of Year
GA	Genetic Algorithm
GE	Gradient Evolution
GRG	Generalized Reduced Gradient
HO	Hours of Operation
I	Inflow Volume
ISO	Implicit Stochastic Optimization

LP	Linear Programming
MaxFR	Maximum Turbine Flow Rate Ratio
MaxPTD	Maximum Possible Turbine Discharge Rate
MaxRL _E	Maximum Possible End-of-Month Reservoir Level
MaxROL	Maximum Reservoir Operation Water Level
MaxROLV	Reservoir Volume at the Maximum Operation Water Level
MaxTD	Maximum Possible Turbine Discharge
MaxVTT	Max Volume That Can Be Turbined
MinFR	Minimum Turbine Flow Rate Ratio
MinROL	Minimum Reservoir Operation Water Level
MinROLV	Reservoir Volume at the Minimum Operation Water Level
MinTD	Minimum Possible Turbine Discharge
MinVTT	Minimum Volume That Should Be Turbined
MMGA	Macro-Evolutionary Multi-Objective Genetic Algorithm
ND	Number of Days in the Month
NI	Net Inflow Volume
NLP	Non-Linear Programming
NPV	Net Present Value
NSGA-II	Non-Dominated Sorting Genetic Algorithm-II
OU	Other Uses from Reservoir
PC _{CON}	Penstock Cost Contingency
PW _{CON}	Penstock Works Contingency Ratio

PCC	Penstock Concrete Cost
PCPM	Average Concrete Amount Per Meter of Penstock
PCUC	Penstock Concrete Unit Cost
PCWC	Powerhouse Civil Works Cost
PCWUC	Powerhouse Civil Works Unit Cost
PEC	Penstock Excavation Cost
PEMC	Powerhouse Electromechanical Cost
PEMUC	Powerhouse Electromechanical Unit Cost
PEPM	Average Excavation Amount Per Meter of Penstock
PEUC	Penstock Excavation Unit Cost
PIC	Powerhouse Installed Capacity
PRC	Penstock Reinforcement Cost
PTC	Penstock Total Cost
PWC _{CON}	Powerhouse Cost Contingency
PWTC	Powerhouse Total Cost
PWW _{CON}	Powerhouse Works Contingency Ratio
RR _P	Reinforcement Ratio of Penstock Concrete
PRUC	Penstock Reinforcement Unit Cost
PSC	Penstock Steel Cost
PSO	Particle Swarm Optimization
PSUC	Penstock Steel Unit Cost
RL _B	Reservoir Level at the Beginning of the Month

RL_E	Reservoir Level at the End of Month
RL_{EU}	User Defined End of Month Minimum Reservoir Level
$RLOR$	Reservoir Level Operation Rule
RR_T	Reinforcement Ratio of Tunnel
RV_B	Reservoir Volume at the Beginning of Month
RV_E	Reservoir Volume at the End of Month
RVN	Revenue
$SLTR$	Steel Liner Thickness Ratio
SV	Spilled Volume
SVC	Storage Volume Capacity
TC_{CON}	Tunnel Cost Contingency
TCC	Tunnel Concrete Cost
$TCUC$	Tunnel Concrete Unit Cost
TD_{min}	Minimum Tunnel Diameter Required
TDD	Total Turbine Design Discharge
TEC	Tunnel Excavation Cost
$TESSC$	Tunnel Excavation Support System Cost
$TESSUC$	Tunnel Excavation Support System Unit Cost
$TEUC$	Tunnel Excavation Unit Cost
TFC	Tunnel Formwork Cost
$TFUC$	Tunnel Formwork Unit Cost
TL	Tailwater Level

TRC	Tunnel Reinforcement Cost
TRUC	Tunnel Reinforcement Unit Cost
TSWC	Tunnel Stabilization Works Cost
TSWUC	Tunnel Stabilization Works Unit Cost
TTC	Total Tunnel Cost
TW _{CON}	Tunnel Works Contingency Ratio
TWWC	Total Water Way Cost
TV _B	Total Water Volume at the Beginning of the Month
VP _{all}	Maximum Allowable Water Velocity in Penstock
VT _{all}	Maximum Allowable Water Velocity in Tunnel
VTT	Volume to be Turbined

LIST OF SYMBOLS

SYMBOLS

η	Overall Efficiency
η_T	Turbine Efficiency
η_G	Generator Efficiency
η_{Tr}	Transformer Efficiency
ϵ	Roughness Height
ν	Kinematic Viscosity of Water
ρ	Density of the Water
A	Variable Between 0 and 1
D	Diameter
D_H	Hydraulic Diameter
E	Energy
f_D	Darcy Weisbach Friction Factor
g	Gravitational Acceleration
h_f	Friction Head Losses
$h_{fpenstock}$	Friction Head Losses in Penstock
$h_{ftunnel}$	Friction Head Losses in Tunnel
h_m	Minor Head Losses
H_{gross}	Gross Head

H_{loss}	Head Loss
H_{net}	Net Head
L	Length of the Pipe or Tunnel
Q	Turbine Discharge
P	Wetted Perimeter
P_i	Power
Re	Reynolds Number
V	Flow Velocity

CHAPTER 1

INTRODUCTION

Energy is becoming more important every day in the global world as demand increases. Global energy consumption growth rate was +2.1% in 2022, higher than its average 2010-2019 growth rate of +1.4%/year (Enerdata, World Energy & Climate Statistics 2023). With this demand increase, using the available energy sources effectively becomes very important. The importance of sustainable energy planning has grown substantially with rising population growth rates, environmental issues, and economic developments (Kocaman et al., 2015). Considering that a significant amount of almost 30% of the global electricity generation is supplied by renewable energy sources, primarily hydropower, using the available potential becomes vital for future energy supply security (The Intergovernmental Panel on Climate Change 2012). According to statistical data, the total global hydropower size surged from 625 GW in 1995 to 1,308 GW in 2019 (Liu et al., 2021). Aside from the increasing demand, electricity prices also increase. According to the International Energy Agency, the global electricity price index has tripled since 2016 (<https://www.iea.org>). The increase in demand and prices forced investors and operators of hydroelectric power plants to focus on optimization. Driven by the growing focus and interest, a significant amount of research and effort was made in recent decades on the optimization of installed capacity and hence investment capital and also on operation optimization for storage and run-of-river hydropower generation either for maximization of energy generation or maximization of revenue.

This thesis study aims to develop operation tools applicable to any single-purpose hydroelectric power plant. Different reservoir operation optimization tools are

created for the design and operation of Single Storage Systems, Run-of-River Systems, and Cascade Storage Systems of hydropower plants.

Three different reservoir operation models were developed for storage systems namely, FRLEO, FRLEY, and RLOR. FRLEO limits the reservoir level at the end of the whole operation duration to a user-specified value. The second model, FRLEY, limits the reservoir level at the end of each water year to a user-specified value. The third and last model, RLOR, fixes the reservoir levels of every same month of the year for the whole operation period and finds 12 end-of-month reservoir levels that maximize the energy generation or revenue. GRG Nonlinear optimization algorithm was used for all the models. A new modeling algorithm was developed to simplify the problem by means of objective function and constraint definitions, which will be explained in the following sections.

For Single Storage Systems, operation tools were developed for three different purposes: maximization of energy, maximization of revenue, and maximization of profit. For maximization of energy and maximization of revenue, three different options were provided for monthly operation for a duration of 49 years, daily operation for a period of 2 years, and hourly operation for a course of 1 month or 12 months. For monthly operation for a duration of 49 years, the user can choose one of the three different reservoir operation models: FRLEO, FRLEY, and RLOR. FRLEO model is used as the default for daily and hourly operation tools. For maximization of profit, the only option is the monthly operation for a duration of 49 years with the FRLEO model, as 49 years of operation is the regulatory requirement for feasibility studies in Turkey.

For Run-of-River Systems, operation tools were developed for two different purposes: maximization of energy and maximization of revenue. For maximization of energy, daily operation for a duration of 2 years is considered for a system with no storage capacity. The aim is to determine which turbine or turbines shall be operated for the forecasted inflow values to generate the maximum energy. For maximization of revenue, a 15-minute time step operation for a duration of 1 day is

considered for a system with a small amount of storage capacity somewhere in the waterway like settling pond, head pond, or power race tunnel. The aim is to determine which turbine or turbines shall be operated and for how long, for the forecasted inflow values and energy prices to maximize the daily revenue.

For Cascade Storage Systems, operation tools were developed for two different purposes, maximization of energy and maximization of revenue with monthly operation for a duration of 20 years. The user can choose one of the three reservoir operation models for energy maximization: FRLEO, FRLEY, and RLOR. Two different reservoir operation options are provided for revenue maximization: FRLEO and FRLEY.

A total of 20 different tools were developed. 13 of the tools developed are for Single Storage Systems, 5 of the tools developed are for Cascade Storage Systems, 2 of the tools are for Run-of-River Systems for different purposes of maximization of energy generation, maximization of revenue and maximization of profit with different operation models. In Table 1.1, the studies carried out in this thesis are summarized.

Developed models are used for a cascade of three dams in Southeast Central Turkey. Three reservoirs were operated both as single and as a cascade. The results provide insight into developing an optimized reservoir operation that increases energy generation. The results of the case study are discussed in detail in the following sections.

In Chapter 2, a comprehensive literature review is provided. In Chapter 3, the methodology is described in detail through the framework, mathematical model, and algorithms used. In Chapter 4, a case study is carried out for a cascade consisting of three dams located in Southeast Central Turkey, and newly developed operation models are compared with each other and with the feasibility report values. In Chapter 5, another case study is carried out for a run-of-river system, and results are compared with the feasibility report values. In Chapter 6, developed tools and models are summarized with the results obtained from case studies. Future development options are evaluated, and recommendations are provided.

Table 1.1 Summary of the Studies Carried out in this thesis

System	Options for Optimization	Options for Time Step	Options for Reservoir Operation Model
Single Storage Systems	Maximization of Energy	Monthly Operation (49 years of operation)	FRLEO
			FRLEY
			RLOR
		Daily Operation (2 years of operation)	FRLEO
		Hourly Operation (1 month of operation)	FRLEO
		Hourly Operation (12 months of operation)	FRLEY
	Maximization of Revenue	Monthly Operation (49 years of operation)	FRLEO
			FRLEY
			RLOR
		Daily Operation (2 years of operation)	FRLEO
		Hourly Operation (1 month of operation)	FRLEO
		Hourly Operation (12 months of operation)	FRLEY
	Maximization of Profit	Monthly Operation (49 years of operation)	FRLEO
Run-of-River Systems	Maximization of Energy	Daily Operation (2 years of operation)	NO STORAGE
	Maximization of Revenue (For a Small Storage Capacity)	15 Minute Operation (1 day of operation)	FRLEO
Cascade Storage Systems	Maximization of Energy	Monthly Operation (20 years of operation)	FRLEO
			FRLEY
			RLOR
	Maximization of Revenue	Monthly Operation (20 years of operation duration)	FRLEO
			FRLEY

CHAPTER 2

LITERATURE REVIEW

As a low operation cost, renewable, and reliable source of energy, hydropower has an essential role in power systems worldwide. Since a day-by-day growing effort is made on optimization of reservoir operations, which is a complex nonlinear optimization problem. Mathematical models and various optimization algorithms are used for hydropower plant reservoir operations and run-of-river system operations. Understanding the spatial and temporal distribution of hydrologic variables, such as streamflow, is essential for sustainable development, especially with global population growth and climate variations (Markert et al., 2019)

Some conclusions may be drawn from these previous studies - hypothetical assumptions and simplifications may be misleading - cost-effectiveness and all inherent parameters such as civil, mechanical, and electrical engineering together with the operation costs and hydrological aspects should be involved in a meaningful design optimization, and optimization process should be justified also by socioeconomic considerations and equipment availability (Najmaii and Movaghar, 1992).

Esat and Hall (1994), Chang and Chen (1998), Sharif and Wardlaw (2000), Huang et al., (2002), Raju and Nagesh Kumar (2004), Chang J.X. et al., (2005) and Chang et al., (2005) used Genetic Algorithms - algorithms that can be defined as auto-adaptive stochastic search techniques and can be classified as a type of evolutionary algorithm (Holland 1975) - to solve different optimization problems of reservoir operation.

Different optimization algorithms and modified versions of the genetic algorithm were also used widely in the search for a more effective way of reservoir operation optimization. Almeida et al., 2006, introduced an optimization model for small hydropower plants to find out the optimal economical configuration. Li and Wei 2007, introduced a hybrid algorithm by combining simulated annealing and genetic algorithms. They applied their model to a 3-reservoir cascade in China on a monthly operation basis for 12 months of operation duration and compared their findings with the classical genetic algorithm. Reddy and Kumar 2007, developed a multi-objective differential evolution (MODE) algorithm and compared the results with the nondominated sorting genetic algorithm-II. Chen et al., 2007, developed an efficient macro-evolutionary multi-objective genetic algorithm (MMGA) for optimizing the rule curves of a multi-purpose reservoir system in Taiwan. They found that MMGA can generate uniformly spread solutions for a two-objective problem involving water supply and hydropower generation. Afshar et al., 2009, studied non-dominated archiving multi-colony ant algorithm for multi-objective reservoir operation for Dez Reservoir in Iran. China's Qing River cascade hydropower reservoirs (the Shuibuya, Geheyan, and Gaobazhou reservoirs) were studied by Liu et al., 2011, for the derivation of operation rule curves. Observed inflows from 1951 to 2005 were used with a monthly operation basis. They used non-dominated sorting genetic algorithm-II (NSGA-II). Moeini and Afshar 2011, studied the ant colony optimization algorithm. Ferreira and Teegavarapu 2012, studied partial constraint satisfaction approaches with the use of mixed integer nonlinear programming and Genetic Algorithm. Celeste and Billib 2012, introduced a reservoir operation model based on implicit stochastic optimization (ISO) in which the forecast of the mean inflow for a given future horizon for flood protection objective guides the release policy. Afshar et al., 2015, studied imperialist competitive algorithm (ICA) for single reservoir operation, Dez Reservoir in Iran. Zhou et al., 2018, followed them with a case study of 21 mega cascade reservoirs located in the Upper Yangtze River Basin of China. They utilized successive approximation approach in the Non-Dominated Sorting Genetic Algorithm-II (NSGA-II), to solve the dimensionality problem raised in

NSGA-II. Samadi-Koucheksaraee et al., 2018, studied the Khersan-1 reservoir and the Dez reservoir in Iran using gradient evolution (GE) algorithm. They compared their results with Linear programming (LP), non-linear programming (NLP), and genetic algorithm (GA). They concluded that the gradient evolution algorithm provides better results for reaching the global optimum. Wang et al., 2021, compared differential evolution (DE), particle swarm optimization (PSO), and artificial physics optimization (APO), which are typical examples of heuristic algorithms. They found that the results do not obviously differ in favor of one of the compared methods. Lai et al., 2022, compared the results of the whale optimization algorithm (WOA), the Levy-flight WOA (LFWOA), and the Harris hawks optimization algorithm (HHO) for the Karun-4 hydroelectric reservoir in Iran and concluded that the HHO algorithm produces the best results in terms of global optimization. Jothiprakash and Arunkumar 2013, Aboutalebi et al., 2015, Azizipour et al., 2016, Ahmadianfar et al., 2019, Feng et al., 2020, Hatamkhani et al., 2021 and Niu et al., 2021, Moghadam et al., 2022, searched the effect of using different optimization algorithms or effect of coupling the genetic algorithm with other algorithms. The common approach in these studies is that the focus is given to the effectiveness of the used algorithm instead of the accuracy of energy production calculations. This joint approach in the end brings simplifications and omissions of some components of energy production calculation, such as the efficiency of electro-mechanical equipment and head loss.

Labadie 2004, made a review study that describes the basics of different optimization methods that are used for dams. He reviewed implicit stochastic optimization (ISO), linear programming (LP), network flow optimization, nonlinear programming, discrete dynamic programming, differential dynamic programming, discrete-time optimal control theory, explicit stochastic optimization (ESO), chance-constrained programming, stochastic linear programming, stochastic dynamic programming, stochastic optimal control, multi-objective optimization, and heuristic programming models. Another review study was conducted by Ahmad and El-Shafie 2014. They studied applications of conventional, especially evolutionary computation methods and a combination of simulation-optimization and multi-objectives optimization in

reservoir operation. Furthermore, Artificial Bee Colony (ABC) and Gravitational Search Algorithm (GSA) as alternative methods were reviewed.

All these studies focused on comparing the results of a new method or algorithm, with a formerly used genetic algorithm. While doing so, the accuracy of the calculations was not a priority as it was not the primary objective, and comparison of the results under the same conditions was not affecting the conclusions. In favor of this objective, many assumptions were made to simplify the problem and effort such as neglecting head losses, environmental flow, and evaporation. In some of the studies, even the reservoir level was assumed to be constant. Also, the efficiency of electromechanical equipment was neglected in some studies or assumed to be constant.

Karamouz et al., 2005, introduced a comprehensive study for Karoon and Dez River-Reservoir Systems in Iran. They developed different modules for the case study able to handle database management, inflow modeling and forecasting, monthly operation management, and real-time operation for the cascade.

Yoo 2009, introduced a linear approach to the non-linear hydropower optimization problem. He formulated a new linear hydropower objective function and optimized it in the model without the iterative algorithm. He performed a case study on the Yongdam dam in South Korea with the inflow data for 38 years from 1963 to 2000. The annual energy (184 GWH) output that can be produced by the optimal operation of the proposed model was 86% of the maximum potential energy production of 214 GWH per year.

Malekmohammadi et al., 2009, utilized Bayesian Network (BN) for developing monthly operating rules for a cascade system of reservoirs which is mainly aimed at controlling floods and supplying irrigation needs. They developed a monthly reservoir operation optimization model to minimize flood damages. The developed models were applied to the cascade system of the Dez and Bakhtiari Reservoirs in the Southwest of Iran. The result of the trained BN was compared with the rules developed using classical and fuzzy linear regressions and it was shown that the total

damage obtained by the BN-based operating rules was about 60 percent less than the total damage obtained using the fuzzy and classical regression analyses.

Short-term operation optimization was also studied by several researchers. A cascade of 4 dams on an hourly operation basis for 24-hour operation duration was studied by Ladurantaye et al., 2009, using deterministic and a stochastic mathematical model for maximizing the profits obtained by selling electricity produced in a spot market. IBM ILOG CPLEX Optimization Studio is used for the mathematical model. They used a power generation function that depends on two variables: water volume at the dam and flow going through the unit. They calculated the head as a function of water volume at the dam. Head losses, environmental flow, and evaporation were neglected and efficiency for electromechanical equipment was assumed to be included in the power generation function. Prices from the Ontario electricity market in Canada have been used. Pérez-Díaz et al., 2010, introduced a non-linear programming-based scheduling model to solve the short-term operation scheduling of a single hydro plant associated with a small reservoir with hourly operation for 24 hours of operation duration with the objective of maximizing revenue. They considered the effects of reservoir level, tailrace elevation with discharge, friction loss, and efficiency curves of electro-mechanical equipment. They performed a case study for a real hydropower plant with Kaplan type turbines with 15 different scenarios in order to demonstrate its applicability. They used the MINOS solver under GAMS software. Another short-term hydro generation scheduling study was performed by Mo et al., 2013, for Three Gorges–Gezhouba cascade hydropower systems. They aimed to determine optimal hydro generation schedule to obtain minimum water consumption for one day or week. Ge et al., 2014 also studied short-term hydropower optimal scheduling problem. They considered the optimization of water time delay. The water time delay was defined as the time required for discharging water from upstream reservoir to its downstream reservoir. They performed a case study with 13 reservoirs and 44 hydropower units using CPLEX commercial software with the implication of mixed-integer nonlinear optimization algorithm.

Kangrang et al., 2013, performed a case study for Lampao Reservoir located in the northeast of Thailand by implementing a conditional ant colony optimization model. They performed monthly operation with available inflow data from 1968 to 2011. Their objective was to minimize the water shortage supply to the downstream irrigation areas by defining an optimum operation rule.

Studies with different purposes and objectives were also performed considering the grid stability and optimization like the one from Ji et al., 2013. They studied the grid stability of Jinsha system in China with reservoir operation optimization with the use of Support Vector Regression method. Assessment of reservoir operation rules, under drought situations for multi-reservoir water resources systems was studied by Lerma et al., 2013, for Júcar River basin in Spain. They used a combination of genetic algorithm and network flow optimization. They found that simple operation rules produce similar results to more sophisticated ones. Xin-Yu et al., 2014, studied scheduling problem of a hydropower system in China Southern Power Grid (CSG). The system consisted of 92 hydro plants with total installed capacity of 41GW occupying 14.7% of the national hydropower capacity at the end of 2013. A short-term hydropower scheduling model for peak shaving of multiple power grids was developed for the operations of the hydropower system of CSG. The model was composed of multi-objective optimal peak shaving (MOPS) model, inter grid power distribution (IGPD) model and load fluctuation balance (LFB) model. Jiang et al., 2015, studied the effect of forecasting error as a fuzzy variable on the reservoir operation for flood control measures. Bai et al., 2016, studied a multi-objective optimization model of two cascade reservoirs in the Upper Yellow River basin in China for decreasing ice/flood threats. Al-Jawad et al., 2017, made a case study for a multipurpose dam in order to fulfil downstream water demands in drought conditions while maintaining a sustainable quantity of water in the reservoir for the next year by using an evolutionary optimization algorithm. The water-supply system of Li River in Guangxi Province, China was studied by Tan et al., 2017, for derivation of a joint operating policy for a multi-purpose multi-reservoir system. Niu et al., 2017, developed a parallel multi-objective particle swarm optimization

algorithm and applied it to resolve the cascade hydropower reservoirs operation balancing benefit and firm output. Barbaros 2019, made a case study on Gökçekaya and Altinkaya pump-storage systems with an hourly operation basis including market energy price analysis. No optimization algorithm was implemented but different operation modes for the pump-storage systems analyzed to increase profit. Liu et al., 2019, Jiang et al., 2018, and Xu et al., 2021, focused on the effect of forecast uncertainties for optimizing reservoir operation. Environmental concerns and effects were considered in the study of Ren et al., 2018. They have focused on the available ratio of water resource of natural or semi-natural rivers for ecological feasible regions using a method that transcends the traditional perspective of designed environmental flow. Their framework involved a modified percent of flow approach to identify the ecological feasible region of water resources utilization, which sequentially acted as a constraint for a reservoir optimization model based on the Cuckoo Search algorithm to obtain an optimal diversion process. They performed a case study for the Han to Wei inter-basin water transfer project of China. Finardi et al., 2016, presented a comparative analysis of different mathematical programming approaches for optimizing the hydro unit commitment problem with cascaded plants, multiple generating units, and a head-dependent hydropower model. The objective of the study was to minimize the cascade outflow while satisfying all constraints, including a power target for each plant, in a day-ahead planning horizon. The decision variables were the on/off status of the units and the respective generation levels. Karami et al., 2019, made a case study for minimizing irrigation deficiencies of Golestan Dam and Voshmgir Dam system in Iran using a hybrid algorithm which integrates the Gravitational Search Algorithm (GSA) with the Particle Swarm Optimization Algorithm (PSOA). Dahmani and Yebdri 2020, made another case study for the purpose of minimizing irrigation deficiencies. They studied Hammam Boughrara reservoir located in Northwest Algeria with the implementation of a hybrid algorithm of particle swarm optimization and grey wolf optimizer. Bilal et al., 2021, studied Mula reservoir supplying water to Major Irrigation Project on River Mula (Godavari basin), Ahmednagar district,

Maharashtra, India. The objective was to determine the optimum release policy for Mula reservoir. They compared the results of six algorithms namely: Simulated Annealing, Genetic Algorithms, Particle Swarm Optimization, Differential Evolution, Artificial Bee Colony, and Cuckoo Search.

Another cascade study was performed by Karaeren 2014. He studied 4 dams on Murat River. Murat River, which is one of the two main streams of Euphrates River is located at the Eastern part of Turkey. Four dams, namely - Upper Kaleköy Dam and HEPP, Lower Kaleköy Dam and HEPP, Beyhan-1 Dam and HEPP and Beyhan-2 Dam and HEPP were studied on monthly operation basis. He tried to maximize the generation by expressing it as a function of turbine discharge and spill. He used a matlab model and interior point optimization algorithm which is a gradient based method. He assumed a constant efficiency for electromechanical equipment, neglected environmental flow requirements, neglected evaporation, and neglected head losses.

Hirsch et al., 2014, developed a hydro-economic model that combines an economic optimization function with hydrological estimators of the water balance of a reservoir. Applying this model, they tried to predict water level fluctuations in a reservoir. The hydro-economic model also allowed them for calculation of how water levels change with climate change scenarios and with a change in operating scheme of the reservoir (increase in turbine capacity).

A case study on Three Gorges Cascade Hydropower System in China was performed by Li and Qiu 2015. Aside from the maximization of energy generated they also tried to maximize the firm energy simultaneously in that study. Non-dominated Sorting Genetic Algorithm-II was used for the optimization model on monthly operation basis. They assumed a constant K in the power output calculation to represent the efficiency for electromechanical equipment and the head losses in the water way.

Vardanyan and Hesamzadeh 2017, performed a case study for the Nordic electricity market to model and predict day-ahead, intra-day, and real-time electricity prices. The Holt–Winter (HW) and the Generalized Autoregressive Conditional

Heteroscedastic (GARCH) predictors were combined using a proposed Markov switch. They developed a bidding curve for a three-reservoir hydropower producer for profit-maximizing.

Ak 2017, made a case study for Çoruh Basin including Arkun, Yusufeli and Artvin Dams in Turkey. He searched the effect of different operation models by using GAMS software with CONOPT solver, implementing Implicit Stochastic Optimization algorithm on a monthly operation basis for maximization of energy production. Four different reservoir operation models were considered for single reservoir operation whereas only one operation model was considered for the cascade reservoir operation. Evaporation losses were not considered, and electromechanical equipment efficiencies were defined as a function of discharge only.

Shiroro Dam, in Nigeria, was studied by Ajibola et al., 2017, for optimizing hydroelectric power generation. They tried to maximize the storage capacity as it is directly related to the energy production capacity for a pump-storage hydropower plant. Similar to the previous studies, a constant efficiency for electromechanical equipment was assumed and the head losses in the water way were neglected.

Singh et al., 2017, made a review study for the earlier research work carried out in the area of operation of reservoir based as well as run of river hydro power plants. They found that the parameters which affect the operation of hydro power plant are head, discharge, turbine and generator and the earlier studies focused on the operation of hydropower system for generation of the power by using various optimization techniques and also considering impact on the environment. They also found out that other parameters such as penstock diameter, types of turbines, number of turbines, generation scheduling were not studied earlier for optimal operation of the hydro power plant and therefore further study was required to consider the effect of those parameters.

Najmaii et al., 1992, Anagnostopoulos 2007, Garrido et al., 2009, Haddad et al., 2011, and Basso et al., 2012, performed studies on run-of-river hydropower plants.

Yıldız 2015, introduced a numerical model, which simulates the daily power production of a single run-of-river (RoR) plant in response to a historical record of daily discharge values. The model was able to simulate both single and parallel turbine systems for a given record of river flows and objective function (maximization of net profit or power production). MATLAB differential evolutionary algorithm was used for the model. He used fixed energy prices for the net profit model and assumed efficiency of electromechanical equipment as a function of turbine discharge. Mamo 2018, developed a decision support tool for RoR power plant optimum installed capacity determination with number and installed capacity of units being the variables on a daily operation basis. The study had some principles, a specific location with known allowable maximum and minimum heads. Allowable water potential was known, daily average river flow hydrograph was used as an input and daily operation was carried. No storage capacity was allocated, rating curves were used for upstream and downstream water levels. Only electromechanical costs were considered as a function of installed capacity and costs of water way components were out of scope of the study. Multiple units were considered but each unit was assumed to be identical. Efficiency curve for electromechanical units was adopted and it was assumed only as a function of unit discharge. Sequential Least Squares Programming was used for optimization model.

Zhou et al., 2020, performed a case study for the joint operation of six cascade reservoirs located in the Jin-Sha River basin in China. They used Kidney Algorithm (KA) and a so-called improved KA algorithm to optimize the hydropower output and compared the results with the standard operating policy.

Another case study was performed by Al-Aqeeli et al., 2020, for Mosul and Badush dams, located in the Tigris River, Northern Iraq. Particle swarm optimization model was used for the maximization of energy generated on monthly operation basis for one year of operation period. They assumed a constant of 0.8 to represent the efficiency for electromechanical equipment and the head losses in the water way.

Sharifi et al., 2021, made a case study for a five-reservoir system along Karun River at Iran. They employed fitness-distance-balance selection method in the moth swarm algorithm for the maximization of energy generated on monthly operation basis for 180 months of operation period and compared the results with genetic algorithm (GA) and particle swarm optimization (PSO) algorithm. Sharifi et al., 2022, studied Karun multi-purpose multi-reservoir system again with application of multi-objective moth swarm algorithm optimization model for the maximization of energy generated on monthly operation basis for 180 months of operation period. The results of multi-objective moth swarm algorithm were compared with two well-known multi-objective algorithms of the non-dominated sorting genetic algorithm-II and the strength pareto evolutionary algorithm-II. They assumed a constant overall efficiency factor to represent the efficiency for electromechanical equipment and the head losses in the water way for power output calculations.

Lai et al., 2022, performed a review study covering 52 articles published between 2011 and 2021. They classified optimization algorithms with the results obtained from the reviewed studies according to their capability, whether they can handle large scale problems or not and level of difficulty of usage. Another review study was made by Beiranvand and Ashofteh 2023. 76 research articles from the most prestigious journals in the world between 2002 and 2021 have been reviewed. They made a classification of the studies with respect to country of origin, algorithm used, reservoir capacity, purpose of use, publication year, published journal and provided a general overview of algorithms used. They found that among individual algorithms, GA algorithm (16.48%) has been the most popular model among researchers. The GA algorithm has been used more to compare with other modern meta-heuristic algorithms and 40.98% of the studied articles considered this algorithm as the best comparison option.

Connolly et al., 2011, carried a study on pumped-hydro power plants for maximum energy storage to sale in the market for maximizing the profit. A recent study was carried by Haktanir and Aydemir 2023, on pump-storage systems. They developed new operation simulation models for pump-storage systems for daily operation.

Steady-rate and the open-loop night-shift-pumped-storage rules were developed and applied on 11 existing dams in Türkiye. They found that the nightshift pumped-storage operations are more profitable than the steady-rate rule for energy benefits with pumping costs computed with a discount rate of 9.5% over a 35-year period.

The current study aims development of generalized models applicable to any single purpose dam and hydroelectric power plant reservoir operation as single or as a cascade with the options of maximization of energy generation, maximization of revenue or maximization of profit.

Moreover, for increased accuracy of power and energy calculations, a real turbine hill chart from Atatürk Dam and HEPP (Su Ener, 2020) was used for the efficiency calculation of electromechanical equipment. Efficiency of turbines was calculated from turbine hill chart for every operation time step separately according to the average net head and turbine discharge of that time step by using the ratios of net head to design net head and discharge to design discharge. Turbine hill chart can be modified for any available hill chart data specific to the turbines.

Furthermore, three different reservoir operation models were derived namely, FRLEO, FRLEY and RLOR. FRLEO limits the reservoir level at the end of whole operation duration to a user specified value maximizing the energy generated for the whole operation duration. Second model, FRLEY, limits the reservoir level at the end of each water year to a user specified value maximizing the energy generated for the whole operation duration. Third and the last model, RLOR, fixes the reservoir levels of every same month of the year for the whole operation period and finds 12 end of month reservoir levels that maximizes the energy generation. GRG Nonlinear optimization algorithm was used for all of the models. A new modeling algorithm was developed for simplification of the problem by means of objective function and constraint definitions, the details of which will be explained in the following sections.

Developed models are used for a cascade consisting of three dams located in Southeast Central Turkey. Three reservoirs were operated in both single and cascade configuration.



CHAPTER 3

METHODOLOGY

Methodology of this thesis study is explained in detail in this section. Firstly, the framework of the study is provided, followed by the optimization algorithm used. Lastly, the newly developed mathematical models are detailed.

3.1 Framework

Developed models in this study are applicable to any single purpose hydroelectric power plant. Different reservoir operation optimization tools are developed for design and operation of Single Storage Systems, Run-of-River Systems and Cascade Storage Systems of hydropower plants.

Three different reservoir operation models were developed for storage systems namely, FRLEO, FRLEY and RLOR. First model, FRLEO limits the reservoir level at the end of whole operation duration to a user specified value. Second model, FRLEY, limits the reservoir level at the end of each water year to a user specified value. Third and the last model, RLOR, fixes the reservoir levels of every same month of the year for the whole operation period and finds 12 end of month reservoir levels that maximizes the energy generation or revenue. GRG Nonlinear optimization algorithm was used for all of the models. A new modeling algorithm was developed for simplification of the problem by means of objective function and constraint definitions, to be explained in the following sections.

A total of 20 different tools are developed. 13 of the tools developed are for Single Storage Systems, 5 of the tools developed are for Cascade Storage Systems, 2 of the tools are for Run-of-River Systems for different purposes of maximization of energy generation, maximization of revenue and maximization of profit with different

operation models. In Table 1.1, the entire studies carried out in the present study are summarized.

3.1.1 Single Storage Systems

For Single Storage Systems, operation tools were developed for three different purposes. Maximization of energy, maximization of revenue and maximization of profit. For maximization of energy and maximization of revenue three different options were provided for monthly operation for a duration of 49 years, daily operation for a duration of 2 years and hourly operation for a duration of 1 month or 12 months. For monthly operation for a duration of 49 years, the user has the option of choosing one of the three different reservoir operation models of FRLEO, FRLEY and RLOR. For daily operation and hourly operation tools, FRLEO model is used as default. For maximization of profit the only option is monthly operation for a duration of 49 years with FRLEO model.

The following characteristic information should be provided into the model by using the user interface developed for maximization of energy.

- Name of the Project
- Length of Power Tunnel (m)
- Diameter of Power Tunnel (m)
- Length of Penstock (m)
- Diameter of Penstock (m)
- Surface Roughness of Power Tunnel (mm)
- Surface Roughness of Penstock (mm)
- Total Number of Units
- Installed Capacity of Each Unit (MWm)
- Design Discharge of Each Unit (m^3/s)
- Maximum Reservoir Operation Level (m)
- Minimum Reservoir Operation Level (m)

- Tailwater Level for Design Discharge (m)
- Design Discharge Net Head (m)
- Initial Reservoir Operation Level (m)
- Final Reservoir Operation Level (m) (not valid for RLOR model)
- First Year of Inflow Data
- Last Year of Inflow Data
- Area-Volume Curve Data in a Tabular Form
- Monthly Evaporation (mm)
- Monthly Other Uses from Reservoir (hm³)
- Monthly Downstream Water Rights (hm³)
- Inflow (hm³) (Monthly, Daily or Hourly according to the preferred operation)

As mentioned before, a real turbine hill chart from Atatürk Dam and HEPP (Su Ener, 2020) for a vertical Francis turbine, was used for the efficiency calculation of electromechanical equipment. A tabular form of the turbine efficiency was implemented for percent turbine discharge (discharge to design discharge ratio) and percent turbine head (net head to design net ratio). Efficiency of turbines was calculated from turbine hill chart for every operation time step separately according to the average net head and turbine discharge of that time step.

Efficiency of generators was calculated by a polynomial function derived from the Kepez HEPP generator efficiency data for percent output power (output power to design output power ratio).

Efficiency of transformers was taken as a constant value of 0.975 (Vito, 2011) as they do not change considerably with different output levels.

η , Overall efficiency of turbine-generator-transformer units is calculated with the following Equation;

$$\eta_i = \eta_{Ti} \eta_{Gi} \eta_{Tri} , \quad i = 1, \dots, 240 \quad (1)$$

where

η_{Ti} = Turbine Efficiency of i_{th} month

η_{Gi} = Generator Efficiency of i_{th} month

η_{Tri} = Transformer Efficiency of i_{th} month

η_T (Turbine Efficiency) is a function of H_{net} and Q . In order to calculate η_T , Turbine Hill Chart Data of Atatürk Dam HEPP, Su Ener, 2020 is used. Hill chart is regenerated from the raw data using UniPlot Software and given in Figure 3.1. Horizontal axis of the figure is the ratio of net head to design net head and vertical axis is the ratio of turbine discharge to turbine design discharge. For any flow rate and net head ratios, respective wicket gate opening (in degrees), turbine power ratio (ratio of turbine power for that instant to installed capacity of turbine) and turbine efficiency can be found from the hill chart. Efficiency data is then converted to a tabular form by using the same software. Efficiency η_T is interpolated for the corresponding H_{net} and Q of each month using the tabular form of efficiency data.

η_G (Generator Efficiency) is a function of Turbine Output Power Percentage. In order to calculate η_G Generator Efficiency Curve of Kepez Dam HEPP (Figure 3.2) is regenerated from the raw data and used with a best fit curve polynomial function. Horizontal axis of Figure 3.2 is turbine power ratio and vertical axis is generator efficiency. For any turbine power ratio, respective generator efficiency can be found from the figure.

η_{Tr} (Transformer Efficiency) is a function of the load factor of the transformer, but the change is so small that it is accepted as a constant value of 0.975 (Vito, 2011).

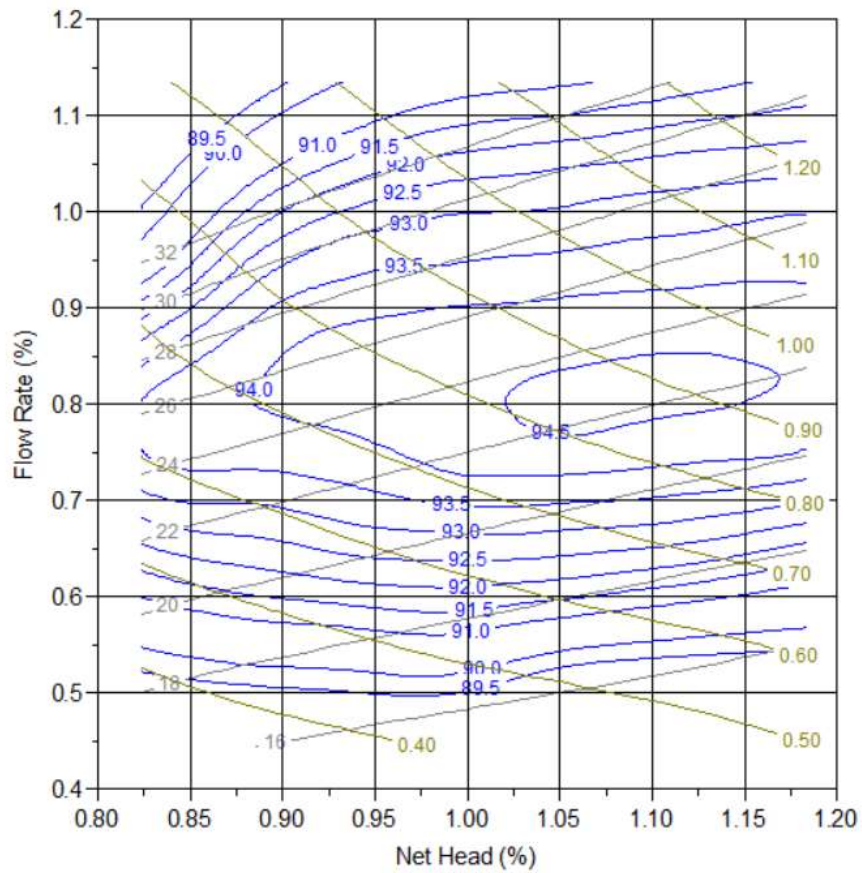


Figure 3.1 Normalized Turbine Hill Chart of Atatürk Dam HEPP (Su Ener, 2020)

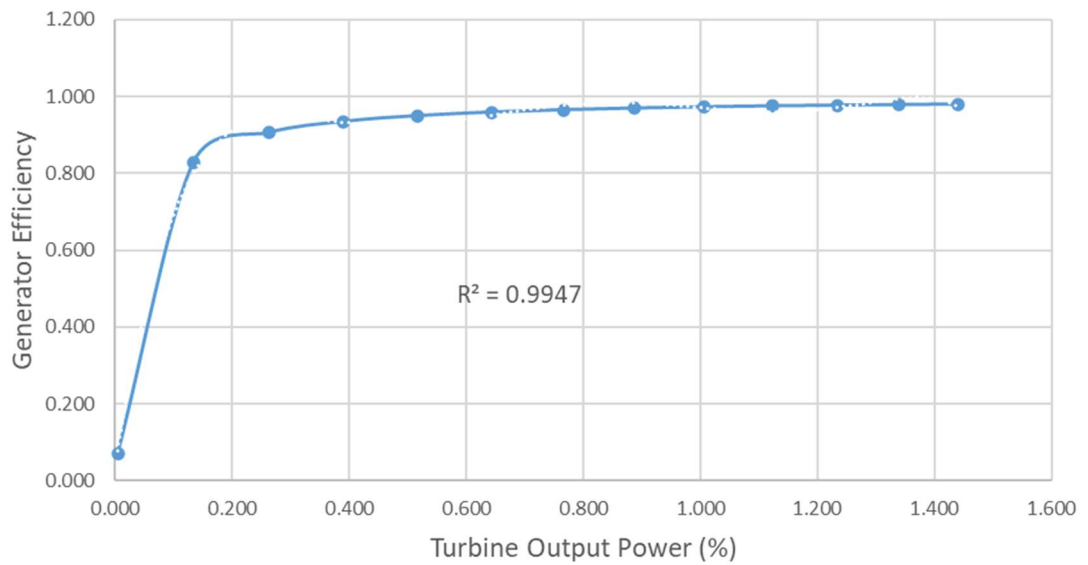


Figure 3.2 Generator Efficiency Curve of Kepez Dam HEPP

In addition to the characteristic information provided for maximization of energy, monthly average Energy Prices (TL/MWh) should also be provided by the user into the tool for maximization of revenue. The following further additional information should be provided into the tool for maximization of profit.

- Tunnel Excavation Unit Cost (TL/m³)
- Tunnel Concrete Unit Cost (TL/m³)
- Tunnel Reinforcement Unit Cost (TL/ton)
- Tunnel Formwork Unit Cost (TL/m²)
- Tunnel Excavation Support System Unit Cost (TL/m)
- Tunnel Stabilization Works (Injection etc.) Unit Cost (TL/m)
- Ratio of Concrete Liner Thickness to Inner Diameter of Tunnel (%)
- Reinforcement Amount (kg) Per Cubic Meter of Concrete (kg/m³)
- Contingency Ratio for Tunnel Works (%)
- Penstock Steel Unit Cost (TL/ton)
- Penstock Excavation Unit Cost (TL/m³)
- Penstock Concrete Unit Cost (TL/m³)
- Penstock Reinforcement Unit Cost (TL/ton)
- Ratio of Steel Thickness to Inner Diameter of Penstock (%)
- Average Excavation Amount Per Meter Alignment Along Penstock (m³/m)
- Average Concrete Amount Per Meter Alignment Along Penstock (m³/m)
- Reinforcement Amount (kg) Per Cubic Meter of Concrete (kg/m³)
- Contingency Ratio for Penstock Works (%)
- Powerhouse EM Equipment Unit Cost (TL/MW)
- Powerhouse Civil Works Unit Cost (TL/MW)
- Contingency Ratio for Powerhouse Works (%)
- Minimum Required Tunnel Inner Diameter (m)
- Maximum Allowable Water Velocity in The Tunnel (m/s)
- Maximum Allowable Water Velocity in The Penstock (m/s)
- Interest Rate (%)

3.1.2 Cascade Storage Systems

For Cascade Storage Systems, operation tools were developed for two different purposes. Maximization of energy and maximization of revenue with monthly operation for a duration of 20 years. For maximization of energy, the user has the option of choosing one of the three different reservoir operation models of FRLEO, FRLEY and RLOR. For maximization of revenue, two different reservoir operation options are provided, FRLEO and FRLEY.

The tools developed covers cascade systems of 3 reservoir-powerhouse schemes. The same characteristic information should be provided into the model for each reservoir-powerhouse scheme as defined in 3.1.1 Single Storage Systems by using the user interface. Overall efficiency of turbine-generator-transformer units is calculated with the same method as defined in 3.1.1 Single Storage Systems.

3.1.3 Run-of-River Systems

For Run-of-River Systems, operation tools were developed for two different purposes, maximization of energy and maximization of revenue. For maximization of energy daily operation for a duration of 2 years is considered for a system with no storage capacity at all. The aim is to determine which turbine or turbines shall be operated for the forecasted inflow values to generate the maximum energy. For maximization of revenue, 15-minute time step operation for a duration of 1 day is considered for a system with a small amount of storage capacity somewhere in the water way like settling pond, head pond or power race tunnel. The aim is to determine which turbine or turbines shall be operated and for how long, for the forecasted inflow values and energy prices to maximize the daily revenue.

Overall efficiency of turbine-generator-transformer units is calculated with the same method as defined in 3.1.1 Single Storage Systems.

The following characteristic information should be provided into the model by using the user interface developed for maximization of energy.

- Name of the Project
- Length of Power Tunnel (m)
- Diameter of Power Tunnel (m)
- Length of Penstock (m)
- Diameter of Penstock (m)
- Surface Roughness of Power Tunnel (mm)
- Surface Roughness of Penstock (mm)
- Total Number of Units
- Installed Capacity of Each Unit (MWm)
- Design Discharge of Each Unit (m^3/s)
- Reservoir Operation Level (m)
- Tailwater Level for Design Discharge (m)
- First Year of Inflow Data
- Last Year of Inflow Data
- Downstream Water Rights (m^3/s)
- Daily Average Inflow (m^3/s)

Instead of “First Year of Inflow Data” and “Last Year of Inflow Data” input, the start and end years of inflow data, provided for maximization of energy, the specific date of the inflow data should be provided for maximization of revenue as it is a one-day operation process. Moreover, instead of Daily Average Inflow data, Hourly Average Inflow (m^3/s) data should be provided. Additionally, Total Storage Capacity (m^3), Available Storage at the Start of Operation (m^3) and average 15-minute duration Energy Prices (TL/MWh) should be provided.

3.2 Generalized Reduced Gradient (GRG) Method

Generalized Reduced Gradient (GRG) methods are algorithms for solving non-linear programs of general structure (Lasdon et al., 1974). The basic ideas of GRG are described as follows by Lasdon et al., 1974.

The nonlinear program to be solved is assumed to have the form

$$\text{minimize } f(X) \quad (2)$$

$$\text{subject to } g_i(X) = 0 \quad , \quad i = 1, \dots, m \quad (3)$$

$$l_i \leq X_i \leq u_i \quad , \quad i = 1, \dots, n \quad (4)$$

where X is n -vector and u_i, l_i are given lower and upper bounds $u_i > l_i$. Assuming $m < n$ since, in most cases, $m \geq n$ implies an infeasible problem or one with a unique solution, The form of Equations (2)-(4) is completely general, since inequality constraints may always be transformed to equalities, as in Equation (3), by the addition of slack variables. The vector X contains as components both the natural variables of the problem and these slacks.

The fundamental idea of GRG is to use the Equation (3) to express m of the variables, called basic variables, in terms of the remaining $n-m$ non-basic variables. Letting $\bar{X}$ be a feasible point and let y be the vector of basic variables and x the non-basic at $\bar{X}$, so that X is partitioned as

$$X = (y, x), \bar{X} = (\bar{y}, \bar{x}) \quad (5)$$

and the Equation (4) can be written as

$$g(y, x) = 0 \quad (6)$$

where

$$g = (g_1, \dots, g_m) \quad (7)$$

Assuming that the objective f and constraint functions g_i are differentiable, by the implicit function theorem, in order that the Equation (6) have a solution $y(x)$ for all x in some neighborhood of $\bar{x}$, it is sufficient that the $m \times m$ basis matrix $\partial g/\partial y$, evaluated at $\bar{X}$, be nonsingular. Then the objective may be expressed as a function of x only:

$$F(x) = f(y(x), x) \quad (8)$$

and the nonlinear program is transformed, at least for x close to $\bar{x}$, to a reduced problem with only upper and lower bounds:

$$\text{minimize } F(x) \quad (9)$$

subject to:

$$l_{NB} \leq x \leq u_{NB} \quad (10)$$

where l_{NB} and u_{NB} are the vectors of bounds for x . GRG solves the original problem (2)-(4) by solving a sequence of problems of the form (9)-(10).

3.3 Mathematical Model

3.3.1 Single Storage Systems

3.3.1.1 Maximization of Energy – FRLEO

The optimal operation of a reservoir should be subject to certain constraints related to decision and state variables. Decision variables represent releases from a reservoir, and state variables represent pool elevations (Al-Aqeeli et al., 2020). The following algorithm scheme given in Figure 3.3, is used for the development of optimization tool for single reservoir operation with the purpose of maximization of energy and utilizing FRLEO model.

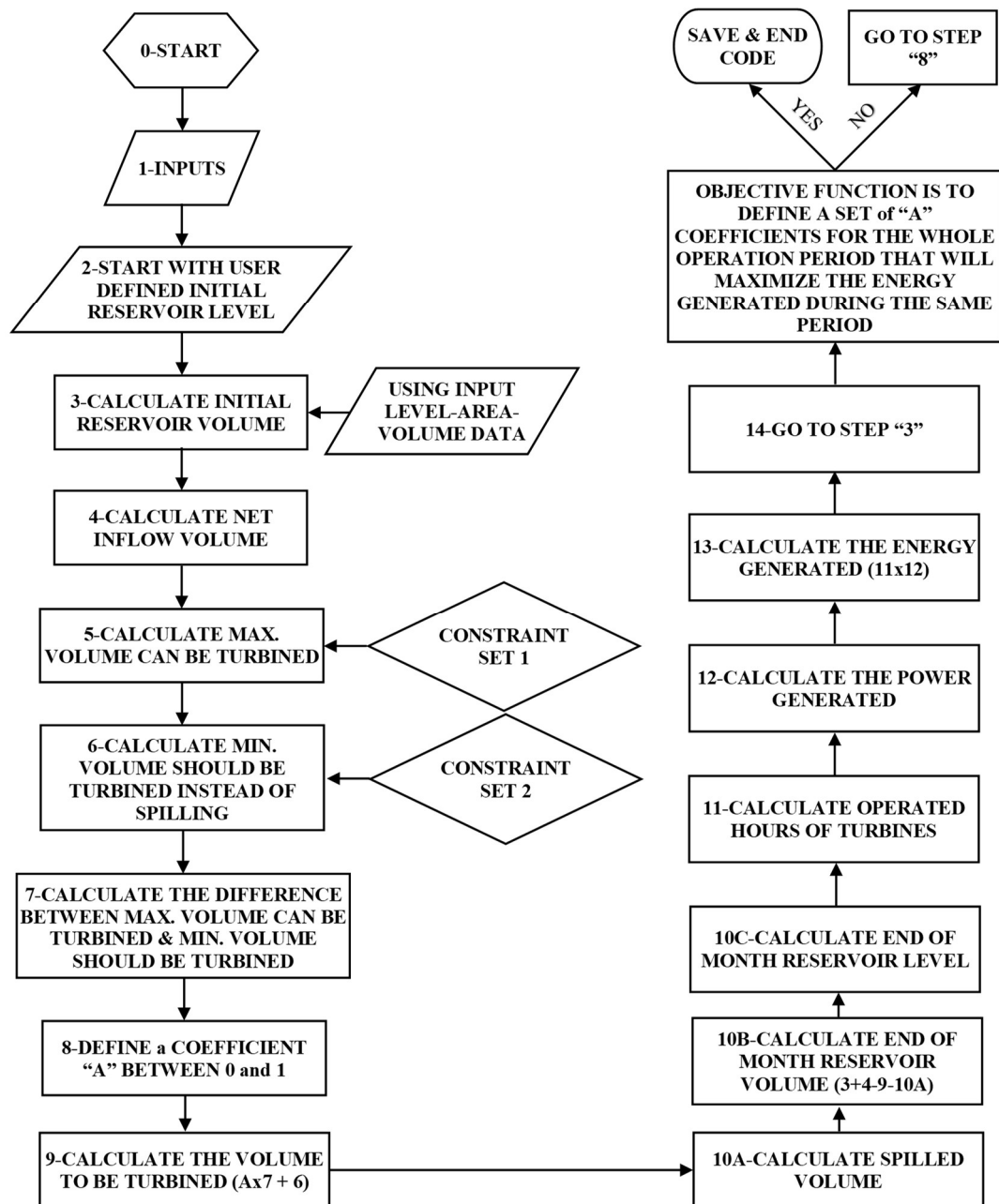


Figure 3.3 Flowchart for single reservoir operation optimization, maximization of energy – FRLEO

Each step and formulation is described as follows:

i. Step (1) Inputs

As mentioned before in Section 3.1.1, characteristic information of the system and monthly inflow data as hm^3 for 49 years, is provided into the model by using the user interface developed.

A real turbine hill chart from Atatürk Dam and HEPP (Su Ener, 2020) is used for the efficiency calculation of electromechanical equipment.

A polynomial function derived from the Kepez HEPP generator efficiency data for percent output power (output power to design output power ratio) is used for the efficiency calculation of generators.

Efficiency of transformers was taken as a constant value of 0.975 (Vito, 2011) as they do not change considerably with different output levels.

ii. Step (2) Start with User Defined Operation Water Level

Reservoir elevation at the start of first month of operation is defined by the user, RL_{B1} (m).

iii. Step (3) Calculate Corresponding Reservoir Volume

Initial reservoir volume is calculated according to user defined RL_{Bi} using Area-Volume Curve Data and developed linear interpolation sub-routine, reservoir volume at the start of month RV_{B1} (hm^3).

iv. Step (4) Calculate Net Inflow Volume

Net inflow volume (hm^3) is calculated by following formulation:

$$NI_i = I_i - OU_i - EV_i , \quad i = 1, \dots, 588 \quad (11)$$

where

NI_i = Net Inflow Volume at i_{th} month (hm^3)

I_i = Inflow Volume at i_{th} month (hm^3) (Input)

OU_i = Other Uses from Reservoir at i_{th} month (hm^3) (Input)

EV_i = Evaporation from The Reservoir at i_{th} month (hm^3) (Input)

v. Step (5) Calculate Max Volume That Can Be Turbined

First calculate capacity of turbines for that month:

$$CPT_i = TDD \times ND_i \times 60 \times 60 \times 24 / 1,000,000 , \quad i = 1, \dots, 588 \quad (12)$$

where

CPT_i = Capacity of turbines at i_{th} month (hm^3)

TDD = Total Turbine Design Discharge (m^3/s) (Input)

ND_i = Number of days at i_{th} month

Then calculate the water volume available for turbinning above min. reservoir water level;

$$MaxVTT_i = RV_{Bi} + NI_i - MinROLV , \quad i = 1, \dots, 588 \quad (13)$$

where

$MaxVTT_i$ = Max volume that can be turbinned at i_{th} month (hm^3)

RV_{Bi} = Reservoir volume at the beginning of i_{th} month (hm^3)

NI_i = Net Inflow Volume at i_{th} month (hm^3)

$MinROLV$ = Reservoir volume at the min operation water level (hm^3)

Subject to;

$$\text{MaxVTT}_i \leq \text{CPT}_i$$

$$\text{MaxVTT}_i \geq 0$$

- vi.** Step (6) Calculate Min Volume That Should Be Turbined Instead of Spilling

$$\text{MinVTT}_i = \text{RV}_{Bi} + \text{NI}_i - \text{MaxROLV}, \quad i = 1, \dots, 588 \quad (14)$$

where

MinVTT_i = Min volume that should be turbined at i_{th} month (hm^3)

RV_{Bi} = Reservoir volume at the beginning of i_{th} month (hm^3)

NI_i = Net Inflow Volume at i_{th} month (hm^3)

MaxROLV = Reservoir volume at the max operation water level (hm^3)

Subject to;

$$\text{MinVTT}_i \leq \text{CPT}_i$$

$$\text{MinVTT}_i \geq \text{DWR}_i \text{ (Downstream Water Rights of } i_{\text{th}} \text{ month)}$$

$$\text{MinVTT}_i \geq 0$$

- vii.** Step (7) Calculate the Difference Between Max Volume That Can Be Turbined and Min Volume That Should Be Turbined Instead of Spilling

$$\text{DVTT}_i = \text{MaxVTT}_i - \text{MinVTT}_i, \quad i = 1, \dots, 588 \quad (15)$$

Where

$DVTT_i$ = Difference between max volume that can be turbined and min volume that should be turbined at i_{th} month (hm^3)

$MaxVTT_i$ = Max volume that can be turbined at i_{th} month (hm^3)

$MinVTT_i$ = Min volume that should be turbined at i_{th} month (hm^3)

viii. Step (8) Define a Coefficient “A” Between 0 and 1

$$A_i = A \text{ coefficient at } i_{th} \text{ month (assumed 0.5 initially),}$$

$$i = 1, \dots, 588$$
(16)

Subject to;

$$A_i \geq 0$$

$$A_i \leq 1$$

ix. Step (9) Calculate the Volume to Be Turbined

$$VTT_i = (DVTT_i \times A_i) + MinVTT_i, \quad i = 1, \dots, 588$$
(17)

Where

VTT_i = volume to be turbined at i_{th} month (hm^3)

$DVTT_i$ = Difference between max volume that can be turbined and min volume that should be turbined at i_{th} month (hm^3)

A_i = A coefficient at i_{th} month (assumed as 0.5 initially)

$MinVTT_i$ = Min volume that should be turbined at i_{th} month (hm^3)

- x.** Step (10) Calculate the End of Month Reservoir Volume, End of Month Reservoir Level and Spilled Volume

- a.** Step (10A) Calculate Spilled Volume

$$SV_i = (RV_{Bi} + NI_i) - VTT_i - \text{MaxROLV}, \quad i = 1, \dots, 588 \quad (18)$$

Where

SV_i = volume spilled at i_{th} month (hm^3)

RV_{Bi} = Reservoir volume at the beginning of i_{th} month (hm^3)

NI_i = Net Inflow Volume at i_{th} month (hm^3)

VTT_i = volume to be turbined at i_{th} month (hm^3)

MaxROLV = Reservoir volume at the max operation water level (hm^3)

Subject to;

$$SV_i \geq 0$$

- b.** Step (10B) Calculate End of Month Reservoir Volume

$$RV_{Ei} = (RV_{Bi} + NI_i) - VTT_i - SV_i, \quad i = 1, \dots, 588 \quad (19)$$

Where

RV_{Ei} = Reservoir volume at the end of i_{th} month (hm^3)

RV_{Bi} = Reservoir volume at the beginning of i_{th} month (hm^3)

NI_i = Net Inflow Volume at i_{th} month (hm^3)

VTT_i = volume to be turbined at i_{th} month (hm^3)

SV_i = volume spilled at i_{th} month (hm^3)

c. Step (10C) Calculate End of Month Reservoir Elevation

Linear interpolation using input Area-Volume Curve Data to find the reservoir elevation at the end of each month RL_{Ei} (m) by developed subroutine.

xi. Step (11) Calculate Hours of Operation Using Design Discharge of Turbines

$$HO_i = \frac{VTT_i}{TDD \times 60 \times 60} \times 1,000,000, \quad i = 1, \dots, 588 \quad (20)$$

Where

HO_i = Hours of operation at i_{th} month (hours)

VTT_i = volume to be turbined at i_{th} month (hm^3)

TDD = Total Turbine Design Discharge (m^3/s) (Input)

xii. Step (12) Calculate the Power Generated

a. Step (12A) Calculate Net Head

H_{net} (Net Water Head) is calculated by subtracting the head losses from the gross head;

$$H_{neti} = H_{grossi} - H_{lossi}, \quad i = 1, \dots, 588 \quad (21)$$

Where

H_{neti} = Net Head at i_{th} month (m)

H_{grossi} = Gross Head at i_{th} month (m)

H_{lossi} = Total Head Loss at i_{th} month (m)

H_{grossi} (Gross Water Head) is calculated by subtracting tailwater level (assumed constant) from the average reservoir water level of that month;

$$H_{grossi} = \frac{(RL_{Bi} + RL_{Ei})}{2} - TL, \quad i = 1, \dots, 588 \quad (22)$$

Where

RL_{Bi} = Reservoir elevation at the start of i_{th} month (m)

RL_{Ei} = Reservoir elevation at the end of i_{th} month (m)

TL = Tailwater level (m) (Input)

H_{lossi} (Total Head Loss) is the sum of friction losses and minor losses of that month;

$$H_{lossi} = h_{fi} + h_{mi}, \quad i = 1, \dots, 588 \quad (23)$$

Where

h_{fi} = Friction head losses of i_{th} month (m) = $h_{ftunnel} + h_{fpenstock}$

h_{mi} = Minor head losses of i_{th} month (m)

Minor head losses (h_m) such as entrance loss, bend losses, expansion losses, contraction losses and valve losses are neglected as they are comparatively small with respect to friction losses.

Friction losses (h_{fi}) are calculated for the tunnel and penstock separately with Darcy-Weisbach (Darcy 1857, Weisbach 1845 and Moody 1944) equation. For a full-flowing circular cross section, Darcy-Weisbach equation becomes;

$$h_{fi} = \frac{f_{Di}LV^2}{2gD_H}, \quad i = 1, \dots, 588 \quad (24)$$

Where

f_{Di} = Darcy-Weisbach Friction factor of i_{th} month

L = Length of the penstock or tunnel (m) (Input)

V = Flow velocity in the penstock or tunnel (m/s) (Calculated by using Input Turbine Design Discharge and Input Tunnel and Penstock diameters)

g = Gravitational Acceleration (m/s^2) = $9.81 m/s^2$

D_H = The hydraulic diameter of the penstock or tunnel (for a circular section, this equals the physical diameter of the penstock or tunnel; otherwise,

$$D_H = 4A/P \quad (25)$$

for a cross-sectional area A (m^2), and wetted perimeter P (m)

Darcy-Weisbach friction factor is calculated by using the Swamee–Jain equation;

$$f_D = \frac{1.325}{\left[\ln \left(\frac{\varepsilon/D_H}{3.7} + \frac{5.74}{Re^{0.9}} \right) \right]^2} \quad (26)$$

Where

ε = Roughness height(m) (Input 0.60 mm for concrete and 0.15 mm for steel if not changed by user)

D_H = The hydraulic diameter (m)

Re = Reynolds Number

Reynolds Number is calculated by using the following equation (Munson et al., 2006);

$$Re = \frac{VD_H}{\nu} \quad (27)$$

Where

V = Flow velocity in the penstock or tunnel (m/s)

D_H = The hydraulic diameter of the penstock or tunnel (m)

ν = Kinematic viscosity of water (m²/s) (assumed as 0.000001519 m²/s)

It is assumed that the turbines are operated only with the design discharge of the turbine because the purpose is maximizing the energy production, and this type of operation would give the maximum results for a HEPP with storage in monthly operation. So, Q (Turbine Discharge) always becomes equal the design discharge as long as the turbines are in operation.

b. Step (12B) Calculate EM Equipment Efficiencies

Overall efficiency of turbine-generator-transformer units is calculated with the method defined in Section 3.1.1.

c. Step (12C) Calculate the Power Generated

Following formula is used to calculate the power generated;

$$P_i = \rho g H_{neti} Q \eta_i, \quad i = 1, \dots, 588 \quad (28)$$

Where

P_i = Power generation at i th month (Watt)

ρ = Density of the water (kg/m³) = 1,000 kg/ m³

g = Gravitational acceleration (m/s²) = 9.81 m/s²

H_{neti} = Net Head at i th month (m)

Q = Turbine design discharge (m^3/s) (Input)

η_i = Overall efficiency of turbine-generator-transformer units at i_{th} month

xiii. Step (13) Calculate the Energy Produced

Following formula is used to calculate the energy produced;

$$E_i = P_i \times HO_i / 1,000,000,000, \quad i = 1, \dots, 588 \quad (29)$$

Where

E_i = Energy generation at i_{th} month (GWh)

P_i = Power generation at i_{th} month (Watt)

HO_i = Hours of operation at i_{th} month (hours)

xiv. Step (14) Go to Step (3) For Next Time Step

$$RV_{Bi+1} = RV_{Ei}, \quad i = 1, \dots, 588 \quad (30)$$

Where

RV_{Bi+1} = Reservoir volume at the start of $i+1_{\text{th}}$ month (hm^3)

RV_{Ei} = Reservoir volume at the end of i_{th} month (hm^3)

xv. Objective Function

$$\text{Max} \sum_{i=1}^{588} E_i, \quad i = 1, \dots, 588 \quad (31)$$

Where

Variables are $A_i \sim A_n$

Subject to;

$$A_i \geq 0, \quad i = 1, \dots, 588 \quad (32)$$

$$A_i \leq 1, \quad i = 1, \dots, 588 \quad (33)$$

Objective function for this kind of problems is generally given as;

$$\text{Max} \sum_{i=1}^n (\rho g H_{neti} Q \eta_i) x \left(\frac{VTT_i}{TDD \times 60 \times 60} \times 1,000,000 \right), \quad i = 1, \dots, n \quad (34)$$

Subject to;

$$VTT_i \leq CPT_i, \quad i = 1, \dots, n \quad (35)$$

$$VTT_i \geq DWR_i, \quad i = 1, \dots, n \quad (36)$$

$$VTT_i \geq 0, \quad i = 1, \dots, n \quad (37)$$

$$VTT_i \leq RV_{Bi} + NI_i - \text{MinROLV}, \quad i = 1, \dots, n \quad (38)$$

$$VTT_i \geq RV_{Bi} + NI_i - \text{MaxROLV}, \quad i = 1, \dots, n \quad (39)$$

$$SV_i = (RV_{Bi} + NI_i) - VTT_i - \text{MaxROLV}, \quad i = 1, \dots, n \quad (40)$$

$$SV_i \geq 0, \quad i = 1, \dots, n \quad (41)$$

$$RV_{Ei} = (RV_{Bi} + NI_i) - VTT_i - SV_i, \quad i = 1, \dots, n \quad (42)$$

$$RV_{Ei} \leq \text{MaxROLV}, \quad i = 1, \dots, n \quad (43)$$

$$RV_{Bi+1} = RV_{Ei}, \quad i = 1, \dots, n \quad (44)$$

where

P_i = Power generation at i^{th} month (Watt)

ρ = Density of the water (kg/m^3) = 1,000 kg/m^3

g = Gravitational acceleration (m/s^2) = 9.81 m/s^2

H_{neti} = Net Head at i_{th} month (m)

Q = Turbine design discharge (m^3/s) (Input)

η_i = Overall efficiency of turbine-generator-transformer units at i_{th} month

VTT_i = volume to be turbined at i_{th} month (hm^3)

TDD = Total Turbine Design Discharge (m^3/s) (Input)

CPT_i = Capacity of turbines at i_{th} month (hm^3)

DWR_i = Downstream Water Rights of i_{th} month

RV_{Bi} = Reservoir volume at the beginning of i_{th} month (hm^3)

NI_i = Net Inflow Volume at i_{th} month (hm^3)

$MinROLV$ = Reservoir volume at the min operation water level (hm^3)

$MaxROLV$ = Reservoir volume at the max operation water level (hm^3)

SV_i = volume spilled at i_{th} month (hm^3)

RV_{Ei} = Reservoir volume at the end of i_{th} month (hm^3)

RV_{Bi+1} = Reservoir volume at the start of $i+1_{th}$ month (hm^3)

By using the above-described method and implementation of coefficient “A” as variable, the objective function is reduced to a form of Equations (31-33).

The described algorithm and formulation above in Equations (11-33) is the case with no constraint applied by the user on reservoir levels except the continuity constraints already exist in the algorithm.

The following constraint is added to the mathematical model in Equation (31) for FRLEO model;

$$RL_{E588} \geq RL_{EU} \quad (45)$$

Where

RL_{E588} = Reservoir level at the end of 588th month (m)

RL_{EU} = User defined minimum reservoir level required at the end of 588th month (m)

3.3.1.2 Maximization of Energy – FRLEY

The algorithm for FRLEY operation model is almost same with the FRLEO operation model. The only difference is the constraint applied in step 15. The following constraint is applied instead of Equation (45) to the mathematical model in Equation (31) for FRLEY model;

$$RL_{En} \geq RL_{EU} \quad , \quad n = 12, 24, 36, 48 \dots, 588 \quad (46)$$

Where

RL_{En} = Reservoir level at the end of each 12th month (m)

RL_{EU} = User defined minimum reservoir level required at the end of each 12th month (m)

3.3.1.3 Maximization of Energy – RLOR

The algorithm for RLOR model is constructed on FRLEO model with major differences. In FRLEO model the variables were so called “A” coefficients and the turbined volume of water of each month was defined as a function of “A”. In RLOR model the variables are again “A” coefficients but end of month reservoir water levels are defined as a function of “A”.

The following algorithm scheme given in Figure 3.4, is used for single reservoir operation with the purpose of maximization of energy and utilizing RLOR model.

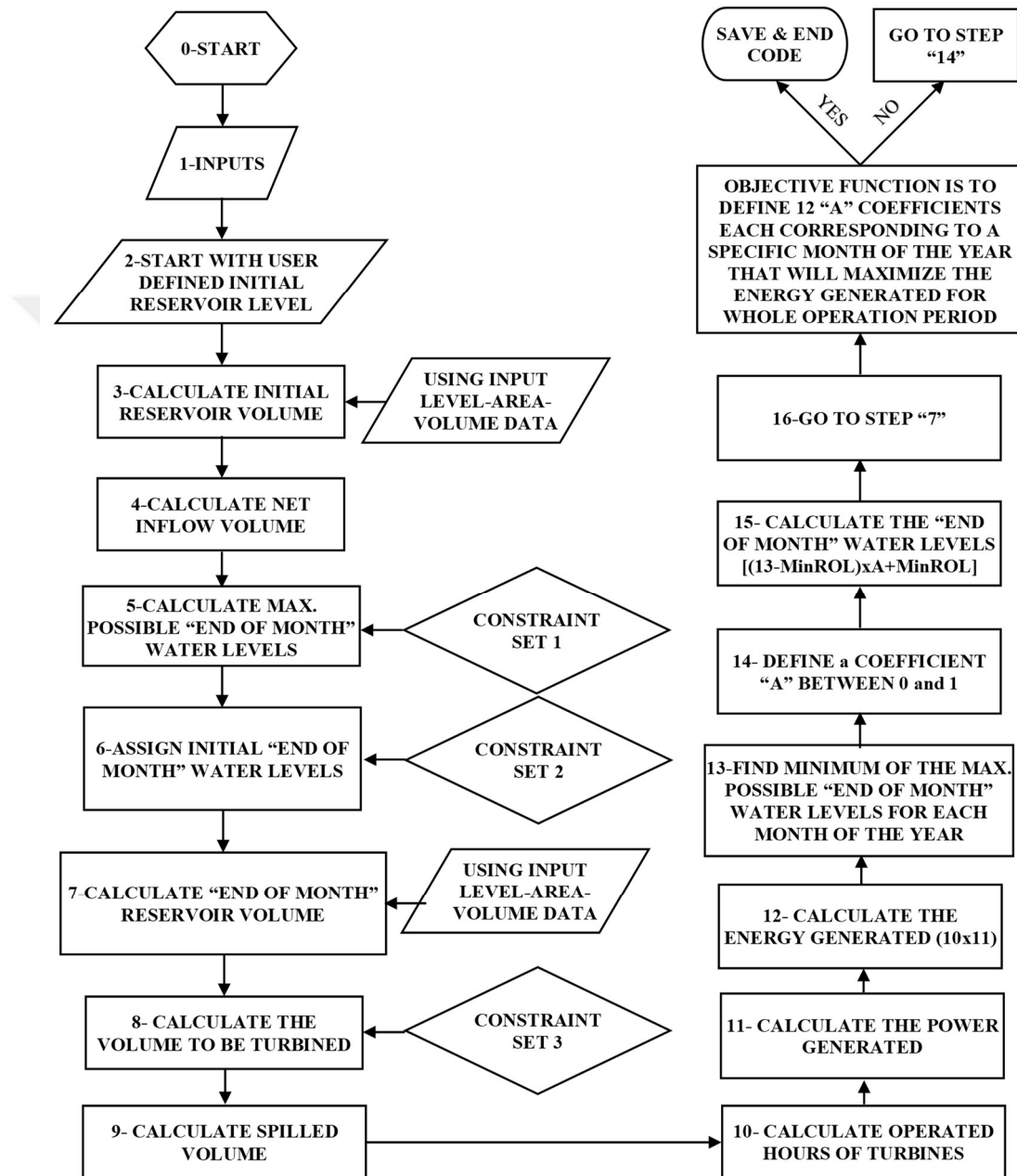


Figure 3.4 Flowchart for single reservoir operation optimization, maximization of energy – RLOR

Each step and formulation is described as follows:

i. Step (1) Inputs

As mentioned before in Section 3.3.1.1, the same characteristic information of the system and data is provided into the model by using the user interface developed.

ii. Step (2) Start with User Defined Operation Water Level

Reservoir elevation at the start of first month of operation is defined by the user, RL_{B1} (m).

iii. Step (3) Calculate Corresponding Reservoir Volume

Initial reservoir volume is calculated according to user defined RL_{Bi} using Area-Volume Curve Data and developed linear interpolation sub-routine, reservoir volume at the start of month RV_{B1} (hm^3).

iv. Step (4) Calculate Net Inflow Volume

Net inflow volume (hm^3) is calculated with Equation (11)

v. Step (5) Calculate Max Possible End of Month Reservoir Levels

First calculate total water volume at the beginning of that month:

$$TV_{Bi} = RV_{B1} + NI_i, \quad i = 1, \dots, 588 \quad (47)$$

where

TV_{Bi} = Total water volume at the beginning of i_{th} month (hm^3)

NI_i = Net inflow volume at i_{th} month (hm^3)

Then, using Area-Volume Curve Data and developed linear interpolation sub-routine, maximum possible end of month reservoir level $MaxRL_{Ei}$, corresponding to TV_{Bi} is calculated with following constraints.

$$MaxRL_{Ei} \leq MaxROL, \quad i = 1, \dots, 588 \quad (48)$$

where

$MaxRL_{Ei}$ = Max possible end of month reservoir level at i_{th} month (m)

$MaxROL$ = Max reservoir operation level (m) (Input)

vi. Step (6) Assign Initial End of Month Reservoir Water Levels

First, sort the maximum possible end of month reservoir levels calculated in step 5, for each month of the year and then find the minimum of them. Considering that the reservoir levels of the same months of every year will be the same, found minimum values are actual maximum possible end of month reservoir level of that specific month. A total of 12 values ($MaxRL_{Em}$) are defined representing maximum possible end of month reservoir levels for whole operation period. 1 value for October, 1 value for November, 1 value for December etc. that are same for every year for whole operation duration. Then assign an initial end of month reservoir level between defined 12 value and minimum operation water level for each month (12 total repeating every year).

$$RL_{Em} = (MaxRL_{Em} - MinROL) \times 0.7 + MinROL \quad (49)$$

$m = \text{October, November, December September}$

where

RL_{Em} = Reservoir level at month m (m)

$MaxRL_{Em}$ = Maximum possible reservoir level at month m (m)

$MinROL$ = Reservoir level at the min operation water level (m)

vii. Step (7) Calculate End of Month Reservoir Volume

End of month reservoir volumes, RV_{Ei} (hm^3), are calculated according to the reservoir levels calculated by Equation (49) using Area-Volume Curve Data and developed linear interpolation sub-routine.

viii. Step (8) Calculate The Volume To Be Turbined

First capacity of turbines for that month (CPT_i) is calculated using Equation (12).

Then the water volume that will be turbined is calculated

$$VTT_i = TV_{Bi} - RV_{Ei}, \quad i = 1, \dots, 588 \quad (50)$$

Subject to;

$$VTT_i \leq CPT_i, \quad i = 1, \dots, 588 \quad (51)$$

Where

VTT_i = volume to be turbined at i_{th} month (hm^3)

ix. Step (9) Calculate Spilled Volume of Water

$$SV_i = TV_{Bi} - VVT_i - RV_{Ei}, \quad i = 1, \dots, 588 \quad (52)$$

Subject to;

$$SV_i \geq 0$$

Where

SV_i = Water volume spilled at i_{th} month (hm^3)

RV_{Ei} = Reservoir volume at the end of i_{th} month (hm^3)

x. Step (10) Calculate Hours of Operation Using Design Discharge of Turbines

The hours that the turbines are operated for the corresponding month is calculated with Equation (20)

xi. Step (11) Calculate the Power Generated

The power generated for the corresponding month is calculated with Equations (21) through (28).

xii. Step (12) Calculate the Energy Produced

The energy produced for the corresponding month is calculated with Equation (29).

xiii. Step (13) Find Minimum of the Max. Possible “End of Month” Water Levels for Each Month of the Year

First, sort the maximum possible end of month reservoir levels calculated in step 5, for each month of the year and then find the minimum of them. Considering that the reservoir levels of the same months of every year will be the same, found minimum values are actual maximum possible end of month reservoir level of that specific month. A total of 12 values (MaxRL_{Em}) are defined representing maximum possible end of month reservoir levels for whole operation period. 1 value for October, 1 value for November, 1 value for December etc. that are same for every year for whole operation duration.

xiv. Step (14) Define a Coefficient “A” Between 0 and 1

$$A_m = A \text{ coefficient at month } m \text{ (assumed 0.7 initially),} \quad (53)$$

$m = \text{October, November, December} \dots \dots \text{September}$

Subject to;

$$1 \geq A_m \geq 0$$

xv. Step (15) Calculate End of Month Reservoir Water Levels

Then calculate end of month reservoir levels using “A” coefficient for each month of the year (12 total repeating every year).

$$RL_{Em} = (MaxRL_{Em} - MinROL) \times A_m + MinROL \quad (54)$$

$m = \text{October, November, December} \dots \dots \text{September}$

xvi. Step (16) Go to Step (7)

End of month reservoir volumes, RV_{Ei} (hm^3), are calculated according to the reservoir levels calculated by Equation (54) and process continues.

xvii. Objective Function

$$Max \sum_{i=1}^{588} E_i, \quad i = 1, \dots, 588 \quad (55)$$

Where

Variables are A_m

Subject to;

$$1 \geq A_m \geq 0, \quad (56)$$

$m = \text{October, November, December} \dots \dots \text{September}$

3.3.1.4 Maximization of Revenue – FRLEO

The algorithm and mathematical formulation of Maximization of Revenue with FRLEO model is identical with Maximization of Energy with FRLEO model as defined in Section 3.3.1.1. There are only three differences. First, the user provides the monthly average energy prices (TL/GWh) as mentioned in Section 3.1.1. Second, an additional step is included in the algorithm defined in Section 3.3.1.1 between steps 13 and 14 for the calculation of revenue with following formulation.

$$RVN_i = E_i \times EP_i, \quad i = 1, \dots, 588 \quad (57)$$

Where

E_i = Energy generation at i_{th} month (GWh)

EP_i = Average monthly energy price at i_{th} month (TL/GWh) (Input)

RVN_i = Revenue at i_{th} month (hours)

Third and the last, objective function is for the maximization of revenue instead of energy generated as defined below.

$$Max \sum_{i=1}^{588} RVN_i, \quad i = 1, \dots, 588 \quad (58)$$

3.3.1.5 Maximization of Revenue – FRLEY

The algorithm and mathematical formulation of Maximization of Revenue with FRLEY model is almost identical with Maximization of Revenue with FRLEO model. The only difference is the constraint applied in step 15. The constraint defined in Equation (46) is applied instead of Equation (45) into the mathematical model in Equation (31) for FRLEY model.

3.3.1.6 Maximization of Revenue – RLOR

The algorithm and mathematical formulation of Maximization of Revenue with RLOR model is almost identical with Maximization of Energy with RLOR model as defined in Section 3.3.1.3. There are only three differences. First, the user provides the monthly average energy prices (TL/GWh) as mentioned in Section 3.1.1. Second, an additional step is included in the algorithm defined in Section 3.3.1.3 between steps 12 and 13 for the calculation of revenue with Equation (57).

Third and the last, objective function is for the maximization of revenue instead of energy generated as defined in Equation (58).

3.3.1.7 Maximization of Profit – FRLEO

The algorithm and mathematical formulation of Maximization of Profit with Fixed End of Reservoir Operation model is built on Maximization of Energy with FRLEO model as defined in Section 3.3.1.1 with some differences. First difference is that the monthly average Energy Prices (TL/MWh) and additional characteristic information as defined in Section 3.1.1 should also be provided into the tool by the user. Additional characteristic information provided into the tool is used for cost calculations and alternative derivations. Ancieta 2009, composed some useful diagrams for the electro-mechanical cost estimation, after compiling statistical data on costs of electrical and mechanical equipment for 81 selected hydro power projects that may be used as a guide. Sachin et al., 2013, also studied electro-mechanical cost estimation and developed correlations with runner diameter of turbine, capacity, and head.

Project characteristics information provided by the user is evaluated as Base Scenario. Base Scenario revenue is calculated as defined in Section 3.3.1.4. Then the costs are calculated for the water way powerhouse as defined below.

i. Step (1) Tunnel Excavation Cost

Tunnel excavation cost is calculated with the following formulation.

$$TEC = \frac{[(D_T \times CLTR \times 2) + D_T]^2 \times \pi}{4} \times L_T \times TEUC \quad (59)$$

Where

TEC = Tunnel excavation cost (TL)

D_T = Tunnel diameter (m) (Input)

CLTR= Concrete liner thickness ratio (ratio of concrete liner thickness to tunnel diameter) (%) (input)

L_T = Length of the tunnel (m) (Input)

TEUC = Tunnel excavation unit cost (TL/m³) (Input)

ii. Step (2) Tunnel Concrete Cost

Tunnel concrete cost is calculated with the following formulation.

$$TCC = D_T \times CLTR \times D_T \times \pi \times L_T \times TCUC \quad (60)$$

Where

TCC = Tunnel concrete cost (TL)

TCUC = Tunnel concrete unit cost (TL/m³) (Input)

iii. Step (3) Tunnel Reinforcement Cost

Tunnel reinforcement cost is calculated with the following formulation.

$$TRC = \frac{D_T \times CLTR \times D_T \times \pi \times L_T \times RR_T \times TRUC}{1000} \quad (61)$$

Where

TRC = Tunnel reinforcement cost (TL)

RR_T = Reinforcement ratio tunnel (kg per m³ of concrete) (kg/m³) (input)

TRUC = Tunnel reinforcement unit cost (TL/ton) (Input)

iv. Step (4) Tunnel Formwork Cost

Tunnel formwork cost is calculated with the following formulation.

$$TFC = D_T \times \pi \times L_T \times TFUC \quad (62)$$

Where

TFC = Tunnel formwork cost (TL)

TFUC = Tunnel formwork unit cost per concrete surface area (TL/m²) (Input)

v. Step (5) Tunnel Excavation Support System Cost

Tunnel excavation support system cost is calculated with the following formulation.

$$TESSC = L_T \times TESSUC \quad (63)$$

Where

TESSC = Tunnel excavation support system cost (TL)

TESSUC = Tunnel excavation support system unit cost (TL/m) (Input)

vi. Step (6) Tunnel Stabilization Works Cost

Tunnel stabilization works cost is calculated with the following formulation.

$$TSWC = L_T \times TSWUC \quad (64)$$

Where

TSWC = Tunnel stabilization works cost (TL)

TSWUC = Tunnel stabilization works unit cost (TL/m) (Input)

vii. Step (7) Tunnel Cost Contingency

Tunnel cost contingency is calculated with the following formulation.

$$TC_{CON} = (TEC + TCC + TRC + TFC + TESSC + TSWC) \times TW_{CON} \quad (65)$$

Where

TC_{CON} = Tunnel cost contingency (TL)

TW_{CON} = Tunnel works contingency ratio (%) (Input)

viii. Step (8) Total Tunnel Cost

Total tunnel cost is calculated with the following formulation.

$$TTC = TEC + TCC + TRC + TFC + TESSC + TSWC + TC_{CON} \quad (66)$$

Where

TTC = Total tunnel cost (TL)

ix. Step (9) Penstock Steel Cost

Penstock steel cost is calculated with the following formulation.

$$PSC = \left(\frac{[(D_p \times SLTR \times 2) + D_p]^2 \times \pi}{4} - \frac{D_p^2 \times \pi}{4} \right) \times L_p \times 7.85 \times PSUC \quad (67)$$

Where

PSC = Penstock steel cost (TL)

D_p = Penstock diameter (m) (Input)

SLTR= Steel liner thickness ratio (ratio of steel liner thickness to penstock diameter) (%) (input)

L_p = Length of the penstock (m) (Input)

7.85 = Penstock steel unit weight (ton/m³) (Input)

PSUC = Penstock steel unit cost (TL/ton) (Input)

x. Step (10) Penstock Excavation Cost

Penstock excavation cost is calculated with the following formulation.

$$PEC = PEPM \times L_p \times PEUC \quad (68)$$

Where

PEC = Penstock excavation cost (TL)

PEPM = Average excavation amount per meter of penstock (m³/m) (Input)

PEUC = Penstock excavation unit cost (TL/m³) (Input)

xi. Step (11) Penstock Concrete Cost

Penstock excavation cost is calculated with the following formulation.

$$PCC = PCPM \times L_p \times PCUC \quad (69)$$

Where

PCC = Penstock concrete cost (TL)

PCPM = Average concrete amount per meter of penstock (m³/m) (Input)

PCUC = Penstock concrete unit cost (TL/m³) (Input)

xii. Step (12) Penstock Reinforcement Cost

Penstock excavation cost is calculated with the following formulation.

$$PRC = \frac{PCPM \times L_p \times RR_p \times PRUC}{1000} \quad (70)$$

Where

PRC = Penstock reinforcement cost (TL)

RR_p= Reinforcement ratio penstock (kg per m³ of concrete) (kg/m³) (input)

PRUC = Penstock reinforcement unit cost (TL/ton) (Input)

xiii. Step (13) Penstock Cost Contingency

Penstock cost contingency is calculated with the following formulation.

$$PC_{CON} = (PSC + PEC + PCC + PRC) \times PW_{CON} \quad (71)$$

Where

PC_{CON} = Penstock cost contingency (TL)

PW_{CON} = Penstock works contingency ratio (%) (Input)

xiv. Step (14) Total Penstock Cost

Total penstock cost is calculated with the following formulation.

$$PTC = PSC + PEC + PCC + PRC + PC_{CON} \quad (72)$$

Where

PTC = Penstock total cost (TL)

xv. Step (15) Powerhouse Electromechanical Cost

Powerhouse electro-mechanical cost is calculated with the following formulation.

$$PEMC = PIC \times PEMUC \quad (73)$$

Where

PEMC = Powerhouse electromechanical cost (TL)

PIC = Powerhouse installed capacity (MWm) (Input)

PEMUC = Powerhouse electromechanical unit cost (TL/MWm) (Input)

xvi. Step (16) Powerhouse Civil Works Cost

Powerhouse civil works cost is calculated with the following formulation.

$$PCWC = PIC \times PCWUC \quad (74)$$

Where

PCWC = Powerhouse civil works cost (TL)

PCWUC = Powerhouse civil works unit cost (TL/MWm) (Input)

xvii. Step (17) Powerhouse Cost Contingency

Powerhouse cost contingency is calculated with the following formulation.

$$PWC_{CON} = (PEMC + PCWC) \times PWW_{CON} \quad (75)$$

Where

PWC_{CON} = Powerhouse cost contingency (TL)

PWW_{CON} = Powerhouse works contingency ratio (%) (Input)

xviii. Step (18) Total Powerhouse Cost

Total powerhouse cost is calculated with the following formulation.

$$PWTC = PEMC + PCWC + PWC_{CON} \quad (76)$$

Where

$PWTC$ = Powerhouse total cost (TL)

xix. Step (19) Total Water Way Cost

Total water way cost is calculated with the following formulation.

$$TWWC = TTC + PTC + PWTC \quad (77)$$

Where

$TWWC$ = Total water way cost (TL)

Calculated cost only includes the water way structures as mentioned. Costs related to dam body, spillway structures, diversion structures, bottom outlet structures and access roads should also be considered by the user separately.

$TWWC$ represents the costs at the time of investment or at the time of provided prices. On the other hand, energy prices provided by the user into the model are forecasted future prices and hence the revenues calculated by using these energy prices are forecasted future revenues. In order to make a healthy financial evaluation, net present value (NPV) is calculated for revenues. Net present value (NPV) is a financial term used for evaluation of an investment. NPV is used for projection of all the future cash flows and discounting all those future cash flows to the present day (Wilson 2015). The idea behind is that one TL is more valuable today than it will be tomorrow.

NPV of revenues are calculated as defined below. First the total revenue of each year is calculated separately.

$$RVN_m = \sum_{i=1}^{12} RVN_i^m, \quad i = 1, \dots, 12, m = 1, \dots, 49 \quad (78)$$

Where

RVN_m = Total revenue of m^{th} year (TL)

RVN_i^m = Revenue of i^{th} month in m^{th} year (TL)

Second, the NPV of the revenue of each year is calculated separately.

$$NPV_m = \frac{RVN_m}{(1+i)^m}, \quad m = 1, \dots, 49 \quad (79)$$

Where

NPV_m = Net present value of the revenue of m^{th} year (TL)

i = Yearly average interest rate (%) (Input)

Third and the last, the total NPV of revenues is calculated.

$$RVNT = \sum_{m=1}^{49} NPV_m, \quad m = 1, \dots, 49 \quad (80)$$

Where

$RVNT$ = Total NPV of revenues (TL)

After the calculation of all revenues and water way costs for base scenario, then alternative scenarios are derived. First, 10 installed capacity alternatives are determined. 5 of these are calculated by decreasing the base scenario installed capacity with 4% decrements. The other 5 are calculated by increasing the base scenario installed capacity with 4% increments. Then, the design discharge for each

alternative installed capacity scenario is calculated with following formulation by assuming design net head and efficiency of electromechanical equipment does not change.

$$TDD_a = \frac{PIC_a \times 1000}{HD_{net} \rho g \eta}, \quad a = 1, \dots, 10 \quad (81)$$

where

TDD_a = Total Turbine Design Discharge for a_{th} alternative (m^3/s)

PIC_a = Powerhouse installed capacity for a_{th} alternative (MWm)

HD_{net} = Design net head (m) (Input)

ρ = Density of the water (kg/m^3) = 1,000 kg/m^3

g = Gravitational acceleration (m/s^2) = 9.81 m/s^2

η = Overall efficiency of turbine-generator-transformer units (determined from the efficiency curves for design discharge and design net head values)

Then, the tunnel diameters for each alternative installed capacity scenario are calculated with following formulation.

$$TD_a = \left(\frac{TDD_a \times 4}{VT_{all} \pi} \right)^{0.5}, \quad a = 1, \dots, 10 \quad (82)$$

Subject to

$$TD_a \geq TD_{min}, \quad a = 1, \dots, 10 \quad (83)$$

where

TD_a = Tunnel diameter for a_{th} alternative (m)

VT_{all} = Maximum allowable water velocity in tunnel (m/s) (Input)

TD_{min} = Minimum tunnel diameter required (m) (Input)

Then, the penstock diameters for each alternative installed capacity scenario are calculated with following formulation.

$$PD_a = \left(\frac{TTD_a \times 4}{VP_{all}\pi} \right)^{0.5}, \quad a = 1, \dots, 10 \quad (84)$$

where

PD_a = Penstock diameter for a_{th} alternative(m)

VP_{all} = Maximum allowable water velocity in penstock (m/s) (Input)

In the end 10 alternatives are determined with different installed capacities, different design discharges, different tunnel diameters and different penstock diameters. Other characteristic information such as, tunnel length, penstock length, minimum and maximum reservoir operation level, level-area-volume curve of reservoir, evaporation, other reservoir uses, downstream water rights, inflow data, normalized efficiency curves and energy prizes are assumed to the same as base scenario.

Then, revenues are calculated for each alternative scenario separately as defined in Section 3.3.1.4. After that, the costs are calculated for the water way and powerhouse as defined in the beginning of this Section using the same input with base scenario. After all calculations are completed for all scenarios, results are plotted on a graph for 11 alternatives including base scenario. Total revenue, total costs, total profit, and installed capacities are plotted on the graph. On this graph the user is able to see the effect of increasing or decreasing installed capacity and optimum installed capacity value for obtaining maximum profit from the project.

3.3.2 Cascade Storage Systems

3.3.2.1 Maximization of Energy – FRLEO

The algorithm developed for cascade storage systems is very similar to single storage systems that defined in Section 3.3.1.1. The following algorithm scheme given in

Figure 3.5, is used for the development of optimization tool for cascade reservoir operation with the purpose of maximization of energy and utilizing FRLEO model.

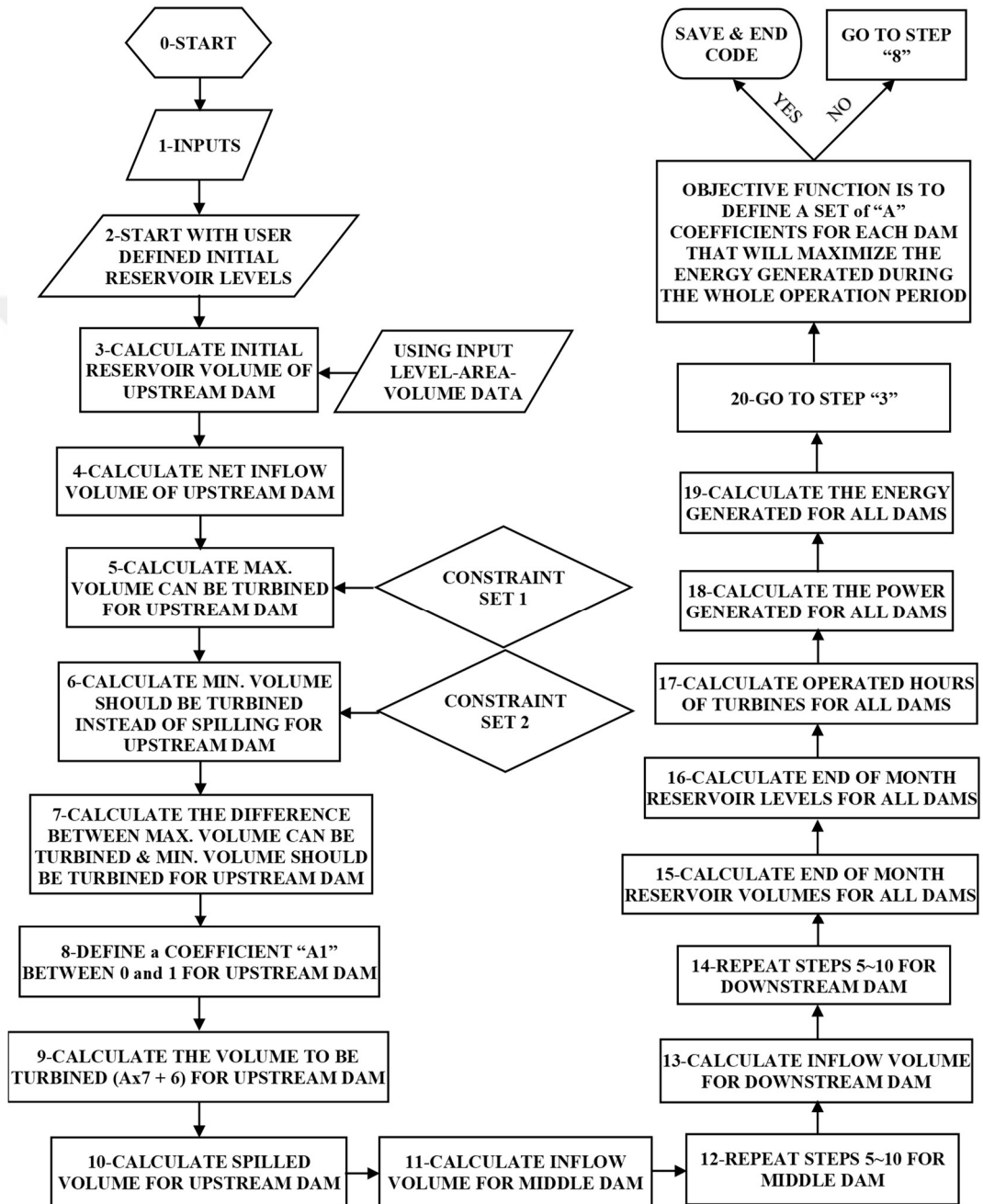


Figure 3.5 Flowchart for cascade reservoir operation optimization, maximization of energy – FRLEO

Each step and formulation is described as follows:

i. Step (1) Inputs

As mentioned before in Section 3.1.1, the same characteristic information of the cascade system for each dam and hydroelectric power station and monthly inflow data as hm^3 for 20 years, is provided into the model by using the user interface developed. Monthly inflow data for the most upstream dam is provided considering the whole catchment area of the upstream dam whereas it is provided considering the interval catchment areas for the middle and downstream dams.

ii. Step (2) Start with User Defined Operation Water Level

Reservoir elevation at the start of first month of operation is defined by the user for each dam separately, RL_{B1} (m).

iii. Step (3) Calculate Corresponding Reservoir Volume of Upstream Dam

Initial reservoir volume is calculated according to user defined RL_{B1} for upstream dam using Area-Volume Curve Data and developed linear interpolation sub-routine, reservoir volume for the upstream dam at the start of month RV_{B1} (hm^3).

iv. Step (4) Calculate Net Inflow Volume for Upstream Dam

Net inflow volume (hm^3) for the upstream dam is calculated by using Equation (11) as defined in Section 3.1.1.

- v.** Step (5) Calculate Max Volume That Can Be Turbined for Upstream Dam

Maximum volume that can be turbined (hm^3) for the upstream dam is calculated by using Equations (12) and (13) as defined in Section 3.1.1.

- vi.** Step (6) Calculate Min Volume That Should Be Turbined Instead of Spilling for Upstream Dam

Minimum volume that should be turbined instead of spilling (hm^3) for the upstream dam is calculated by using Equation (14) as defined in Section 3.1.1.

- vii.** Step (7) Calculate the Difference Between Max Volume That Can Be Turbined and Min Volume That Should Be Turbined Instead of Spilling for Upstream Dam

The difference between maximum volume that can be turbined and minimum volume that should be turbined instead of spilling (hm^3) for the upstream dam is calculated by using Equation (15) as defined in Section 3.1.1.

- viii.** Step (8) Define a Coefficient “A1” Between 0 and 1 for Upstream Dam

Coefficient “A1” is defined for the upstream dam as described in Equation (16) in Section 3.1.1.

- ix.** Step (9) Calculate the Volume to Be Turbined for Upstream Dam

The water volume to be turbined (hm^3) for the upstream dam is calculated by using Equation (17) as defined in Section 3.1.1.

x. Step (10) Calculate Spilled Volume for Upstream Dam

The water volume that will be spilled (hm^3) for the upstream dam is calculated by using Equation (18) as defined in Section 3.1.1.

xi. Step (11) Calculate Net Inflow Volume for Middle Dam

Net inflow volume (hm^3) is calculated by following formulation:

$$NI_i = I_i - OU_i - EV_i + VTT_i + SV_i, \quad i = 1, \dots, 240 \quad (85)$$

where

NI_i = Net Inflow Volume at i_{th} month (hm^3)

I_i = Inflow Volume from the Intermediate Basin at i_{th} month (hm^3) (Input)

OU_i = Other Uses from Reservoir at i_{th} month (hm^3) (Input)

EV_i = Evaporation from The Reservoir at i_{th} month (hm^3) (Input)

VTT_i = volume to be turbined at the upstream dam at i_{th} month (hm^3)

SV_i = volume spilled at the upstream dam at i_{th} month (hm^3)

xii. Step (12) Repeat Steps (5) through (10) for Middle Dam

Steps (5) through (10) are repeated with a new coefficient set “A2” for middle dam.

xiii. Step (13) Calculate Net Inflow Volume for Downstream Dam

Net inflow volume (hm^3) for downstream dam is calculated using Equation (85).

xiv. Step (14) Repeat Steps (5) through (10) for Downstream Dam

Steps (5) through (10) are repeated with a new coefficient set “A3” for downstream dam.

xv. Step (15) Calculate End of Month Reservoir Volumes for All Dams

End of month reservoir water volumes are calculated by using Equation (19) as defined in Section 3.1.1 for each dam separately.

xvi. Step (16) Calculate End of Month Reservoir Elevations for All Dams

End of month reservoir elevations for all dams are calculated by linear interpolation using input Area-Volume Curve Data as defined in Section 3.1.1 for each dam separately.

xvii. Step (17) Calculate Hours of Operation Using Design Discharge of Turbines for all Dams

Hours of turbine operation for each optimization time step are calculated by using Equation (20) as defined in Section 3.1.1 for each dam separately.

xviii. Step (18) Calculate the Power Generated for all Dams

Power generated for each optimization time step are calculated by using Equations (21) to (28) as defined in Section 3.1.1 for each dam separately.

xix. Step (19) Calculate the Energy Produced for all Dams

Energy produced for each optimization time step is calculated by using Equation (29) as defined in Section 3.1.1 for each dam separately.

xx. Step (20) Go to Step (3) For Next Time Step

Process restarts from step (3), calculated end of month reservoir levels becomes the beginning of month reservoir levels for the next time step as defined in Equation (30) in Section 3.1.1.

xxi. Objective Function

$$\text{Max} \sum_{i=1}^{240} (E_i^1 + E_i^2 + E_i^3), \quad i = 1, \dots, 240 \quad (86)$$

Where

E_i^1 = Energy produced at i_{th} month by upstream power plant (GWh)

E_i^2 = Energy produced at i_{th} month by middle power plant (GWh)

E_i^3 = Energy produced at i_{th} month by downstream power plant (GWh)

Variables are $A1_i$, $A2_i$ and $A3_i$

Subject to;

$$A1_i, A2_i, A3_i \geq 0, \quad i = 1, \dots, 240 \quad (87)$$

$$A1_i, A2_i, A3_i \leq 1, \quad i = 1, \dots, 240 \quad (88)$$

The following constraints are added to the mathematical model in Equation (86) for FRLEO model;

$$RL1_{E240} \geq RL1_{EU} \quad (89)$$

$$RL2_{E240} \geq RL2_{EU} \quad (90)$$

$$RL3_{E240} \geq RL3_{EU} \quad (91)$$

Where

$RL1_{E240}$ = Reservoir level at the end of 240th month for upstream dam(m)

$RL1_{EU}$ = User defined minimum reservoir level required at the end of 240th month for upstream dam(m)

$RL2_{E240}$ = Reservoir level at the end of 240th month for middle dam(m)

$RL2_{EU}$ = User defined minimum reservoir level required at the end of 240th month for middle dam(m)

$RL3_{E240}$ = Reservoir level at the end of 240th month for downstream dam(m)

$RL3_{EU}$ = User defined minimum reservoir level required at the end of 240th month for downstream dam(m)

3.3.2.2 Maximization of Energy – FRLEY

The algorithm for FRLEY operation model is almost the same with FRLEO operation model for cascade systems. The only difference is the constraints applied in objective function. The following constraints are applied instead of Equations (89), (90) and (91) to the mathematical model in Equation (86) for FRLEY model;

$$RL1_{En} \geq RL1_{EU} \quad , \quad n = 12, 24, 36, 48 \dots, 240 \quad (92)$$

$$RL2_{En} \geq RL2_{EU} \quad , \quad n = 12, 24, 36, 48 \dots, 240 \quad (93)$$

$$RL3_{En} \geq RL3_{EU} \quad , \quad n = 12, 24, 36, 48 \dots, 240 \quad (94)$$

Where

$RL1_{En}$ = Reservoir level at the end of each 12th month for upstream dam(m)

$RL1_{EU}$ = User defined minimum reservoir level required at the end of each 12th month for upstream dam(m)

$RL2_{En}$ = Reservoir level at the end of each 12th month for middle dam(m)

$RL2_{EU}$ = User defined minimum reservoir level required at the end of each 12th month for middle dam(m)

$RL3_{En}$ = Reservoir level at the end of each 12th month for downstream dam(m)

$RL3_{EU}$ = User defined minimum reservoir level required at the end of each 12th month for downstream dam(m)

3.3.2.3 Maximization of Energy – RLOR

The algorithm for RLOR model is constructed on FRLEO model with major differences. In FRLEO model the variables were so called “A1, A2 and A3” coefficients and the turbined volume of water of each month for each power plant was defined as a function of “A1, A2 and A3”. In RLOR model the variables are again “A1, A2 and A3” coefficients but end of month reservoir water levels are defined as a functions of “A1, A2 and A3” similar to the methodology defined in Section 3.3.1.3 for single storage systems.

The following algorithm scheme given in Figure 3.6, is used for RLOR model.

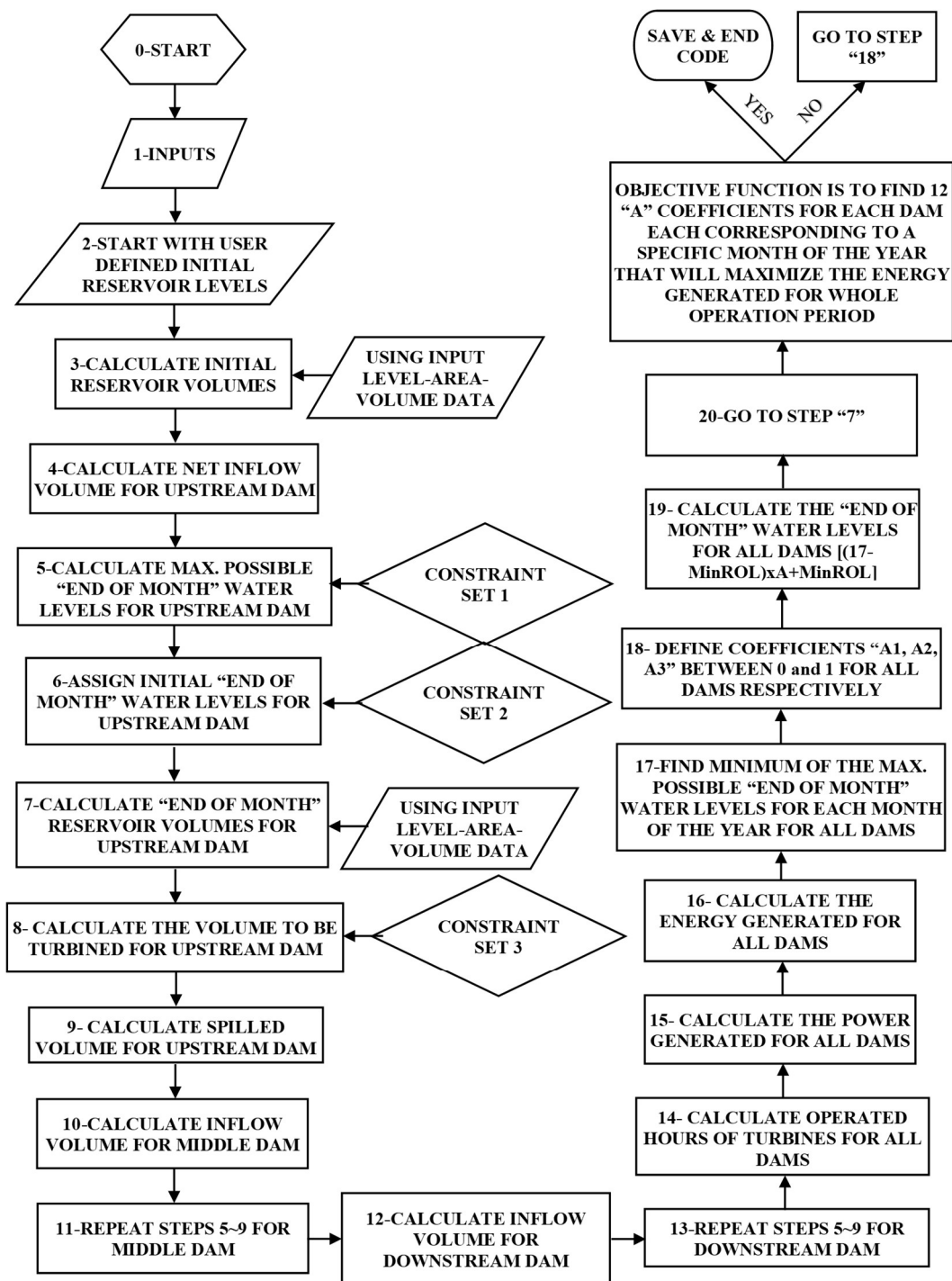


Figure 3.6 Flowchart for cascade reservoir operation optimization, maximization of energy – RLOR

Each step and formulation are described as follows:

i. Step (1) Inputs

As mentioned before in Section 3.3.2.1, same characteristic information of the system and data is provided into the model by using the user interface developed.

ii. Step (2) Start with User Defined Operation Water Levels

Reservoir elevation at the start of first month of operation is defined by the user for each dam separately, RL_{B1} (m).

iii. Step (3) Calculate Corresponding Reservoir Volume of All Dams

Initial reservoir volume is calculated according to user defined RL_{B1} for all dams using Area-Volume Curve Data of each dam and developed linear interpolation subroutine, reservoir volumes of dams at the start of month $RV1_{B1}$, $RV2_{B1}$ and $RV3_{B1}$ (hm^3).

iv. Step (4) Calculate Net Inflow Volume for Upstream Dam

Net inflow volume (hm^3) for the upstream dam is calculated by using Equation (11) as defined in Section 3.1.1.

v. Step (5) Calculate Max Possible End of Month Reservoir Level for Upstream Dam

Maximum possible end of month reservoir water level (m) for the upstream dam is calculated by using Equations (47) and (48) as defined in Section 3.3.1.3.

- vi.** Step (6) Assign Initial End of Month Reservoir Water Level for Upstream Dam

Initial end of month reservoir water level (m) for the upstream dam is assigned by using Equation (49) as defined in Section 3.3.1.3.

- vii.** Step (7) Calculate End of Month Reservoir Volume for Upstream Dam

End of month reservoir volume for upstream dam, $RV1_{Ei}$ (hm^3), is calculated according to the reservoir level assigned in step (6), using Area-Volume Curve Data, and developed linear interpolation sub-routine.

- viii.** Step (8) Calculate the Volume to Be Turbined for Upstream Dam

Volume to be turbined (hm^3) for the upstream dam is calculated by using Equations (50) and (51) as defined in Section 3.3.1.3.

- ix.** Step (9) Calculate Spilled Volume of Water for Upstream Dam

Spilled volume of water (hm^3) for the upstream dam is calculated by using Equation (52) as defined in Section 3.3.1.3.

- x.** Step (10) Calculate Net Inflow Volume for Middle Dam

Net inflow volume (hm^3) for the middle dam is calculated by using Equation (85) as defined in Section 3.3.2.1.

xi. Step (11) Repeat Steps (5) through (9) for Middle Dam

Steps (5) through (9) are repeated for middle dam with the inflow calculated in step (10).

xii. Step (12) Calculate Net Inflow Volume for Downstream Dam

Net inflow volume (hm^3) for the downstream dam is calculated by using Equation (85) as defined in Section 3.3.2.1.

xiii. Step (13) Repeat Steps (5) through (9) for Downstream Dam

Steps (5) through (9) are repeated for downstream dam with the inflow calculated in step (12).

xiv. Step (14) Calculate Hours of Operation Using Design Discharge of Turbines for all Dams

Hours of turbine operation for the corresponding optimization time step is calculated by using Equation (20) as defined in Section 3.1.1 for each dam separately.

xv. Step (15) Calculate the Power Generated for all Dams

Power generated for the corresponding optimization time step is calculated by using Equations (21) to (28) as defined in Section 3.1.1 for each dam separately.

xvi. Step (16) Calculate the Energy Produced for all Dams

Energy produced for the corresponding optimization time step is calculated by using Equation (29) as defined in Section 3.1.1 for each dam separately.

xvii. Step (17) Find Minimum of the Max. Possible “End of Month” Water Levels for Each Month of the Year for Each Dam Separately

First, sort the maximum possible end of month reservoir levels calculated in step 5, for each month of the year and then find the minimum of them for each dam separately. Considering that the reservoir levels of the same months of every year will be the same, found minimum values are actual maximum possible end of month reservoir level of that specific month. A total of 12 values (MaxRL_{Em}) are defined representing maximum possible end of month reservoir levels for whole operation period for each dam separately. 1 value for October, 1 value for November, 1 value for December etc. that are same for every year for whole operation duration for each dam separately resulting a total of 36 values for the cascade.

xviii. Step (18) Define Coefficients “A1, A2 and A3” Between 0 and 1 for All Dams Respectively

$A1_m$ = A coefficient at month m for upstream dam

$A2_m$ = A coefficient at month m for middle dam

$A3_m$ = A coefficient at month m for downstream dam

(all assumed 0.7 initially),

m = October, November, December September

Subject to;

$$1 \geq A1_m \geq 0$$

$$1 \geq A2_m \geq 0$$

$$1 \geq A3_m \geq 0$$

xix. Step (19) Calculate End of Month Reservoir Water Levels for All Dams

Then calculate end of month reservoir levels using “A1, A2, A3” coefficient for each month of the year for each dam separately (12 total repeating every year for each dam).

$$RL1_{Em} = (MaxRL1_{Em} - MinROL1) \times A1_m + MinROL1 \quad (95)$$

$$RL2_{Em} = (MaxRL2_{Em} - MinROL2) \times A2_m + MinROL2 \quad (96)$$

$$RL3_{Em} = (MaxRL3_{Em} - MinROL3) \times A3_m + MinROL3 \quad (97)$$

$m = \text{October, November, December September}$

xx. Step (20) Go to Step (7)

End of month reservoir volumes, $RV1_{Ei}$, $RV2_{Ei}$ and $RV3_{Ei}$ (hm^3), are calculated according to the reservoir levels calculated by Equations (95), (96) and (97) for each dam separately and process continues.

xxi. Objective Function

Objective function is same as Equation (86) as defined in Section 3.3.2.1. Given again below for easy reference.

$$Max \sum_{i=1}^{240} (E_i^1 + E_i^2 + E_i^3), \quad i = 1, \dots, 240 \quad (86)$$

Where

E_i^1 = Energy produced at i_{th} month by upstream power plant (GWh)

E_i^2 = Energy produced at i_{th} month by middle power plant (GWh)

E_i^3 = Energy produced at i_{th} month by downstream power plant (GWh)

Variables are $A1_m$, $A2_m$ and $A3_m$

Subject to;

$$1 \geq A1_m \geq 0$$

$$1 \geq A2_m \geq 0$$

$$1 \geq A3_m \geq 0$$

$m = October, November, December \dots \dots \dots September$

3.3.2.4 Maximization of Revenue – FRLEO

The algorithm and mathematical formulation of Maximization of Revenue with FRLEO model is identical with Maximization of Energy with FRLEO model as defined in Section 3.3.2.1. There are only three differences. First, the user provides the monthly average energy prices (TL/GWh) as mentioned in Section 3.1.1. Second, an additional step is included in the algorithm defined in Section 3.3.2.1 between steps 19 and 20 for the calculation of revenue with following formulation.

$$RVN1_i = E1_i \times EP_i, \quad i = 1, \dots, 240 \quad (98)$$

$$RVN2_i = E2_i \times EP_i, \quad i = 1, \dots, 240 \quad (99)$$

$$RVN3_i = E3_i \times EP_i, \quad i = 1, \dots, 240 \quad (100)$$

Where

$E1_i$ = Energy generation at i_{th} month of upstream dam (GWh)

$E2_i$ = Energy generation at i_{th} month of middle dam (GWh)

$E3_i$ = Energy generation at i_{th} month of downstream dam (GWh)

EP_i = Average monthly energy price at i_{th} month (TL/GWh) (Input)

$RVN1_i$ = Revenue at i_{th} month of upstream dam (TL)

$RVN2_i$ = Revenue at i_{th} month of middle dam (TL)

$RVN3_i$ = Revenue at i_{th} month of downstream dam (TL)

Third and the last, objective function is for the maximization of sum of the revenues of all dams instead of energy generated as defined below.

$$Max \sum_{i=1}^{240} (RVN1_i + RVN2_i + RVN3_i) \quad , \quad i = 1, \dots, 240 \quad (101)$$

3.3.2.5 Maximization of Revenue – FRLEY

The algorithm and mathematical formulation of Maximization of Revenue with FRLEY model is almost identical with Maximization of Energy with FRLEY model. The differences defined in Section 3.3.2.4 also apply for the FRLEY model.

3.3.3 Run-of-River Systems

3.3.3.1 Maximization of Energy

For maximization of energy daily operation for a duration of 2 years is considered for a system with no storage capacity at all. The aim is to determine which turbine or turbines shall be operated and at which capacity for the forecasted daily inflow values to generate the maximum energy. Developed toll can be used for power houses having up to 4 units. The following algorithm scheme given in Figure 3.7 is used.

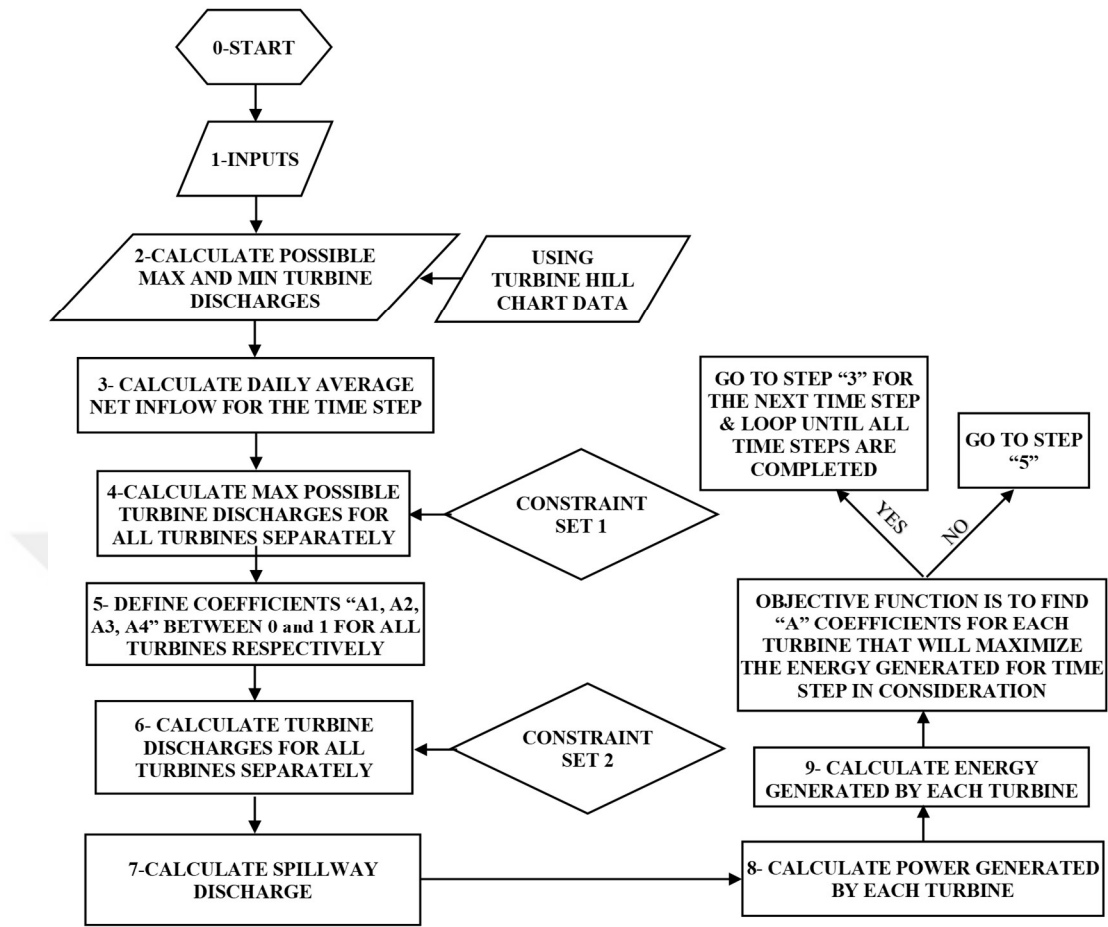


Figure 3.7 Flowchart for run-of-river system operation optimization for maximization of energy.

Each step and formulation are described as follows:

i. Step (1) Inputs

As mentioned before in Section 3.1.3, characteristic information of the system and daily average inflow data as m^3/s for 2 years, is provided into the model by using the user interface developed.

A real turbine hill chart from Atatürk Dam and HEPP (Su Ener, 2020) is used for the efficiency calculation of electromechanical equipment.

A polynomial function derived from the Kepez HEPP generator efficiency data for percent output power (output power to design output power ratio) is used for the efficiency calculation of generators.

Efficiency of transformers was taken as a constant value of 0.975 (Vito, 2011) as they do not change considerably with different output levels.

ii. Step (2) Calculate Maximum Possible and Minimum Possible Turbine Discharges (Operating Ranges)

Using the turbine hill chart data, operating range of each unit is calculated with the following equations.

$$\text{MaxTD}_u = TDD_u \times \text{MaxFR} , \quad u = 1, 2, 3, 4 \quad (102)$$

$$\text{MinTD}_u = TDD_u \times \text{MinFR} , \quad u = 1, 2, 3, 4 \quad (103)$$

Where

MaxTD_u = Maximum possible turbine discharge of u_{th} unit (m^3/s)

MinTD_u = Minimum possible turbine discharge of u_{th} unit (m^3/s)

TDD_u = Turbine design discharge of u_{th} unit (m^3/s) (Input)

MaxFR = Maximum flow rate ratio of u_{th} unit (unitless) (Input from hill chart)

MinFR = Minimum flow rate ratio of u_{th} unit (unitless) (Input from hill chart)

iii. Step (3) Calculate Daily Average Net Inflow for The Corresponding Time Step

Daily average net inflow (m^3/s) is calculated by following formulation:

$$DANI_i = DAI_i - OU_i , \quad i = 1, \dots, 732 \quad (104)$$

where

$DANI_i$ = Daily Average Net Inflow at i^{th} day (m^3/s)

DAI_i = Daily Average Inflow at i^{th} day (m^3/s) (Input)

OU_i = Other Uses Such as Downstream Water Rights and Environmental Release at i^{th} day (m^3/s) (Input)

- iv. Step (4) Calculate Maximum Possible Turbine Discharges for Each Turbine Separately

Maximum possible turbine discharge (m^3/s) for the corresponding time step is calculated by following formulation:

$$MaxPTD_i^u = DANI_i, \quad u = 1,2,3,4, \quad i = 1, \dots, 732 \quad (105)$$

Subject to;

$$MaxPTD_i^u \leq MaxTD_u$$

If $DANI_i < MinTD_u$ then $MaxPTD_i^u = 0$

where

$MaxPTD_i^u$ = Maximum possible turbine discharge of u^{th} unit at i^{th} day (m^3/s)

- v. Step (5) Define Coefficients A_1, A_2, A_3, A_4 Between 0 and 1 For All Turbines Respectively

$$A_i^u = A \text{ coefficient at } i_{th} \text{ day for } u^{th} \text{ unit} \quad (106)$$

(assumed 0.7 initially), $u = 1,2,3,4, \quad i = 1, \dots, 732$

Subject to;

$$A_i^u \geq 0$$

$$A_i^u \leq 1$$

vii. Step (6) Calculate Turbine Discharges Separately for All Turbines

$$TD_i^u = MaxPTD_i^u \times A_i^u, \quad u = 1, 2, 3, 4, \quad i = 1, \dots, 732 \quad (107)$$

Subject to;

$$(TD1_i + TD2_i + TD3_i + TD4_i) \leq DAI_i, \quad i = 1, \dots, 732 \quad (108)$$

where

TD_i^u = Turbine discharge of u^{th} unit at i^{th} day (m^3/s)

viii. Step (7) Calculate Spillway Discharge

$$SWD_i = DAI_i - (TD1_i + TD2_i + TD3_i + TD4_i), \quad i = 1, \dots, 732 \quad (109)$$

Where

SWD_i = Spillway discharge at i^{th} day (m^3/s)

ix. Step (8) Calculate the Power Generated by Each Turbine

Power generated by each turbine for the corresponding optimization time step P_i^u is calculated by using Equations (21) to (28) as defined in Section 3.1.1.

x. Step (9) Calculate the Energy Generated by Each Turbine

Energy produced by each turbine for the corresponding optimization time step E_i^u is calculated by using Equation (29) as defined in Section 3.1.1.

xi. Objective Function

$$Max \sum_{u=1}^4 E^u, \quad u = 1, 2, 3, 4 \quad (110)$$

Where

Variables are $A_1 \sim A_4$

Subject to;

$$A_i \geq 0, \quad i = 1, \dots, 4 \quad (111)$$

$$A_i \leq 1, \quad i = 1, \dots, 4 \quad (112)$$

After four A coefficients for each turbine that maximizes the total energy production for that time step is determined, process starts again from step (3) for the next time step until all time steps for the whole operation duration is completed.

3.3.3.2 Maximization of Revenue

For maximization of revenue, 15-minute time step operation for a duration of 1 day is considered for a system with a small amount of storage capacity somewhere in the water way like settling pond, head pond or power race tunnel. The aim is to determine which turbine or turbines shall be operated and for how long, for the forecasted inflow values and energy prices to maximize the daily revenue. Instead of Daily Average Inflow data, Hourly Average Inflow (m^3/s) data should be provided by the user into the tool. Moreover, Total Storage Capacity (m^3), Available Storage At The Start of Operation (m^3) and average 15 minute duration Energy Prices (TL/MWh) should be provided. Developed toll can be used for power houses having up to 4 units. The following algorithm scheme given in Figure 3.8 is used.

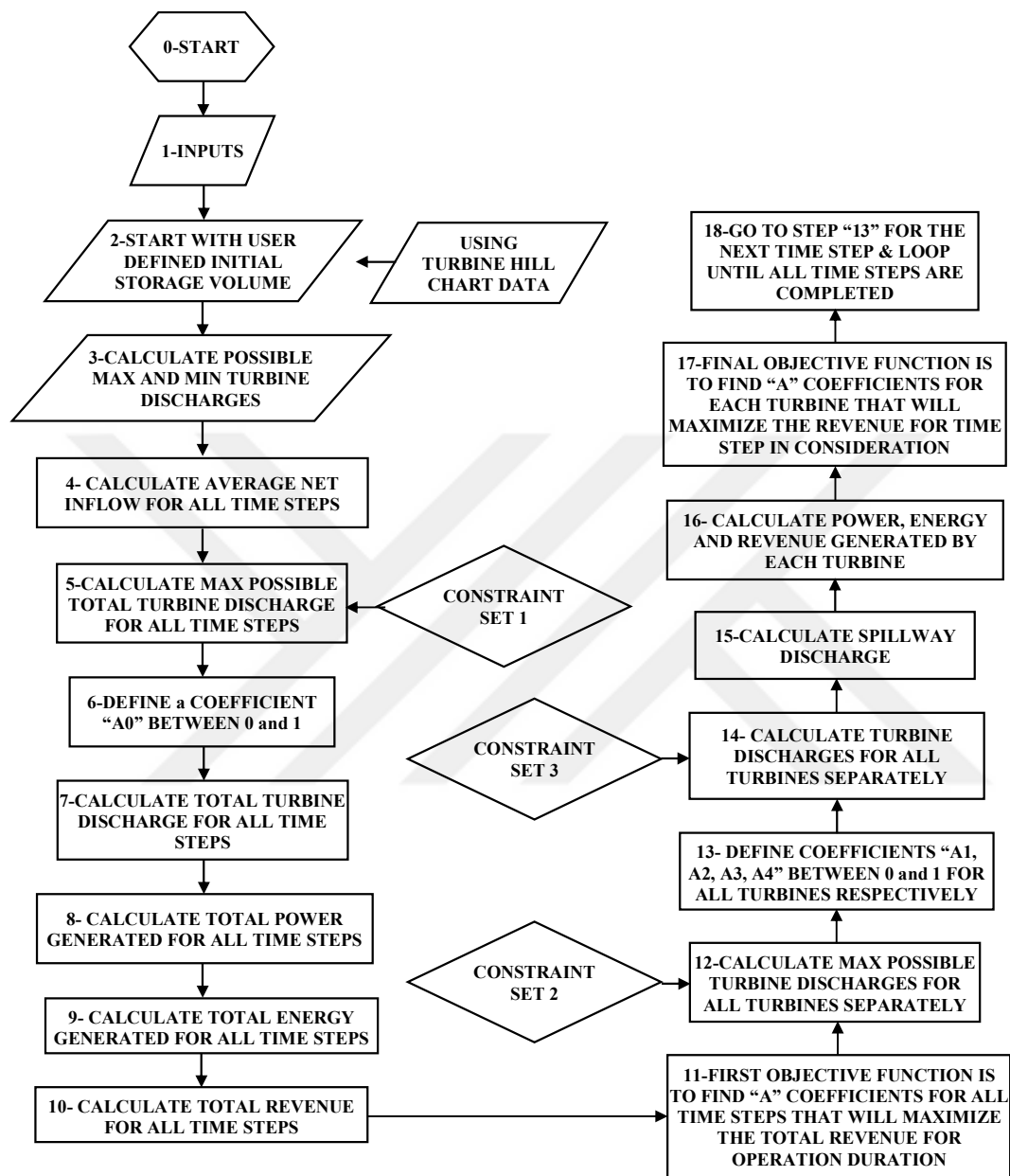


Figure 3.8 Flowchart for run-of-river system operation optimization for maximization of revenue.

Each step and formulation are described as follows:

i. Step (1) Inputs

As mentioned before in Section 3.1.3, characteristic information of the system, hourly average inflow data as m^3/s for 1 day and average 15 minute duration Energy Prices (TL/MWh), is provided into the model by using the user interface developed.

A real turbine hill chart from Atatürk Dam and HEPP (Su Ener, 2020) is used for the efficiency calculation of electromechanical equipment.

A polynomial function derived from the Kepez HEPP generator efficiency data for percent output power (output power to design output power ratio) is used for the efficiency calculation of generators.

Efficiency of transformers was taken as a constant value of 0.975 (Vito, 2011) as they do not change considerably with different output levels.

ii. Step (2) Start with User Defined Initial Storage Volume

Initial available storage volume at the start of operation is defined by the user, SV_{B1} (m^3).

iii. Step (3) Calculate Maximum Possible and Minimum Possible Turbine Discharges (Operating Ranges)

Using the turbine hill chart data, operating range of each unit is calculated by using Equations (102) and (103) as described in Section 3.3.3.1.

iv. Step (4) Calculate Average Net Inflow Rate for All Time Steps

Average net inflow rate (m^3/s) for each 15-minute time step is calculated by using Equation (104).

- v. Step (5) Calculate Maximum Possible Turbine Discharges for Each Turbine Separately and in Total

Maximum possible turbine discharge (m^3/s) for the corresponding time step is calculated by following formulation:

$$MaxPTD_i^u = \frac{SV_{Bi}}{60 \times 15} + DANI_i, \quad u = 1, 2, 3, 4, \quad i = 1, \dots, 96 \quad (113)$$

$$TPTD_i = MaxPTD_i^1 + MaxPTD_i^2 + MaxPTD_i^3 + MaxPTD_i^4 \quad (114)$$

subject to;

$$MaxPTD_i^u \leq MaxTD_u$$

If $[SV_{Bi}/(60 \times 15) + DANI_i] < MinTD_u$ then $MaxPTD_i^u = 0$

$$TPTD_i \leq \frac{SV_{Bi}}{60 \times 15} + DANI_i$$

where

$MaxPTD_i^u$ = Maximum possible turbine discharge of u^{th} unit at i_{th} time step (m^3/s)

$TPTD_i$ = Total max possible turbine discharge of powerhouse at i_{th} time step (m^3/s)

- vi. Step (6) Define a Coefficient “A0” Between 0 and 1

$$A_i = A \text{ coefficient at } i_{\text{th}} \text{ time step (assumed 0.7 initially)}, \quad (115)$$

$$i = 1, \dots, 96$$

Subject to;

$$A_i \geq 0$$

$$A_i \leq 1$$

vii. Step (7) Calculate Total Turbine Discharge for All time Steps

$$TTD_i = TPTD_i \times A0_i, \quad i = 1, \dots, 96 \quad (116)$$

Subject to;

where

TTD_i = Total turbine discharge at i_{th} time step (m^3/s)

viii. Step (8) Calculate the Total Power Generated

Power generated by powerhouse for the each optimization time step P_i is calculated by using Equations (21) to (28) as defined in Section 3.1.1.

ix. Step (9) Calculate the Total Energy Generated

Energy produced by powerhouse for the each optimization time step E_i is calculated by using Equation (29) as defined in Section 3.1.1.

x. Step (10) Calculate the Total Revenue

Revenue created by powerhouse for each optimization time step RVN_i is calculated by using Equation (57) as defined in Section 3.3.1.4.

xi. Step (11) Objective Function Maximize the Total Revenue

First objective function is for the maximization of total revenue as defined below.

$$Max \sum_{i=1}^{96} RVN_i, \quad i = 1, \dots, 96 \quad (117)$$

xii. Step (12) Calculate Maximum Possible Turbine Discharges for Each Turbine Separately

At the end of step (11) required total discharge that should be turbinated at each time step to create the maximum revenue at the end of whole operation duration is found. After that, the total discharge at each time step is distributed to each turbine as similar to the method defined in Section 3.3.3.1. Maximum possible turbine discharge (m^3/s) for the corresponding time step is calculated by following formulation:

$$MaxPTD_i^u = TTD_i, \quad u = 1,2,3,4, \quad i = 1, \dots, 96 \quad (118)$$

Subject to;

$$MaxPTD_i^u \leq MaxTD_u$$

If $TTD_i < MinTD_u$ then $MaxPTD_i^u = 0$

xiii. Step (13) Define Coefficients A1, A2, A3, A4 Between 0 and 1 For All Turbines Respectively

$$A_i^u = A \text{ coefficient at } i_{th} \text{ time step for } u^{th} \text{ unit} \quad (119)$$

(assumed 0.7 initially), $u = 1,2,3,4, \quad i = 1, \dots, 96$

Subject to;

$$A_i^u \geq 0$$

$$A_i^u \leq 1$$

xiv. Step (14) Calculate Turbine Discharges Separately for All Turbines

$$TD_i^u = MaxPTD_i^u \times A_i^u, \quad u = 1,2,3,4, \quad i = 1, \dots, 96 \quad (120)$$

Subject to;

$$(TD1_i + TD2_i + TD3_i + TD4_i) \leq TTD_i, \quad i = 1, \dots, 96 \quad (121)$$

where

TD_i^u = Turbine discharge of u^{th} unit at i^{th} time step (m^3/s)

xv. Step (15) Calculate Spillway Discharge

$$SWD_i = \frac{SV_{Bi}}{60 \times 15} + DAN_i - TTD_i - \frac{SVC}{60 \times 15} \quad i = 1, \dots, 96 \quad (122)$$

Where

SVC = Storage volume capacity (m^3) (Input)

xvi. Step (16) Calculate the Power, Energy and Revenue Generated by Each Turbine

Power generated by each turbine for the corresponding optimization time step is calculated by using Equations (21) to (28) as defined in Section 3.1.1.

Energy generated by each turbine for the corresponding optimization time step is calculated by using Equation (29) as defined in Section 3.1.1.

Revenue generated by each turbine for the corresponding optimization time step are calculated by using Equation (57) as defined in Section 3.3.1.4.

xvii. Step (17) Objective Function

$$\text{Max } RVN_i, \quad i = 1, \dots, 96 \quad (123)$$

Where

Variables are $A_1 \sim A_4$

Subject to;

$$A_u \geq 0 , \quad u = 1, \dots, 4 \quad (124)$$

$$A_u \leq 1 , \quad u = 1, \dots, 4 \quad (125)$$

After four A coefficients for each turbine that maximizes the total revenue for that time step is determined, process starts again from step (13) for the next time step until all time steps for the whole operation duration is completed.



CHAPTER 4

CASE STUDY FOR SINGLE AND CASCADE STORAGE SYSTEMS

4.1 Introduction

As stated previously, the models developed in the present study for storage systems were used for the operation of a cascade consisting of three dams located in Southeastern Turkey as shown in Figure 4.1. The dams will be named Dam 1, Dam 2, and Dam 3 from upstream to downstream in the study as given in Figure 4.2. At first, three reservoirs were operated separately as single with three different operation models, FRLEO, FRLEY, and RLOR for both maximization of energy and maximization of revenue separately. Then they were operated as a cascade with the same models again for the purpose of maximization of energy and maximization of revenue separately. Finally, Dam 2 is operated for the purpose of maximization of profit with FRLEO model. Monthly inflow data available for the years 1957~2005 is used from the feasibility report of dams. The main characteristics of the projects are given below in Table 4.1 with the main hydrology data.



Figure 4.1 Location of the Cascade in Turkey

Table 4.1 Main Characteristics of the Cascade

Dam 1	
Installed Capacity	: 7.91 MW
Total Design Discharge	: 64.04 m ³ /s
Total Reservoir Volume	: 1.01 hm ³
Water Way Length	: 42.30 m
Annual Average Inflow	: 979.93 hm ³
Dam 2	
Installed Capacity	: 202.45 MW
Total Design Discharge	: 105.75 m ³ /s
Total Reservoir Volume	: 438.68 hm ³
Water Way Length	: 9762.70 m
Annual Average Inflow	: 1176.12 hm ³
Dam 3	
Installed Capacity	: 98.42 MW
Total Design Discharge	: 96.61 m ³ /s
Total Reservoir Volume	: 59.40 hm ³
Water Way Length	: 5637.30 m
Annual Average Inflow	: 1200.67 hm ³

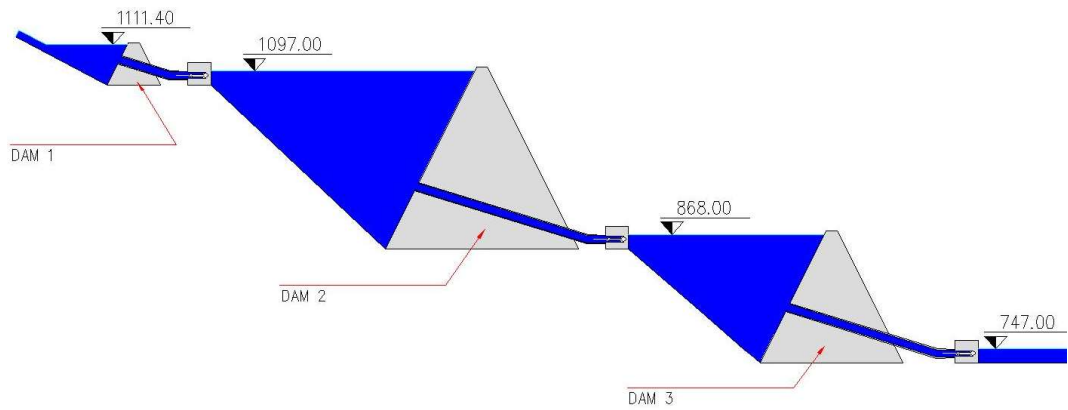


Figure 4.2 Schematic Profile of the Cascade

4.2 Single Operation – Maximization of Energy

Three reservoirs were operated separately as a single with three different operation models, FRLEO, FRLEY, and RLOR for the purpose of maximization of energy generation. The results are given below in Table 4.2 through Table 4.5.

Table 4.2 Dam 1 Single Operation Annual Average Energy Production

Dam 1	
FRLEO	: 26.77 GWh
FRLEY	: 26.77 GWh
RLOR	: 23.53 GWh
Feasibility Report	: 24.25 GWh

Table 4.3 Dam 2 Single Operation Annual Average Energy Production

Dam 2		
FRLEO	:	463.16 GWh
FRLEY	:	456.77 GWh
RLOR	:	450.21 GWh
Feasibility Report	:	435.35 GWh

Table 4.4 Dam 3 Single Operation Annual Average Energy Production

Dam 3		
FRLEO	:	259.36 GWh
FRLEY	:	259.08 GWh
RLOR	:	258.77 GWh
Feasibility Report	:	238.66 GWh

Table 4.5 Cascade Total Single Operation Annual Average Energy Production

Cascade Total as Single Operation		
FRLEO	:	749.26 GWh
FRLEY	:	742.62 GWh
RLOR	:	732.50 GWh
Feasibility Report	:	698.26 GWh

Dam 1 has a considerably small reservoir capacity compared to other dams in the cascade. There is no deviation in annual energy generation capacity between the FRLEO model and the FRLEY model for Dam 1. Whereas there is an 12.13% reduction in annual energy generation between the FRLEO model and the RLOR model. When compared to the feasibility report energy generation results, developed models increase energy generation 10.40% with FRLEO and FRLEY models whereas decreases the energy generation 2.99% for RLOR model.

Dam 2 has the largest reservoir capacity compared to other dams in the cascade. There is a 1.38% decrease in annual energy generation capacity between the FRLEO model and the FRLEY model for Dam 2. Whereas there is a 2.80% reduction in annual energy generation between the FRLEO model and the RLOR model. When compared to the feasibility report energy generation results, developed models increase energy generation 6.39%, 4.92% and 3.41% with FRLEO, FRLEY and RLOR models respectively.

Dam 3 is in the middle for reservoir capacity compared to other dams in the cascade. There is a 0.11% decrease in annual energy generation capacity between the FRLEO model and the FRLEY model for Dam 3. Whereas there is a 0.23% reduction in annual energy generation between the FRLEO model and the RLOR model. When compared to the feasibility report energy generation results, developed models increase energy generation 8.67%, 8.56% and 8.43% with FRLEO, FRLEY and RLOR models respectively.

Comparing the results of this study with the feasibility report values, optimization of reservoir operation with developed models results an increase between 4.67% and 6.81% in total cascade energy generation.

Aside from the annual average energy generation capacities, annual average spilled water volumes are also compared for different operation models. The results are given below in Table 4.6 through Table 4.9.

Table 4.6 Dam 1 Single Operation Annual Average Spilled Volume

Dam 1		
FRLEO	:	136.91 hm ³
FRLEY	:	136.91 hm ³
RLOR	:	138.81 hm ³

Table 4.7 Dam 2 Single Operation Annual Average Spilled Volume

Dam 2		
FRLEO	:	12.80 hm ³
FRLEY	:	14.65 hm ³
RLOR	:	55.92 hm ³

Table 4.8 Dam 3 Single Operation Annual Average Spilled Volume

Dam 3		
FRLEO	:	88.68 hm ³
FRLEY	:	88.98 hm ³
RLOR	:	93.38 hm ³

Table 4.9 Cascade Total Annual Average Spilled Volume

Cascade Total as Single Operation	
FRLEO	: 238.39 hm ³
FRLEY	: 240.54 hm ³
RLOR	: 288.11 hm ³

There is no deviation in annual average spilled volume between the FRLEO model and the FRLEY model for Dam 1. Whereas there is a 1.39% increase in annual average spilled volume between the FRLEO model and the RLOR model.

There is a 14.45% increase in annual average spilled volume between the FRLEO model and the FRLEY model for Dam 2. Whereas there is a 337.03% increase in annual average spilled volume between the FRLEO model and the RLOR model.

There is a 0.34% increase in annual average spilled volume between the FRLEO model and the FRLEY model for Dam 3. Whereas there is a 5.30% increase in annual average spilled volume between the FRLEO model and the RLOR model.

There is a 0.90% increase in annual average spilled volume between the FRLEO model and the FRLEY model for cascade total. Whereas there is a 20.86% increase in annual average spilled volume between the FRLEO model and the RLOR model.

In order to search for the effect of developed electro-mechanical efficiency calculation method, a second set of analysis was performed with the FRLEO model keeping the efficiency as constant to the value used in the feasibility report studies. The value was taken as 0.881 in feasibility studies. The developed tools were modified, and the efficiency is taken as constant 0.881 in this second set of analysis. Obtained energy generation results are 27.24 GWh, 464.93 GWh and 262.45 GWh for Dam1, Dam 2 and Dam 3 respectively. When compared to the feasibility results of 24.25 GWh, 435.35 GWh and 238.66 GWh in the same order, energy generation

increases 12.3%, 6.80% and 10.00% for Dam 1, Dam 2 and Dam 3 respectively. When compared to the first set of results of 26.77 GWh, 463.16 GWh and 259.36 GWh in the same order obtained in this study, energy generation increases 1.8%, 0.40% and 1.20% for Dam 1, Dam 2 and Dam 3 respectively. This indicates that the overall efficiency of the electro-mechanical equipment was overestimated in the feasibility study.

4.3 Cascade Operation – Maximization of Energy

Three reservoirs were operated together as a cascade with the same three different operation models, FRLEO, FRLEY, and RLOR. The results are given below in Table 4.10.

Table 4.10 Cascade Operation Annual Average Energy Generation

Dam 1	
FRLEO	: 26.77 GWh
FRLEY	: 26.77 GWh
RLOR	: 23.53 GWh
Dam 2	
FRLEO	: 477.63 GWh
FRLEY	: 460.73 GWh
RLOR	: 459.56 GWh
Dam 3	
FRLEO	: 268.00 GWh
FRLEY	: 262.02 GWh

Table 4.10 (cont'd)

RLOR : 254.81 GWh

Cascade Total

FRLEO : 772.41 GWh

FRLEY : 749.52 GWh

RLOR : 737.90 GWh

There is no deviation in annual energy generation capacity for Dam 1 between single and cascade operations.

There is a 3.03%, 0.86% and 2.04% increase in annual average energy generation between the single and cascade operation of Dam 2 for the FRLEO, FRLEY, and RLOR models respectively.

There is a 3.23%, 1.12% increase and 1.55% decrease in annual average energy generation between the single and cascade operation of Dam 3 for the FRLEO, FRLEY, and RLOR models respectively.

There is a 2.99%, 0.92% and 0.73% increase in total annual energy generation capacity between the single and cascade operation of dams for the FRLEO, FRLEY, and RLOR models respectively.

Aside from the annual average energy generation capacities, annual average spilled water volumes are also compared for different operation models. The results are given below in Table 4.11.

Table 4.11 Cascade Operation Annual Average Spilled Water Volume

Dam 1	
FRLEO	: 136.91 hm ³
FRLEY	: 136.91 hm ³
RLOR	: 138.81 hm ³
Dam 2	
FRLEO	: 14.96 hm ³
FRLEY	: 29.86 hm ³
RLOR	: 45.20 hm ³
Dam 3	
FRLEO	: 33.25 hm ³
FRLEY	: 52.25 hm ³
RLOR	: 71.62 hm ³
Cascade Total	
FRLEO	: 185.12 hm ³
FRLEO	: 218.12 hm ³
RLOR	: 255.63 hm ³

There is no deviation in the annual average spilled water volume for Dam 1 between single and cascade operations.

There is 14.48% $\{(14.96-12.80)/14.96\}$, 49.42% $\{(28.96-14.65)/28.96\}$, increase and 23.73% $\{(45.20-55.92)/45.20\}$ decrease in annual average spilled water volumes

between the single and cascade operation of Dam 2 for the FRLEO, FRLEY, and RLOR models respectively.

There is 166.73% $\{(33.25-88.68)/33.25\}$, 70.30% $\{(55.25-88.98)/55.25\}$ and 30.38% $\{(71.62-93.38)/71.62\}$ decrease in annual average spilled water volumes between the single and cascade operation of Dam 3 for the FRLEO, FRLEY, and RLOR models respectively.

There is 28.77% , 10.28% and 12.71% decrease in total annual average spilled water volumes between the single and cascade operation of dams for the FRLEO, FRLEY, and RLOR models respectively.

4.4 Single Operation – Maximization of Revenue

Three reservoirs were operated separately as a single with three different operation models, FRLEO, FRLEY, and RLOR for the purpose of maximization of revenue. Same project characteristic information and inflow data is used with maximization of revenue. Monthly average energy prices varying between 2,200 TL/MWh and 3,000 TL/MWh was used for the optimization keeping the energy prices same within the same year. For the first year of operation 2,200 TL/MWh was used and it was increased gradually 100 TL per MWh yearly until reaching 3,000 TL/MWh. After reaching 3,000 TL/MWh it was decreased 100 TL per MWh yearly until 2,200 TL/MWh and the loop continued covering whole operation duration. Purpose was to see the effect of periodically varying energy prices. The results are given below in Table 4.12.

Table 4.12 Single Operation Annual Average Energy Generation and Revenue

System	Operation Model	Annual Average Energy Generation (GWh)	Annual Average Revenue (TL)
Dam 1	FRLEO	26.77	70,139,817
	FRLEY	26.76	70,104,723
	RLOR	23.53	61,517,854
Dam 2	FRLEO	463.18	1,220,707,561
	FRLEY	456.80	1,203,460,486
	RLOR	450.21	1,185,228,695
Dam 3	FRLEO	259.08	680,695,625
	FRLEY	259.00	680,520,390
	RLOR	258.77	679,875,148
Cascade Total	FRLEO	749.03	1,971,543,003
	FRLEY	742.56	1,954,085,598
	RLOR	732.51	1,926,621,697

Results obtained for the average annual energy generation are quite similar compared to the ones obtained for energy maximization in Section 4.2.

There is a 0.05% decrease in annual average revenue between the FRLEO model and the FRLEY model for Dam 1. Whereas there is a 14.02% reduction in annual energy generation between the FRLEO model and the RLOR model.

There is a 1.43% decrease in annual average revenue between the FRLEO model and the FRLEY model for Dam 2. Whereas there is a 2.99% reduction in annual energy generation between the FRLEO model and the RLOR model.

There is a 0.03% decrease in annual average revenue between the FRLEO model and the FRLEY model for Dam 3. Whereas there is a 0.12% reduction in annual energy generation between the FRLEO model and the RLOR model.

Aside from the annual average energy generation capacities, annual average spilled water volumes are also compared for different operation models. The results are given below in Table 4.13.

Table 4.13 Single Operation Annual Average Spilled Water Volume

Dam 1		
FRLEO	:	136.91 hm ³
FRLEY	:	136.91 hm ³
RLOR	:	138.81 hm ³
Dam 2		
FRLEO	:	12.75 hm ³
FRLEY	:	14.65 hm ³
RLOR	:	55.92 hm ³
Dam 3		
FRLEO	:	88.85 hm ³
FRLEY	:	89.39 hm ³
RLOR	:	93.38 hm ³
Cascade Total		
FRLEO	:	238.51 hm ³
FRLEY	:	240.95 hm ³
RLOR	:	288.11 hm ³

Results obtained for the average annual spilled water volumes are quite similar compared to the ones obtained for energy maximization in Section 4.2.

4.5 Cascade Operation – Maximization of Revenue

Three reservoirs were operated together as a cascade with the two operation models, FRLEO and FRLEY for maximization of revenue with the same energy prices as defined in Section 4.4. The results are given below in Table 4.14.

Table 4.14 Cascade Operation Annual Average Energy Generation and Revenue

System	Operation Model	Annual Average Energy Generation (GWh)	Annual Average Revenue (TL)
Dam 1	FRLEO	26.77	70,139,817
	FRLEY	26.76	70,104,723
Dam 2	FRLEO	477.60	1,240,895,857
	FRLEY	460.71	1,221,581,323
Dam 3	FRLEO	268.03	696,754,190
	FRLEY	262.01	681,016,453
Cascade Total	FRLEO	772.40	2,007,789,864
	FRLEY	749.48	1,972,702,499

There is no deviation in annual average energy generation capacity and annual average revenue for Dam 1 between single and cascade operations.

There is a 3.02% and 0.85% increase in annual average revenue between the single and cascade operation of Dam 2 for the FRLEO and FRLEY models respectively.

There is a 3.34% and 1.15% increase in annual average revenue between the single and cascade operation of Dam 3 for the FRLEO and FRLEY models respectively.

There is a 3.03% and 0.92% increase in total annual energy generation capacity between the single and cascade operation of dams for the FRLEO and FRLEY models respectively.

Aside from the annual average energy generation capacities, annual average spilled water volumes are also compared for different operation models. Results obtained for the average annual spilled water volumes are quite similar compared to the ones obtained for energy maximization in Section 4.2, so are not provided again in this section.

4.6 Single Operation – Maximization of Profit

Dam 2 was operated as single with FRLEO operation model for the purpose of maximization of profit. Same project characteristic information, inflow data and monthly average energy prices are used with maximization of revenue. Following unit costs and ratios given in Table 4.15 was used as input into the developed optimization tool for the calculation of cost items and net present value as defined in Section 3.3.1.7.

Table 4.15 Input Unit Costs and Ratios for Maximization of Profit

Tunnel Excavation Unit Cost	25.00	TL/m ³
Tunnel Concrete Unit Cost	2200.00	TL/m ³
Tunnel Reinforcement Unit Cost	15000.00	TL/ton
Tunnel Formwork Unit Cost	250.00	TL/m ²
Tunnel Excavation Support System Unit Cost	500.00	TL/m
Tunnel Stabilization Works (Injection etc.) Unit Cost	500.00	TL/m
Contingency Ratio for Tunnel Works	10.00%	%
Ratio of Concrete Liner Thickness to Inner Diameter of Tunnel	10.00%	%
Reinforcement Amount (kg) Per Cubic Meter of Concrete	80.00	kg/m ³
Penstock Steel Unit Cost	15000.00	TL/ton
Penstock Excavation Unit Cost	25.00	TL/m ³
Penstock Concrete Unit Cost	2200.00	TL/m ³

Table 4.15 (cont'd)

Penstock Reinforcement Unit Cost	15000.00	TL/ton
Contingency Ratio for Penstock Works	10.00%	%
Ratio of Steel Thickness to Inner Diameter of Penstock	1.00%	%
Average Excavation Amount Per Meter Alignment Along Penstock	40.00	m ³ /m
Average Concrete Amount Per Meter Alignment Along Penstock	5.00	m ³ /m
Reinforcement Amount (kg) Per Cubic Meter of Concrete	80.00	kg/m ³
Powerhouse EM Equipment Unit Cost	12,000,000.00	TL/MW
Powerhouse Civil Works Unit Cost	1,200,000.00	TL/MW
Contingency Ratio for Powerhouse Works	10.00%	%
Minimum Required Tunnel Inner Diameter	3.00	m
Maximum Allowable Water Velocity in The Tunnel	3.74	m/s
Maximum Allowable Water Velocity in The Penstock	5.39	m/s
Interest Rate	10.00%	%

Then as described in Section 3.3.1.7, provided installed capacity and characteristics into the tool are accepted as base scenario and 10 alternatives are defined by the tool by increments and decrements of installed capacity. Since Dam 2 is used for Maximization of Profit case study, provided characteristic data in Section 4.1 constitute the base scenario and alternatives are built upon this base scenario. Following are the characteristics and installed capacities for the alternatives derived by the tool.

Table 4.16 Alternative Installed Capacities Derived for Maximization of Profit

Scenario	Installed Capacity (MW)	Design Discharge (m³/s)	Tunnel Diameter (m)	Penstock Diameter (m)
Alt 1	161.96	83.10	5.32	4.43
Alt 2	170.06	87.26	5.45	4.54
Alt 3	178.16	91.41	5.58	4.65
Alt 4	186.25	95.57	5.70	4.75
Alt 5	194.35	99.72	5.83	4.86
Base Scenario	202.45	105.75	6.00	5.00
Alt 6	210.55	108.04	6.06	5.05
Alt 7	218.65	112.19	6.18	5.15
Alt 8	226.74	116.35	6.29	5.24
Alt 9	234.84	120.50	6.40	5.34
Alt 10	242.94	124.66	6.51	5.43

After the alternatives are derived, the tool first calculates associated costs of water ways for each alternative with the provided input data, then optimizes reservoir operation of each alternative separately for maximization of energy generation with FRLEO model as defined in Section 3.3.1.1 and as the case study given in Section 4.2.

In the end, results are plotted on graphs leaving the decision to the user as the optimum point of installed capacity is affected by the forecasted energy prices and constructions costs of both civil items and electromechanical items. The results obtained for Dam 2 are given in Figure 4.3 and Figure 4.4.

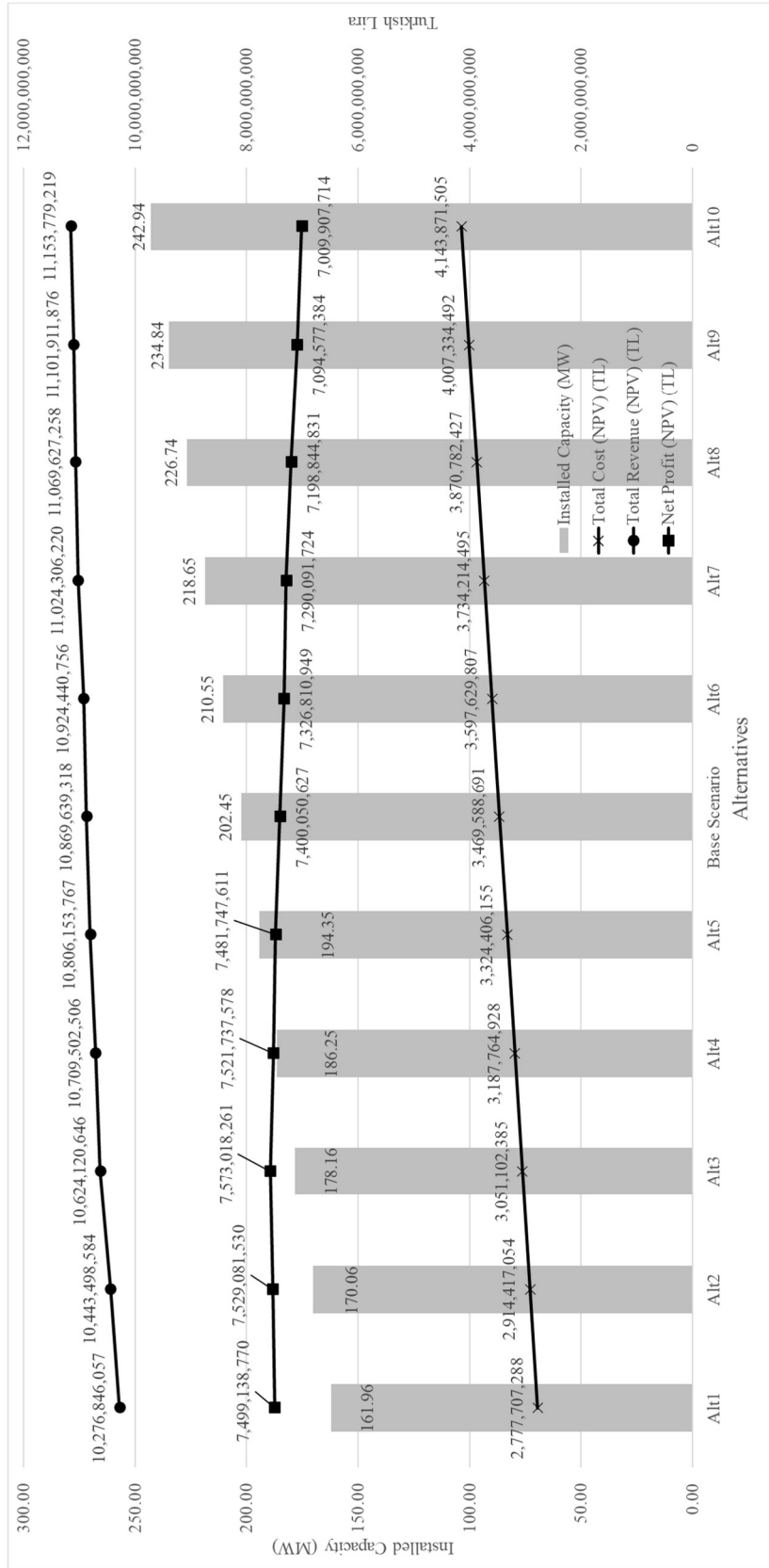


Figure 4.3 Results for Dam 2 Maximization of Profit Installed Capacity vs Total cost, Total Revenue and Net Profit

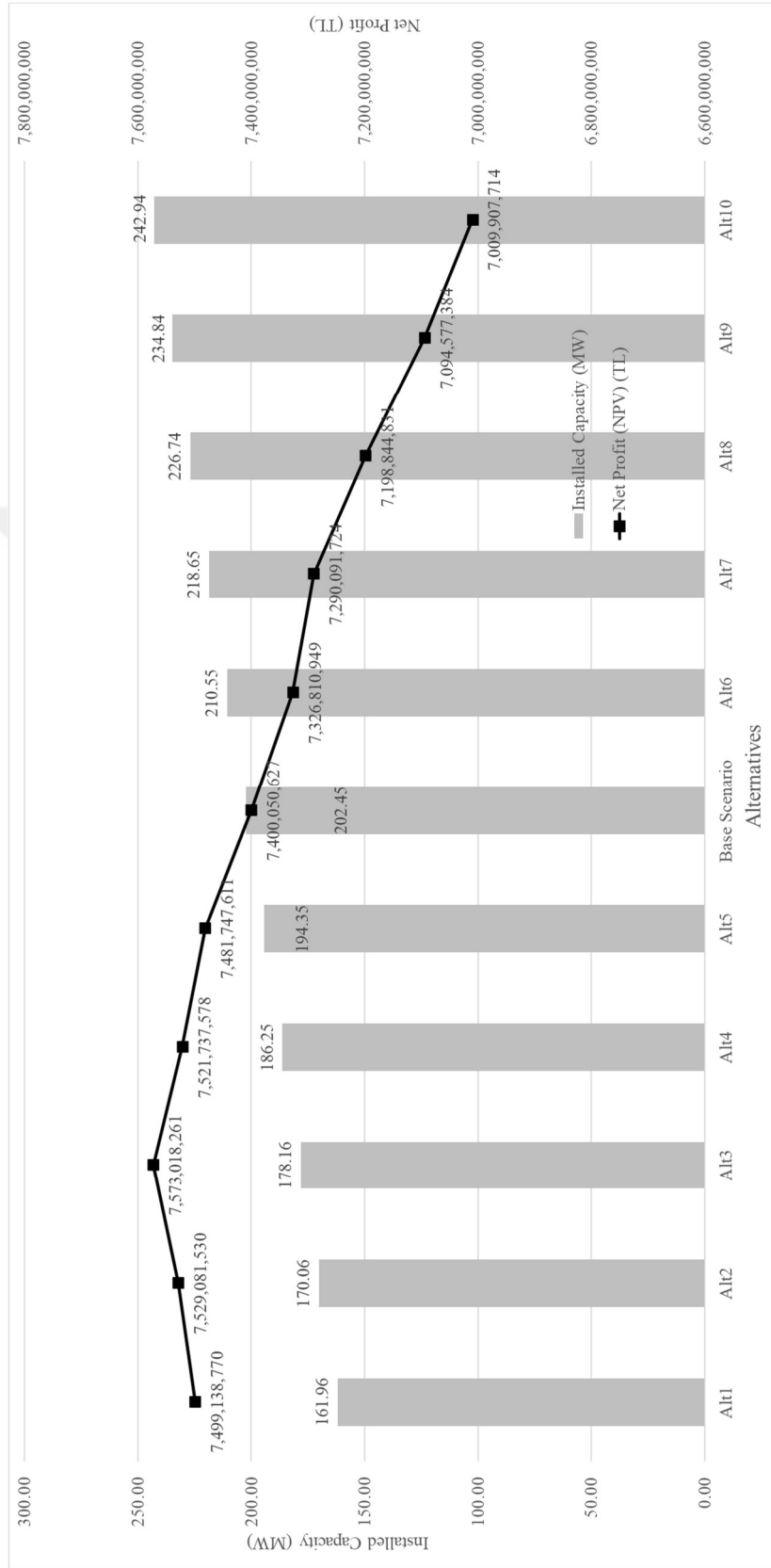


Figure 4.4 Results for Dam 2 Maximization of Profit Installed Capacity vs Net Profit

According to the results, optimum installed capacity for the investigated hydropower scheme is 178.16 MW which is 12% less than the original characteristic installed capacity of 202.45 MW (base scenario).

4.7 Discussion of Results

The results were acquired through the application of the developed models to a cascade comprising three dams. Initially, these three reservoirs were individually operated using three distinct operation models: FRLEO, FRLEY, and RLOR designed for energy generation maximization. In the second phase, they were collectively operated as a cascade, utilizing the same models aimed at optimizing energy generation. In the third phase, they were individually operated using the same model for revenue maximization. In the fourth phase they were collectively operated as a cascade, utilizing the same models for revenue maximization. In the fifth and last phase, Dam 2 was operated individually with FRLEO model for the purpose of maximization of profit and alternative installed capacities were investigated.

Table 4.17 shows the average annual energy generation of each dam separately for each operation model as single and cascade, also, it shows the total average annual energy generation of all three dams combined for each operation model as single and as cascade for maximization of energy.

Table 4.17 Results for Annual Average Energy Generation of Storage Systems for Maximization of Energy (GWh)

	Dam 1	Dam 2	Dam 3	Cascade Total
Single FRLEO (GWh)	26.77	463.16	259.36	749.26
Single FRLEY (GWh)	26.77	456.77	259.08	742.62
Single RLOR (GWh)	23.53	450.21	258.77	732.50
Cascade FRLEO (GWh)	26.77	477.63	268.00	772.41
Cascade FRLEY (GWh)	26.77	460.73	262.02	749.52
Cascade RLOR (GWh)	23.53	459.56	254.81	737.90

Based on the results obtained, it is evident that making a generalized conclusion is challenging, given that the impact of operation model varies considerably for each dam. This is because each dam of the cascade has different characteristics and quite different storage capacities. Since Dam 1 has a considerably small storage capacity it is not considerably affected by different operation models while operated as individually. It is also not affected by the cascade effect of operation because it is the most upstream dam of the cascade and has a small storage capacity.

Dam 2 on the other hand has the largest storage capacity in the cascade with a considerable amount of 438.68 hm³. Additional constraints on the end-of-month reservoir levels for different operation models affected Dam 2 adversely and reduced average annual energy generation. Whereas cascade operation had a positive effect and increased energy generation.

Dam 3, the most downstream dam of the cascade has a modest storage capacity of 59.40 hm³. Consequently, it is not affected as much by the additional constraints on the end-of-month reservoir levels for different operation models used for single

operation. On the other hand, cascade operation had the utmost positive effect and increased energy generation considerably.

Table 4.18 shows the average annual energy generation and revenue of each dam separately for each operation model as single and cascade, also, it shows the total average annual energy generation and revenue of all three dams combined for each operation model as single and as cascade for maximization of revenue.

Table 4.18 Results for Annual Average Energy Generation and Revenue of Storage Systems for Maximization of Revenue

	Dam 1	Dam 2	Dam 3	Cascade Total
Single FRLEO (Energy GWh)	26.77	463.18	259.08	749.03
Single FRLEY (Energy GWh)	26.76	456.80	259.00	742.56
Single RLOR (Energy GWh)	23.53	450.21	258.77	732.51
Single FRLEO (Revenue TL)	70,139,817	1,220,707,561	680,695,625	1,971,543,003
Single FRLEY (Revenue TL)	70,104,723	1,203,460,486	680,520,390	1,954,085,598
Single RLOR (Revenue TL)	61,517,854	1,185,228,695	679,875,148	1,926,621,697
Cascade FRLEO (Energy GWh)	26.77	477.60	268.03	772.40
Cascade FRLEY (Energy GWh)	26.76	460.71	262.01	749.48
Cascade FRLEO (Revenue TL)	70,139,817	1,240,895,857	696,754,190	2,007,789,864
Cascade FRLEY (Revenue TL)	70,104,723	1,221,581,323	681,016,453	1,972,702,499

There is a slight deviation if not at all in annual average energy generation results obtained for maximization of energy and maximization of revenue. This is due to the assumed energy prices for the analysis performed. As mentioned before energy prices were kept constant within the same year of operation and varied along the

years. Even if the reservoir capacity of the analyzed dam is high, reservoir operations has a recurring nature for operation years. Especially for FRLEY and RLOR models where there are constraints to keep the reservoir level same at the end of year and same for each month of the year for whole operation duration respectively. Keeping the energy prices same within the year and explained nature and constraints the governing input on the energy generation outcome becomes the inflows, which are same for both maximization of energy and maximization of revenue.

Results obtained for the reservoir levels and spillway discharges were analyzed in more detail to provide an insight for verification of the developed models. Only Dam 2 is analyzed for this instance for a consecutive 3 years between 1968 and 1970 to provide more detail instead of more data for reservoir levels whereas the whole operation period was analyzed for spillway discharges.

It is clearly visible in Figure 4.5 that no constraint is applied except for the end of operation level for FRLEO model as the reservoir level oscillates freely. On the other hand, when operated with FRLEY model, 1980m reservoir level, that is defined as a user input and becomes the constraint for end of year reservoir levels, is obtained at the end of each water year which is month September. Furthermore, when ROLR model is used for operation, the reservoir levels of each month within the year replicates for all years of operation, which verifies the purpose of the developed model of finding 12 end of month reservoir levels for each month of the year that maximizes energy generation.

The effect of different operation models on amount of spillway discharges was also analyzed in more detail for Dam 2 in Figure 4.6 and Figure 4.7. As another verification of the developed models, spilled volume of water and the frequency of spillway operation increases as the operation models gets stricter from FRLEO model to ROLR model as clearly seen in Figure 4.6.

Another parameter that can be used for verification and to analyze the effectiveness of the developed models is the reservoir operation before and during flood seasons. The reservoir should be operated in a manner to minimize the spilled volume of water

so more amount of water can be allocated for turbinning. So, the lesser the amount of water spilled the higher will be the energy generation. In order to verify the effectiveness of the developed models with this parameter one should see Figure 4.7. As clearly seen for both FRLEO and FRLEY models, spillway discharge occurs on in two months, April, and May 1969. It is not extraordinary as those months of the year are in rainy season. The important parameter is that if the reservoir operation was managed well to minimize the amount of water spilled. This can only be possible by lowering the reservoir level to the minimum operation water level before the flood season and operating the turbines with full capacity during flood season. This can be checked by examining Figure 4.5 to find out the reservoir level drops to minimum reservoir operation water level in February 1969 just before the flood season. Further examination of the details from the tool newly developed, it was seen that turbines were operated at full capacity from the beginning of January 1969 till the end of May 1969. This confirms and verifies the effectiveness of the developed models.

Similar verification with the same parameter cannot be done for ROLR model as the purpose of this model is keeping reservoir levels same for the same month of the year. On the other hand, the effect of this constraint is clearly visible in Figure 4.7, as the spillway operation starts earlier compared to other developed models.

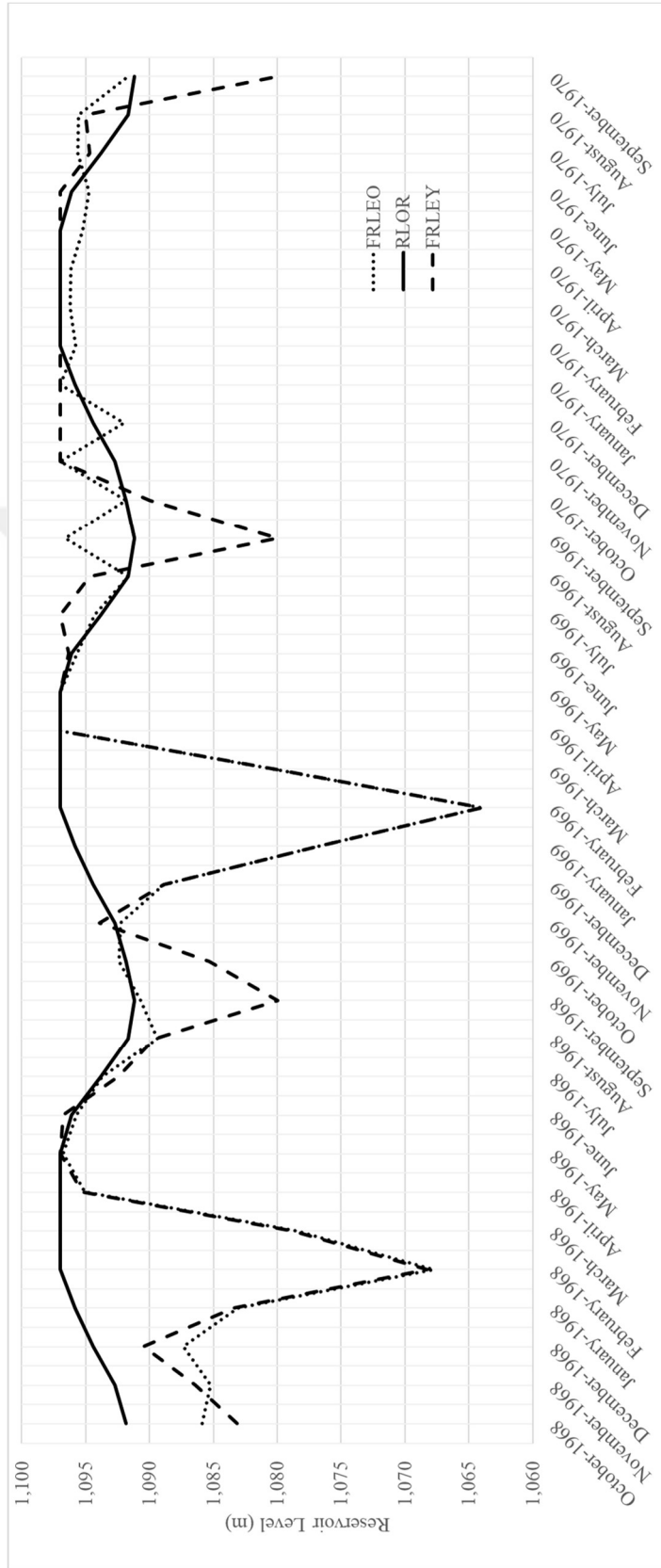


Figure 4.5 Reservoir Levels of Dam 2 for Maximization of Energy for Years 1968 to 1970

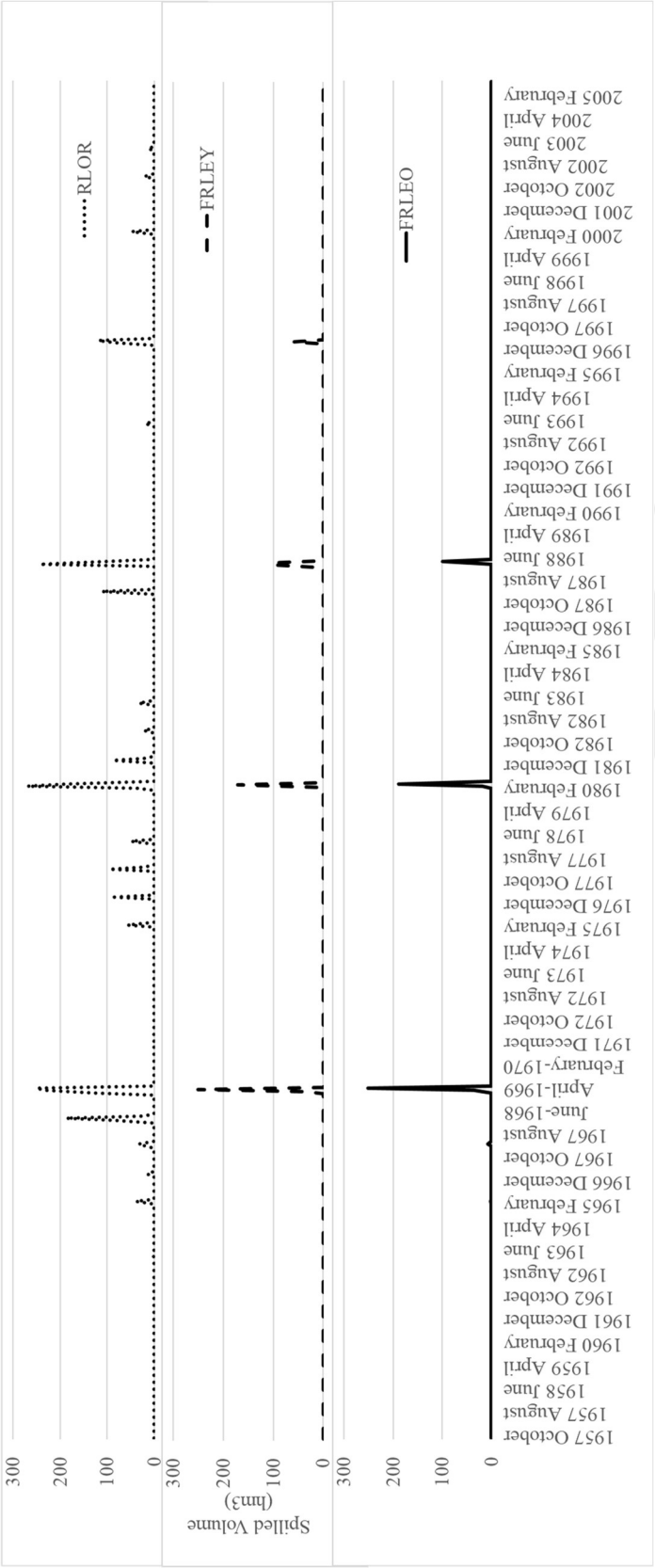


Figure 4.6 Spillway Discharges of Dam 2 for Maximization of Energy for Whole Operation Period

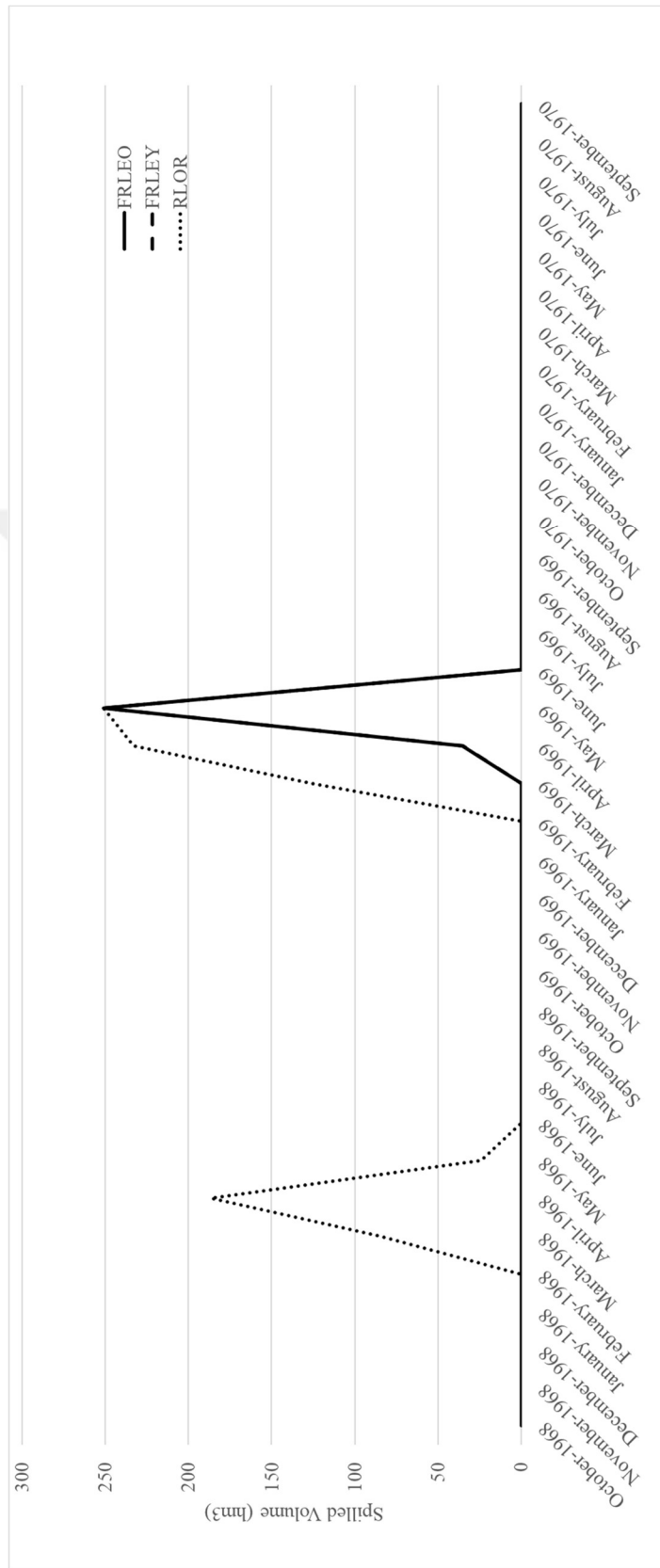


Figure 4.7 Spillway Discharges of Dam 2 for Maximization of Energy for Years 1968 to 1970

For the maximization of profit, 11 alternatives, one of them being the base scenario, is analyzed with the tool developed with FRLEO model. Results were provided in Section 4.6. Result of the optimization is not provided as a single solution on purpose and instead graphs showing results of all alternatives are given in Figure 4.3 and Figure 4.4. The purpose of this is to give the user a chance to examine the results in graph and make a judgement accordingly on the installed capacity, energy generation, created revenue and profit. One should keep in mind that the governing cost item in this analysis is the unit cost of electromechanical equipment (EME) and the only revenue creating item is energy prices. So, the optimum point of installed capacity vs. profit graphs depend on the relation between unit cost of electro mechanical equipment and energy prices. As the energy prices are high compared to unit cost of EME the optimum point will shift to the right of the graph giving higher installed capacities maximizing profit. As the energy prices are low compared to the unit cost of EME the optimum point will shift to the left of the graph giving lower installed capacities maximizing profit.

CHAPTER 5

CASE STUDY FOR RUN-OF-RIVER SYSTEMS

5.1 Introduction

As stated previously, the models developed in the present study for run-of-river systems were used for the operation of a hydroelectric power plant (HEPP) located in Southeastern Turkey as shown in Figure 5.1. At first, HEPP was operated on a daily basis for maximization of energy without consideration of any storage volume. Then it was operated for a duration of one day with 15-minute time steps, for the purpose of maximization of revenue. In this case, the small storage in the head pond was taken into consideration. Daily average inflow rate for the years 1995 and 1996 is used from the feasibility report of HEPP. The main characteristic of the project is given below with the main hydrology data.



Figure 5.1 Location of the HEPP in Turkey

Table 5.1 Main Characteristics of the HEPP

Installed Capacity	: 10.14 MW
Total Design Discharge	: 13.40 m ³ /s
Power Tunnel Length	: 3000 m
Power Tunnel Diameter	: 4.00 m
Penstock Length	: 139.00 m
Penstock Diameter	: 2.10 m
Gross Head	: 88.65 m

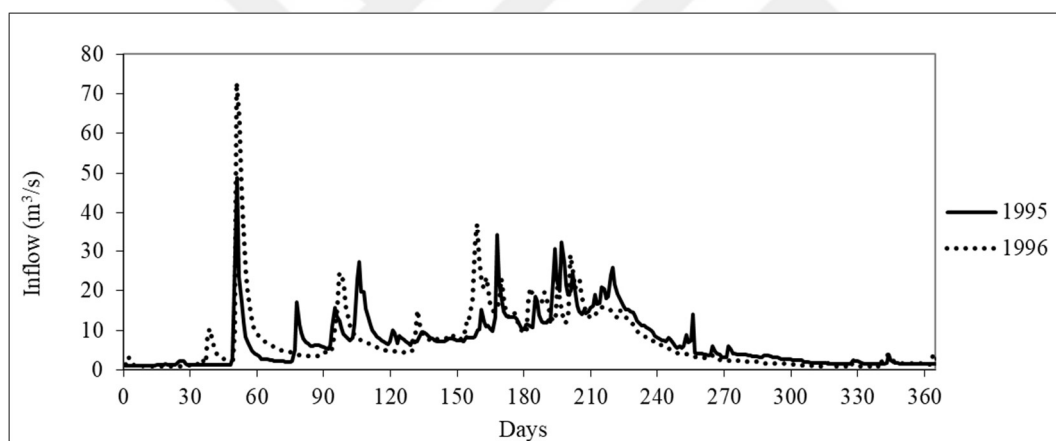


Figure 5.2 Daily Average Inflow of the HEPP (From Feasibility Report)

5.2 Maximization of Energy

For maximization of energy daily operation for a duration of 2 years is considered for the HEPP with no storage capacity at all. The aim is to determine which turbine or turbines shall be operated and at which capacity for the forecasted daily inflow values to generate the maximum energy. The HEPP with characteristics defined in Section 5.1 was operated with inflow rates provided in the feasibility report and following results are obtained.

Table 5.2 HEPP Energy Production Results for Maximization of Energy

Year 1995 with the developed tool in this study	:	38.85 GWh
Year 1996 with the developed tool in this study	:	37.57 GWh
Year 1995 feasibility report	:	42.19 GWh
Year 1996 feasibility report	:	40.57 GWh

Annual energy productions calculated with the tool developed in this study are 7.91% and 7.39% less than feasibility report values for years 1995 and 1996 respectively. The main reason of finding lower values with the tool developed in this study compared to feasibility study is that turbines have certain operating ranges defined with the turbine hill charts. In this study, this operating range is incorporated according to the sample turbine hill chart used and when the inflow rates are below a certain value, turbines are not operable since there is no storage capacity. However, in feasibility studies this was not considered, and it was assumed that the turbines are operable for all inflow rates. As shown in Figure 5.3, both turbines of the studied HEPP are not operable up to a certain inflow rate but this was not considered

in the feasibility studies which result in calculation of higher energy production than it can be.

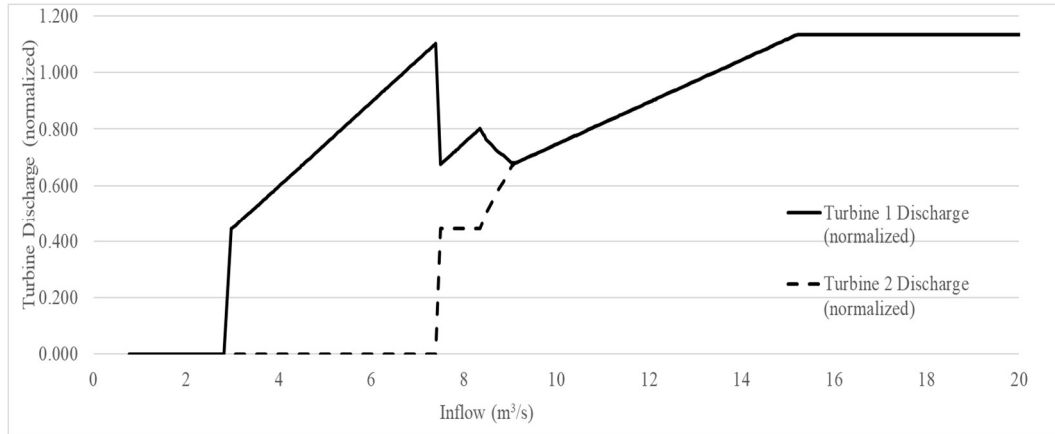


Figure 5.3 HEPP Normalized Turbine Discharges vs Inflow

5.3 Maximization of Revenue

For maximization of revenue, 15-minute time step operation for a duration of 1 day is considered for the same HEPP with also consideration of the 5,000 m³ storage capacity available in the head pond. The aim is to determine which turbine or turbines shall be operated and for how long, for the forecasted inflow values and energy prices to maximize the daily revenue. Available storage volume at the start of operation was defined as 5,000 m³ and a constraint was defined to have at least 95% of the initial storage at the end of the day. Energy Prices (TL/MWh) given in Table 5.3 was used for the analysis. Analysis was performed again with the inflow rates provided in the feasibility report for three different dates to identify the effect of different inflow rates. Inflow rates on 14 April 1995, 10 March 1995 and 05 March 1995 are used with daily average inflows of 32.29 m³/s, 12.08 m³/s and 8.10 m³/s respectively. Obtained results are given in Figure 5.4 through Figure 5.9.

Table 5.3 Energy Prices Used for Maximization of Revenue of HEPP

Time Step	Energy Price (TL/MWh)	Time Step	Energy Price (TL/MWh)	Time Step	Energy Price (TL/MWh)
00:00~00:15	1,250.00	08:00~08:15	2,850.00	16:00~16:15	3,850.00
00:15~00:30	1,300.00	08:15~08:30	2,900.00	16:15~16:30	3,750.00
00:30~00:45	1,350.00	08:30~08:45	2,950.00	16:30~16:45	3,650.00
00:45~01:00	1,400.00	08:45~09:00	3,000.00	16:45~17:00	3,550.00
01:00~01:15	1,450.00	09:00~09:15	3,050.00	17:00~17:15	3,450.00
01:15~01:30	1,500.00	09:15~09:30	3,100.00	17:15~17:30	3,350.00
01:30~01:45	1,550.00	09:30~09:45	3,150.00	17:30~17:45	3,250.00
01:45~02:00	1,600.00	09:45~10:00	3,200.00	17:45~18:00	3,150.00
02:00~02:15	1,650.00	10:00~10:15	3,250.00	18:00~18:15	3,050.00
02:15~02:30	1,700.00	10:15~10:30	3,300.00	18:15~18:30	2,950.00
02:30~02:45	1,750.00	10:30~10:45	3,350.00	18:30~18:45	2,850.00
02:45~03:00	1,800.00	10:45~11:00	3,400.00	18:45~19:00	2,750.00
03:00~03:15	1,850.00	11:00~11:15	3,450.00	19:00~19:15	2,650.00
03:15~03:30	1,900.00	11:15~11:30	3,500.00	19:15~19:30	2,550.00
03:30~03:45	1,950.00	11:30~11:45	3,550.00	19:30~19:45	2,450.00
03:45~04:00	2,000.00	11:45~12:00	3,600.00	19:45~20:00	2,350.00
04:00~04:15	2,050.00	12:00~12:15	3,650.00	20:00~20:15	2,250.00
04:15~04:30	2,100.00	12:15~12:30	3,700.00	20:15~20:30	2,150.00
04:30~04:45	2,150.00	12:30~12:45	3,750.00	20:30~20:45	2,050.00
04:45~05:00	2,200.00	12:45~13:00	3,800.00	20:45~21:00	1,950.00
05:00~05:15	2,250.00	13:00~13:15	3,850.00	21:00~21:15	1,850.00
05:15~05:30	2,300.00	13:15~13:30	3,900.00	21:15~21:30	1,750.00
05:30~05:45	2,350.00	13:30~13:45	3,950.00	21:30~21:45	1,650.00
05:45~06:00	2,400.00	13:45~14:00	4,000.00	21:45~22:00	1,550.00
06:00~06:15	2,450.00	14:00~14:15	4,050.00	22:00~22:15	1,450.00
06:15~06:30	2,500.00	14:15~14:30	4,100.00	22:15~22:30	1,350.00
06:30~06:45	2,550.00	14:30~14:45	4,150.00	22:30~22:45	1,250.00
06:45~07:00	2,600.00	14:45~15:00	4,200.00	22:45~23:00	1,250.00
07:00~07:15	2,650.00	15:00~15:15	4,250.00	23:00~23:15	1,250.00
07:15~07:30	2,700.00	15:15~15:30	4,150.00	23:15~23:30	1,250.00
07:30~07:45	2,750.00	15:30~15:45	4,050.00	23:30~23:45	1,250.00
07:45~08:00	2,800.00	15:45~16:00	3,950.00	23:45~00:00	1,250.00

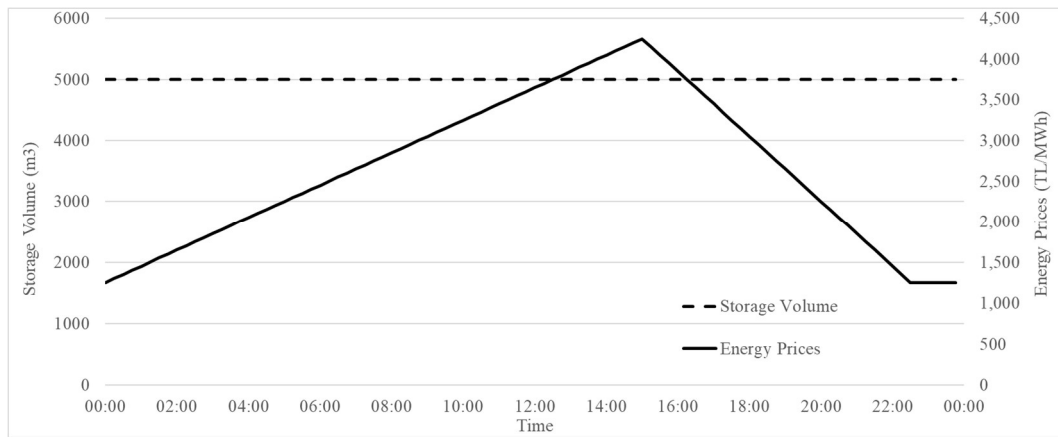


Figure 5.4 Storage Volume and Energy Prices for the HEPP Operated for Maximization of Revenue with Daily Average Inflow of 32.29 m³/s

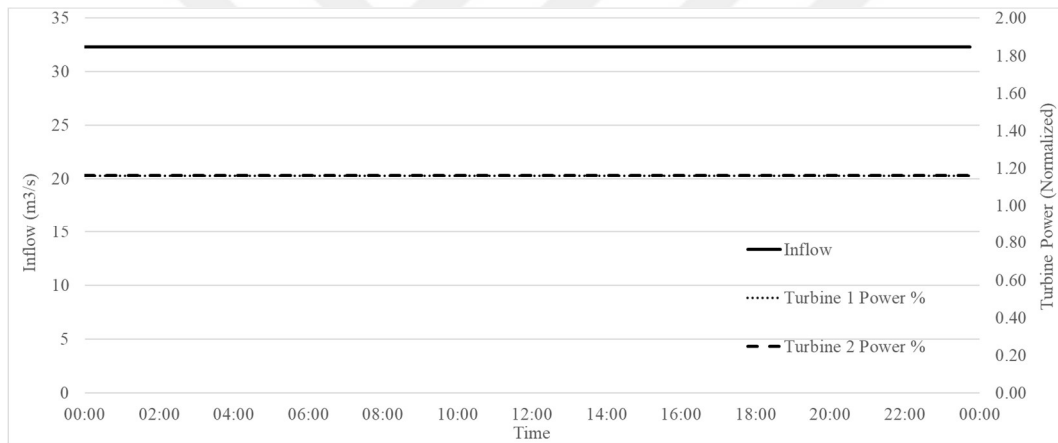


Figure 5.5 Normalized Turbine Powers and Inflow Rates for the HEPP Operated for Maximization of Revenue with Daily Average Inflow of 32.29 m³/s

Since the average daily inflow rate is higher than the total discharge capacity of turbines, both turbines operate with maximum capacity for the whole operation duration and storage capacity is not used as shown in Figure 5.4 and Figure 5.5.

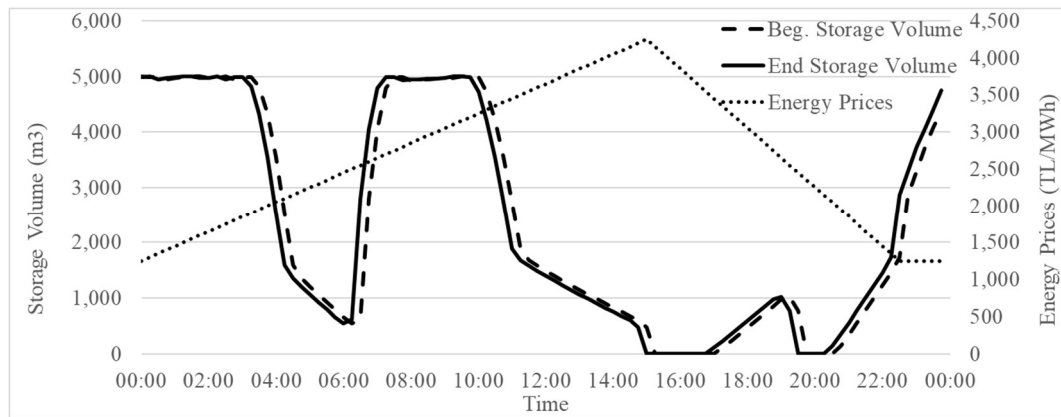


Figure 5.6 Storage Volume and Energy Prices for the HEPP Operated for Maximization of Revenue with Daily Average Inflow of $12.08 \text{ m}^3/\text{s}$

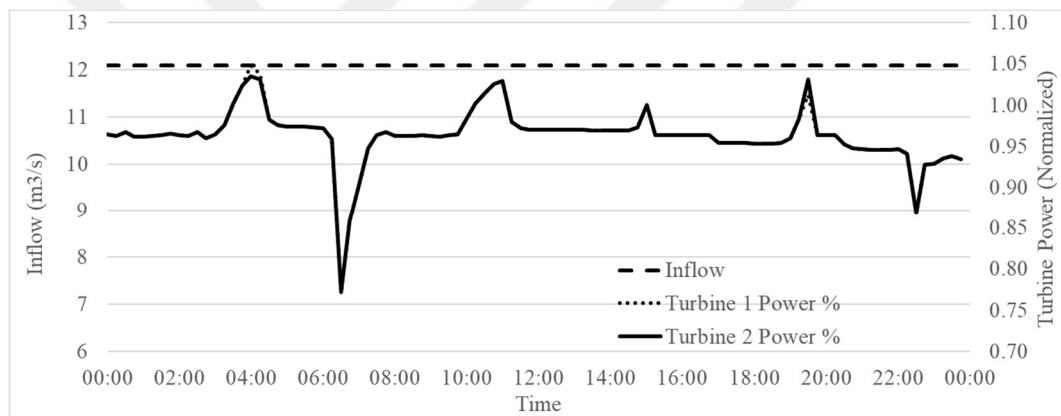


Figure 5.7 Normalized Turbine Powers and Inflow Rates for the HEPP Operated for Maximization of Revenue with Daily Average Inflow of $12.08 \text{ m}^3/\text{s}$

Since the average daily inflow rate is lower than the total discharge capacity of turbines but higher than a single turbine discharge capacity, turbines operate with different capacities in the second case analyzed as shown in Figure 5.7. Available storage capacity is utilized when the energy prices are at the highest level as shown in Figure 5.6 which indicates that the developed optimization algorithm performs well. Moreover, due to the storage capacity constraint defined as 95% of the initial storage capacity shall be available at the end of operation, at some point utilized

storage shall be refilled. As clearly visible from Figure 5.6, it is done by the algorithm when the energy prices are lowest, which is again a verification for the performance of the algorithm. It should also be noted that although the storage capacity is consumed when the energy prices at its peak, turbines continue to operate since there is a constant river inflow of $12.08 \text{ m}^3/\text{s}$. Finally, it is worth to point out that the storage capacity is relatively small compared to the discharge capacity of turbines, it is only sufficient to operate the turbines for 373 seconds, and even small changes in the turbine power causes volume of water stored decrease or increase.

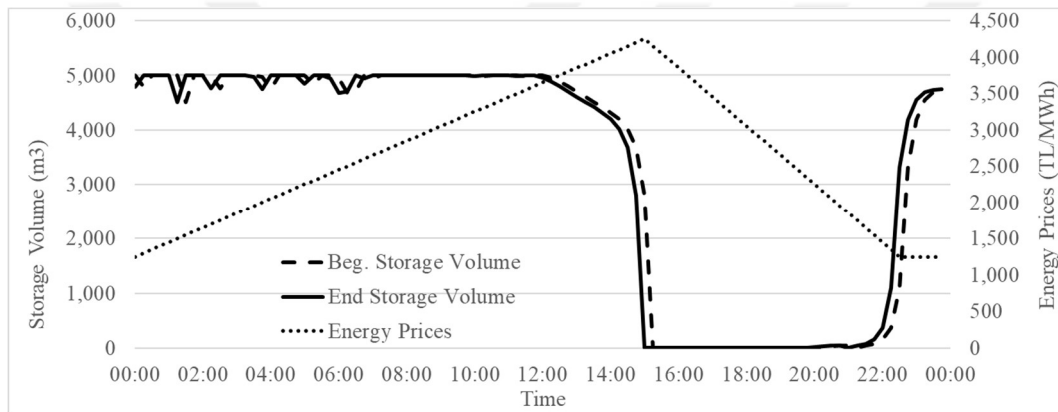


Figure 5.8 Storage Volume and Energy Prices for the HEPP Operated for Maximization of Revenue with Daily Average Inflow of $8.10 \text{ m}^3/\text{s}$

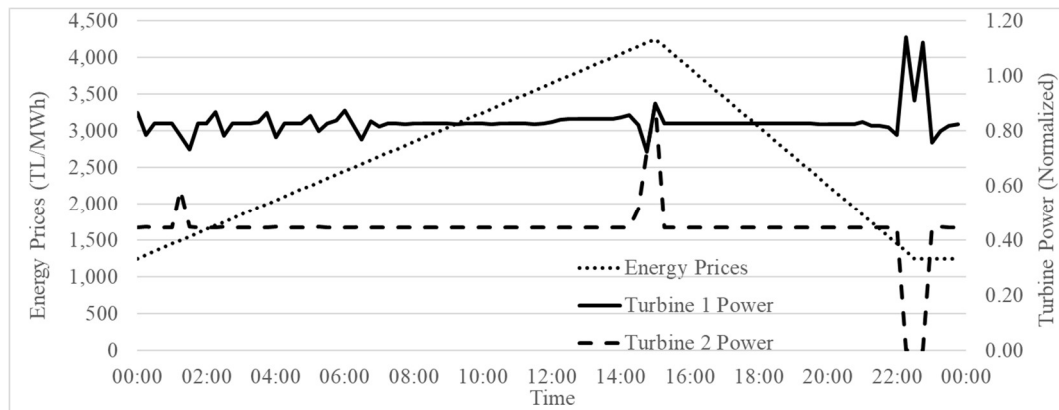


Figure 5.9 Normalized Turbine Powers and Energy Prices for the HEPP Operated for Maximization of Revenue with Daily Average Inflow of $8.10 \text{ m}^3/\text{s}$

The average daily inflow rate is lower than the total discharge capacity of turbines but again higher than a single turbine discharge capacity for the third case analyzed. Turbines operate with different capacities in the third case also but the effect of energy prices on the operation optimization is more visible as shown in Figure 5.8. Available storage capacity is utilized when the energy prices are at the highest level and both turbines operate with optimum efficiency levels as shown in Figure 5.9 which indicates that the developed optimization algorithm performs quite well. Furthermore, similar to the second case with $12.08 \text{ m}^3/\text{s}$, refilling of the storage is done by the algorithm when the energy prices are lowest. As stated for the second case previously, “the continuous operation of turbines even the storage capacity is consumed” is also valid for the third case since there is a constant river inflow of $8.10 \text{ m}^3/\text{s}$. In addition, the storage capacity is relatively small compared to the discharge capacity of turbines, same as the second case, and even small changes in the turbine power causes the volume of water stored to decrease or increase. Finally, it is more evident in the third case that the turbines reach peak turbine power when the energy prices are also at its peak.

5.4 Discussion of Results

The results were acquired through the application of the developed tools to a single HEPP. Initially, HEPP was operated on daily basis for two years without taking any storage capacity into account for maximization of energy.

Inflow rates given in the feasibility report for years 1995 and 1996 were used for maximization of energy. As mentioned in Section 5.2 obtained results with the developed tools in study are 7.91% and 7.39% less than feasibility report values. Operating ranges of the turbines were not considered in feasibility study. The turbines were operated with as low as 10% of the design discharge, which is not technically possible, and energy calculations were made accordingly in the feasibility study. This is the reason of finding lower values in this study.

In order to make a meaningful comparison of the results obtained in this study with the results of feasibility studies, total energy generation calculated in feasibility studies is revised. Analyzed HEPP's turbine design discharge is $6.70 \text{ m}^3/\text{s}$ and according to the hill chart, minimum required inflow is $2.97 \text{ m}^3/\text{s}$ to operate the turbine. The calculated energy generation in feasibility studies, with average daily inflows lower than $2.97 \text{ m}^3/\text{s}$ was ignored in total energy generation calculation and the result was found as 38.09 GWh for 1995 and 36.83 GWh for 1996. Comparing those results with the ones obtained in this study as 38.85 GWh and 37.57 GWh for the same years respectively gives 2.0% increase in energy generation for both years. It should be mentioned that even those results do not reflect the real effect of the developed tools as efficiency of the EME is assumed to be constant with a value of 0.88 in feasibility studies whereas the calculated efficiency values in this study using a real hill chart given as low values as 0.79.

In second phase, the same HEPP was operated with 15-minute time steps for a total duration of 1 day with considering the storage capacity available in head pond for maximization of revenue. Inflow rates on 14 April 1995, 10 March 1955 and 05

March 1995 are used with daily average inflows of 32.29 m³/s, 12.08 m³/s and 8.10 m³/s respectively.

Since the average daily inflow rate is higher than the total discharge capacity of turbines for 32.29 m³/s, both turbines operate with maximum capacity for the whole operation duration without utilization of any storage capacity, which verifies the developed tool performs well for high-rate discharges.

Since the average daily inflow rate is lower than the total discharge capacity of turbines for 12.08 m³/s but higher than a single turbine discharge capacity, turbines operate with different capacities in the second case analyzed as shown in Figure 5.7. Available storage capacity is utilized when the energy prices are at the highest level as shown in Figure 5.6 which indicates that the developed optimization algorithm performs well again. Moreover, due to the storage capacity constraint defined as 95% of the initial storage capacity shall be available at the end of operation, at some point utilized storage shall be refilled. As clearly visible from the same figure, it is done by the algorithm when the energy prices are lowest, which is again a verification for the performance of the algorithm.

The average daily inflow rate is lower than the total discharge capacity of turbines but again higher than a single turbine discharge capacity for 8.10 m³/s. Turbines operate with different capacities in the third case also but the effect of energy prices on the operation optimization is more visible as shown in Figure 5.8. Available storage capacity is utilized when the energy prices are at the highest level and both turbines operate with optimum efficiency levels as shown in Figure 5.9 which indicates that the developed optimization algorithm performs quite well. Furthermore, similar to the second case with 12.08 m³/s, refilling of the storage is done by the algorithm when the energy prices are lowest.

CHAPTER 6

CONCLUSION

Extensive research has been conducted to address the optimization challenge of reservoir operations and run-of-river systems in hydroelectric power plants. These studies have encompassed a diverse array of methodologies and variables, including reservoir volume, turbined water volume, turbine operation durations, energy production, capacity utilization, capacity deficit, and more. One prominent characteristic of these investigations is the complex interplay of numerous variables, often characterized by vast numerical ranges and project-specific constraints. Constraints separate the solution space into feasible and infeasible spaces. The resulting feasible solution space is generally limited and can be discontinuous, even when the optimization problem is not (Bureau of Reclamation 2012).

Although the mathematical expression of reservoir operation problem is well known and well expressed in terms of continuity equations, solving the problem and having meaningful results in a feasible meaningful time and establishing a stable solution algorithm and method providing consistent results at every run is difficult because of the complexities defined above, nonlinear nature and the size of the problem.

In the first part of this study, a new approach has been introduced to enhance the efficiency of the Generalized Reduced Gradient (GRG) optimization algorithm for optimization of reservoir operation of hydroelectric power plants. This involves the incorporation of a variable denoted as "A" which assumes values between 0 and 1. By implementing this concept, key parameters such as turbined water volume, reservoir volume, and head are expressed as functions of "A". This adaptation allows for the simplification of the reservoir operation optimization challenge using a single variable while imposing predefined bounds, thereby reducing the complexities associated with managing a multitude of variables with undefined ranges.

This advancement opens the door to the practical application of the method in the context of single-purpose dams and hydroelectric power plants. Moreover, it results in the development of generalized models applicable to the reservoir operations of single-purpose dams and hydroelectric power plants, whether considered in isolation or as part of a cascading system aimed at maximizing energy generation or maximizing revenue or maximizing profit. The defining strength of this methodology lies in the variable "A" which is systematically integrated into the optimization algorithm and consistently operates within well-defined boundaries (0 to 1). This solution effectively resolves the challenge of struggling with massive sets of variables and promotes more streamlined and efficient reservoir operation optimizations.

Furthermore, to improve the accuracy of power and energy calculations, actual data from turbine hill charts and generator specifications were utilized to calculate the efficiency of electromechanical equipment. The turbine hill chart data can be adjusted to match the specific hill chart data available for the turbines being considered in the project. Additionally, the impact of head and discharge on the efficiency of electromechanical equipment, as well as friction losses in the system, were taken into consideration. As described in Section 4.7 and 5.4 this approach provides a higher level of accuracy for the energy generation or revenue results and eliminates the possibility of underestimation or overestimation.

Using this new method, three different optimization models for reservoir operation were developed to design and operate single or multiple storage hydropower plants, as described in the previous sections. These models were applied to three dams located in Southeastern Turkey, operating the reservoirs both individually and in a cascade configuration.

When comparing the results of the case study to the values of feasibility study for the cascade configuration, it was found that the newly developed methods in the present study increased energy production and could easily be applied to any project using the user interface generated. However, it is important to note that the impact

of the operation models varied significantly depending on the characteristics of the dams being considered.

For small storage capacity dams, the different operation models had minimal effect. The cascade effect was also not clearly observed in these dams. On the other hand, dams with considerably large storage capacity were significantly affected by both the different operation models and the cascade effect. Moderate storage capacity dams showed no significant effect from different operation models, but demonstrated a positive impact from cascade operation, particularly when there was a large storage capacity dam upstream.

In the second part of this study, a similar approach has been introduced to run-of-river systems. This time incorporation of the variable denoted as "A", which again assumes values between 0 and 1, is used to determine the capacity of turbines to be operated for each time step considered. By implementing this concept, key parameters such as turbine discharge and head are expressed as functions of "A". This adaptation allows defining which turbine should be operated and when should be operated by using a single variable with predefined bounds either for energy or revenue maximization.

Using this new method, two different optimization models for run-of-river systems were developed to design and operate hydropower plants, as described in the previous sections. These models were applied to a hydropower plant located in Southeastern Turkey.

When comparing the results of the case study to the feasibility study values for the run-of-river hydropower plant, it was found that the developed methods increased energy production and could easily be applied to any project using the user interface developed.

Comparison of the results obtained in case studies of this study with the feasibility studies clearly shows that the lack of accuracy in the calculations, consideration of efficiency and working range of electro-mechanical equipment and lack of

optimization of powerhouse operation may result in underestimation or over estimation of energy generation values. This will eventually lead to mis planning of investment and possible loss of profit. Usage of the developed models in this study will eliminate mis intelligence associated with operation studies of hydroelectric power plants.

Developed models and tools in this study can be used during feasibility stage, design stage and operation stage of hydroelectric power plants. Table 6.1 summarizes which model can be used at which stage.

Table 6.1 Usability of Developed Models at Different Stages of a Hydropower Investment

System	Options for Optimization	Operation Model	Feasibility Stage	Design Stage	Operation Stage
Single Storage Systems	Maximization of Energy	FRLEO	√	√	√
		FRLEY	√	√	√
		RLOR			√
	Maximization of Revenue	FRLEO	√	√	√
		FRLEY	√	√	√
		RLOR			√
	Maximization of Profit	FRLEO	√	√	
Run-of-River Systems	Maximization of Energy	NA	√	√	
	Maximization of Revenue	FRLEO			√
Cascade Storage Systems	Maximization of Energy	FRLEO	√	√	√
		FRLEY	√	√	√
		RLOR			√
	Maximization of Revenue	FRLEO	√	√	√
		FRLEY	√	√	√

In conclusion, the suitability and effectiveness of the operation models for single or cascade systems depend on the specific characteristics of the system under consideration. It is important to conduct trials and evaluate the results before deciding on the most appropriate option. Nevertheless, the models developed in this

study can be used to determine the optimal operation rules for any single or multi-reservoir system as well as run-of-river systems.

Recommendations for Future Studies

In this thesis, single storage systems, cascade storage systems and run-of-river system hydropower plants were studied for the objectives of maximization of energy generation, maximization of revenue and maximization of profit. In this context, different models and tools are developed that can be applied to any system with single purpose of operation, energy generation. In future studies, optimization models for multi-purpose systems can be developed considering different purposes of operation such as irrigation, flood protection and utility water or a combination of those.

Moreover, the model developed for maximization of profit in this study considers only the cost associated with water way structures, electromechanical equipment, and powerhouse construction costs. In future studies, cost estimation for the water retaining structures can be developed.

Furthermore, an estimation model for the future energy prices can be incorporated into the tools developed instead of user provided energy prices.

REFERENCES

- Aboutalebi, M., Haddad, O. B., Loáiciga, H. A. 2015. Optimal Monthly Reservoir Operation Rules for Hydropower Generation Derived with SVR-NSGAIL. *Journal of Water Resources Planning and Management*, 2015, 141(11): 04015029. [https://doi.org/10.1061/\(ASCE\)WR.1943-5452.0000553](https://doi.org/10.1061/(ASCE)WR.1943-5452.0000553)
- Afshar, A., Sharifi, F., Jalali, M. R. 2009. Non-dominated archiving multi-colony ant algorithm for multi-objective optimization: Application to multi-purpose reservoir operation. *Engineering Optimization*, 41:4, 313-325. <https://doi.org/10.1080/03052150802460414>
- Afshar, A., Skardi, M. J. E., Masoumi, F. 2015. Optimizing water supply and hydropower reservoir operation rule curves: An imperialist competitive algorithm approach. *Engineering Optimization*, 47:9, 1208-1225. <https://doi.org/10.1080/0305215X.2014.958732>
- Ahmad, A., El-Shafie, A. 2014. Reservoir Optimization in Water Resources: a Review. *Water Resources Management* (2014) 28:3391–3405. <https://doi.org/10.1007/s11269-014-0700-5>
- Ahmadianfar, I., Bozorg-Haddad, O., Chu, X. 2019. Optimizing Multiple Linear Rules for Multi-Reservoir Hydropower Systems Using an Optimization Method with an Adaptation Strategy. *Water Resources Management* (2019) 33:4265–4286. <https://doi.org/10.1007/s11269-019-02364-y>
- Ajibola, O. O. E., Ajala, O. S., Akanmu, J. O. and Balogun, O. J. 2017. Optimizing Hydroelectric Power Generation: The Case of Shiroro Dam. *Proceedings of the World Congress on Engineering 2017 Vol I*
- Ak, M. 2017. Rule curves for operating single- and multi-reservoir hydropower plants. (PhD Thesis), Department of Civil Engineering METU, Ankara
- Al-Aqeeli, Y. H., Agha, O.M., Mahmood, A. 2020. Optimal Operation of Multi-reservoir System for Hydropower Production Using Particle Swarm

- Optimization Algorithm. *Water Resources Management* (2020) 34:3099–3112. <https://doi.org/10.1007/s11269-020-02583-8>
- Al-Jawad, J. Y., Tanyimboh, T.T. 2017. Reservoir operation using a robust evolutionary optimization algorithm. *Journal of Environmental Management* 197 (2017) 275-286. <https://doi.org/10.1016/j.jenvman.2017.03.081>
- Almeida, J.P.P.G.L. de, Lejeune, A.G.H., Marques, J.A.A. Sa, Cunha, M.C. 2006. OPAH a model for optimal design of multipurpose small hydropower plants. *Advances in Engineering Software* 37 (2006) 236–247. <https://doi.org/10.1016/j.advengsoft.2005.06.004>
- Anagnostopoulos, J.S., Papantonis, D.E. 2007. Optimal sizing of a run-of-river small hydropower plant. *Energy Conversion and Management* 2007;48(10):2663–70.
- Ancieta, C. A. 2009. Estimating E&M powerhouse costs. *International Water Power and Dam Construction* (February 2009) 21-25.
- Azizipour, M., Ghalenoei, V., Afshar, M. H., Solis S. S. 2016. Optimal Operation of Hydropower Reservoir Systems Using Weed Optimization Algorithm. *Water Resources Management* (2016) 30:3995–4009. <https://doi.org/10.1007/s11269-016-1407-6>
- Bai, T., Kan, Y.-B., Chang, J.-X., Huang, Q., Chang, F.-J. 2016. Fusing feasible search space into PSO for multi-objective cascade reservoir optimization. *Applied Soft Computing* 51 (2017) 328–340. <https://doi.org/10.1016/j.asoc.2016.12.005>
- Barbaros, E. 2019. Feasibility of pumped-storage hydraulic systems based on hourly variation of electricity prices. (MSc Thesis), Department of Civil Engineering METU, Ankara
- Basso, S., Botter, G., Streamflow variability and optimal capacity of run-of-river hydropower plants. *Water Resources Research* 2012;48:10.

- Beiranvand, B., Ashofteh, P.-S. 2023. A Systematic Review of Optimization of Dams Reservoir Operation Using the Meta-heuristic Algorithms. *Water Resources Management* (2023). <https://doi.org/10.1007/s11269-023-03510-3>
- Bilal, Pant, M., Rani, D. 2021. Large scale reservoir operation through integrated meta-heuristic approach. *Memetic Computing* (2021) 13:359–382. <https://doi.org/10.1007/s12293-021-00327-8>
- Celeste, A.B., Billib, M. 2012. Improving Implicit Stochastic Reservoir Optimization Models with Long-Term Mean Inflow Forecast. *Water Resources Management* (2012) 26:2443–2451. <https://doi.org/10.1007/s11269-012-0025-1>
- Chang, F.-J., Chen, L. 1998. Real-coded genetic algorithm for rule-based flood control reservoir management. *Water Resources Management* 12(3):185–198
- Chang, F.-J., Chen, L., Chang, L.-C. 2005. Optimizing the reservoir operating rule curves by genetic algorithms. *Hydrological Processes*, 19, (2005) 2277–2289. <https://doi.org/10.1002/hyp.5674>
- Chang, J.X., Huang, Q., Wang, Y.M. 2005. Genetic algorithms for optimal reservoir dispatching. *Water Resources Management* 19:321–331
- Chen, L., McPhee J., Weh W. W. G. 2007. A diversified multiobjective GA for optimizing reservoir rule curves. *Advances in Water Resources* 30 (2007) 1082–1093. <https://doi.org/10.1016/j.advwatres.2006.10.001>
- Connolly, D., Lund, H., Finn, P., Mathiesen, B.V., Leahy, M. 2011. Practical operation strategies for pumped hydroelectric energy storage (PHES) utilizing electricity price arbitrage. *Energy Policy* 2011;39(7):4189–96.
- Dahmani, S., Yebdri, D. 2020. Hybrid Algorithm of Particle Swarm Optimization and Grey Wolf Optimizer for Reservoir Operation Management. *Water*

Resources Management (2020) 34:4545–4560.
<https://doi.org/10.1007/s11269-020-02656-8>

Darcy, H. 1857. Recherches expérimentales relatives au mouvement de l'eau dans les tuyaux. Mallet-Bachelier, Paris.

Enerdata. (2023). World Energy & Climate Statistics 2023.
<https://www.enerdata.net/publications/world-energy-statistics-supply-and-demand.html>

Esat, V., Hall, M. 1994. Water resources system optimization using genetic algorithms. In: A Verwey, A Minns, V Babovic, C Maksimovic (eds) Proc.1st Int. Conf. Hydroinform '94, Balkema, Rotterdam, The Netherlands, pp 225–231

Feng, Z.-K., Niu, W.-J., Jiang, Z.-Q., Qin, H., Song, Z.-G. 2020. Monthly Operation Optimization of Cascade Hydropower Reservoirs with Dynamic Programming and Latin Hypercube Sampling for Dimensionality Reduction. Water Resources Management (2020) 34:2029–2041.
<https://doi.org/10.1007/s11269-020-02545-0>

Ferreira, A. R., Teegavarapu, R. S.V. 2012. Partial constraint satisfaction approaches for optimal operation of a hydropower system. Engineering Optimization, 44:9, 1073-1093. <https://doi.org/10.1080/0305215X.2011.632007>

Finardi, E. C., Takigawa, F.Y.K., Brito, B.H. 2016. Assessing solution quality and computational performance in the hydro unit commitment problem considering different mathematical programming approaches. Electric Power Systems Research 136 (2016) 212–222.
<https://doi.org/10.1016/j.epsr.2016.02.018>

Garrido, J., Zafra, Á., Vázquez, F. 2009. Object oriented modelling and simulation of hydropower plants with run-of-river scheme: a new simulation tool. Simulation Modeling Practice Theory 2009;17(10):1748–67.

- Ge, X.-L., Zhang, L.-Z., Shu, J., Xu, N.-F. 2014. Short-term hydropower optimal scheduling considering the optimization of water time delay. *Electric Power Systems Research* 110 (2014) 188–197. <https://doi.org/10.1016/j.epsr.2014.01.015>
- Haddad O. B., Moradi-Jalal M., Mariño M.A. 2011. Design–operation optimization of run-of-river power plants. In: *Proceeding of the ICE-Water Management*. 2011;164(9):463–475.
- Haktanir, T., Aydemir, A., 2023. Simulation Models for Hydro-Electric Energy by Steady-Rate and Night-Shift-Pumped-Storage Operations. *Turkish Journal of Civil Engineering*. <https://doi.org/10.18400/tjce.1310667>
- Hatamkhani, A., Shourian, M., Moridi A. 2021. Optimal Design and Operation of a Hydropower Reservoir Plant Using a WEAP-Based Simulation–Optimization Approach. *Water Resources Management* (2021) 35:1637–1652. <https://doi.org/10.1007/s11269-021-02821-7>
- Hirsch, P. E., Schillinger, S., Weigt, H., Burkhardt-Holm P. 2014 A Hydro-Economic Model for Water Level Fluctuations: Combining Limnology with Economics for Sustainable Development of Hydropower. *PLoS ONE* 9(12): e114889. <https://doi.org/10.1371/journal.pone.0114889>
- Holland, J.H. 1975 *Adaptation in natural and artificial system*. The University of Michigan Press, Ann Arbor, MI
- Huang, W.C., Yuan, L.C., Lee, C.M. 2002. Linking genetic algorithms with stochastic dynamic programming to the long-term operation of a multi reservoir system. *Water Resources Research* 38(2):401–409
- International Energy Agency. (2023). *Electricity Market Report 2023*. <https://www.iea.org/reports/electricity-market-report-2023/executive-summary>
- Ji, C.-M, Zhou, T., Huang, H.-T. 2014. Operating Rules Derivation of Jinsha Reservoirs System with Parameter Calibrated Support Vector Regression.

- Water Resources Management (2014) 28:2435–2451. <https://doi.org/10.1007/s11269-014-0610-6>
- Jiang, Z., Li, R., Li, A., Ji, C. 2018. Runoff forecast uncertainty considered load adjustment model of cascade hydropower stations and its application. Energy 158 (2018) 693–708. <https://doi.org/10.1016/j.energy.2018.06.083>
- Jiang, Z., Sun, P., Ji, C., Zhou, J. 2015. Credibility theory based dynamic control bound optimization for reservoir flood limited water level. Journal of Hydrology 529 (2015) 928–939. <https://doi.org/10.1016/j.jhydrol.2015.09.012>
- Jothiprakash, V. and Arunkumar, R. 2013. Optimization of Hydropower Reservoir Using Evolutionary Algorithms Coupled with Chaos. Water Resources Management (2013) 27:1963–1979. <https://doi.org/10.1007/s11269-013-0265-8>
- Kangrang, A. and Lokham, C. 2013. Optimal Reservoir Rule Curves Considering Conditional Ant Colony Optimization with Simulation Model. Journal of Applied Sciences, 13 (1):154–160. <https://doi.org/10.3923/jas.2013.154.160>
- Karaeren, V. 2014. Maximizing energy generation of a cascade hydropower system. (MSc Thesis), Department of Civil Engineering METU, Ankara
- Karami, H., Farzin, S., Jahangiri, A., Ehteram, M., Kisi, O., El-Shafie, A. 2019. Multi-Reservoir System Optimization Based on Hybrid Gravitational Algorithm to Minimize Water-Supply Deficiencies. Water Resources Management (2019) 33:2741–2760. <https://doi.org/10.1007/s11269-019-02238-3>
- Karamouz, M., Zahraie, B., Araghinejad, S. 2005. Decision Support System for Monthly Operation of Hydropower Reservoirs: A Case Study. Journal of Computing in Civil Engineering, 2005, 19(2): 194–207. [https://doi.org/10.1061/\(ASCE\)0887-3801\(2005\)19:2\(194\)](https://doi.org/10.1061/(ASCE)0887-3801(2005)19:2(194))

- Kocaman, A. S., Abad, C., Troy, T. J., Huh, W. T., Modi, V. 2015. A stochastic model for a macro scale hybrid renewable energy system. *Renewable and Sustainable Energy Reviews* 54 (2016) 688–703. <https://doi.org/10.1016/j.rser.2015.10.004>
- Labadie, J. W. 2004. Optimal Operation of Multi reservoir Systems: State-of-the-Art Review. *Journal of Water Resources Planning and Management*, 2004, 130(2): 93-111. [https://doi.org/10.1061/\(ASCE\)0733-9496\(2004\)130:2\(93\)](https://doi.org/10.1061/(ASCE)0733-9496(2004)130:2(93))
- Ladurantaye, D.De, Gendreau, M., Potvin, J.-Y. 2009. Optimizing profits from hydroelectricity production. *Computers & Operations Research*, 36(2), 499-529. <https://doi.org/10.1016/j.cor.2007.10.012>
- Lai, V., Essam, Y., Huang, Y. F., Ahmed, A. N., El-Shafie, A. 2022. Investigating dam reservoir operation optimization using metaheuristic algorithms. *Applied Water Science* (2022) 12:280. <https://doi.org/10.1007/s13201-022-01794-1>
- Lai, V., Huang, Y. F., Koo, C. H., Ahmed, A. N., El-Shafie, A. 2022. A Review of Reservoir Operation Optimisations: from Traditional Models to Metaheuristic Algorithms. *Archives of Computational Methods in Engineering* (2022) 29:3435–3457. <https://doi.org/10.1007/s11831-021-09701-8>
- Lasdon, L.S., Fox, R.L., Ratner, M.W. 1974. Nonlinear Optimization Using the Generalized Reduced Gradient Method. *R.A.I.R.O* November 1974, v-3, 73-104.
- Lerma, N., Paredes-Arquiola, J., Andreu, J., Solera, A. 2013. Development of operating rules for a complex multi-reservoir system by coupling genetic algorithms and network optimization. *Hydrological Sciences Journal* 58:4, 797-812. <https://doi.org/10.1080/02626667.2013.779777>
- Li, Fang-Fang, Qiu, Jun. 2015. Multi-Objective Reservoir Optimization Balancing Energy Generation and Firm Power. *Energies* 2015, 8, 6962-6976. <https://doi.org/10.3390/en8076962>

- Li, X.-G., Wei, X. 2007. An Improved Genetic Algorithm-Simulated Annealing Hybrid Algorithm for the Optimization of Multiple Reservoirs. *Water Resources Management* (2008) 22:1031–1049. <https://doi.org/10.1007/s11269-007-9209-5>
- Liu, B., Yang, Z., Chen, Y., Li, L., Chen, S. 2021. A decision making framework for scheme selection for sustainable hydropower development. *International Journal of Green Energy*, 18:9, 951-965. <https://doi.org/10.1080/15435075.2021.1890081>
- Liu, H., Sun, Y., Yin, X., Zhao, Y., Cai, Y., Yang, W. 2019. A reservoir operation method that accounts for different inflow forecast uncertainties in different hydrological periods. *Journal of Cleaner Production*, 256 (2020) 120471. <https://doi.org/10.1016/j.jclepro.2020.120471>
- Liu, P., Guo, S., Xu, X., Chen, J. 2011. Derivation of Aggregation-Based Joint Operating Rule Curves for Cascade Hydropower Reservoirs. *Water Resources Management* (2011) 25:3177–3200. <https://doi.org/10.1007/s11269-011-9851-9>
- Malekmohammadi, B., Kerachian, R., Zahraie, B. 2009. Developing monthly operating rules for a cascade system of reservoirs: Application of Bayesian Networks. *Environmental Modelling & Software* 24 (2009) 1420–1432. <https://doi.org/10.1016/j.envsoft.2009.06.008>
- Mamo, G.E. 2018. Methods for optimal design of run-of-river power plants, a decision support tool for RoR power plant design. (MSc Thesis), UNESCO-IHE Institute for Water Education, Delft
- Markert, K. N., Pulla, S. T., Lee, H., Markert, A. M., Anderson, E. R., Okeowo, M. A., Limaye, A.S. 2019. AltEx: An open source web application and toolkit for accessing and exploring altimetry datasets. *Environmental Modelling and Software* 117 (2019) 164–175. <https://doi.org/10.1016/j.envsoft.2019.03.021>
- Mo, L., Lu, P., Wang, C., Zhou, J. 2013. Short-term hydro generation scheduling of Three Gorges–Gezhouba cascaded hydropower plants using hybrid MACS-

ADE approach. Canadian Journal of Civil Engineering, 38 (7), pp. 811-824.
<https://doi.org/10.1139/L11-051>

Moeini, R., Afshar, M. H. 2011. Arc-based constrained ant colony optimisation algorithms for the optimal solution of hydropower reservoir operation problems. Canadian Journal of Civil Engineering, 38 (7), pp. 811-824.
<https://doi.org/10.1139/L11-051>

Moghadam, A. B., Ebrahimi, H., Siuki, A. K., Akbarpour, A. 2022. Reliability-based Operation of Reservoirs Using Combined Monte Carlo Simulation Model and a Novel Nature-inspired Algorithm. Water Resources Management (2022) 36:4447–4468. <https://doi.org/10.1007/s11269-022-03163-8>

Moody, L. F. 1944. Friction factors for pipe flow. Trans. ASME, 66,671-678.

Munson, B. R., Young, D. F., & Okiishi, T. H. 2006. Fundamentals of fluid mechanics. Hoboken, NJ: J. Wiley & Sons., 2006

Najmائي, M., Movaghar, A. 1992. Optimal Design of Run-of-River Power Plants. Water Resources Reserach 28(4), 991-997

Niu, W.-J., Feng, Z.-K., Cheng, C.-T., Wu, Z.-Y. 2017. A parallel multi-objective particle swarm optimization for cascade hydropower reservoir operation in southwest China. Applied Soft Computing 70 (2018) 562–575.
<https://doi.org/10.1016/j.asoc.2018.06.011>

Niu, W.-J., Feng, Z.-K., Li, W.-R., Liu S. 2021. Cooperation Search Algorithm for Power Generation Production Operation Optimization of Cascade Hydropower Reservoirs. Water Resources Management (2021) 35:2465–2485. <https://doi.org/10.1007/s11269-021-02842-2>

Pérez-Díaz, J. I., Wilhelmi, J. R., Sánchez-Fernández, J. A. 2010. Short-term operation scheduling of a hydropower plant in the day-ahead electricity market. Electric Power Systems Research 80 (2010) 1535–1542.
<https://doi.org/10.1016/j.epsr.2010.06.017>

- Raju, K.S., Kumar, D.N. 2004. Irrigation planning using Genetic Algorithms. *Water Resources Management* 18 (2):163–176.
- Reddy, M. J. and Kumar, D. N. 2007. Multi objective Differential Evolution with Application to Reservoir System Optimization. *Journal of Computing in Civil Engineering*, 2007, 21(2): 136-146.
- Ren, K., Huang, S., Huang, Q., Wang, H., Leng, G., Cheng, L., Fang, W., Li, P. 2018. A nature-based reservoir optimization model for resolving the conflict in human water demand and riverine ecosystem protection. *Journal of Cleaner Production*, 231 (2019) 406-418.
<https://doi.org/10.1016/j.jclepro.2019.05.221>
- Sachin Mishra, S. K. Singal, D. K. Khatod. 2013. Cost Analysis for Electromechanical Equipment in Small Hydropower Projects. *International Journal of Green Energy*, 10:8, 835-847.
<https://doi.org/10.1080/15435075.2012.727367>
- Samadi-koucheksaraee, A., Ahmadianfar, I., Bozorg-Haddad, O., Asghari-pari, S. A. 2018. Gradient Evolution Optimization Algorithm to Optimize Reservoir Operation Systems. *Water Resources Management* (2019) 33:603–625.
<https://doi.org/10.1007/s11269-018-2122-2>
- Sharif, M., Wardlaw, R. 2000. Multi-reservoir systems optimization using genetic algorithm: Case study. *Journal of Computing in Civil Engineering* 14(4):255–263
- Sharifi, M. R., Akbarifard, S., Kourosh, Q., Madadi, M. R. 2021. Developing MSA Algorithm by New Fitness-Distance-Balance Selection Method to Optimize Cascade Hydropower Reservoirs Operation. *Water Resources Management* (2021) 35:385–406. <https://doi.org/10.1007/s11269-020-02745-8>
- Sharifi, M. R., Akbarifard, S., Madadi, M. R., Kourosh, Q., Akbarifard, H. 2022. Application of MOMSA algorithm for optimal operation of Karun multi objective multi reservoir dams with the aim of increasing the energy generation. *Energy Strategy Reviews*, 42 (2022) 100883.
<https://doi.org/10.1016/j.esr.2022.100883>

- Singh, V. K., Singal, S. K. 2017. Operation of hydro power plants-a review. *Renewable and Sustainable Energy Reviews*, 69 (2017) 610–619. <https://doi.org/10.1016/j.rser.2016.11.169>
- Su Ener Engineering and Energy Services. 2020. Computational Fluid Dynamics Report for Atatürk HEPP, Ankara
- Tan, Q.-F., Wang, X., Wang, H., Wang, C., Lei, X.-H., Xiong, Y.-S., Zhang, W. 2017. Derivation of optimal joint operating rules for multi-purpose multi-reservoir water-supply system. *Journal of Hydrology* 551 (2017) 253–264. <https://doi.org/10.1016/j.jhydrol.2017.06.009>
- The Intergovernmental Panel on Climate Change. 2012. Renewable Energy Sources and Climate Change Mitigation Special Report, USA
- U.S. Department of the Interior Bureau of Reclamation. 2012. Advanced Algorithms for Hydropower Optimization, USA
- Wang, W., Jia, B., Simonovic, S. P., Wu, S., Fan, Z., Ren, L. 2021. Comparison of Representative Heuristic Algorithms for Multi-Objective Reservoir Optimal Operation. *Water Resources Management* (2021) 35:2741–2762. <https://doi.org/10.1007/s11269-021-02864-w>
- Weisbach, J. 1845. *Lehrbuch der Ingenieur- und Maschinen-Mechanik*, Vol. 1. Theoretische Mechanik, Vieweg und Sohn, Braunschweig.
- Wilson, R. 2015. Capital improvement project evaluation: a hydroelectric generation economic perspective. *International Journal of Energy Research* 2015; 39:1402–1419. <https://doi.org/10.1002/er.3343>
- Vardanyan, Y., Hesamzadeh, M. R. 2017. The coordinated bidding of a hydropower producer in three-settlement markets with time-dependent risk measure. *Electric Power Systems Research* 151 (2017) 40–58. <https://doi.org/10.1016/j.epsr.2017.05.007>

Vito Flemish Institute for Technological Research NV. 2011. LOT 2: Distribution and power transformers Tasks 1-7, Mol

Xin-Yu, W., Chun-Tian, C., Jian-Jian, S., Bin, L., Sheng-Li, L., Gang, L. 2014. A multi-objective short term hydropower scheduling model for peak shaving. *Electrical Power and Energy Systems* 68 (2015) 278–293. <https://doi.org/10.1016/j.ijepes.2014.12.004>

Xu, B., Huang, X., Mo, R., Zhong, P., Lu, Q., Zhang, H., Si, W., Xiao, J., Sun, Y. 2021. Integrated real-time flood risk identification, analysis, and diagnosis model framework for a multi reservoir system considering temporally and spatially dependent forecast uncertainties. *Journal of Hydrology* 600 (2021) 126679. <https://doi.org/10.1016/j.jhydrol.2021.126679>

Yıldız, V. 2015. Numerical simulation model of run of river hydropower plants: Concepts, Numerical modeling, Turbine system and selection, and design optimization. (MSc Thesis), Department of Civil Engineering University of California, Irvine

Yoo, Ju-Hwan. 2009. Maximization of hydropower generation through the application of a linear programming model. *Journal of Hydrology* 376 (2009) 182–187. <https://doi.org/10.1016/j.jhydrol.2009.07.026>

Zhou, Y., Guo, S., Chang, F.-J., Xu, C.-Y. 2018. Boosting hydropower output of mega cascade reservoirs using an evolutionary algorithm with successive approximation. *Applied Energy* 228 (2018) 1726–1739. <https://doi.org/10.1016/j.apenergy.2018.07.078>

Zhou, Y., Guo, S., Xu, C.-Y., Chang, F.-J., Chen, H., Liu, P., Ming, B. 2020. Stimulate hydropower output of mega cascade reservoirs using an improved Kidney Algorithm. *Journal of Cleaner Production* 244 (2020) 118613. <https://doi.org/10.1016/j.jclepro.2019.118613>

APPENDICES

A. Storage Systems Characteristic Data Input Sheet

OPERATION OF HYDROPOWER PLANTS WITH STORAGE CAPACITY									
Name of Project		DAM 1 AND HEPP							
Tunnel Length (m)		10		Tunnel Diameter (m)		10			
Penstock Length (m)		32.3		Penstock Diameter (m)		4.15			
Tunnel Concrete (c) mm=		0.6		Penstock Steel (c) mm=		0.15			
Total Installed Capacity (MWm)		7.91		Number of Units		2			
Installed Capacity Unit1 (MWm)		3.955		Unit1 Design Discharge (m ³ /s)		32.02			
Installed Capacity Unit2 (MWm)		3.955		Unit2 Design Discharge (m ³ /s)		32.02			
Installed Capacity Unit3 (MWm)				Unit3 Design Discharge (m ³ /s)					
Installed Capacity Unit4 (MWm)				Unit4 Design Discharge (m ³ /s)					
				Total Design Discharge (m ³ /s)		64.04			
Maximum Reservoir Operation Level (m)		1111.4		Minimum Reservoir Operation Level (m)		1111			
Tailwater Level for Project Discharge (m)=		1097		Design Net Head (m)		14.398			
Inflow Data First Year		1957		Initial Reservoir Operation Level (m)		1111.400			
Inflow Data Last Year		2005		End of Year Min. Reservoir Operation Level (m)		1111.000			

Area-Volume Curve Data				Evaporation		Other Uses From Reservoir		Downstream Water Rights	
	Level (m)	Area (km ²)	Volume (hm ³)	Months	mm	Months	hm ³	Months	hm ³
1	1105.00	0.82	0.00	October	0.00	October	1.30	October	0.00
2	1111.00	0.92	1.00	November	0.00	November	0.78	November	0.00
3	1111.40	0.93	1.01	December	0.00	December	0.80	December	0.00
4				January	0.00	January	0.80	January	0.00
5				February	0.00	February	0.73	February	0.00
6				March	0.00	March	0.80	March	0.00
7				April	0.00	April	0.78	April	0.00
8				May	0.00	May	3.80	May	0.00
9				June	0.00	June	19.04	June	0.00
10				July	0.00	July	28.34	July	0.00
11				August	0.00	August	24.78	August	0.00
12				September	0.00	September	6.58	September	0.00
13				Annual	0.00	Annual	88.53	Annual	0.00
14									
15									
16									
17									
18									
19									
20									

Run

B. Storage Systems Inflow Data Input Sheet

	October	November	December	January	February	March	April	May	June	July	August	September	Annual
1957	43.51	44.16	44.21	45.03	47.74	146.90	94.82	123.06	61.83	26.34	22.11	26.03	725.74
1958	32.31	34.27	49.02	49.48	49.48	131.42	198.04	126.89	68.50	19.06	19.12	25.27	802.87
1959	35.81	35.17	44.82	43.69	37.04	80.49	126.82	82.08	30.87	19.46	19.79	23.36	579.39
1960	32.61	31.57	34.11	47.98	44.54	82.73	220.91	147.93	41.87	27.49	22.62	28.57	762.93
1961	25.82	29.08	32.27	37.05	40.60	53.08	133.84	79.89	19.99	12.75	12.53	18.60	495.49
1962	26.32	30.11	44.22	36.58	43.44	143.73	142.47	114.62	30.70	12.00	11.02	19.31	654.52
1963	28.96	28.03	48.65	62.62	115.61	140.17	227.04	246.30	129.58	22.52	18.32	27.61	1095.41
1964	46.38	53.18	52.30	45.71	42.29	147.72	124.71	71.69	29.60	12.03	11.08	16.23	652.93
1965	29.61	32.84	42.82	42.66	39.70	180.30	276.96	186.46	71.41	24.48	20.33	26.78	974.35
1966	40.21	44.40	63.07	224.37	160.01	218.21	262.21	178.53	70.61	25.30	19.34	34.23	1340.50
1967	42.67	72.21	146.90	130.77	93.13	157.28	278.34	270.62	89.39	39.50	29.72	35.05	1385.57
1968	55.95	100.17	109.73	119.57	119.21	306.20	414.26	298.76	110.28	37.53	34.13	42.77	1748.56
1969	54.70	129.27	172.58	155.37	137.80	393.64	391.78	482.93	188.02	88.72	64.95	76.62	2336.37
1970	105.24	99.03	117.82	115.20	122.62	228.53	237.71	154.47	73.69	42.14	33.11	36.46	1366.03
1971	59.16	60.51	83.35	80.36	69.66	130.77	257.71	175.80	65.06	22.63	25.34	29.64	1059.99
1972	47.39	48.41	56.68	54.24	52.32	68.58	128.14	141.64	74.32	30.24	28.26	32.26	762.50
1973	45.04	50.25	41.62	40.19	38.75	53.79	99.67	70.60	17.10	8.53	9.62	13.89	489.04
1974	25.58	28.49	31.88	30.17	27.34	86.37	111.76	55.50	13.26	8.17	8.34	17.08	443.92
1975	24.58	26.17	31.47	32.88	28.77	96.86	302.90	234.73	55.28	14.92	15.13	19.86	883.55
1976	28.12	34.38	36.58	35.40	34.12	106.06	331.76	262.15	104.73	22.15	18.54	24.95	1038.94
1977	46.77	66.50	101.81	69.98	133.36	260.57	335.46	283.73	88.60	25.47	18.20	24.00	1454.43
1978	45.17	40.17	46.64	65.74	109.66	196.08	296.59	237.55	96.79	23.37	20.28	26.23	1204.27
1979	41.22	67.19	79.89	181.87	162.23	197.72	217.79	155.03	98.91	27.52	18.25	21.40	1269.03
1980	35.20	72.25	74.74	86.87	86.16	291.17	493.06	431.83	157.61	71.95	37.76	44.30	1882.91
1981	68.74	83.28	86.64	83.82	100.08	341.65	269.02	242.68	150.67	81.46	59.98	57.39	1625.41
1982	61.82	61.28	104.23	97.57	68.91	95.41	271.66	207.70	95.41	55.58	48.46	43.41	1211.45
1983	41.08	58.19	59.93	59.57	48.31	143.03	284.16	213.53	92.11	33.51	27.09	18.14	1078.66
1984	37.43	78.90	110.69	78.28	90.07	159.19	211.97	156.15	50.39	21.40	17.18	19.94	1031.60
1985	32.51	35.88	36.08	39.01	42.22	62.83	122.21	72.53	18.13	9.18	13.98	15.17	499.74
1986	43.21	38.12	39.04	46.71	49.01	79.26	72.91	69.82	56.10	10.73	9.34	10.73	524.98
1987	26.66	35.61	37.08	67.77	86.85	127.73	354.56	262.17	119.08	22.51	21.53	24.89	1186.45
1988	41.27	73.75	167.94	91.15	86.75	216.30	477.99	355.07	159.81	51.44	35.76	40.54	1797.76
1989	90.67	106.49	118.48	108.97	105.07	140.61	89.01	36.03	18.88	15.43	18.36	22.75	870.73
1990	44.54	63.84	88.27	60.89	82.43	125.75	124.17	94.67	33.62	23.11	15.41	19.12	775.83
1991	33.49	33.60	29.81	28.01	26.21	91.19	185.70	136.60	56.06	39.62	32.53	30.84	723.68
1992	30.36	34.31	37.38	37.64	33.93	101.90	231.49	215.84	115.80	56.24	42.79	40.79	978.47
1993	40.98	38.08	43.67	44.54	46.53	92.57	221.69	281.14	134.84	72.66	59.22	52.79	1128.72
1994	53.57	48.28	46.03	49.58	57.58	70.38	133.90	110.92	49.35	38.69	32.15	28.91	719.34
1995	32.23	33.63	32.01	38.23	56.37	93.64	174.96	189.61	101.26	46.52	36.01	33.91	868.38
1996	32.68	47.35	58.38	81.38	72.39	160.25	327.46	363.94	154.67	73.00	63.71	66.52	1501.73
1997	75.46	76.23	97.76	102.21	78.61	81.31	165.10	164.20	74.90	48.46	38.38	34.56	1037.19
1998	37.10	33.95	34.38	39.36	41.26	78.96	208.52	184.42	96.76	50.71	40.43	34.88	880.73
1999	39.47	40.39	74.93	81.06	95.54	138.36	207.67	150.81	72.54	44.39	35.90	36.24	1017.30
2000	38.48	36.22	34.67	33.57	29.21	77.92	285.06	201.91	75.00	46.75	37.46	34.70	930.95
2001	38.61	33.32	33.42	32.29	29.58	55.79	66.26	72.62	30.21	22.36	20.92	17.50	452.88
2002	20.21	20.90	29.73	31.86	32.28	139.87	270.20	192.62	102.05	52.72	38.87	38.81	970.13
2003	36.26	34.04	31.96	35.72	36.93	80.67	266.66	196.99	99.94	49.18	39.35	35.28	942.98
2004	35.65	35.30	37.14	40.71	62.94	180.07	163.78	136.06	59.57	34.73	29.31	25.95	841.21
2005	32.23	33.63	32.01	38.23	56.37	93.64	174.96	189.61	101.26	46.52	36.01	33.91	868.38
AVERAGE	42.10	50.46	63.04	66.98	68.39	141.36	225.83	185.93	79.72	34.92	28.33	30.78	1017.84

C. Electro-Mechanical Equipment Efficiency Data Input Sheet

	Net Head(%)							
Flow(%)	0.823	0.833	0.842	0.851	0.860	0.870	0.879	0.888
0.444	87.924	87.948	87.966	87.978	87.983	87.986	87.991	88.007
0.462	88.282	88.315	88.342	88.364	88.380	88.392	88.404	88.424
0.479	88.643	88.684	88.720	88.752	88.779	88.802	88.822	88.845
0.497	89.004	89.054	89.101	89.142	89.179	89.213	89.244	89.271
0.515	89.364	89.424	89.479	89.530	89.577	89.622	89.661	89.692
0.532	89.721	89.789	89.852	89.912	89.968	90.020	90.067	90.101
0.550	90.072	90.147	90.218	90.284	90.346	90.404	90.455	90.492
0.568	90.416	90.497	90.573	90.644	90.710	90.771	90.824	90.865
0.585	90.752	90.837	90.918	90.992	91.060	91.122	91.176	91.219
0.603	91.080	91.170	91.253	91.329	91.396	91.456	91.509	91.554
0.621	91.401	91.494	91.581	91.656	91.720	91.774	91.823	91.867
0.639	91.719	91.816	91.904	91.977	92.034	92.079	92.118	92.158
0.656	92.039	92.140	92.228	92.295	92.342	92.373	92.399	92.431
0.674	92.367	92.470	92.552	92.609	92.644	92.661	92.670	92.693
0.692	92.692	92.796	92.870	92.915	92.936	92.941	92.938	92.951
0.709	92.996	93.101	93.168	93.202	93.212	93.208	93.200	93.206
0.727	93.254	93.365	93.430	93.456	93.460	93.453	93.445	93.448
0.745	93.449	93.571	93.637	93.662	93.665	93.660	93.657	93.660
0.763	93.573	93.706	93.776	93.805	93.813	93.816	93.822	93.829
0.780	93.615	93.756	93.833	93.873	93.895	93.912	93.929	93.946
0.798	93.550	93.703	93.800	93.861	93.906	93.942	93.976	94.008
0.816	93.374	93.547	93.676	93.770	93.845	93.909	93.965	94.016
0.833	93.115	93.309	93.473	93.606	93.718	93.814	93.899	93.974
0.851	92.802	93.015	93.210	93.380	93.531	93.665	93.784	93.886
0.869	92.448	92.677	92.896	93.102	93.293	93.467	93.622	93.753
0.886	92.049	92.295	92.539	92.779	93.011	93.226	93.417	93.576
0.904	91.594	91.864	92.139	92.419	92.693	92.950	93.176	93.362
0.922	91.099	91.400	91.714	92.037	92.352	92.646	92.904	93.116
0.940	90.621	90.948	91.297	91.654	92.001	92.322	92.606	92.839
0.957	90.226	90.558	90.916	91.287	91.650	91.987	92.285	92.534
0.975	89.916	90.235	90.581	90.945	91.306	91.646	91.950	92.207
0.993	89.652	89.956	90.282	90.627	90.974	91.304	91.604	91.863
1.010	89.405	89.697	90.003	90.325	90.651	90.965	91.254	91.510
1.028	89.165	89.444	89.734	90.034	90.337	90.632	90.907	91.156
1.046	88.929	89.195	89.468	89.749	90.031	90.306	90.567	90.806
1.064	88.695	88.948	89.206	89.469	89.732	89.990	90.236	90.466
1.081	88.462	88.703	88.947	89.194	89.441	89.684	89.917	90.136
1.099	88.230	88.459	88.691	88.924	89.157	89.386	89.608	89.819
1.117	88.000	88.218	88.437	88.658	88.879	89.096	89.307	89.509
1.134	87.771	87.978	88.186	88.395	88.604	88.810	89.011	89.205

D. Single Storage Systems Calculation Summary Sheet

YEAR	Inflow (10 ⁶ m ³)	Evaporation (10 ⁶ m ³)	Other Uses From Reservoir (10 ⁶ m ³)	Downstream Water Rights (10 ⁶ m ³)	Spilled Volume (10 ⁶ m ³)	Volume Used For Energy (10 ⁶ m ³)	Power Average (MW)	Energy (GWh)
1957	725.736	0.000	88.526	0.000	0.000	640.881	6.267	20.996
1958	802.873	0.000	88.526	0.000	31.267	697.013	6.266	22.913
1959	579.390	0.000	88.526	0.000	0.000	503.734	6.266	16.458
1960	762.925	0.000	88.526	0.000	54.144	622.268	6.264	20.279
1961	495.486	0.000	88.526	0.000	0.000	433.799	6.265	14.260
1962	654.518	0.000	88.526	0.000	0.000	595.092	6.265	19.677
1963	1095.406	0.000	88.526	0.000	131.249	886.910	6.266	29.240
1964	652.927	0.000	88.526	0.000	0.000	593.400	6.266	19.723
1965	974.346	0.000	88.526	0.000	129.294	763.830	6.266	25.116
1966	1340.500	0.000	88.526	0.000	200.936	1058.510	6.265	34.804
1967	1385.572	0.000	88.526	0.000	206.868	1090.177	8.354	36.770
1968	1748.564	0.000	88.526	0.000	504.802	1155.236	8.356	38.968
1969	2336.375	0.000	88.526	0.000	756.930	1490.666	8.356	50.282
1970	1366.031	0.000	88.526	0.000	127.145	1150.360	8.356	38.803
1971	1059.993	0.000	88.526	0.000	90.945	884.748	6.880	29.766
1972	762.504	0.000	88.526	0.000	0.000	673.978	8.356	22.734
1973	489.044	0.000	88.526	0.000	0.000	436.418	5.570	14.508
1974	443.922	0.000	88.526	0.000	0.000	396.782	5.569	13.063
1975	883.549	0.000	88.526	0.000	195.538	621.553	6.265	20.550
1976	1038.936	0.000	88.526	0.000	251.813	710.032	6.266	23.364
1977	1454.430	0.000	88.526	0.000	365.340	1009.019	6.265	33.479
1978	1204.274	0.000	88.526	0.000	215.803	908.420	6.265	30.011
1979	1269.034	0.000	88.526	0.000	92.531	1094.327	6.265	36.444
1980	1882.906	0.000	88.526	0.000	701.646	1092.733	8.353	36.857
1981	1625.412	0.000	88.526	0.000	338.930	1197.956	8.356	40.409
1982	1211.451	0.000	88.526	0.000	137.276	985.649	8.356	33.247
1983	1078.659	0.000	88.526	0.000	155.599	834.535	8.356	28.150
1984	1031.603	0.000	88.526	0.000	45.198	911.415	6.267	30.327
1985	499.740	0.000	88.526	0.000	0.000	441.076	5.569	14.621
1986	524.978	0.000	88.526	0.000	0.000	468.505	6.265	15.694
1987	1186.455	0.000	88.526	0.000	274.637	831.370	6.265	27.458
1988	1797.756	0.000	88.526	0.000	534.943	1174.286	8.354	39.608
1989	870.732	0.000	88.526	0.000	0.000	800.699	6.233	26.497
1990	775.826	0.000	88.526	0.000	0.000	700.894	6.265	23.249
1991	723.679	0.000	88.526	0.000	18.931	616.221	8.355	20.785
1992	978.472	0.000	88.526	0.000	105.244	784.702	8.356	26.469
1993	1128.718	0.000	88.526	0.000	160.742	879.450	8.356	29.665
1994	719.336	0.000	88.526	0.000	0.000	630.810	8.356	21.278
1995	868.383	0.000	88.526	0.000	22.481	757.376	8.356	25.547
1996	1501.729	0.000	88.526	0.000	349.305	1063.898	8.356	35.887
1997	1037.186	0.000	88.526	0.000	0.000	948.660	8.356	32.000
1998	880.730	0.000	88.526	0.000	50.854	741.350	8.356	25.007
1999	1017.305	0.000	88.526	0.000	40.902	887.876	8.356	29.949
2000	930.948	0.000	88.526	0.000	144.880	697.542	8.356	23.529
2001	452.883	0.000	88.526	0.000	0.000	373.190	6.267	12.254
2002	970.126	0.000	88.526	0.000	120.728	760.871	8.354	25.664
2003	942.980	0.000	88.526	0.000	121.561	732.893	8.356	24.722
2004	841.214	0.000	88.526	0.000	7.745	744.943	8.356	25.128
2005	868.383	0.000	88.526	0.000	22.481	757.376	8.356	25.547
Annual Average	1017.835	0.000	88.526	0.000	136.912	800.682	7.258	26.771
Max.	2336.375	0.000	88.526	0.000	756.930	1490.666	8.356	50.282
Min.	443.922	0.000	88.526	0.000	0.000	373.190	5.569	12.254

E. Storage Systems Energy Price Data Input Sheet

[illegible]

F. Storage Systems Cost Data Input Sheet

Tunnel Excavation Unit Cost	25.00	TL/m ³
Tunnel Concrete Unit Cost	2200.00	TL/m ³
Tunnel Reinforcement Unit Cost	15000.00	TL/ton
Tunnel Formwork Unit Cost	250.00	TL/m ²
Tunnel Excavation Support System Unit Cost	500.00	TL/m
Tunnel Stabilization Works (Injection etc.) Unit Cost	500.00	TL/m
Contingency Ratio For Tunnel Works	10.00%	%

Penstock Steel Unit Cost	15000.00	TL/ton
Penstock Excavation Unit Cost	25.00	TL/m ³
Penstock Concrete Unit Cost	2200.00	TL/m ³
Penstock Reinforcement Unit Cost	15000.00	TL/ton
Contingency Ratio For Penstock Works	10.00%	%

Powerhouse EM Equipment Unit Cost	12,000,000.00	TL/MW
Powerhouse Civil Works Unit Cost	1,200,000.00	TL/MW
Contingency Ratio For Powerhouse Works	10.00%	%

Minimum Required Tunnel Inner Diameter	3.00	m
Maximum Allowable Water Velocity In The Tunnel	3.74	m/s
Maximum Allowable Water Velocity In The Penstock	5.39	m/s

Interest Rate	10.00%	%
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Ratio of Concrete Liner Thickness To Inner Diameter of Tunnel	10.00%	%
Reinforcement Amount (kg) Per Cubic Meter of Concrete	80.00	kg/m ³

Ratio of Steel Thickness To Inner Diameter of Penstock	1.00%	%
Average Excavation Amount Per Meter Alignment Along Penstock	40.00	m ³ /m
Average Concrete Amount Per Meter Alignment Along Penstock	5.00	m ³ /m
Reinforcement Amount (kg) Per Cubic Meter of Concrete	80.00	kg/m ³

G. Run-of-River Systems Characteristic Data Input Sheet

OPERATION OF HYDROPOWER PLANTS WITHOUT STORAGE CAPACITY			
Name of Project		HEPP 1	
Tunnel Length (m)	3000	Tunnel Diameter (m)	4
Penstock Length (m)	139	Penstock Diameter (m)	2.1
Tunnel Concrete (e) mm=	0.6	Penstock Steel (e) mm=	0.15
Total Installed Capacity (MWm)	10.14	Number of Units	4
From Smaller to Larger		From Smaller to Larger	
Installed Capacity Unit1 (MWm)	5.07	Unit1 Design Discharge (m ³ /s)	6.7
Installed Capacity Unit2 (MWm)	5.07	Unit2 Design Discharge (m ³ /s)	6.7
Installed Capacity Unit3 (MWm)		Unit3 Design Discharge (m ³ /s)	
Installed Capacity Unit4 (MWm)		Unit4 Design Discharge (m ³ /s)	
		Total Design Discharge (m ³ /s)	13.4
Reservoir Operation Level (m)	1000		
Tailwater Level for Project Discharge (m)=	911.35	Design Gross Head (m)	88.650
Inflow Data Day	14.04.1995		
Total Storage Capacity (m ³)	5,000		
Available Storage At The Start of Operation (m ³)	5,000		
Downstream Water Rights & Environmental Release Daily Average		Run	
	m ³ /s		
14.04.1995	0.00		

H. Run-of-River Systems Inflow Data Input Sheet

	14.04.1995
00:00~01:00	32.290
01:00~02:00	32.290
02:00~03:00	32.290
03:00~04:00	32.290
04:00~05:00	32.290
05:00~06:00	32.290
06:00~07:00	32.290
07:00~08:00	32.290
08:00~09:00	32.290
09:00~10:00	32.290
10:00~11:00	32.290
11:00~12:00	32.290
12:00~13:00	32.290
13:00~14:00	32.290
14:00~15:00	32.290
15:00~16:00	32.290
16:00~17:00	32.290
17:00~18:00	32.290
18:00~19:00	32.290
19:00~20:00	32.290
20:00~21:00	32.290
21:00~22:00	32.290
22:00~23:00	32.290
23:00~00:00	32.290
AVERAGE	32.290

I. Run-of-River Systems Energy Price Data Input Sheet

	14.04.1995	11:45~12:00	3,600.00
00:00~00:15	1,250.00	12:00~12:15	3,650.00
00:15~00:30	1,300.00	12:15~12:30	3,700.00
00:30~00:45	1,350.00	12:30~12:45	3,750.00
00:45~01:00	1,400.00	12:45~13:00	3,800.00
01:00~01:15	1,450.00	13:00~13:15	3,850.00
01:15~01:30	1,500.00	13:15~13:30	3,900.00
01:30~01:45	1,550.00	13:30~13:45	3,950.00
01:45~02:00	1,600.00	13:45~14:00	4,000.00
02:00~02:15	1,650.00	14:00~14:15	4,050.00
02:15~02:30	1,700.00	14:15~14:30	4,100.00
02:30~02:45	1,750.00	14:30~14:45	4,150.00
02:45~03:00	1,800.00	14:45~15:00	4,200.00
03:00~03:15	1,850.00	15:00~15:15	4,250.00
03:15~03:30	1,900.00	15:15~15:30	4,150.00
03:30~03:45	1,950.00	15:30~15:45	4,050.00
03:45~04:00	2,000.00	15:45~16:00	3,950.00
04:00~04:15	2,050.00	16:00~16:15	3,850.00
04:15~04:30	2,100.00	16:15~16:30	3,750.00
04:30~04:45	2,150.00	16:30~16:45	3,650.00
04:45~05:00	2,200.00	16:45~17:00	3,550.00
05:00~05:15	2,250.00	17:00~17:15	3,450.00
05:15~05:30	2,300.00	17:15~17:30	3,350.00
05:30~05:45	2,350.00	17:30~17:45	3,250.00
05:45~06:00	2,400.00	17:45~18:00	3,150.00
06:00~06:15	2,450.00	18:00~18:15	3,050.00
06:15~06:30	2,500.00	18:15~18:30	2,950.00
06:30~06:45	2,550.00	18:30~18:45	2,850.00
06:45~07:00	2,600.00	18:45~19:00	2,750.00
07:00~07:15	2,650.00	19:00~19:15	2,650.00
07:15~07:30	2,700.00	19:15~19:30	2,550.00
07:30~07:45	2,750.00	19:30~19:45	2,450.00
07:45~08:00	2,800.00	19:45~20:00	2,350.00
08:00~08:15	2,850.00	20:00~20:15	2,250.00
08:15~08:30	2,900.00	20:15~20:30	2,150.00
08:30~08:45	2,950.00	20:30~20:45	2,050.00
08:45~09:00	3,000.00	20:45~21:00	1,950.00
09:00~09:15	3,050.00	21:00~21:15	1,850.00
09:15~09:30	3,100.00	21:15~21:30	1,750.00
09:30~09:45	3,150.00	21:30~21:45	1,650.00
09:45~10:00	3,200.00	21:45~22:00	1,550.00
10:00~10:15	3,250.00	22:00~22:15	1,450.00
10:15~10:30	3,300.00	22:15~22:30	1,350.00
10:30~10:45	3,350.00	22:30~22:45	1,250.00
10:45~11:00	3,400.00	22:45~23:00	1,250.00
11:00~11:15	3,450.00	23:00~23:15	1,250.00
11:15~11:30	3,500.00	23:15~23:30	1,250.00
11:30~11:45	3,550.00	23:30~23:45	1,250.00
11:45~12:00	3,600.00	23:45~00:00	1,250.00
		AVERAGE	2656.250

CURRICULUM VITAE

Surname, Name: Aslankara, Vedat

EDUCATION

Degree	Institution	Year of Graduation
MS	METU Civil Engineering	2007
BS	METU Civil Engineering	2004
High School	Orhan Dengiz Anatolian High School, Uşak	1999

WORK EXPERIENCE

2023-Present	Bechtel Corporation	Engineering Mng.
2017-2023	CVS Engineering	Partner
2015-2017	Erges Engineering	Business D. Mng.
2011-2015	Enerjisa Energy Generation	Senior Engineer
2009-2011	Tractebel Hidro Dizayn	Project Manager
2008-2009	Military Obligation	Reserve Officer
2005-2008	Tractebel Hidro Dizayn	Project Engineer

FOREIGN LANGUAGES

Fluent English

PUBLICATIONS

1. Bozkus, Z., and Aslankara, V., "Tailwater Effect on the Energy Dissipation through Screens", Proceedings of the 8th International Congress on Advances in Civil Engineering, Eastern Mediterranean University, Famagusta, North Cyprus, September 15-17, 2008