RULE CURVES FOR OPERATING SINGLE- AND MULTI-RESERVOIR HYDROPOWER PLANTS

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RULE CURVES FOR OPERATING SINGLE- AND MULTI-RESERVOIR HYDROPOWER PLANTS

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ABSTRACT

RULE CURVES FOR OPERATING SINGLE- AND MULTI-RESERVOIR HYDROPOWER PLANTS

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Hydropower has the largest share in the energy budget of Turkey among renewable energy sources. Thus, planning and operation of hydropower plants (HPPs) are critical for the country. Currently, sustainable use and development of water resources to maximize possible benefits are the two big challenges to be overcome and efficient use of hydropower forms a significant component of this. The Çoruh Basin has an economically high hydropower potential, as such there are many HPPs that are in operation, under construction and in planning phase in this basin. Arkun, Yusufeli and Artvin are three of those HPPs located consecutively on the Çoruh River. In the first part of this study, a single reservoir system (Yusufeli HPP) with the single purpose of energy generation is considered under two separate objectives, which are the maximization of average annual energy generation and the maximization of average annual revenue, and rule curves are derived to obtain optimum reservoir operation. The results show that hourly price variations in the market should be taken into account for the maximization of the energy revenue objective and the corresponding optimal rule curves should be derived accordingly. In the second part of the study, the multi-reservoir system composed of Arkun, Yusufeli and Artvin HPPs is investigated separately considering the single purpose of energy generation under three objectives, maximization of energy, revenue and net profit. Finally, performance of the multi-reservoir system under additional purposes such as supply of municipal and irrigation water, and flood control is evaluated through hypothetical scenarios. The multi-reservoir case is operated as a pumped-storage system as well and the amount of increase in the net revenue is explored. These studies demonstrate that through integrated management of the reservoirs higher net profit with smaller installed capacity can be obtained compared to decentralized management. This reveals that integrated management of a hydropower system is very important especially for the determination of installed capacities. It is concluded that effective utilization of water resources can be achieved using optimum rule curves derived for the correct objectives.

Keywords: Hydropower, Rule Curves, Reservoir Operation Study, Single-Reservoir System, Multi-Reservoir System.

ÖZ

TEK VE ARDIŞIK HİDROELEKTRİK SANTRALLER İÇİN İŞLETME EĞRİLERİ

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Yenilenebilir enerji kaynakları arasında hidroelektrik, Türkiye enerji bütçesindeki en büyük paya sahiptir. Bu nedenle hidroelektrik santrallerinin planlanması ve işletmesi ülke için çok önemlidir. Muhtemel faydaları en üst düzeye çıkarmak için su kaynaklarının sürdürülebilir kullanımı ve geliştirilmesi, aşılması gereken iki büyük zorluktur ve hidroelektrik santrallerin (HES) etkili işletimi bunun önemli bir bileşenini oluşturmaktadır. Çoruh havzası ekonomik açıdan yüksek bir hidroelektrik potansiyeline sahip olup, planlama aşamasında, inşaat halinde ve işletmede birçok hidroelektrik santrali içermektedir. Arkun, Yusufeli ve Artvin, Çoruh Nehri üzerinde bulunan ardışık üç hidroelektrik santraldir. Bu çalışmanın ilk kısmında, tek amacı enerji üretimi olan bir rezervuarın (Yusufeli HES) yıllık ortalama enerji üretimi ve yıllık ortalama geliri olmak üzere iki farklı amaç fonksiyonunun en iyilenmesi ele alınmış ve optimum rezervuar işletimini sağlamak amacıyla işletme eğrileri üretilmiştir. Sonuçlar, enerji gelirinin maksimize edilmesi hedefi için piyasadaki saatlik enerji fiyat değişimlerinin dikkate alınmasının ve daha fazla gelir elde edebilmek için optimal kural eğrilerinin bu doğrultuda üretilmesinin gerekli olduğunu göstermektedir. Çalışmanın ikinci kısmında, Arkun, Yusufeli ve Artvin hidroelektrik santrallerinden oluşan çok rezervuarlı bir sistem, sadece enerji üretimi amacı düşünülerek üç farklı amaç fonksiyonu (enerji üretimi, gelir ve net kar maksimizasyonu) altında ayrı ayrı incelenmiştir. Son olarak, çok amaçlı rezervuar sisteminin performansı içme ve sulama suyu temini ve taşkın kontrolü gibi ek amaçlar göz önünde bulundurularak, bazı hipotetik senaryolar için değerlendirilmiştir. Çok rezervuarlı durum pompa depolamalı bir sistem olarak kabul edilerek de işletilmiş ve net gelirdeki artış araştırılmıştır. Bu çalışmalar, ayrı ayrı yönetim için elde edilen değerlere kıyasla, entegre yönetim ile daha küçük kurulu kapasitede daha fazla net faydanın elde edilebileceğini göstermektedir. Bu, bir hidroelektrik santaller sistemi için entegre yönetimin, özellikle kurulu kapasitelerin belirlenmesi açısından çok önemli olduğunu ortaya koymaktadır. Su kaynaklarının etkili kullanımı için optimum işletim eğrilerinin, doğru amaç fonksiyonları kullanılarak çıkartılmasının gerekli olduğu sonucuna varılmıştır.

Anahtar Kelimeler: Hidroelektrik, İşletme Eğrileri, Rezervuar İşletme Çalışması, Tek Rezervuarlı Sistem, Çok Rezervuarlı Sistem

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION AND SCOPE OF THE THESIS STUDY

1.1. Introduction

Most socio-technical systems depend on energy to operate, thus energy has a crucial role in social and economic development. There are two types of energy resources, namely; non-renewable resources and renewable resources. Major non-renewable energy sources are fossil fuels but vast usage of fossil fuels damages the environment and negatively affects public health in comparison with renewable energy resources like hydropower, solar and wind. Excessive pollution (due to toxic emissions) caused by fossil fuels and the consequent results such as global warming or acid rains are examples of that damage (Cao and Pawlowski, 2013). Moreover, non-renewable energy sources are bound to run out. In order to decrease the detrimental effects of non-renewable energy resources, share of renewable energy resources in world's energy supply should be increased. As a renewable and clean energy resource, hydropower energy has an outstanding place. Almost no greenhouse gases are emitted as a result of energy generation via hydropower, large amounts of potential energy electricity can be stored at low costs, and it gives a considerable amount of flexibility in meeting consumer demands (Luis et. al., 2013). In addition, during energy production, hydropower does not produce any waste byproducts which contaminate the air or water, and the water is not consumed within the water cycle. Low operation and maintenance costs, usability of the reservoirs for multiple purposes, ability of quick switch on (from zero power to the maximum output) are listed as the other advantages of hydropower.

As long as the sustainment and enhancement of life is concerned, significance of water cannot be neglected. Dams are commonly used to conserve and maintain continuous availability of water throughout the year. Therefore, since ancient times, dams are constructed extensively throughout the world. The most common usages of dams are municipal and industrial water supply, recreation, fish farming, irrigation, hydroelectric power production, and protection from floods. Due to their versatility in use, dams are essential for humans. Turkey has a considerable amount of exploitable water resources (Kentel and Alp, 2013) and there are many dams constructed on the rivers of Turkey for various purposes and some of these dams are utilized for hydroelectric power production.

In the north east of Turkey, there are many hydroelectric power plants (HPP) on Çoruh River at various project stages (in design, construction and operation). In this thesis, the reservoir operation studies for Arkun, Yusufeli and Artvin HPPs which are located in the middle part of the Çoruh River, are carried out.

The main aim of this thesis study is to generate reservoir operation strategies for single- and multi-reservoir HPPs. The operation strategies are applied to a real-life case study which is the multi-reservoir system of Arkun, Yusufeli and Artvin HPPs. In the remainder of the thesis the term an *operating policy* and a *rule curve* will be used interchangeably. A rule curve can be defined as the set of the target end-of-period storage (or elevation) values in a reservoir. The rule curves derived in this study took into account the stochastic nature of the inflows, however the structure of the policies are deterministic. Thus, algorithms used in this study falls under the class of implicit stochastic optimization. In this thesis, to obtain the rule curves, non-linear mathematical models are constructed.

The thesis study is guided by several important research questions. First, a single-reservoir system with a single purpose is studied (Chapter 4). The main aim of this first part is to construct an optimal and easy-to-implement operating policy using historical inflow values for two different objectives. In Chapter 4, the objectives are taken as maximization of energy generation and maximization of revenue. When maximizing the revenue, hourly energy prices are incorporated into the long-term plan of operating policy for more accurate estimation of average annual revenue. The research questions under consideration are how does the developed operating policy perform compared to the other practical policies and compared to the possibly best operating policy, and how do decision criteria affect the cross-performances of the policies. To address these questions, the HPP at Yusufeli is considered as an isolated single-reservoir system. Findings show that the generated rule curves perform close to the best possible policy. Furthermore, it is seen that the optimum rule curves derived under different objectives are relatively different from each other.

In Chapter 5, the study is extended to a cascade-type multi-reservoir system which is very common in Turkey. The research questions in this part are: what is the benefit that can be tapped through integrated basin management, and how does the benefit change with respect to different objectives? To address these questions, three objectives, namely; maximization of energy generation, maximization of revenue and maximization of net profit are considered. The objective function values obtained under integrated management and decentralized management are contrasted. Moreover, in this chapter, different from the studies carried out for a sole HPP, the installed capacity values of the HPPs are determined through nonlinear mathematical models under the objective of maximization of the net profit. The results show that, higher profit can be obtained with smaller installed capacities under integrated management compared to decentralized management. Therefore, it can be concluded that integrated management is very important at the stage of determination of optimum installed capacities.

In Chapter 6, a multi-purpose multi-reservoir system is studied. In this part, some additional hypothetical purposes are taken into account. The objective functions for the multi-purpose multi-reservoir system are maximization of energy generation and maximization of net revenue. In this chapter; specifically, i) municipal water supply, ii) irrigation, iii) flood control, and iv) pumped-storage are selected as additional purposes (in addition to energy generation). Four different scenarios are considered to see the effects of these purposes on HPP performances in satisfying the selected objectives. The results show that, for this case study, the additional purposes such as municipal water supply, irrigation and flood control do not affect the optimum rule curves considerably although the total average annual energy generation and revenue decrease because of the irrigation and municipality water demand. In addition, it is observed that pumped-storage system gives different optimum rule curves regarding the current system. In Table 1.1, the studies carried out in this thesis are summarized.
In the scope of this thesis, a comprehensive literature review about reservoir operation studies is provided in Chapter 2, to enable the readers to have a general

overview about reservoir operation of HPPs. In Chapter 3, hydropower potential of Turkey is evaluated and compared with the hydropower potential values of Europe and other parts of the world. Besides, the study area, Çoruh Basin, is introduced in detail. In Chapter 4, the single purpose single reservoir system is modelled under two objectives (maximization of average annual energy and maximization of average annual revenue) and the analyses' results are given. In Chapter 5, a single purpose multi-reservoir system having energy generation purpose is investigated. In Chapter 6, multi-purpose multi-reservoir systems are studied by developing additional hypothetical purposes. In Chapter 7, main results obtained in this thesis are summarized. Recommendations are made for the future studies.

Table 1.1 Summary of the Studies Carried out in this Thesis

<table>
<tr><th>Chapter</th><th>System</th><th>HPP</th><th>Purpose</th><th>Objective</th><th>Aim of Study</th></tr>
<tr><td rowspan="2">4</td><td rowspan="2">Single Reservoir</td><td rowspan="2">Yusufeli HPP</td><td rowspan="2">Energy Generation</td><td>Maximization of Average Annual Energy Generation</td><td rowspan="2">Comparison of rule curves</td></tr>
<tr><td>Maximization of Average Annual Revenue</td></tr>
<tr><td rowspan="3">5</td><td rowspan="3">Multi Reservoir</td><td>Arkun HPP</td><td rowspan="3">Energy Generation</td><td>Maximization of Average Annual Energy Generation</td><td rowspan="3">Comparison of integrated basin management and decentralized management</td></tr>
<tr><td>Yusufeli HPP</td><td>Maximization of Average Annual Revenue</td></tr>
<tr><td>Artvin HPP</td><td>Maximization of Average Annual Net Profit</td></tr>
<tr><td rowspan="5">6</td><td rowspan="5">Multi Reservoir</td><td>Arkun HPP</td><td>Energy Generation</td><td rowspan="2">Maximization of Average Annual Energy Generation</td><td rowspan="5">To investigate the effects of additional purposes on the operation strategies and evaluation of the benefits of pumped-storage</td></tr>
<tr><td rowspan="2">Yusufeli HPP</td><td>Municipality Water</td></tr>
<tr><td>Irrigation Water</td><td rowspan="3">Maximization of Average Annual Net Revenue</td></tr>
<tr><td rowspan="2">Artvin HPP</td><td>Flood Control</td></tr>
<tr><td>Pumped-Storage</td></tr>
</table>

CHAPTER 2

LITERATURE REVIEW

2.1. General Overview for Reservoir Operation Studies

The water demand in the world is growing day by day with the increasing population and living standards, and the optimum reservoir operation of dams becomes very crucial. Optimization and simulation models for optimum operations of water resources systems have been developed since the early 1960s (Maas et al., 1962). Results of such studies are used in the planning and management of reservoirs.

Reservoir operation rule curves are widely used to guide the system operators in decision making for long term reservoir operation (Kangrang and Lokham, 2013). A rule curve can be defined as the set of target end-of-period storage (or elevation) values in a reservoir (Labadie, 2004). Past studies on management of reservoir operations either use heuristic approaches (such as evolutionary algorithms, or simulated annealing, see for instance Chen et al. (2007), Chang et al. (2005), Hossain and El-shafie (2013), Ahmad et al. (2014), Hıncal (2008), Yang et al. (2015), Li et al. (2015)) or mathematical programming based optimization approaches when deriving the rule curves. The choice depends on the complexity of the objective and the structure of the reservoir system.

Methods for optimization of reservoir operations can roughly be classified into two as deterministic optimization and stochastic optimization. A reservoir system can be characterized as a stochastic system due to the randomness in unregulated inflows. There may be other factors (model inputs) that contribute to the randomness, such as evaporation, or required periodic demand for water. Deterministic optimization methods do not explicitly incorporate the randomness in the model inputs into the method, but rather, either use historical data of inputs or future forecasts as if the forecasts are exact. The rule curve provides the operation policy that best achieves the selected objective throughout the simulation period or period-of-record (i.e. period for which historical data is available). When past data is used, the assumption is that the hydrological situation, mainly inflows to the reservoir, will be similar to those of the simulation period and thus rule curve will achieve the selected objective in the future as well.

Deterministic optimization methods for optimization of reservoir operations can be exemplified by linear programming (LP), nonlinear programming (NLP), deterministic dynamic programming (DDP), or network flow optimization (NFO), the last being more suitable for multi-reservoir systems (Labadie et al. 2004, Ahmad et al. 2014). As the systems get more complex, the corresponding mathematical models become large-scale and each of these methods may suffer due to the size of the model (the curse of dimensionality). In that case, some approximation algorithms are developed to find optimal or near-optimal solutions (for instance successive linear/quadratic programming (LQP) techniques can be applied to solve a NLP model, see Barros et al. (2003)). The reservoir operation problem in this study has a nonlinear objective function (i.e. the energy generated or the revenue obtained or the profit to be maximized) but the constraints are linear (i.e. continuity equation, lower or upper bounds in the reservoir, minimum and maximum powers, and so on.). Although the nonlinearity of the objective function introduces difficulty, NLP provides a more accurate model, and is more appropriate for real-time operations. If a single-reservoir is under consideration, it is possible to obtain the optimal solution using nonlinear optimization packages. On the other hand, it is not an easy task to obtain global optimal solution for a NLP model developed for a multi-reservoir system. The output of the deterministic optimization methods is the storage levels associated with each time point in the period-of-record, i.e., an operation plan for that specific inflow series. Thus, in the raw form it is not possible to directly adopt the provided curve in real-time. As inflow data changes, the operation plan will no longer be applicable. Labadie (2004) stated that outputs of these optimization models require post processing of the results in order to develop operation plans. Methods for post-processing the output include Artificial Neural Networks (ANN) or Multiple Linear Regression (MLR) models. This approach is named as implicit stochastic optimization (ISO). Many recent studies (i.e. Barros, et al., 2003; Kim et al., 2008, Liu et al., 2011; Vicuna et al., 2008; Yoo, 2009; Celeste and Billib, 2012; Moeini and

Afshar et al., 2011; Chang et al., 2013; Hirsch et al., 2014; Goodarzi et al., 2014; Ji et al., 2014) adopted ISO approach to obtain operation plans for reservoir systems.

Stochastic optimization methods explicitly consider the random nature of the inflows (Lamond and Boukuta, 1996; Fleten and Kristoffersen, 2008; Pan et al., 2015; Datta and Houck, 1984; Karamouz and Vasiliadis, 1992). A first step in applying this method is to come up with the underlying probability distribution for the inflows. Since inflows are correlated temporarily, fitting a probability distribution is usually a challenging task. Among the methods that incorporate the random nature of the input are stochastic dynamic programming (SDP), chance-constraint programming (CCP), and stochastic programming (SP) models. The scale of the problem is much larger in these problems, which may result in computational difficulties.

The SDP models require the definition of an information vector (namely; the state vector) to determine the optimal expected value of the objective function. As the information required increases, so does the dimension of the state vector and the computational effort to obtain the optimal policy. There are studies that evaluate the effect of increasing the depth of information or the effect of updating the state vector on the performance of the operation policies (see Mujumdar and Nirmala, 2007). Although obtaining the optimal policy requires computationally more effort compared to deterministic optimization, the output of a stochastic optimization model can be directly used for future operations. The reason is for each value of the state vector, or for each scenario realized, the output provides target storage levels. Thus the performance of the policy depends on how well the state vector is defined (in SDP) or how well the scenarios are defined (in SP). In stochastic optimization, depending on the status of the information vector the reservoir operator is guided as to which action to take, the guidance provided is more complex and is thus more difficult to follow. Furthermore, to accurately reflect the underlying probability distribution of the random components is an arduous task due to the complex dependence relations between the components. This difficulty, which may arise especially in CCP models, was also mentioned in Labadie (2004) as: "… reliability factors do not represent the true risk associated with violating storage constraints, but can only be regarded as parameters that influence risk aversion in the solution."

Chang et al. (2005) conducted a study, in which the rule curve for Shih-Men reservoir in Taiwan was developed using genetic algorithms (GA). In their study, they coupled a simulation and an optimization model to evaluate performances of potential rule curves mainly in satisfying multiple demands. Since the main goal was to minimize the shortage index, maximization of energy generation, energy revenue and net benefit was not explicitly considered. Chang et al. (2005) tried to optimize the rule curves of a system by using GA. Hıncal et al. (2011) studied the multi-reservoir system composed of three reservoirs in the Colorado River Storage Project, and developed a computer code using GA. The results obtained in this study show that GA yielded an optimum value very close to global optimum and can be utilized as an alternative technique to other traditional optimization techniques (see also Hıncal, (2008)). Sharifi et al. (2009) used system dynamics (SD) approach and Ant Colony Optimization (ACO) to derive a set of monthly target storage elevations as a rule curve. The efficient ISO is widely applied for the derivation of optimal rule curves for the long-term operation of a single reservoir and/or multi-reservoir systems (Liu et al., 2011). For more on optimization methods in reservoir operations see Yeh (1985), Wurbs (1993), ReVelle (1997), Labadie (2004) and Rani and Moreira (2010).

The method proposed in this study falls into the class of ISO methods, in that deterministic nonlinear programs are solved to obtain operation rule curves. However, in contrast to the general ISO approach, post-processing of the storage levels is not carried out. Rather, the mathematical model is constructed such that, the model gives a single target storage level for each month of the year throughout the whole planning horizon. This ensures that the output of the model can directly be used as guidance for future operation of the reservoir. The performances of the proposed rules are tested using the historical data (see Barros et al. (2003); Madani et al. (2014), for other studies that use historical data), and it is shown that substantial benefits over a naive policy can be achieved.

When deriving the rule curves for reservoir operations, past studies consider a variety of objectives. A common objective is maximizing the hydropower generated from the reservoir. Liu et al. (2011) developed rule curves for China's Qing River cascade hydropower reservoirs with the objective of increasing annual power generation.

However, in their long-term operation study they did not consider hourly electricity price variations. Some other objectives studied are revenue (energy price × power generated, Catalao et al. (2011), deLadurantaye et al. (2009)), energy generated compared to energy demanded (Cai et al., 2001), minimizing water shortage (Chang et al. 2005), minimization of water consumption rate (Lu et al., 2013), maximizing utilization of installed capacity of the plant (Aboutalebi et al., 2015). These studies aimed at achieving the selected single objective. Other line of research aimed at obtaining an operation plan in the presence of multi-objectives. In multi-objective optimization, several objectives are considered simultaneously, where those might be conflicting or even noncommensurable objectives. Reddy and Kumar (2007) proposed efficient frontier for operation of a single-reservoir system with three objectives: minimizing flood risk, maximizing hydropower production, and minimize irrigation deficits in a year, using differential evolution algorithm. Choudhari and Raj (2010) solved a multi-objective optimization problem for obtaining operation rules in a multi-reservoir system. Two objectives were under consideration, maximization of returns from irrigation release, maximization of returns from power releases. The objectives were consolidated into a single objective through a weighting method. Goodarzi et al. (2014) presented an overview of multi-objective optimization models in the reservoir management.

Generally, optimization models with revenue maximization objective operate on hourly time steps and aims short-term operation scheduling, typically one day (Catalao et al., 2011; Catalao et al., 2012; Pousinho et al., 2013; Wang, 2009; Yuan et al., 2008). For applications such as hydropower generation, a longer time step may not be sufficient to model the desired system operations since hydropower reservoirs commonly make releases based on energy prices which fluctuate on a sub-daily basis (Adamec, 2011). Due to this constraint, the simulation period is usually restricted to a year and various assumptions are made in order to reduce the complexity in identifying optimum reservoir releases. Among the main causes of complexity are correct modeling of the head variation and its effects on the turbines’ efficiency and operating limits (maximum and minimum flows); and for the sake of simplicity head effects are usually neglected (Péréz-Díaz et al., 2010a). One of the main goals of this study is to develop a model where monthly head effects and daily price variations are taken into consideration simultaneously.

Past studies in the literature for the operation of single and multi-reservoir systems and pumped-storage systems are provided in the following for more information.

2.2. Single Reservoir Systems

There exists a significant body of work on optimal operation of single reservoir systems. Some examples of the recent studies are provided below.

Péréz-Díaz et al. (2010b) used a short time horizon (24 h) and their NLP model was deterministic in water inflows, energy prices and units' availability. Daily operation schedules of a real hydropower plant were produced for 15 different scenarios where different values of the forecast water inflows and of the initial and final reservoir volumes were used. The forecast water inflows have been considered constant over the entire time horizon and hourly energy prices of June 28th, 2006 is used in each scenario. In another study, Péréz-Díaz and Wilhelmi (2010) proposed a mixed integer linear programming (MILP) model to calculate the daily operation schedule of the plant that maximizes the revenue obtained from selling energy in the day-ahead electricity market while satisfying several constraints of different classes: technical, strategic and environmental. They concluded that it would be interesting to extend the time-scale of the study in order to draw conclusions about the economic impacts of the environmental constraints on an annual, or even longer basis. Finally, Péréz-Díaz et al. (2010a) proposed a dynamic programming model which determines, in each hour of the planning horizon (one week) both the optimal number of units in operation and the power generated by the committed units. Energy prices from June 2 to 8, 2006 were used in the case study. The hourly water inflows were provided by the company that owns the plant. Since the main goal in all these studies were short-term scheduling of hydropower plants, long-term variations in energy prices and inflows were not considered in the optimization models.

Uncertainty in electricity market prices and reservoir inflows are treated in various studies. For example, Fleten and Kristoffersen (2008) modeled day-ahead market prices and water inflows using time series analysis and developed 1-day production plan that strikes a balance between current profits and expected future profits (i.e. following 6 days). The generation of water inflows for 2005 was based on observations from the year 2004. This might be considered as a mid-term operation scheduling. De Ladurantaye et al. (2009) maximized the profit of a single production day using different possible price scenarios however lacks consideration of the stochastic nature of the inflows. Catalao et al. (2012) introduced market uncertainty into the short-term optimization model (24 hour time horizon) via price scenarios. Equally probably 100 price scenarios were used and expected profit versus standard deviation of profit curve was generated. In their model uncertainty in inflow was neglected and deterministic inflow values for the 24 hour time horizon was used. Olivares and Lund (2012) compared an approximate method with an exact method when deriving operating rules for a one-week duration. The exact method incorporated the hourly changes in energy prices and monitors the changes in head throughout the day whereas approximate method, proposed by Madani and Lund (2009) assumed that the total head did not depend on the storage level, i.e., was constant. In Madani and Lund (2009), an average monthly energy price function was taken as an input to maximize the annual revenue. The price function related the hours of power generated to the price, reflecting the fact that marginal revenues of generation decreased with increased hours of generation. These studies provided distinct approaches on how to incorporate short-term fluctuations in price into longer-term planning. In a more recent study, Nakib et al. (2014) used hourly time steps with a horizon of one year and assumed a fixed inflow to the reservoir for one-year period of simulation. Thus, their approach focused on identification of water amounts to be turbined each hour of the simulation year. In these studies, long-term variations in inflows were not considered.

There exists a body of work on reservoir operation that incorporates the prices in the electricity market for a longer planning horizon. Gjelsvik et al. (2010) considered a 3-5 year period when determining the reservoir operation policy that maximizes expected future revenues. Prices in the market fluctuated over time. Probability distribution of weekly averaged spot prices was used as an input for the SDP model. Madani et al. (2014) extends the planning horizon in Madani and Lund (2009), which was one-year, to a 14-year time period with monthly-steps. The effect of climate change was also taken into consideration when obtaining the price as a function of hours of power generated.

Ak (2011), studied alternative feasibility for a single reservoir system with energy generation purpose (Altıparmak Dam and HPP) and provided a comprehensive reservoir optimization study using sequential stream flow method. In his study, detailed analyses were carried out. Some concepts related to reservoir operation like tail water level change, turbines' efficiency, evaporation and precipitation on the reservoir surface, the head variation in the reservoir level, the head losses through the structures and rule curves (set of optimum seasonal storage volumes in a year) were taken into account in that study. VPM was used rather than using single price method in the estimation of energy revenue to get more accurate results. Different from Ak, (2011), in this thesis, we evaluate rule curves as set of target end-of- month storages rather than set of end-of-season storages.

Kim et al. (2008) developed a monthly operating rule, for single reservoir operation. In this study, a time series model [AR(1)] was utilized to generate the synthetic inflow data over 100 years and, using the ISO, piecewise-linear operation rules composed of 4-5 linear lines were determined. The results show that, using inflow forecasts, the current status of a reservoir can be evaluated quantitatively by the system operators. However, although two objectives (minimization of shortage index and maximization of energy) were used in their study, maximization of revenue was not considered as an alternative objective.

It is also worth to mention about the studies about the adverse effects of hydropeaking to the environment. Bieri et al. (2016) discussed about this issue and they concluded that hydropeaking causes rapid fluctuations and change flow depth, velocity, temperature and bed shear stresses which are important parameters for habitat. They tried to mitigate these negative effects of hydropeaking by defining the best performing intervention strategy. Effects of hydropeaking to the environment are out of the scope of the current study.

2.3. Multi-Reservoir Systems

Multi-reservoir systems are widely studied to derive optimum operational rules for either single purpose or multi-purpose reservoirs. Some of the recent studies are presented as examples in the following paragraphs.

Barros et al. (2003) developed a practical monthly optimization model (called SISOPT) for a very large scale of hydropower system which consists of 75 hydropower plants with an installed capacity of 69,375 MW. NLP was used for the modelling of the system. The NLP model was linearized by using two different linearization techniques and the new model was solved by LP. The obtained results from LP and NLP model were compared, and it was concluded that LP (without iteration) can be utilized for planning purposes and NLP yielded indications of better performances compared to historical operation records. In their study, maximization of revenue for secondary energy generation was considered as an objective. However a fixed price was utilized for a specific time period for the estimation of revenue, and thus the hourly variation of energy prices was not taken into account.

Jothiprakash and Arunkumar (2014) studied a multi-reservoir system serving various purposes like irrigation, multiple hydropower plants and flood control. In this study, multiple reservoirs were optimized to maximize energy generation and to meet the irrigational needs. A NLP was utilized. This technique was applied to a project named Koyna Hydro-Electric in Maharashtra. Three different dependable inflow scenarios were considered to solve the NLP model to maximize energy generation under different policies of operation. In this study, similar optimum rule curves were obtained for different inflow scenarios. However, Jothiprakash and Arunkumar (2014) did not consider maximization of revenue in their study.

In the study carried out by Haddad et al. (2008), honey-bee mating optimization (HBMO) algorithm was taken into examination and its applicability and performance in highly non-convex hydropower system design and operation was illustrated and tested under two hydropower problems: single reservoir and multi-reservoir. Minimization of the total present net cost of the system was considered as an objective of these two problems and at the same time, the maximum possible ratio for generated power to the installed capacity was also tried to be achieved. The results obtained for multi-reservoir system showed that, the proposed method HBMO algorithm yielded a near optimal solution, whereas LINGO 8.0 Software failed to find a feasible solution. Similarly, HBMO provided much better solution than that of LINGO 8.0 Software in the case of single reservoir system. Different from this thesis, in their study, monthly releases are tried to be optimized instead of using rule curves. Moreover, maximization of revenue was not under consideration in their study. An improved version of HBMO was also utilized by Afshar et al. (2011), and operating rules were derived for multi-reservoir system. The recommended model's performance was checked over for an operation problem by comparing the results obtained from a real coded GA that was set up for a 60-month-period with a single reservoir and the results obtained from the sensitivity analysis. It is concluded that HBMO can be utilized for solving complex multi-reservoir systems operation problem. In their study, maximization of revenue was not considered, as well. In addition, in our study, flood control and pumped-storage purposes are also investigated different from their study.

A recently popular technique, particle swarm optimization (PSO), was used by Ghimire and Reddy (2013) for the derivation of optimal operation policies to maximize the annual hydropower production in the Upper Seti Hydro-Power Reservoir system in Nepal. Compared to the planned hydropower production, 3% increase in annual hydropower production was obtained by using elitist-mutated particle swarm optimization (EMPSO) technique for the weekly reservoir operation. The studies were also carried out for wet, dry and normal water years, and significant differences were observed for the release policies for different hydrologic conditions. In this study, only single purpose of energy generation is considered in the analysis, and maximization of revenue objective is not utilized for the efficiency of hydropower system. Another study for the determination of the optimum operation of a large scale of hydropower system in Yangtze River Basin in China, Li et al. (2014) used an improved decomposition-coordination and discrete differential dynamic programming (IDC-DDDP) under the objective of maximizing total power generation. This study showed that IDC-DDDP has satisfactory and competitive performances in total energy generation and convergence speed, compared to the other methods that can be used for large scale of hydropower systems. Different from this thesis, in their study, maximization of revenue was not considered as an objective, as well. Moreover, in this study NLP model is used to solve the complex multi-reservoir system, and thus optimum reservoir levels are identified instead of choosing among discrete reservoir levels.

Teegavarapu and Simonovic (2014) developed a simulation model to investigate the dynamic behavior of a hydraulically coupled multiple reservoir system. This model was developed using the principles of SDs and an object-oriented simulation environment is constructed for the model. Specifically, the tail water level change is considered in the developed model in detail by deriving tail water curves. The results showed that in a serial system of reservoirs, the operational decision taken by one reservoir would affect the whole system. Similar results are obtained in Chapter 5, in the determination of installed capacity studies. However, their study dealt with the single purpose of energy generation for a multi-reservoir system and thus flood control, municipal and irrigation water supply and pumped-storage are not considered as additional purposes. Moreover, in their study, maximization of revenue is not used as an objective.

2.4. Pumped-Storage Systems

Beside the total energy generation of power plants in a country, the energy load balance for peak and off-peak electricity hours are also important. Although the total energy generation is sufficient, sometimes the energy demand cannot be met during peak hours because of the inadequate energy generation during this period. On the other hand, the energy generation obtained from the wind, run-of-river hydropower and thermal energy sources cannot be totally consumed during off-peak hours since energy demand is lower than the generation. If this excessive energy is not stored in some way for this period, revenues obtained from energy generation become very low in the electricity market. This problem can be solved by utilizing pumped hydroelectric energy storage (PHES) which is a type of large amount of energy storage for load balancing and widely used in European countries, USA and Japan. This system pumps water from a lower reservoir to the higher reservoir when the energy demand is low, and generates energy by releasing the stored water from the upper reservoir through the turbines during peak hours (Capilla et al., 2016).

Although there is no pumped-storage hydroelectricity system in Turkey, hydropower is the most important renewable energy source and has the largest share in the energy budget among other renewable energy sources (Kentel and Alp, 2013). Therefore, in this study, the multi-reservoir system composed of Arkun, Yusufeli and Artvin HPPs on Çoruh River is modeled as a pumped-storage system to investigate additional benefits of the pumped-storage system. Some of the studies about PHES in the literature are summarized below.

Haddad et al. (2013) studied a combined system of pumped-storage and hydropower system. The problem is modeled as NLP and solved using LINGO 11.0 Software. Two models are developed in their study: i) The pumped-storage + hydropower system, and ii) Hydropower system (alone). These two models are compared using four different criteria, net benefit, benefit/cost ratio, system efficiency criteria, and mean, firm, and secondary energies. The results show that pumped-storage system gives higher outcomes based on these four criteria. This study is very similar to the studies carried out for pumped-storage system in this thesis (Chapter 6). However, Haddad et al. (2013) used only two different energy prices for off-peak and peak hours instead of using hourly prices as done in this thesis. Using fixed prices may lead to wrong decisions about pumped-storage investment and operational strategies. Thus, to overcome the uncertainties about energy prices during off-peak and peak hours, hourly, daily and monthly variations on prices should be taken into account in such an analysis. Perez-Diaz et al. (2015) reviewed the current trends in the PHES operation. The main challenges faced by PHES operators and the definition of the optimal strategy for PHES are presented in their study.

A multistage looping algorithm (MLA) is developed by Kanakasabapathy and Swarup (2010) to maximize the profit of a pumped-storage plant based on forecasted hourly electricity market prices. The nonlinear relationships between the energy stored, reservoir head and the power output were taken into account in their model, and the developed policy was validated on a typical pumped-storage system and had proven as effective in finding optimal daily and weekly operation schedules. They concluded that their proposed strategy yielded more profit than that of traditional method under a weekly operation. Different form their study, hourly prices of one-year-data set are evaluated for the estimation of revenue in this thesis, thus monthly change of hourly prices are also taken into consideration in the current study.

Connolly et al. (2011) developed practical operation strategies for pumped hydroelectric energy storage (PHES) taking the advantage of the electricity price difference between peak and off-peak hours in a day. A PHES facility with a 360 MW pump and 300 MW turbine and a 2.0 GWh storage was analyzed using three practical operation strategies (24Optimal, 24Prognostic, and 24Historical). The authors concluded that PHES is not a very sensible investment even for low investment costs, low interest rates and suitable electricity market.

2.5. Positioning This Study in the Literature

This thesis study can be categorized into three parts. In the first part of this study, a single-reservoir system and two different objectives are evaluated: maximizing hydropower generation and maximizing the revenue. The first objective represents the goal of a centralized public agency, whereas the second one represents that of a profit-maximizing firm. These objectives are treated separately; insights are obtained as to how a change in the objective affects the rule curve. In the second part of the thesis, the multi-reservoir system is considered with a single purpose of energy generation under three objectives (maximization of average annual energy generation, revenue and net benefit, respectively). These three objectives are also considered separately when developing the related models. In the third part of the studies, multi-reservoir systems with multi-purpose are investigated. The objectives are maximization of energy generation and maximization of net revenue.

Rule curves under various objectives are derived in this study. Since a monthly time step is used in deriving the rule curve, as a result of the optimization model, optimum monthly releases are identified. In practice, hourly electricity prices are used in the energy market in Turkey. Thus, when the objective is maximization of the average annual revenue, effect of hourly electricity prices on optimum monthly releases need to be integrated into the optimization model. The variable price method (VPM) developed by Ak et al. (2011) is used to achieve this purpose. Thus, this study is an attempt to couple development of a rule curve based on long-term energy generation maximization and revenue maximization based on hourly varying energy prices (i.e. simplification of short-term scheduling). Therefore, this study is different than the ones in the literature since an optimization model that considers both production (i.e. through the rule curve) and revenue (i.e. through the VPM) simultaneously is developed. Moreover, the coupled model is used to investigate operation performance of single and multi-reservoir systems both for a government agency that wants to maximize the energy generation and for a private entity that wants to maximize its revenue.

Commonly, operation strategies of HPPs are developed separately, even if they are located on the same river, in Turkey. However, since cascade reservoirs are linked with each other through their releases, an integrated management strategy is necessary. In this thesis, separate management versus integrated management is studied as well. The results show that higher total revenue can be reached with smaller total installed capacity.

In our study, the current multi-reservoir system composed of three HPPs is modeled as a pumped-storage system as well. The maximization of average annual net revenue is considered as the objective. Monthly head variations in the reservoirs, the efficiency of the turbines and pumps with respect to the discharge used during pumping and energy generation are also taken into consideration in our study. The analysis results are compared with that of the current system and the benefit of pumped-storage in a cascade multi-reservoir system is quantified.

In summary, our approach considers stochastic behavior of inflows together with short time price variations simultaneously and generates rule curves for each reservoir of the system. Specifically, maximization of revenue objective is investigated for both single- and multi-reservoir systems based on hourly price variations. In addition, the pumped-storage system together with hydropower system is also studied for multi-reservoir system.

CHAPTER 3

THE HYDROPOWER POTENTIAL OF TURKEY AND ÇORUH BASIN

3.1. Introduction

According to common belief, Turkey is a water-rich country, although this is not the fact. Moreover, its fresh water resources have been polluted recently (Ay and Kişi, 2011). Being about 250 mm in the Central Anatolia, and over 2500 mm in the north-eastern Black Sea region, Turkey’s annual average precipitation is approximately 643 mm. Considering the data obtained between years 1935 and 2008, the economically available water potential of Turkey is calculated as 112 billion m³/year (DSİ, 2009). Turkey’s 2016 population is 79.65 million and the corresponding water amount per capita per year is about 1406.15 m³. The world average is 7600 m³, hence it can be concluded that Turkey is a water-stressed country (Kankal et. al., 2014).

Theoretical, technically feasible, and economically feasible hydroelectric potentials of Turkey and the World are compared in Table 3.1 (DSİ, 2016). It can be seen that economically viable energy per capita of Turkey is greater than the average values of the World and Europe.

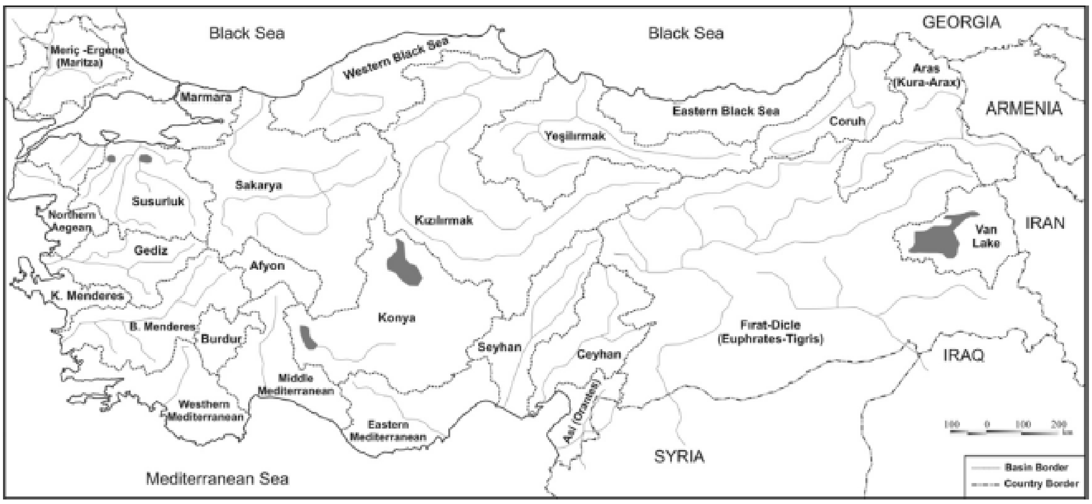


Figure 3.1 Turkey’s River Basins (Kankal et. al., 2014)

Table 3.1 Hydroelectric Potential of the World and Turkey (adapted from DSİ, 2016 and IHA, 2016)

	WORLD	EUROPE	TURKEY
Gross Theoretical Potential of HPP (TWh/year)	40150	3150	433
Technically Viable Potential of HPP (TWh/year)	14060	1225	216
Economically Viable Potential of HPP (TWh/year)	8905	800	127
2016 Population (10^6)	7435.11	738.85	79.65
Economically Viable Energy Per Capita (kWh)	1197.7	1082.76	1599.26
Total Hydropower Production for 2015 (TWh)	3969	599	67

A considerable part of Turkey's hydropower potential comes from the Eastern Black Sea Region. The ratio of actual operating hour per year to total hours per year, namely capacity factor, is very high for that region (Küçükali and Barış, 2009). General Directorate of State Hydraulic Works (DSİ) calculates Turkey's economically feasible hydropower potential as 127 TWh/year. In Table 3.2 Turkey's annual hydroelectric potential according to DSİ is presented.

Table 3.2 Turkey's Annual Hydroelectric Potential According to DSİ (Yüksek et. al., 2007)

Name of Basin	Gross Potential (GWh)	Economically Feasible Potential (GWh)	Installed Capacity (MW)
Euphrates-Tigris	132,828	56,750	15,761
Eastern Black Sea	48,478	11,474	3,257
Eastern Mediterranean	27,455	5,216	1,490
Middle Mediterranean	23,079	5,355	1,537
Çoruh	22,601	10,933	3,361
Ceyhan	22,163	4,825	1,515
Seyhan	20,875	7,853	2,146
Kızılırmak	19,552	6,555	2,245
Yeşilırmak	18,685	5,494	1,350
Western Black Sea	17,914	2,257	669
Western Mediterranean	13,595	2,628	723
Aras	13,114	2,372	631
Sakarya	11,335	2,461	1,175
Susurluk	10,573	1,662	544
Others	30,744	1,788	546
Total	**432,991**	**127,623**	**36,950**

As seen in Table 3.2, the hydropower potential of Turkey is 36,950 MW, of this potential 26,231 MW (71%) is utilized and in operation as of 31 May 2016 (TEIAS, 2016). The total installed capacity of Turkey is 75,081 MW, and approximately 35% of the current installed capacity of 75,081 MW is due to hydropower plants (TEIAS, 2016). The installed capacities in Turkey with respect to energy resources are given in Figure 3.2.

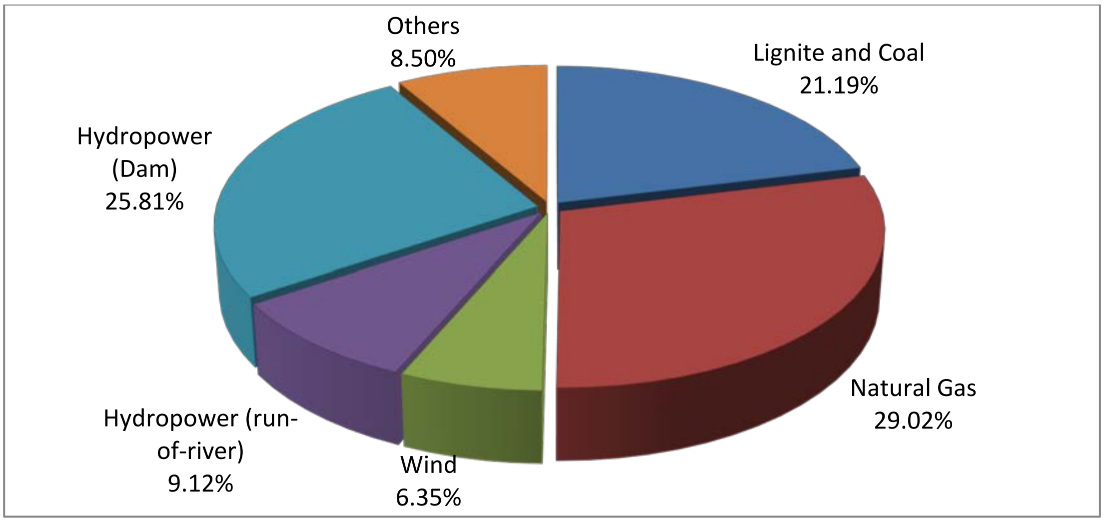


Figure 3.2 Installed Capacity in Turkey with respect to Energy Sources (TEIAS, 2016)

3.2. The Çoruh River Basin

Not only a single benefit but also multiple benefits can be achieved by designing multi-dam power projects. To achieve multiple benefits, ensure the safety of all dams, and manage the available water properly; operation of dams should be carried out efficiently. In multi-dam systems, use of water in the reservoirs affects the functions of all dams. Water can be used for once in the case of single dam but as far as multi-dam systems are concerned, repetitive usage of water is possible (Cassidy, 2016). In this chapter, hydropower potential of multi-dam power project of a Çoruh basin in Turkey is discussed in detail.

One of the most important rivers of Turkey in terms of economically exploitable electricity potential is the Çoruh River. It is the longest river of the Eastern Black Sea Region and a great portion of its potential is not developed (Akpınar et. al., 2011a).

3.2.1. Climatic and Geographic Properties

The Çoruh River Basin is located in the north-eastern part of Turkey. Most of its area is in Turkey and a small portion is in Georgia. The total catchment area of the Çoruh basin is 21,962 km², 19,872 km² of this area is located in Turkey, and 2,090 km² is located in Georgia. The length of the Çoruh River is 427 km. 400 km of the river is in Turkey border (DSİ, 2011). There are 2 main tributaries of the Çoruh River in Turkey. These are the Oltu and the Tortum Streams. The Adzharis and the Tsakali Streams are the main tributaries located in Georgia (Kibaroğlu et.al, 2005; Akpınar et. al., 2011b). The Çoruh River Basin is illustrated in Figure 3.3.

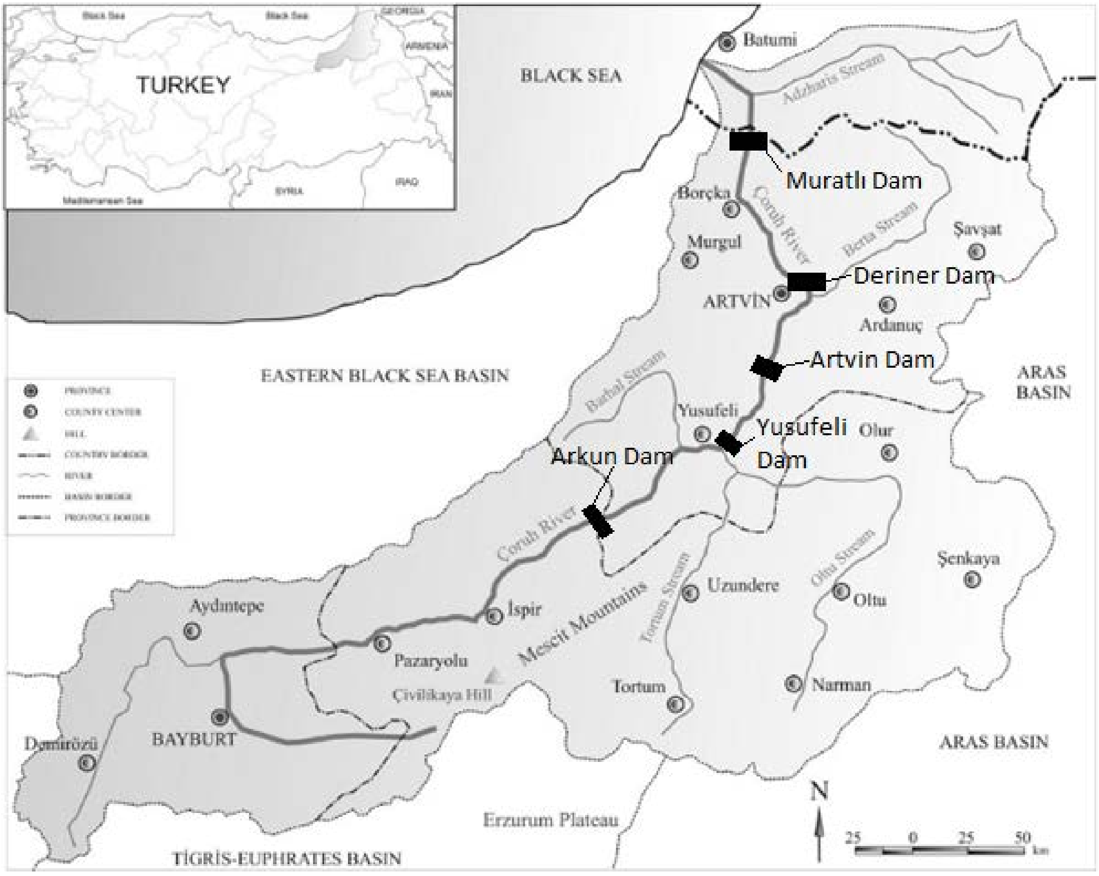


Figure 3.3 Çoruh River Basin (adopted from Kankal et. al., 2014)

3.2.2. The Hydrological Regime of Surface Waters

Without doubt, the Çoruh River has significant amount of hydropower potential and is one of the most important water resources in Turkey. About 3,67% of the total surface run-off of Turkey is provided by the Çoruh River and it has a 6,824 hm^3 of annual average water potential (DSİ, 2011). High and variable flow rates are observed in the river (Kibaroğlu et.al., 2005). The average flow rate, the highest, and the lowest run-off values are monitored as 202 m^3/s, 2,431 m^3/s, and 37.6 m^3/s, respectively via the Muratlı dam site flow monitoring station operated by DSİ. High water availability of the river is due to rainfall and more significantly due to snowmelt from high mountains located nearby (Kibaroğlu et. al., 2005). A great portion (about 85%) of the total annual flow of the river is observed in May, June, and July (DSİ, 2011). Although the drainage area can be considered relatively small, high slope of the river provides high hydropower production potential. So, topographic conditions of the basin can be counted as a significant advantage in terms of hydropower potential. The river carries great amount of sediment throughout the year (estimated as 5 million m³ every year) due to high slope.

3.2.3. Current Situation of Çoruh Basin

Laleli Dam is located at the most upstream part of the Çoruh River and the most downstream part there is Muratlı Dam. The total cascade head of the river is 1.420 m. The Çoruh River Development Plan includes fifteen dam projects. Five of these projects are located on the tributaries and the rest is on the main branch. A longitudinal illustration of these dams is shown in Figure 3.4.

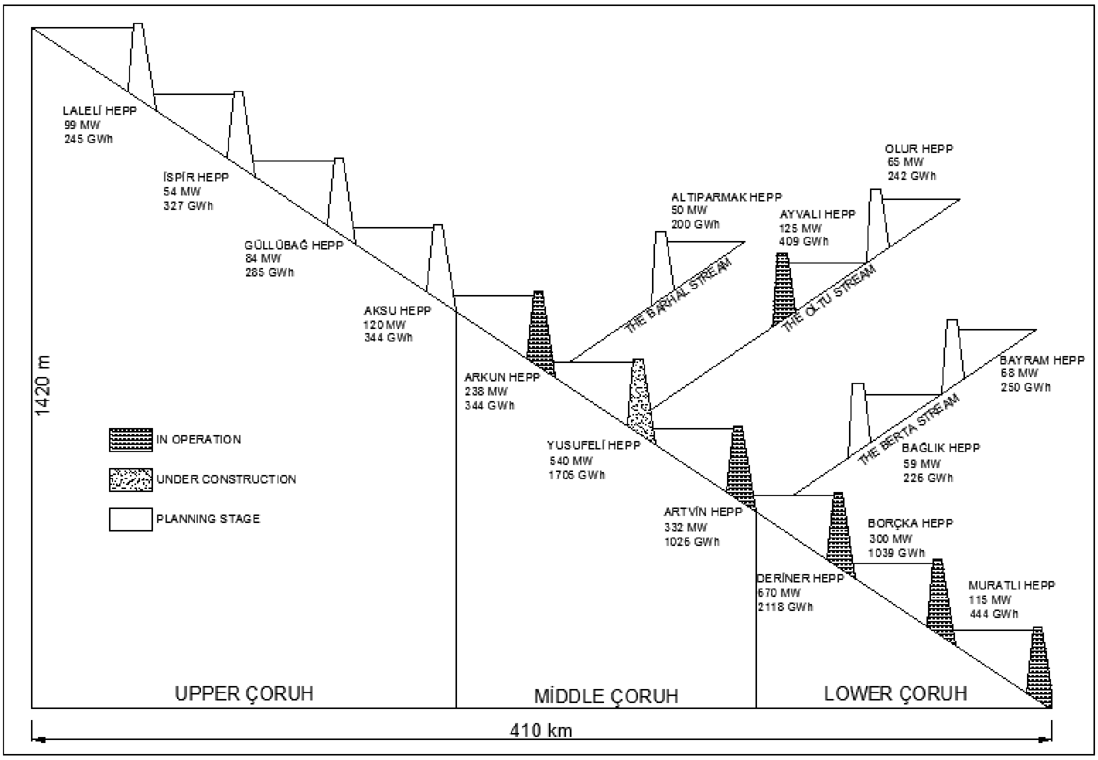


Figure 3.4 Longitudinal Profile of the Çoruh River Basin Projects

The hydropower projects considered in the Çoruh River Basin are divided into three groups which are the lower, middle, and upper Çoruh projects. The middle Çoruh project which is the main concern of this study will be completed when Yusufeli Dam is completed. Besides all these dams, twenty four run-of-the-river HPP's are planned within this development plan (DSİ, 2006).

3.2.4. Hydropower Potential

In 2011, the amount of energy generated in Turkey was 229.395 GWh (TEIAS, 2012) while hydroelectric energy generation was 52,339 GWh (Kankal et. al., 2014). In Çoruh River Basin, there are 39 HPPs developed by the government at various project stages (in design, construction and operation). The installed capacity and the average annual energy generation of these HPPs are 3,179.7 MW and 10,724.16 GWh, respectively. Energy generation of all these 39 HPPs corresponds to 4.67% and 20.50% of the total energy generation and hydroelectric energy generation of Turkey in 2011, respectively.

In addition to 39 HPPs developed by the government, private sector also contributes to the projects in the Çoruh River Basin by developing 129 more HPP projects in the basin. Being at various project stages, when all these projects are completed, the total installed capacity will be 4.487 MW. The average energy generation will rise to 14.593 GWh/year. As a result, considering 2011 data, 27.9 % of the hydroelectric energy generation of Turkey will be met by the Çoruh River Basin (Kankal et. al., 2014).

3.2.5. Study Area: The Middle Çoruh Region

In this section, the middle Çoruh area and the related projects; Artvin, Yusufeli and Arkun HPPs are discussed in detail. These three projects are placed consecutively in the middle part of the Çoruh River (see Figure 3.4). Sole purpose of these three dams is energy generation. The main characteristics of these dams are given in Table 3.3.

Table 3.3 The Characteristics of Arkun, Yusufeli and Artvin Dams (DOLSAR, 2010)

No	Characteristics	Arkun	Yusufeli	Artvin	Unit
1	Purpose	Energy	Energy	Energy	-
2	Average Annual Flow	1860.70	3684.24	3754.32	hm^3
3	Dead Storage Volume	163.65	692.70	98.60	hm^3
4	Maximum Storage Volume	283.24	2156.68	166.80	hm^3
5	Active Storage Volume	119.59	1463.98	68.20	hm^3
6	Reservoir Area	5.53	33.21	15.43	km^2
7	Design Discharge	124.98	321.00	160.89	m^3/s
8	Installed Capacity	238.00	540.00	332.00	MW
9	Gross Head	225.86	208.90	116.20	m
10	Net Head	222.65	199.68	107.21	m

The monthly inflow data belonging to the years between 1993 and 2011 are obtained from the General Directorate of State Hydraulic Works. The average annual flows of the three reservoirs are 1860.70 hm^3, 3684.24 hm^3 and 3754.32 hm^3 for Arkun, Yusufeli and Artvin dams, respectively. The statistical properties of monthly average inflows are given in Figure 3.5, Figure 3.6, Figure 3.7. As seen in the figures, maximum flows are observed in April, May, and June.

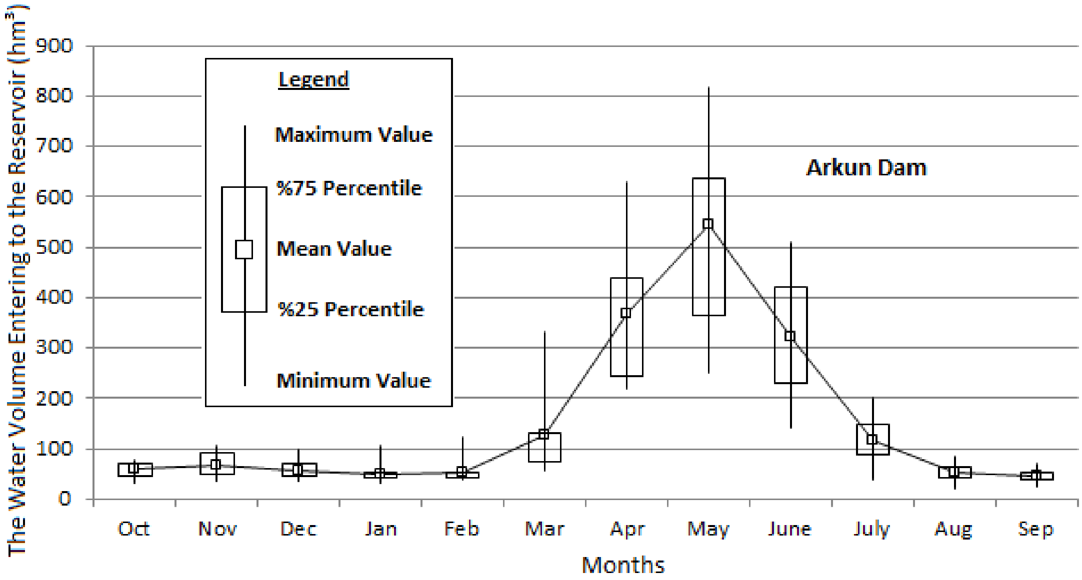


Figure 3.5 Average Inflow Values for Arkun Dam

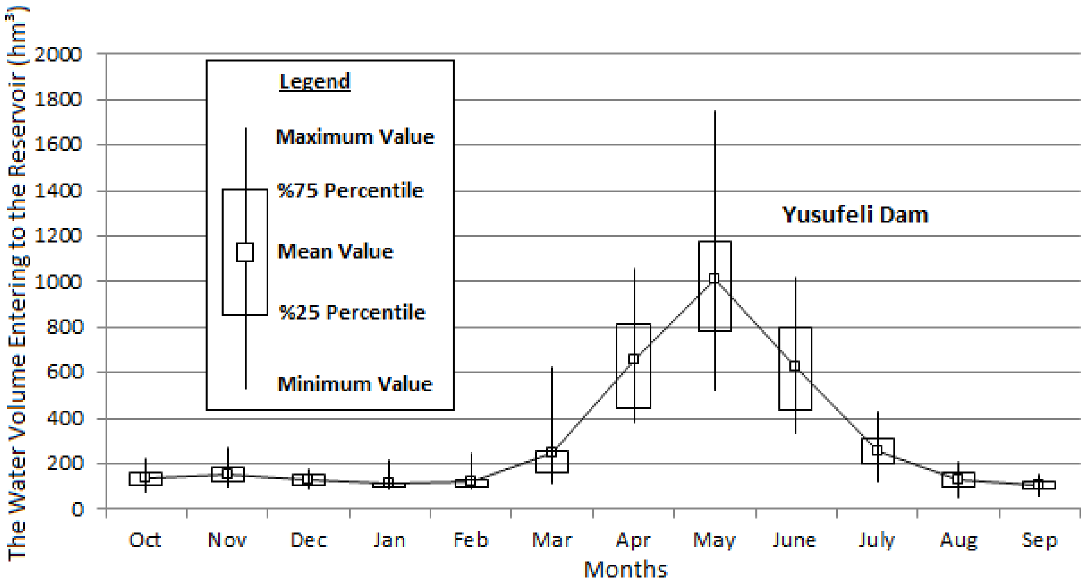


Figure 3.6 Average Inflow Values for Yusufeli Dam

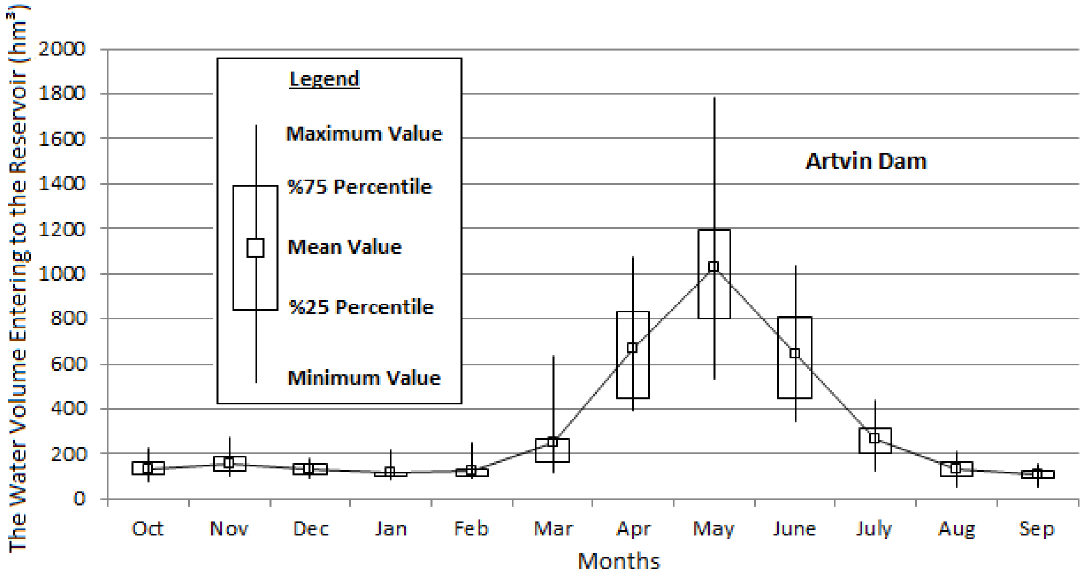


Figure 3.7 Average Inflow Values for Artvin Dam

The inflow data belonging to the projects are used in the estimation of average annual energy generation, and this procedure will be explained in the following chapters. In addition to the inflow data, the volume-elevation curves belonging to the reservoir of the HPPs will also be utilized in the estimation of average annual energy generation. The volume-elevation information for all three HPPs are obtained from the feasibility reports of these HPPs (DOLSAR, 2010). The related curves are given in Figure 3.8, Figure 3.9, and Figure 3.10.

To derive the volume-elevation curves, firstly, the corresponding amount of storage area for any reservoir level should be determined. The related 1/25000-scaled maps of the reservoir are generally utilized to determine the storage areas. Contour lines which have an interval of 10 meters are encircled and the corresponding areas for each contour line are calculated. Then, the storage volumes between two successive contour lines are calculated by multiplying the average corresponding storage areas and the interval height (10.0 m). In other words, for each two successive reservoir levels, the intermediary storage volumes are calculated by using linear interpolation.

Finally, the cumulative storage volumes are estimated starting from the river bed to the maximum reservoir level by adding the intermediary storage volumes to the cumulative storage volume for each reservoir level.

For all reservoirs, an equation is derived for the best fitted curve of active storage as seen in the figures.

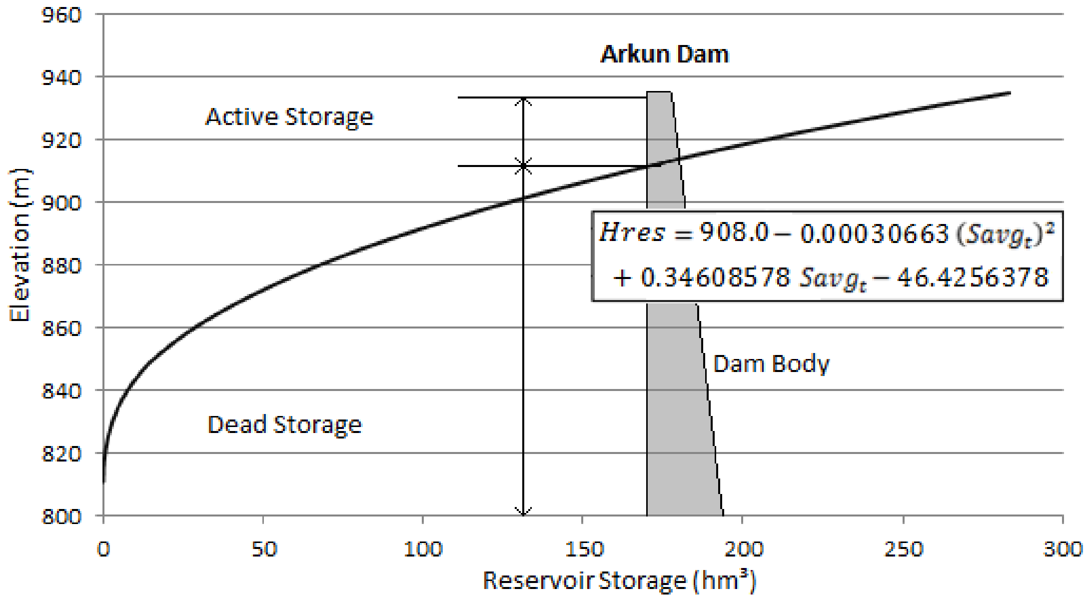


Figure 3.8 The Volume-Elevation Curve for Reservoir of Arkun HPP

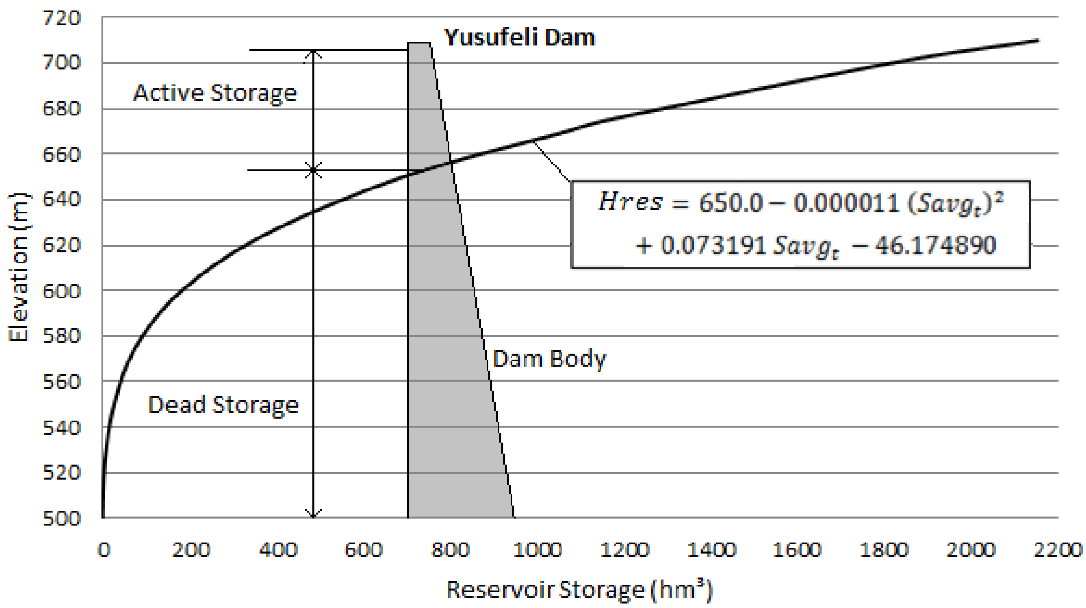


Figure 3.9 The Volume-Elevation Curve for Reservoir of Yusufeli HPP

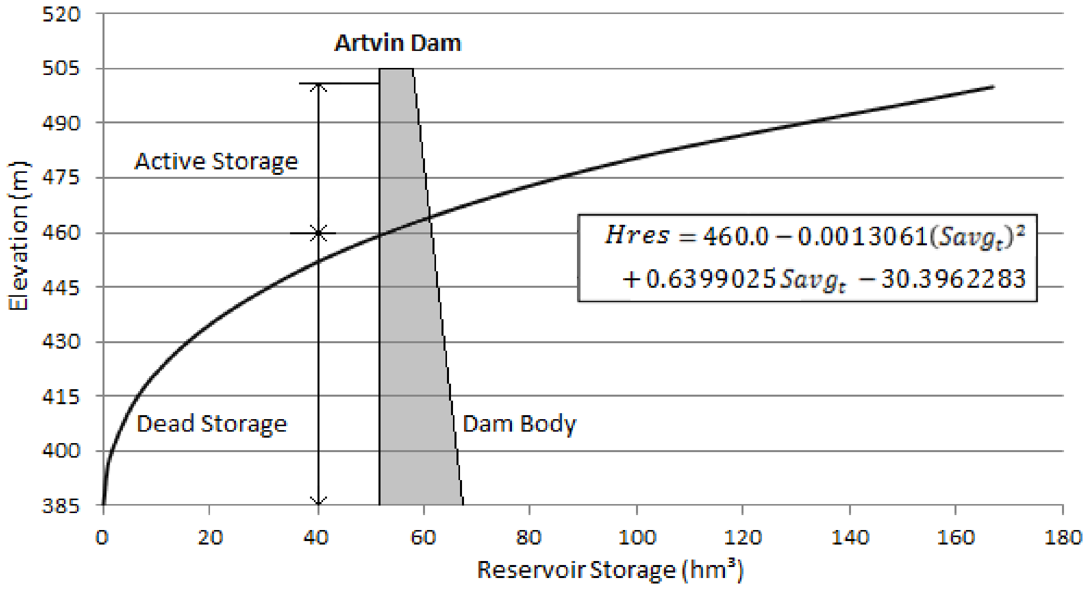


Figure 3.10 The Volume-Elevation Curve for Reservoir of Artvin HPP

CHAPTER 4

OPTIMIZATION STUDIES FOR A SINGLE RESERVOIR WITH SINGLE PURPOSE OF ENERGY GENERATION: YUSUFELI DAM AND HPP

4.1. Introduction

In this chapter, development of operating policies for a single purpose, single-reservoir hydropower plant is under consideration. The dam is assumed to be designed for energy generation, which is a common design purpose in construction of power plants. For the plants in Turkey, other purposes might include (i) water supply for irrigation, (ii) flood prevention, (iii) drinking water supply, (iv) fishery (In Turkey, approximately 80% of the hydropower plants serve single purpose. Of single-purpose plants 88% is constructed for irrigation purposes, Çalamak et al., 2013).

When developing the operating policies for the single-reservoir plant, the aim is to obtain both well-performing and practical policies. The policies developed here fall into the class of *rule-curves*. A rule curve can be defined as the set of the target end-of-period storage (or elevation) values in a reservoir (Lerma et. al., 2013). The rule curve provides guidance to the operator about the end-of-period storages over a planning horizon based on historical data (especially inflows) to maintain the maximum benefit. A specific rule curve needs to be derived for each reservoir, ideally, using optimization techniques. The period is a time bucket and may change depending on the level of detail when deriving the curve. In this study, an aggregate approach is taken by defining the time period as one month. Planning horizon on the other hand spans at least several years.

Four different rule curves are derived using non-linear programming models. Each rule curve has a different characteristic; they vary from naïve to complex. After the models are developed, using data from a real-life case study, the performances of the rule curves are compared and discussed. In the following section the rule curves are described in detail. Then the models are developed, and finally a discussion is provided on the results.

4.2. Rule Curves

The simplest rule curve under consideration is the one which is commonly used for the preliminary design of the HPP projects. This rule curve is named as Rule Curve Fixed (**RCFixed**), and considers a unique reservoir operation level (storage) throughout the whole year, and from one year to the other. This is the easiest in terms of operation. It will serve as a benchmark for the comparison of the other reservoir policies (rule curves) developed in this study. Next, we propose a more advanced rule curve, Rule Curve Strict (**RCStrict**). This rule curve gives a set of 12 end-of-month storage values for each month of the year and the storage values dictated by the rule curve need to be strictly obeyed during the reservoir operation. However, in real time operations, the end-of-month storages dictated by the rule curves cannot always be satisfied because of inadequate inflows that may occur during dry seasons. Therefore to overcome this problem, a rule curve named Rule Curve Guidance (**RCGuidance**) is developed. Different from the RCStrict, for this policy, the rule curve is used just as guidance. Strict obedience to the rule curve is not required for this policy, but the monthly turbine releases are decided according to this guidance curve if suitable. Finally, as a fourth rule curve type, Rule Curve Dynamic (**RCDynamic**) is developed. This policy gives an end-of-month storage value for each month of the simulation period. The target end-of-month storage levels can take any value between the minimum and maximum storage levels throughout the whole operation period This policy cannot be directly used for real-time operation, since it does not provide monthly end-of-storage values (i.e. 12 optimal end-of-month storage values). Indeed, the aim in deriving this policy is to obtain an upper bound on the objective function value of the nonlinear programming model for the specific historical data set. Note that the policy does not directly produce a rule curve that can be used for future reservoir operation, whereas RCFixed, RCStrict, RCGuidance can be used for future operations.

When deriving the rule curves through mathematical models, a deterministic approach is adopted. In fact, any reservoir system can be characterized as a stochastic system due to the randomness in certain factors (model inputs) such as inflows to the reservoir, evaporation, or required periodic demand for water. Deterministic optimization methods do not explicitly incorporate the randomness in the model inputs into the method, but rather either use past historical data of inputs or future forecasts as if the forecasts are exact. The rule curve provides the operation policy that best achieves the selected objective throughout the simulation period or period-of-record (i.e. period for which historical data is available). The motivation of using the historical data is the expectation of the occurrence of similar inflows in the near future. Thus, rule curve will achieve the selected objective in the future as well.

For each of the four rule curves, it is assumed that the simulation period is n years. The inflow data of $12 \times n$ months is used as the input in the model and rule curve is obtained as the output. For our case study (Yusufeli Dam in Turkey) 19 years of historical inflow data (1993-2011) is available.

While these rule curves are constructed, several assumptions are made and several restrictions are taken into consideration. Those are, flow continuity constraints, upper and lower bounds on the reservoir level, and minimum environmental flow requirements for the downstream habitat. Evaporation losses and the precipitation over the reservoir are assumed to be equal to each other in a year and both are neglected for the sake of simplicity.

Next, we discuss the objective functions under consideration when deriving the rule curves.

4.3. Objectives of a HPP

Commonly, the performance of an operation policy for a HPP is measured by the amount of energy generation. This objective generally represents the goal of a centralized public agency in order to satisfy the increasing energy demand in the country from domestic resources. If, on the other hand, plant is owned by a private company the objective would be stated as maximization of the revenue instead of energy generation.

In this chapter, firstly the public agency's point of view is taken and the maximization of energy generation is considered as the objective function of the models. Then, the private company's point of view is taken and the objective function is revised to maximize the revenue. To ensure economic feasibility, especially for private investors, the revenue potential must exceed the capital investment requirement. This makes maximization of average annual energy revenue generated a relevant objective measure for private sector. In Turkey, as of 2016, there are a total of 285 private, for-profit firms with share of 73% of all generated energy, and the remaining 27% is generated by Electricity Generation Inc. (EÜAŞ), a state-owned enterprise. A few of the private firms are major players (such as ENKA, EnerjiSA, Limak Enerji) and their share in the energy generation can be around 3-5% (Canbilen et al., 2017). Others are small firms, whose energy generating quantities do not affect the electricity prices significantly. When considering the maximizing revenue objective, the hourly day-ahead prices are taken as the prices, which the energy can be sold at. The assumption is that, since the size of the firm is small, it can sell whatever energy is generated at the market electricity price.

When measuring the performances, the policies obtained under one objective are compared with that of the other objective. (Firm energy amount could have been yet another objective to consider. However, firm energy amount is not taken as a performance measure in this study because in Turkey, hydropower systems are responsible for peak-period energy generation, not for firm energy generation).In the following, the objective functions (i) maximization of the average annual energy generation (AE(kWh)), and (ii) maximization of the average annual revenue from energy generation (AER(TL)), are described in details.

4.3.1. The Average Annual Energy Generation

When the objective is maximization of the average annual energy generation (AE), the mathematical expression is as follows:

$$Max. AE = \frac{\sum_{t=1}^{12\times n} E_t}{n} \quad (1)$$

Here, E_t is the energy generation in month t (kWh), n is the total number of years in the simulation period and $t \in T = \{1,2,3, \dots, 12\times n\}$. The monthly energy generation for a hydropower plant, E_t , is a function of several elements:

$$E_t = Hnet_t \times Q_t \times \mu_t \times \gamma \times Tm_t, t \in T \quad (2)$$

where $Hnet_t$ is the net head (m), Q_t is the discharge passing through the turbine (m^3/s), Tm_t, is the duration of energy generation (hr), μ_t is the efficiency for turbine in month t, and γ is the specific weight of the water (9.81 kN/m^3).

The net head in month t, $Hnet_t$, is calculated using:

$$Hnet_t = H_t - hl_t, t \in T \quad (3)$$

$$H_t = f_1(Savg_t), t \in T \quad (4)$$

where H_t is the gross head (m) and $Savg_t$ is the average reservoir storage in month t (hm^3) (defined in Equation (8)). The gross head for each month is calculated as the difference between the average reservoir level estimated using the $Hres$ equation derived from the volume-elevation curve of the reservoir (see Chapter 3) and the tail water elevation. In this study, tail water elevation is taken as a fixed value of 500.10 m.

The head loss through the tunnel and the penstock in month t, hl_t (m) is estimated using:

$$hl_t = Kl \frac{\left(\frac{Q_t}{\pi Dl^2/4}\right)^2}{2g} + Kp \frac{\left(\frac{Q_t}{\pi Dp^2/4}\right)^2}{2g}, t \in T \quad (5)$$

where Kl and Kp are the summations of coefficients for head losses that occur through the tunnel and the penstock, respectively, Dl and Dp are the diameters of the tunnel and the penstock (m), respectively, and g is the gravitational acceleration (m/s^2).

The efficiency of the turbine in month t, μ_t, is expressed as:

$$\mu_t = f_2\left(\frac{Q_t}{Qd}\right), t \in T \tag{6}$$

where Qd is the design discharge of the turbine (m^3/s). In Equation (6) f_2 defines an efficiency curve, which provides the relation between Q_t/Qd and the efficiency of the turbine. In the literature, efficiency curves for different types of turbines are provided. Instead of using a traditional constant output coefficient, a detailed consideration of turbine efficiency for the energy generation is aimed in order to decrease the inaccuracies.

The duration of energy generation in month t, Tm_t is calculated using:

$$Tm_t = \frac{\min(O_t, Omax) \times 10^6}{3600 \times Q_t}, t \in T \tag{7}$$

where $Omax$ is the maximum amount of water that can be turbined within a month (i.e. if turbine works with the design discharge for 720 hours) (hm^3), O_t is the total amount of water released from the reservoir (spilling over the spillway or through the bottom outlet plus released water volume for energy generation) during time period t.

The average storage in month t, $Savg_t$ (hm^3) is approximated by:

$$Savg_t = \frac{S_{t-1} + S_t}{2}, t \in T \tag{8}$$

where, S_t is the reservoir storage (hm^3) at the end of month t. The relation between S_t and S_{t-1} (i.e. the continuity equation) is given in Equation (12).

4.3.2. The Average Annual Revenue

When the objective is maximization of the average annual revenue from energy generation (AER), there is a need to reflect the daily price fluctuations in the revenue function. This is challenging, since the time scale used for the estimation of average annual energy generation is based on monthly time steps. Therefore, in order to be compatible with energy maximization objective, hourly prices should be considered in terms of monthly time scale. Thus, this study is an attempt to couple development of a rule curve for long-term energy generation with revenue generation based on hourly varying energy prices (i.e. an aggregate view for short-term scheduling).

In previous studies, revenue obtained from energy generation in a hydropower plant has been generally estimated using an average fixed electricity price (Olivares, 2008; Ak et al., 2014). However an average fixed electricity price does not represent the real situation correctly, since electricity prices oscillate within a day and from month to month. Hourly electricity prices are used in the electricity market in Turkey and the revenue of a hydropower plant is estimated by using hourly electricity prices that form in the market (Ak, 2011). Thus, it is more realistic to use hourly electricity prices instead of a fixed price for the estimation of revenue. In order to better estimate average annual revenue using hourly prices, the Variable Price Method (VPM) developed by Ak (2011) is used in this study. In the VPM method, hourly electricity prices for each month are used for the revenue estimation.

To adopt VPM in this study, a representative price for each month throughout the simulation period is estimated using hourly prices of the related month. The procedure for the estimation of the representative price can be summarized as follows:

i) The average of hourly electricity prices formed in the market in month t are calculated;

ii) Average hourly electricity prices in month, t are sorted from the highest to the lowest;

iii) An average of highest electricity prices corresponding to all possible durations of energy generation within a day is calculated.

iv) The data obtained in one step before is graphed and an equation is derived for the best fitted curve for this data (see Figure 4.1).

v) The average daily duration for energy generation is estimated and the related representative electricity price is estimated from the equation derived for the corresponding month.

For example, the average electricity price for one hour of energy generation within a day is equal to the maximum hourly electricity price; and for two hours of energy generation within a day, the average electricity price is estimated as the average of the highest and the second highest hourly electricity prices. Such an approach assumes that generation of electricity is prioritized based on its price. In other words, if the average duration of energy generation within a day is known as 5 hours, then electricity is generated during 5 hours in which the electricity prices are the highest. So, the average of maximum 5 electricity prices is calculated for the representative electricity price of 5-hour-daily energy generation. In this study, electricity prices belong to the year 2014 are used. However, the suggested procedure is not restricted to one year's data; it can be used with electricity price data for multiple years as well.

The objective function and the procedure for the estimation of representative electricity price are formulated as follows:

$$Max.AER = \frac{\sum_{t=1}^{12xn} ER_t}{n} \tag{9}$$

where

$$ER_t = \; E_t \times P_t, t \in T \tag{10}$$

where ER_t is the revenue from energy generation in month t (TL), P_t is representative price of electricity for month t (TL/kWh) which is a function of the duration of energy generation within a day:

$$P_t = \; f_3(Tm_t/30), t \in T \tag{11}$$

where $Tm_t/30$ is the average duration of energy generation in a day of month t (hr).

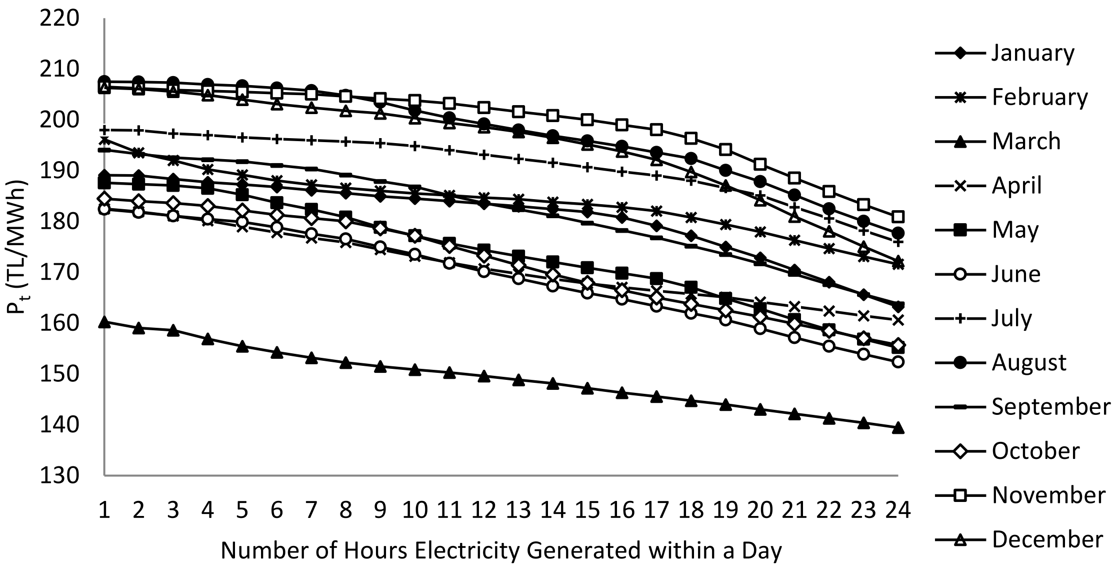


Figure 4.1 Representative Prices with respect to the Duration of Electricity Generation in a Day (PMUM, 2015)

4.4. Determining the Installed Capacity and Discharge

The installed capacity of a hydropower system is determined based on the selection of design discharge of the hydropower system. Design discharge is defined as the discharge passing through the turbines when the turbine gates are fully opened and the reservoir level and the tail water level are in their design levels. The design discharge of a hydropower is selected based on the optimization studies. In this chapter, the current design discharge is considered for the model system. In Chapter 5, the design discharge will be determined through the optimization studies.

In real operation, the energy generation in a hydropower can be made using any turbine discharge between the minimum turbine discharge (the minimum discharge that can be utilized for energy generation) and the design discharge. In this study, two settings (scenarios) are considered for the turbine discharge selection. In the first setting, a fixed turbine discharge (i.e. the design discharge) is used throughout the simulation period. In the second setting, discharge is defined as a decision variable and the **optimal dynamic discharge** (ODD) is calculated for each month throughout the simulation period and used in the operation. By comparing the results under these two settings, the impact of the turbine discharge on the performance measures is assessed.

4.5. Models

The mathematical models of four different rule curves are presented in this section. The common sets, scalars, parameters, and variables are presented below for each of these models. The RCDynamic policy is the base model and given here. The models for the remaining policies are explained by contrasting them with the base model.

Sets

t (month) : Time step ($t \in T = \{1,2,3, \dots ,228\}$)

j : Rank of the month in the year ($j \in J = \{1,2,3, \dots ,12\}$)

Scalars

$Smin$ (hm³) : Minimum level of reservoir storage

$Smax$ (hm³) : Maximum level of reservoir storage

S_0 (hm³) : Initial reservoir storage

Rw (hm³) : Minimum water release as environmental flow

$Qmin$ (m³/s) : Minimum turbine discharge

Qd (m³/s) : Design discharge

n : The number of years in the operation period

Parameters

I_t (hm³) : Water volume entering the reservoir in month t

Variables

S_t (hm³) : End-of-month reservoir storage for month t

$Savg_t$ (hm³) : The average reservoir storage for month t

O_t (hm³) : The amount of water released in month t (summation of spilled water and water used for energy generation)

R_t (hm³) : The water released as environmental flow in month t

Q_t (m³/s) : Discharge passing through the turbines for energy generation month t

As stated before, two objectives (maximization of the average annual energy generation and maximization of the average annual revenue) are utilized for this study, and two different assumptions for the discharge passing through the turbines are investigated for the policies. The first assumption is that a fixed discharge (the design discharge) is used for the energy generation throughout the simulation period (this assumption is named as "***design discharge***"). The second assumption is that discharge is regarded as a variable and the discharge is optimized for each month throughout the simulation period (this assumption is named as "***optimum dynamic discharge***").

4.5.1. Base Model: Dynamic Rule Curve Policy (RCDynamic)

The model constraints belong to the RCDynamic Model are presented below.

Model Constraints:

$$S_t = S_{t-1} + I_t - R_t - O_t, t \in T \quad (12)$$

$$Smin \leq S_t \leq Smax, t \in T \quad (13)$$

$$R_t \geq Rw, t \in T \quad (14)$$

$$S_0 = S_T, (\equiv S_0 = S_{228}) \quad (15)$$

$$Q_t = Qd, t \in T \quad (16a)$$

$$Qmin \leq Q_t \leq Qd, t \in T \quad (16b)$$

In the model, (12) is the continuity equation, (13) limits the end-of-month reservoir storages in accordance with the physical limitations of the reservoir, (14) sets a lower bound on the released water volume for environmental requirements, (15) forces the initial and final storage levels of the simulation period to be the same (initial reservoir level is assumed to be at its maximum level). Constraint (16a) is used if turbine discharge is forced to be the design discharge, and (16b) is used if optimum dynamic discharges are used and discharges are limited by the design discharge. Note that either (16a) or (16b) is included in the model, not both.

4.5.2. Fixed Rule Curve Policy (RCFixed)

Equation (17) is added to the base model to implement the RCFixed policy, which in effect results in a single decision variable for reservoir storage.

$$S_t = S_{t+1}, \ 0 < t < 227 \tag{17}$$

4.5.3. Strict Rule Curve Policy (RCStrict)

To implement the RCStrict policy, Equation (18) is added to the base model. Note that in this policy in effect there are 12 decision variables for reservoir storages.

$$S_t = S_{t+12}, \ 0 < t < 217 \tag{18}$$

4.5.4. Guidance Rule Curve Policy (RCGuidance)

The structure of the guidance policy is as follows. There exists a guidance level for month j of the year, $Srule_j$, such that when the storage level, S_t, is above $Srule_j$ the water is released until $Srule_j$, otherwise if S_t is below $Srule_j$, nothing is released. In RCGuidance the additional variable $Srule_j$ is included in the model, and in place of O_t, decision variables Sp_t and OT_t are defined as follows:

$Srule_j$ (hm^3)	:	Desired end-of-month reservoir storage suggested by the rule curve in month j of a year
Sp_t (hm^3)	:	Amount of water spilled over the spillway in month t
OT_t (hm^3)	:	Amount of water used for energy generation in month t (Note, $O_t = Sp_t + OT_t$)

In the RCGuidance model, Equation (9) of the base model is replaced with Equations (19), (20) and (21).

$$S_t = S_{t-1} + I_t - R_t - Sp_t - OT_t, t \in T \tag{19}$$

$$Sp_t = \max(S_{t-1} + I_t - R_t - Omax - Smax, 0), t \in \{2,3, \dots ,228\} \tag{20}$$

$$OT_t = \max(\min(S_{t-1} + I_t - R_t - Sp_t - Srule_j, Omax), Omin), \quad j = mod(t, 12) \ and \ t \in \{2,3, \dots ,228\} \tag{21}$$

Among the middle projects of Çoruh River, Yusufeli HPP has the biggest reservoir storage (see Chapter 3). Reservoir operation studies are more important for larger reservoirs. So Yusufeli HPP is selected as the most suitable project for the evaluation of a reservoir operation in this study.

4.6. Discussion of Results

In this section, the performances of the operating policies under the two objectives, for the case study under consideration, are contrasted and discussed, and the optimum rule curves (end-of-month storage levels) suggested by the policies are compared. Averagely, the optimal solutions are found in 30 seconds by using CONOPT Solver of GAMS Software.

The objective function values are presented in Table 4.1. for all policies under the two objectives. The objective function values under the design discharge and optimum dynamic discharges are also given for the comparison purposes. The objective function value is given in the corresponding cell, and the corresponding value of the other objective is also estimated by using the policy (rule curve) suggested for the main objective function and this value is also presented as a performance measure. For example, under the objective of maximization of energy generation using the design discharge, the objective function value is obtained as 1705.22 GWh considering the RCFixed policy. The corresponding revenue is read to be 300.96 million TL from the Table 4.1.

According to the optimal results obtained from optimization studies, the maximum objective function values are obtained for the RCDynamic, and it is followed by the RCGuidance, the RCStrict, and the the RCFixed, respectively. This rank is expected since the RCDynamic policy has the largest feasible solution area, and the RCGuidance has the second largest feasible solution area, and it is followed by the RCStrict policy, and the RCFixed policy has the smallest feasible solution area.

Objective function values are ranked from the highest to the lowest for both objectives under the optimal solution in such a way that: objective function value is determined as the highest under RCDynamic policy and it is followed by the RCGuidance, the RCStrict, and the RCFixed, respectively. This is an expected result since the sorting of sizes of the feasible solution areas belonging to the aforementioned policies are the same.

Table 4.1 Results of Optimization Studies for Yusufeli Dam

	Objective	**Maximization of Average Annual Energy Generation**				**Maximization of Average Annual Revenue**			
	Assumption	Design Discharge		Optimal Dynamic Discharge		Design Discharge		Optimal Dynamic Discharge	
		Energy (GWh)	**Revenue (10^6 TL)**	**Energy (GWh)**	**Revenue (10^6 TL)**	**Energy (GWh)**	**Revenue (10^6 TL)**	**Energy (GWh)**	**Revenue (10^6 TL)**
MODELS	RC_Fixed	1705.22	300.96	1746.50	306.64	1705.20	300.96	1745.10	306.93
	RC_Strict	1767.64	311.09	1821.03	318.94	1750.10	318.56	1801.80	326.77
	RC_Guidance	1773.43	305.78	1823.84	313.74	1743.30	319.39	1796.40	327.41
	RC_Dynamic	1817.12	316.89	1868.91	323.85	1782.80	326.89	1833.60	334.68

4.6.1. Comparison of the Results under the Objective of Maximization of the Average Annual Energy Generation

According to the results of the RCFixed policy, when the reservoir is kept at its maximum storage level, the maximum average annual energy generation is obtained. Comparing with the other rule curves, the energy generation obtained for the RCFixed policy can be evaluated as the practical lower bound. Conversely, the RCDynamic policy is actually the combination of the optimum rule curves for each year and its flexibility provides the highest average annual energy generation. However, it should be noted that the RCDynamic policy cannot be directly used as an operating policy for the future periods, since the monthly outflows (water volume) suggested by this policy change every month throughout the simulation period. Therefore, the RCDynamic can be regarded as the theoretical upper bound throughout the corresponding simulation period.

The solutions obtained by using the RCStrict and the RCGuidance policies are very similar. The end-of-month storage values suggested by the rule curve of the RCGuidance policy are almost attained throughout the simulation period. Therefore, the RCGuidance and the RCStrict give very close solutions. The average annual energy generations (when optimum dynamic discharges are used) for the RCStrict and the RCGuidance policies are 4.27% and 4.43% greater than that of the RCFixed policy, and 2.47% and 2.63% lower than that of the RCDynamic policy, respectively. Average end-of-month storage levels over years obtained for the RCDynamic policy are illustrated for comparison purposes in Figure 4.2 together with other rule curve policies. Almost the same curves are obtained for the RCStrict and the RCGuidance policies as seen in Figure 4.2. However, the average values obtained for the RCDynamic policy are slightly different from these policies.

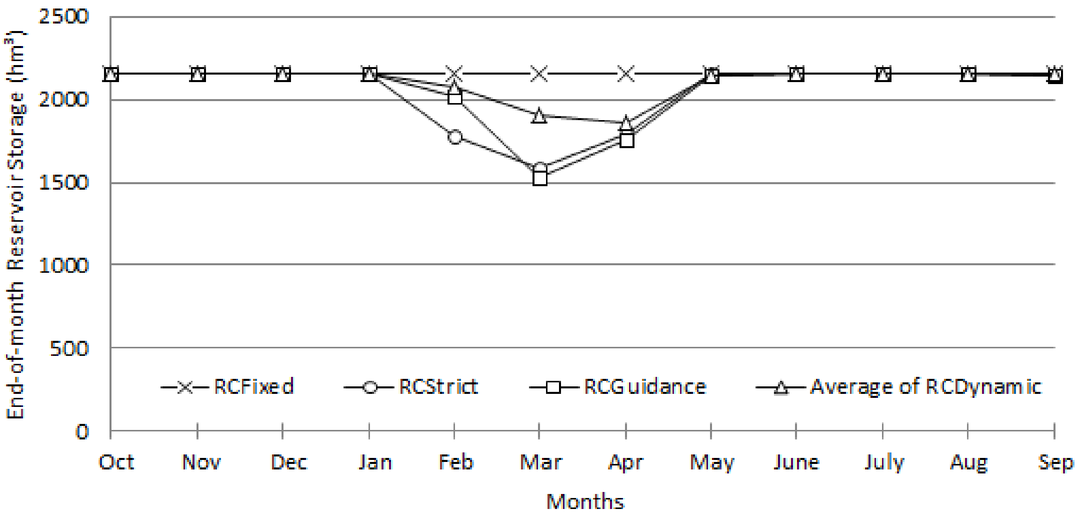


Figure 4.2 Comparison of Optimum Rule Curves under Maximization of the Average Annual Energy Generation Objective

The results show that, optimal policy is to keep the reservoir storage volume at its maximum level at all times under the RCFixed policy. On the other hand, additional storage volume for the excess water can be provided by reducing the reservoir level to a lower level temporarily before the wet period (see the levels in Feb-Apr in Figure 4.2) and this strategy enables the hydropower plant to generate energy in future. In other words, larger amount of energy generation is obtained in the future due to the additional storage freed up in the previous months, although the net head is decreased during this period.

4.6.2. Comparison with respect to the Discharge Assumption: The Design Discharge versus Optimal Dynamic Discharges

Discharge (Q_t) is taken as a scalar and set equal to the project design discharge in the first part of the study. And in the second part, discharge values of each month are set as decision variables and are allowed to take any value between the minimum turbine discharge and the project design discharge (see Equation 16b). Thus, in addition to the optimum end-of-month storages, optimum turbine discharges for each month are calculated in the NLP models. From the results obtained, it can be concluded that setting turbine discharges as decision variables increases the energy generated up to 3.00% under all policies.

In Figure 4.3, the optimal dynamic discharges versus amount of water used for energy generation obtained through the simulation period graph which is generated considering the RCGuidance policy is illustrated. The optimum discharge value is observed about 276 m³/s in the large part of the simulation period. In these periods, energy generation duration is seen to be smaller than or equal to 720 hours (i.e. . In other words, the duration of energy generation for each month is selected in such a way that the total available water for the energy generation is turbined with the optimum discharge of 276 m³/s whenever a month-long period (720 hours) is enough to turbine all available water. The discharge value is specified for the condition of full-time turbine operation (720 hours) when the total available water for energy generation in a month is greater than 715 hm³ (i.e. 720 hours with 276 m³/s discharge). When the inflow values are high in wet periods, the optimum dynamic discharge exceeds 276 m³/s.

The results obtained from the study explained above can be utilized as a useful tool during the selection of the optimal design discharge (Q_d) for future energy generation. The discharge value for dry months gives a lower bound on the optimal design discharge (here, 276 m³/s). To cover for the wet months, one should set the design discharge higher than this lower bound. This is because a higher design discharge would allow for higher energy generation for wet months. Depending on the inflows in the beginning of the wet month, turbine discharge can be adjusted in accordance with the target end-of-month storage value.

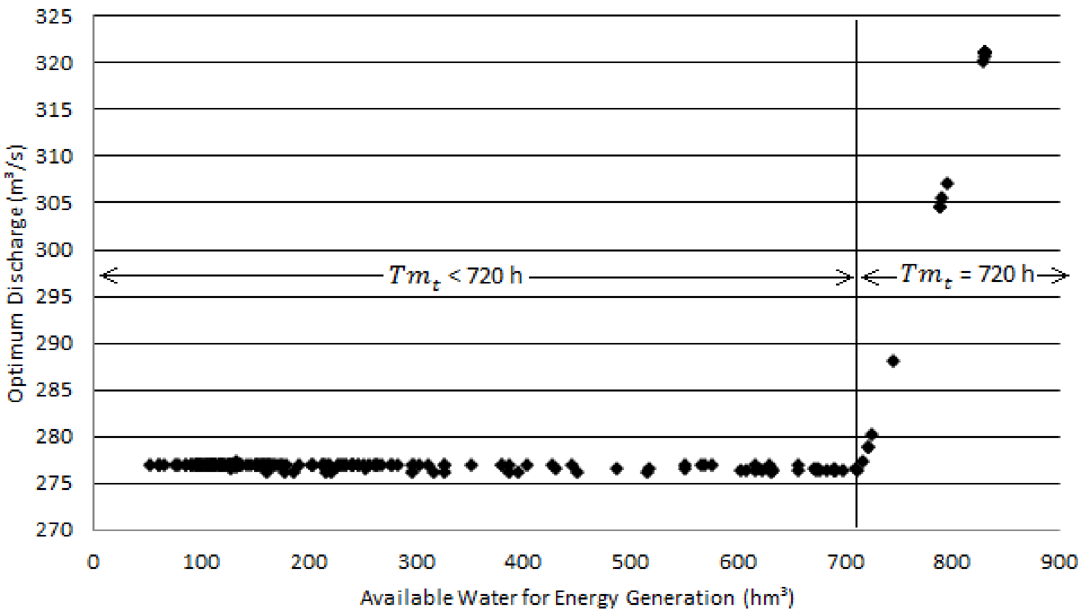
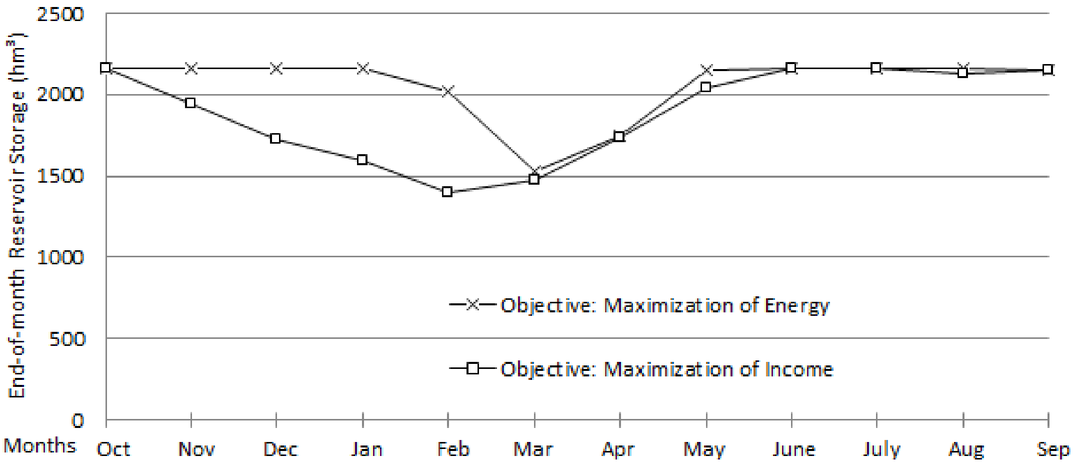


Figure 4.3 Amount of Water Used for Energy Generation versus Optimum Dynamic Discharges (The results are obtained for the maximization of the average annual energy generation and the RCGuidance Policy).

4.6.3. Comparison of the Results under the Objective of Maximization of the Average Annual Revenue

For maximization of the average annual revenue objective, the same studies are carried out under the four policies and two assumptions (design discharge and optimal dynamic discharge assumptions) and the results are presented in Table 4.1. The RCGuidance and the RCStrict policies yield very close solutions again (around 0.2% difference) for this objective (see Table 4.1.) As seen in Table 4.1, switching from the objective of maximizing the energy generation to the objective of maximizing the revenue decreases the energy generated by an amount of 1.50%, while increases the average annual revenue values by 4.36% (values obtained under the RCGuidance policy and under optimum dynamic discharge). For the RCStrict and the RCDynamic policies, similar solutions are obtained. Optimum rule curves obtained under the RCGuidance policy for both objectives are given in Figure 4.4.

The solutions for both objective functions under the RCGuidance Policy are compared (see Figure 4.4) and it is seen that optimum rule curves are different from each other in the first half of the year (from October to March), whereas they are very similar for the second half of the year (from April to September). The electricity prices oscillate throughout the year hourly and monthly as stated before (the average electricity prices for the months are given in Figure 4.4 as well). The electricity prices directly affect the energy revenue and the hydropower plant is preferred to run when the energy prices are higher. By this way, it is aimed to maximize the revenue. For example, as seen in Figure 4.4, the electricity prices are relatively higher for the period between November and February and thus it is logical to generate electricity in this period. That’s why the rule curves are different from each other in the first half of the year. In other words, it can be said that, the head (one of the main multipliers of energy equation) is not as important as the energy prices during November, December and January for the objective function of revenue maximization. For March, April, and May, as done in the energy maximization, the additional water storage is formed to use the excessive water in future energy generation to maximize the revenue. During the dry period (from June to October) the reservoir is kept at its maximum level in order to preserve the head to generate more energy and revenue. As a result, it can be concluded from Figure 4.4 that, the rule curve should be derived in accordance with the objective. Otherwise there could be loss of benefit and resource. In addition, the variations in hourly and monthly electricity prices should be taken into consideration for more accurate results, because using fixed electricity prices causes inaccuracies in the estimation of revenue.



171.77	199.08	194.83	180.68	183.93	149.30	171.15	173.66	169.14	190.96	197.17	181.81

Average Electiricty Prices (TL/MWh)

Figure 4.4 Optimum Rule Curves for the Objectives (for the RCGuidance Policy)

CHAPTER 5

OPTIMIZATION STUDIES FOR MULTI-RESERVOIR SYSTEM WITH SINGLE PURPOSE OF ENERGY GENERATION: ARKUN, YUSUFELI AND ARTVIN HPPS

5.1. Introduction

Reservoir operation studies are carried out only for a single dam namely Yusufeli HPP in Chapter 4, and two objective functions: energy and revenue maximization are studied disjointly. A more realistic approach to reservoir management is to consider multi-reservoir systems. In real multi-system reservoir operations, upstream HPPs' reservoir operating policy directly affects the operation of the reservoir located at the downstream. Total inflow to the downstream reservoir can be accepted as equal to the summation of the water released from upstream reservoirs and the water coming from intermediate basins. Therefore, during reservoir operation studies one should take the integrated basin management concept into account.

In this study, we consider the integrated system which is composed of Arkun, Yusufeli and Artvin hydropower plants from upstream to downstream. Two cases are taken into account when handling the problem. In the first case, plants are managed separate (decentralized management) and in the second case they are managed simultaneously as a one system (integrated system) under three objectives.

The objectives are the maximization of energy, maximization of revenue and maximization of net profit. Maximization of energy and maximization of revenue objectives are already defined in Chapter 4. As an additional objective, in this chapter, the maximization of net profit will be studied. All three objectives will be studied both for the separate and the integrated systems. When maximization of energy and maximization of revenue objectives are studied, it is assumed that the installed capacities of all the HPPs of the multi-reservoir system are known (i.e.

obtained from the feasibility reports). On the other hand, under the maximization of net profit objective, optimal installed capacities of each of the three HPPs are treated as decision variables. The optimal installed capacities obtained from the solution of the optimization problem are compared with the values provided in the feasibility reports of the HPPs.

In Chapter 4, for the reservoir operation studies carried out for Yusufeli HPP, 4 different rule curves are considered (RCFixed, RCStrict, RCGuidance and RCDyanmic). In this study, only Strict Rule Curve (**RCStrict**) Policy is used for all models.

To summarize, the aim of this chapter is to compare the separate system and the integrated system using RCStrict policy. The comparison is carried out under three objectives mentioned above and the results are discussed at the end of this chapter.

5.2. Objective Functions

The definitions and the mathematical formulations of the objective functions, maximization of energy generation and revenue, are presented for a single HPP (Yusufeli HPP) in Chapter 4. In this chapter, these two objectives are revised for a multi-reservoir system composed of Arkun, Yusufeli and Artvin HPPs. An additional objective, the maximization of net profit, is also considered. Under the maximization of net profit objective the optimum installed capacities of all the HPPs of the multi-reservoir system are obtained.

5.2.1. The Average Annual Energy Generation

This objective function represents the goal of a centralized public agency. Satisfying the increasing energy demand in the country from domestic resources is commonly the main aim of the agency. In this study, this objective function is first studied for each HPP separate and then for the integrated system as a whole. In the following, maximization of the average annual energy generation objective is explained for the integrated system.

Objective: Maximization of the total average annual energy generation (TAE)

$$TAE = \sum_{i=1}^{i=K} AE_i \tag{5.1}$$

where K is the total number of hydropower plants which form a cascade system, and AE_i is the average annual energy generation of hydropower plant *i*, and estimated as follows:

$$AE_i = \frac{\sum_{t=1}^{12xn} E_{ti}}{n} \tag{5.2}$$

where E_{ti} is the monthly energy generation in month t (kWh) for the hydropower *i*, n is the total number of years in the simulation period and $t \in T = \{1,2,3, \dots, 12\times n\}$.

For the hydropower plant *i*, the monthly energy generation, E_{ti}, is a function of several elements:

$$E_{ti} = Hnet_{ti} \times Q_{ti} \times \mu_{ti} \times \gamma \times Tm_{ti}, \quad t \in T \; and \; i \in K \tag{5.3}$$

where $Hnet_{ti}$ is the net head (m), Q_{ti} is the discharge passing through the turbine (m^3/s), Tm_{ti}, is the duration of energy generation (hr), μ_{ti} is the efficiency for turbine in month t for the hydropower plant *i*, and γ is the specific weight of the water (9.81 kN/m^3).

The net head in month t, $Hnet_{ti}$, is calculated using:

$$Hnet_{ti} = H_{ti} - hl_{ti}, t \in T \tag{5.4}$$

$$H_{ti} = f_2(Savg_{ti}), t \in T \; and \; i \in K \tag{5.5}$$

where H_{ti} is the gross head (m) and $Savg_{ti}$ is the average reservoir storage in month t (hm^3) for the hydropower plant i (defined in Equation (5.9)). The gross head for each month is calculated as the difference between the average reservoir level estimated using the $Hres_i$ equation derived from the volume-elevation curve of the reservoir and the tail water elevation. In this study, tail water elevation is taken as a fixed value for each reservoir.

The head loss through the tunnel and the penstock in month t, hl_{ti} (m) is estimated using:

$$hl_{ti} = Kl_i \frac{\left(\frac{Q_{ti}}{\pi Dl_i^2/4}\right)^2}{2g} + Kp_i \frac{\left(\frac{Q_{ti}}{\pi Dp_i^2/4}\right)^2}{2g}, \quad t \in T \text{ and } i \in K \tag{5.6}$$

where Kl_i and Kp_i are the summations of coefficients for head losses that occur through the tunnel and the penstock, respectively, Dl_i and Dp_i are the diameters of the tunnel and the penstock (m), respectively, and g is the gravitational acceleration (m/s^2).

The efficiency of the turbine in month t, μ_{ti}, is expressed as:

$$\mu_{ti} = f_2\left(\frac{Q_{ti}}{Qd_i}\right), \quad t \in T \text{ and } i \in K \tag{5.7}$$

where Qd_i is the design discharge of the turbine (m^3/s). In Equation (5.7) f_2 defines an efficiency curve, which provides the relation between Q_{ti}/Qd_i and the efficiency of the turbine.

The duration of energy generation in month t, Tm_{ti} is calculated using:

$$Tm_{ti} = \frac{\min(O_{ti}, Omax_i) \times 10^6}{3600 \times Q_{ti}}, t \in T \text{ and } i \in K \tag{5.8}$$

where $Omax_i$ is the maximum amount of water that can be turbined within a month (i.e. if turbine works with the design discharge for 720 hours) (hm^3), O_{ti} is the total amount of water released from the reservoir (spilling over the spillway or through the bottom outlet plus released water volume for energy generation) during time period *t*.

The average storage in month *t*, $Savg_{ti}$ (hm^3) is approximated by:

$$Savg_{ti} = \frac{S_{t-1i} + S_{ti}}{2}, t \in T \; and \; i \;\; \in K \tag{5.9}$$

where, S_{ti} is the reservoir storage (hm^3) at the end of month t. The relation between S_{ti} and S_{t-1i} (i.e. the continuity equation) is given in Equation (5.9).

5.2.2. The Average Annual Revenue Generated

This objective function represents the goal of a privately-owned revenue-maximizing power plant. The company may prefer to generate energy when the market prices are high, since the main goal of the company is to maximize its revenue. Maximization of the revenue may result in a decrease in the average annual energy generation. The average annual revenue generated for each HPP is tried to be optimized separate and for the integrated system. The total average annual revenue obtained for the integrated system is maximized under this objective function.

<u>Objective</u>: Maximization of the total average annual revenue (TAE)

$$TAER = \sum_{i=1}^{i=K} AER_i \tag{5.10}$$

where $TAER$ is the total average annual revenue due to energy generation for the integrated system and estimated as the summation of the average annual energy generation revenues of each HPP.

$$AER_i = \frac{\sum_{t=1}^{12xn} ER_i}{n} \tag{5.11}$$

$$ER_{ti} = \; E_{ti} \times P_{ti}, t \in T \; and \; i \;\; \in K \tag{5.12}$$

In Equation (5.10), K denotes the total number of plants (in our study, $K = 3$) and AER_i is the average revenue for hydropower plant i. In Equation (5.11), ER_{ti} is the revenue in month t (kWh) for plant i, n is the total number of years used in the optimization problem and $t \in T = \{1,2,3, \dots, 12{\times}n\}$. In Equation (5.12), E_{ti} is the energy generated at plant i, in month t, P_{ti} is the representative price of electricity for month t (TL/kWh) which is a function of the duration of energy generation within a day, $Tm_{ti}/30$. The estimation of representative price for each month is explained in Chapter 4.

$$P_{ti} = \; f_1(Tm_{ti}/30), t \in T \tag{5.13}$$

where Tm_{ti} is the duration of energy generation in month t (hr). Note Tm_{ti} depends on energy generation E_{ti}, and $Tm_{ti}/30$ is the duration of energy generation in a day.

5.2.3. The Average Annual Net Profit

The net profit is defined as the difference between the average annual revenue and the equivalent annual cost of capacity installment. In a real hydropower project, the investment cost generally includes the costs associated with the dam body, the tunnel, the penstock, the surge tank, the power house, the turbine, the transformer, the generator, and expropriation costs. But in the optimization studies carried out in this thesis, only the costs which are highly dependent on the selected installed capacity are taken into account for the sake of simplicity. In this study, total cost obtained by considering the turbine, the transformer, the generator and the power house and related components is called as "***installed capacity costs***" (Plansu, 2010; Çetinkaya, 2013). Since annual cost of the HPP is a function of its installed capacity, the installed capacity is defined as a decision variable as well. Thus, optimum installed capacities are identified while maximizing the average annual net profit as well.

A number of alternative market prices are utilized to estimate the cost of the unit installed capacities. The estimation of annual revenue generation is carried out similar to that of Chapter 4. In the objective function, the net profit is determined by subtracting the annual equivalent of HPP cost (which is a function of the installed capacity of the HPP) from annual revenue obtained by energy generation.

Best installed capacities obtained when each HPP is treated separate versus those obtained when an integrated system is considered are compared with those provided in the feasibility reports of corresponding HPPs. Integrated river basin management's importance is of no doubt since the results obtained from system-wide analysis provided higher profits.

Objective: Maximization of the total average annual net profit (NB) for the system.

$$Max. NB = TAER - TICC \tag{5.14}$$

where $TAER$ is the total average annual revenue due to energy generation for the integrated system and estimated as the summation of the average annual energy generation revenues of each HPP (see Equation (5.10)). $TICC$ is the equivalent annual total cost of the installed capacities:

$$TICC = \sum_{i=1}^{i=K} ICC_i \tag{5.15}$$

where

$$ICC_i = NetH_i \times Qd_i \times \gamma \times Eff_i \times UP_i \times CRF \tag{5.16}$$

In this equation, ICC_i is the equivalent annual installed capacity cost for HPP i, $NetH_i$ is the designed net head value of the HPP i, Qd_i is the design discharge of the turbine (m^3/s), γ is the specific weight of the water (9.81 kN/m^3), Eff_i is the turbine efficiency value for design discharge for HPP i, UP_i is the unit cost of installed capacity (\$/kW), CRF is the capital recovery factor used for the conversion of the present cost of the installed capacity to the annually distributed cost.

5.3. Model Formulation

In this section, reservoir operations of three consecutive hydropower plants (Arkun, Yusufeli and Artvin Hydropower Plants) are described. First the integrated system where decisions for all three plants are made simultaneously is discussed in Section 5.3.1. Then in Section 5.3.2, the models in which optimum installed capacity of each HPP is identified separate are explained. The mathematical model for the separate system is already provided in Chapter 4, so it is not given here again.

The three objective functions mentioned above are taken into consideration:

(i) maximization of the total average annual energy generation (AE(kWh)),

(ii) maximization of the total average annual revenue from energy generation (AER(TL)),

(iii) maximization of the total average annual net profit (NB) for the system.

5.3.1. Model for the Integrated System

In the following, the mathematical formulation of the optimization problem for the integrated system (system-wide approach) is provided. Three consecutive HPPs are considered all together as the integrated system.

5.3.1.1. Mathematical Model

In this section, the common mathematical model for the three objective functions is presented. The sets, scalars, parameters, variables and model constraints are presented below.

Sets:

t (month)	:	Time step ($t \in T = \{1,2,3, \dots ,228\}$)
i (Plant)	:	Hydropower plant ($i \in K = \{1,2,3\}$)

Scalars:

$Smin_i$ (hm³)	:	Minimum level of reservoir storage for HPP i
$Smax_i$ (hm³)	:	Maximum level of reservoir storage for HPP i
S_{0i} (hm³)	:	Initial reservoir storage for HPP i
Rw_i (hm³)	:	Minimum water release as environmental flow for HPP i
$Qmin_i$ (m³/s)	:	Minimum turbine discharge for HPP i
Qd_i (m³/s)	:	The design discharge of HPP i (**this scalar is evaluated as a variable for the maximization of total average annual net profit objective**)
$NetH_i$ (m)	:	Design net head of the HPP i (used only for maximization of net profit objective)
Eff_i	:	Efficiency of the HPP i (used only for maximization of net

		profit objective)
UP_i ($/kW)	:	Unit cost for installed capacity for HPP i(used only for maximization of net profit objective)
CRF	:	Capital recovery factor (used only for maximization of net profit objective)
n	:	The number of years in the operation period

Parameters:

I_{ti} (hm³)	:	Water volume entering the reservoir naturally for power plant i, in month t

Variables:

IA_{ti} (hm³)	:	Actual water volume entering the reservoir for power plant i in month t
S_{ti} (hm³)	:	The reservoir water volume at the end of month t for HPP i
$Savg_{ti}$ (hm³)	:	The average reservoir storage for month t
O_{ti} (hm³)	:	The amount of water released in month t (summation of spilled water and water used for energy generation)
R_{ti} (hm³)	:	The water released as environmental flow in month t
Q_{ti} (m³/s)	:	Discharge passing through the turbines for energy generation in month t
Qd_{ti} (m³/s)	:	The design discharge of HPP i (**this scalar is evaluated as a scalar for the maximization of total average annual energy and revenue objectives**)

Model Constraints:

$$IA_{ti} = R_{ti-1} + O_{ti-1} + I_{ti} - I_{ti-1} \qquad t \in T \text{ and } i \in K \text{ for } i > 1 \tag{5.17}$$

$$IA_{ti} = I_{ti} \qquad t \in T \text{ and } i \in K \text{ for } i = 1 \tag{5.18}$$

$$S_{ti} = S_{t-1i} + IA_{ti} - R_{ti} - O_{ti}, \ t \in T \text{ and } i \in K \tag{5.19}$$

$$Smin_i \leq S_{ti} \leq Smax_i,\ t \in T \ and \ i \ \in K \tag{5.20}$$

$$R_{ti} \geq Rw_i,\ t \in T \ and \ i \ \in K \tag{5.21}$$

$$S_{0i} = S_{Ti}, (\equiv S_{0i} = S_{228i}) \tag{5.22}$$

$$Qmin_i \leq Q_{ti} \leq Qd_i, t \in T \ and \ i \ \in K \tag{5.23}$$

$$S_{ti} = S_{t+12i},\ 0 < t < 217 \ and \ i \ \in K \tag{5.24}$$

Equations (5.17) and (5.18) are for the estimation of actual water volume amount to the reservoir area of hydropower plant i, (5.19) is the continuity equation, (5.20) limits the end-of-month reservoir storages in accordance with the physical limitations of the reservoir, (5.21) sets a lower bound on the released water volume for environmental requirements, (5.22) forces the initial and final storage levels of the simulation period to be the same (initial reservoir levels are assumed to be at their maximum levels). Equation (5.23) is used if optimum dynamic discharges are used and discharges are limited by the design discharge and finally (5.24) is used for the derivation of rule curve (RCStrict).

5.3.2. Separate Management of HPPs

The objective functions are maximized for each plant separate considering they are operated as stand-alone HPPs. Summation of optimum outflow values of the upstream HPP and the intermediate flows are used as inflow values for the downstream HPP. Thus, three consecutive optimization problems for three HPPs are solved one after the other.

5.4. Discussion of Results

In this section, the performances of Arkun, Yusufeli and Artvin HPPs under three objective functions (maximization of energy, revenue and net profit) are compared and discussed. The objective functions are evaluated for both the separate system and the integrated system. Rule Curve Strict is used for the optimization studies. This approach successfully mimics the real situation since rule curves are used for the reservoir operations in practice as well. Non-linear programming models are constructed and CONOPT Solver of GAMS Software is used to solve the models, and optimum solutions are obtained in one minute.

The simulation period is taken as 19 years. For the maximization of profit objective, the unit cost of installed capacity ($/kW) is taken as an input to the model, to determine the optimum installed capacities (for all plants). In this study, based on an initial market research and the literature survey (Plansu, 2010; Çetinkaya, 2013), the unit cost value is varied from 200 to 400$/kW.

5.4.1. Comparison of Separate System with Integrated System under Maximization of Energy Generation and Maximization of Revenue Objectives

In Table 5.1, the solutions obtained for the separate and the integrated systems are given. The optimum solution is given for the related objective function and the corresponding solution of the other objective is also given in the next column in italic for comparison purposes.

5.4.1.1. Comparison under Maximization of Energy Generation

Under the maximization of energy objective, the total energy generation is estimated as 3641.28 GWh, while the summation of the energy generations obtained separate for the three HPPs is calculated as 3637.11 GWh. In other words, the integrated system gives only 0.11% better solution than that of separate system. In conclusion, the energy generations of the separate and integrated system are similar.

5.4.1.2. Comparison under Maximization of Revenue

Under the maximization of revenue objective, the integrated system gives 0.34% better solution for the total revenue (i.e., 655.24 and 653.00 million TL for integrated and separate systems, respectively).

Table 5.1 The Objective Function Values Obtained for Maximization of Energy and Revenue

Objective	Maximization of Energy				Maximization of Revenue			
System	Separate		Integrated		Separate		Integrated	
	Energy (GWh)	Revenue (10^6 TL)	Energy (GWh)	Revenue (10^6 TL)	Energy (GWh)	Revenue (10^6 TL)	Energy (GWh)	Revenue (10^6 TL)
Arkun	771.01	*134.00*	768.84	*135.01*	*763.99*	135.66	*758.11*	134.96
Yusufeli	1830.11	*320.11*	1832.22	*319.93*	*1811.00*	328.87	*1794.00*	329.07
Artvin	1035.99	*181.52*	1040.22	*182.02*	*1035.10*	188.47	*1040.10*	191.21
Total	**3637.11**	***635.63***	**3641.28**	***636.96***	***3610.09***	**653.00**	***3592.21***	**655.24**

5.4.1.3. The Comparison under Both Objectives

As seen in Table 5.1, under both objective functions, the objective function values obtained for the integrated system are greater than that of the separate system.

For a cascade system, inflow to the HPP increases in the flow direction since the basin areas increase along the river reach. Thus, the design discharges of the HPPs should be selected according to their location on the river. The most upstream HPP should have the smallest design discharge and the most downstream HPP should have the largest design discharge.

For the cascade system studied here, the design discharges are selected according to this rule. Thus results obtained for the integrated system do not differ significantly than those obtained for the separate system. Effect of separate and integrated optimization is expected to be significant when the design discharges are not chosen correctly (i.e. increasing in the flow direction).

When the objectives are compared with each other under both the separate and the integrated systems, the value of the objective functions differ considerably for the two objectives. Under the maximization of revenue objective, the total revenue can be increased by 2.73% and 2.87% in comparison with energy objective, for the separate and the integrated systems, respectively. On the other hand under the revenue objective, the total energy generations are decreased by 0.74% and 1.34% for the separate and integrated systems, respectively. When each HPP (Arkun, Yusufeli and Artvin HPPs) is evaluated separate, similar results are obtained. This shows that, selection of an appropriate objective function is important for both the separate and the integrated systems.

5.4.2. Maximization of Total Net Profit Objective

For the maximization of total net profit objective, the installed capacities of the HPPs are modeled as decision variables as well. Optimum installed capacities for three consecutive HPPs are determined both for the separate and the integrated system. Five different unit prices ranging between 200 and 400 $/kW are used to estimate installed capacity costs. Current installed capacities obtained from feasibility reports and net profits for each HPPs and the optimum results obtained for separate and integrated system optimizations are presented in Table 5.2 and Table 5.3, respectively. The current values are given for comparison purposes.

Table 5.2 The Current and Optimum Installed Capacities for Varying Unit Cost for Installed Capacity

		Unit Price for Installed Capacity ($/kW)				
		200.00	250.00	300.00	350.00	400.00
	Dams	Installed Capacity (MW)				
Arkun	Current Value (separate)	244.83	244.83	244.83	244.83	244.83
	Current Value (integrated)	244.83	244.83	244.83	244.83	244.83
	Optimization Results (separate)	254.99	244.14	234.53	225.52	218.69
	Optimization Results (integrated)	249.83	242.99	233.88	226.25	219.26
Yusufeli	Current Value (separate)	540.00	540.00	540.00	540.00	540.00
	Current Value (integrated)	540.00	540.00	540.00	540.00	540.00
	Optimization Results (separate)	512.38	492.38	466.86	445.42	431.28
	Optimization Results (integrated)	475.35	452.98	435.00	419.11	409.94
Artvin	Current Value (separate)	332.00	332.00	332.00	332.00	332.00
	Current Value (integrated)	332.00	332.00	332.00	332.00	332.00
	Optimization Results (separate)	255.24	246.08	238.06	230.13	224.49
	Optimization Results (integrated)	276.97	263.72	253.75	243.82	236.22
Total System	Current Value (separate)	1116.83	1116.83	1116.83	1116.83	1116.83
	Current Value (integrated)	1116.83	1116.83	1116.83	1116.83	1116.83
	Optimization Results (separate)	1022.61	982.60	939.45	901.07	874.46
	Optimization Results (integrated)	1002.16	959.70	922.62	889.18	865.42

Table 5.2 reveals that as the unit cost for installed capacity increases, optimum installed capacities decreased. This is observed under both separate and integrated systems. In separate system approach, response of Arkun dam to unit cost change is really high since energy generation potential of that dam is low and any increase in unit cost results in a lower installed capacity. On the other hand, in integrated system approach, increase in the unit cost does not lead to a sharp decrease in installed capacity. The reason is that, Arkun Dam is the first dam in the system (most upstream dam) and any decrease in installed capacity will affect all downstream dams.

It is also deduced from Table 5.2 that, selection of the unit costs used to estimate the installed capacity cost can cause changes in installed capacity values up to 16%.

Table 5.3 The Current and Optimum Profit Values for Varying Unit Cost for Installed Capacity

		Unit Price for Installed Capacity ($/kW)				
		200.00	250.00	300.00	350.00	400.00
Dams		Net Profit (10^6 TL)				
Arkun	Current Value (separate)	121.94	118.51	115.08	111.65	108.22
	Current Value (integrated)	121.24	117.81	114.38	110.95	107.52
	Optimization Results (separate)	122.13	118.64	115.28	112.05	108.94
	Optimization Results (integrated)	121.35	117.93	114.58	111.37	108.26
Yusufeli	Current Value (separate)	298.60	291.03	283.46	275.89	268.32
	Current Value (integrated)	298.80	291.23	283.66	276.09	268.52
	Optimization Results (separate)	298.02	291.07	284.44	278.12	271.99
	Optimization Results (integrated)	298.25	291.45	284.95	278.63	272.61
Artvin	Current Value (separate)	169.86	165.20	160.55	155.90	151.24
	Current Value (integrated)	172.60	167.94	163.29	158.64	153.98
	Optimization Results (separate)	173.50	170.60	167.63	165.05	162.52
	Optimization Results (integrated)	177.09	173.83	170.72	167.76	164.76
Total System	Current Value (separate)	590.39	574.74	559.09	543.44	527.79
	Current Value (integrated)	592.63	576.98	561.33	545.68	530.03
	Optimization Results (separate)	593.65	580.31	567.35	555.22	543.45
	Optimization Results (integrated)	596.69	583.21	570.25	557.76	545.63

It is seen in Table 5.3 that, as unit cost decreases profit increases. All the results demonstrate the importance of unit installed capacity costs and the necessity of carrying out a comprehensive preliminary market survey before selecting turbines and associated components for HPPs. This will allow more realistic net profit estimations at the feasibility stage.

It can be concluded that, for all unit cost alternatives, optimization studies carried out for integrated systems resulted in the highest total net profit values as seen in Figure

5.1. It can also be inferred that, net profit values calculated by considering all HPPs individually in optimization studies (marked as Optimum Value (separate) in Total System row of Table 5.3) are higher than those calculated by HPPs with installed capacities provided in the feasibility reports (marked as Current Value in Tables 5.2 and 5.3). The optimization study carried out for the integrated system demonstrates that higher net profits obtained with smaller installed capacities. For instance, total net profits are determined as 596.69 and 593.65 million TL (unit price for installed capacity: 200 $/kW) for the integrated system and separate system, respectively. On the other hand, the installed capacities are determined as 1002.16 and 1022.61 MW for the integrated system and separate system, respectively. In other words, with lower initial investments, higher net profits can be obtained if the cascade system of HPPs is optimized in an integrated manner. Thus, for multi-reservoir systems it is beneficial to determine installed capacities through optimization studies by adopting a system-wide approach, in the planning stage.

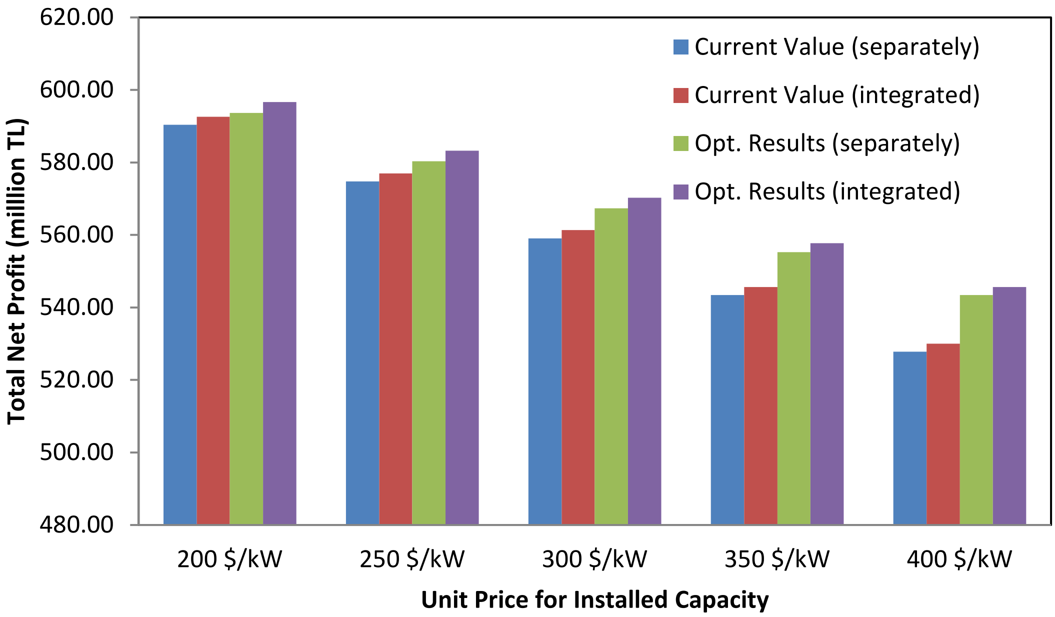


Figure 5.1 The Total Net profits for Each Unit Cost Alternative

The difference between selected current installed capacities and optimum installed capacities is due to the fact that generally a fixed unit price (for example: an average energy price of the previous year) is used for the estimation of revenue in the feasibility studies. However, this approach leads to overestimation of the energy revenue, because the energy prices are oscillating throughout the year. The energy prices are higher for the summer months when the energy generation is low for HPPs and inversely, the energy prices are lower when the energy generation is higher. This situation can be seen better in Figure 5.2. Using an average value for price rather than actual values results in misestimating of the energy revenue and this leads to the selection of higher installed capacity. This shows the importance of using hourly energy prices on the revenue estimation.

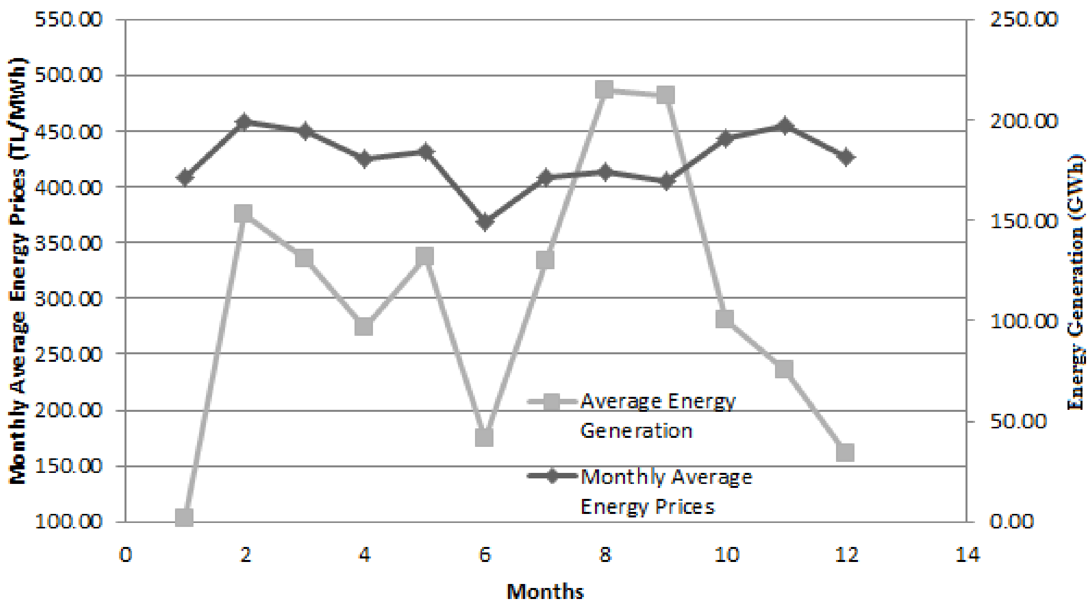


Figure 5.2 The Average Energy Generation versus Monthly Average Energy Generation (the Results Obtained for Yusufeli HPP)

CHAPTER 6

OPTIMIZATION STUDIES FOR MULTI-RESERVOIR MULTI-PURPOSE SYSTEMS WITH PUMPED-STORAGE: ARKUN, YUSUFELI, ARTVIN DAMS AND HPPS

6.1. Introduction

In Chapter 4, a single reservoir single purpose system is studied (Yusufeli HPP). The purpose of the reservoir is only “energy generation”. Alternative operating policies are proposed and performances of those policies with respect to the objective of maximization of energy generation and with respect to the objective of maximization of revenue, are contrasted. In Chapter 5, to reflect the real situation better, a multi-reservoir system is studied. The reservoir system is still assumed to be operated for the single purpose of energy generation. This system is exemplified by three HPPs, namely, Arkun, Yusufeli, and Artvin, respectively. The objectives under consideration are maximization of energy generation, maximization of revenue and maximization of net profit.

A multi-purpose reservoir may be operated to satisfy multiple purposes such as hydroelectric power generation, municipal or irrigation water supply, flood control, pumped-storage, avoiding soil erosion, environmental management, navigation and so on (Wurbs, 1993). Balancing such competing purposes is an important challenge in management of multi-purpose systems and managing agencies should be thoughtful during operation. The following are examples of potential trade-offs: for instance, reservoir level is tried to be kept as high as possible in HPPs because higher heads result in higher electricity generation. On the other hand, one should also be watchful about flood control and enough storage should be left to store flood runoff. Therefore the optimum reservoir operation strategy obtained considering a single purpose is likely to change when additional purposes are added to the system. This means that the reservoir operation studies should be carried out considering all existing purposes.

In this chapter, some additional hypothetical purposes are taken into account in reservoir operation studies and maximization of energy generation and maximization of net revenue are considered separately as the objective functions for the cascade system. A number of scenarios are developed for the current multi-reservoir system composed of Arkun, Yusufeli and Artvin HPPs to investigate effects of multiple purposes.

For the first scenario, it is assumed that Arkun Dam supplies municipal water demand of a nearby settlement. For the second scenario, an irrigation water demand is assumed to be met from Yusufeli HPPs' reservoir. For the third scenario, all three dams are assigned flood mitigation purpose. Finally, in the fourth scenario, the cascade system is treated as a pumped-storage system. As done in the previous chapters, rule curves are derived for each HPP as an operation policy.

Throughout this chapter, firstly details of the hypothetical scenarios are explained in Section 6.2, then mathematical formulations are given in Section 6.3, and the results obtained from this study are discussed at the end of this chapter (Section 6.4).

6.2. Scenarios

In this chapter; specifically, (i) water supply, (ii) irrigation, (iii) flood control, and (iv) pumped-storage are selected as additional purposes (in addition to the energy generation purpose). Four different scenarios are devised to evaluate effects of multiple purposes on HPP performances in satisfying the selected objectives. A summary of four scenarios is given in Figure 6.1. For the first three scenarios, municipal water supply, irrigation water supply and flood control purposes are added to the system one after the other in each scenario.

The pumped-storage purpose is added as the second purpose for the fourth scenario excluding municipal and irrigation water supplies and flood control purposes. In all scenarios, energy generation is kept as the basic purpose.

	Scenario 1			Scenario 2			Scenario 3			Scenario 4		
Purpose	Arkun	Yusufeli	Artvin	Arkun	Yusufeli	Artvin	Arkun	Yusufeli	Artvin	Arkun	Yusufeli	Artvin
Energy	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Municipal Water Supply	✓	□	□	✓	□	□	✓	□	□	□	□	□
Irrigation Water Supply	□	✓	□	□	✓	□	□	✓	□	□	□	□
Flood Mitigation	✓	✓	✓	✓	✓	✓	✓	✓	✓	□	□	□
Pumped-Storage	□	□	□	□	□	□	□	□	□	✓	✓	✓

Figure 6.1. Developed Scenarios for the Multi-Purpose Reservoir Operation

For the municipal water supply purpose (Scenario 1), it is assumed that Arkun Dam's reservoir will be used to supply municipal water demand of a settlement area with a population of one million people. Assuming the average daily water demand is 200 lt/day for capita, total monthly municipal water demand is calculated as 6.0 hm^3. All this demand is assumed to be strictly met by Arkun Dam's reservoir. In other words, total municipal water demand is extracted from Arkun Dam's reservoir through an intake structure. Since municipal water demand is a basic need for people it is given priority with respect to energy generation. In the mathematical formulation of the problem, monthly municipal water demand is subtracted from the Arkun Dam's reservoir volume which is reflected in the mass balance equation (continuity equation) of the Arkun Dam's reservoir. The objective of the multi-reservoir system for this scenario is maximization of total average annual energy generation.

In the second scenario, the irrigation water supply purpose is added to the system together with municipal water supply (see Figure 6.1) and irrigation demand is assumed as 100 hm^3 for July, August, and September. It is assumed that Yusufeli Dam supplies the irrigation demand (Scenario 2). Similar to municipal water demand, monthly irrigation water demand is deducted from Yusufeli Dam's reservoir. Unlike municipal water demand, irrigation water demand does not need to be strictly met, so it is included in the objective function with a penalty term (i.e. the deficit between the irrigation water demand and actual supply for irrigation is multiplied by a penalty coefficient determined by the decision maker). Necessary modifications are done in the mass balance equation of Yusufeli Dam's reservoir as well. The objective is again maximization of total average annual energy generation of the multi-reservoir system.

In the third scenario, the flood control purpose is also taken into account and all three reservoirs are considered to take part in flood mitigation (see Figure 6.1). Reservoir operations are carried out in monthly cycles in this thesis. Therefore, the flood discharge should be evaluated regarding monthly operation. Flood discharge with a maximum return period of 50 years is assumed not to cause any damage at the downstream of Artvin HPP. The corresponding discharge is estimated in the feasibility studies of Artvin Dam and HPP as 1518 m^3/s (DOLSAR, 2010). However, such high inflows did not exist in the historical inflow time series. To test the flood mitigation performance of the multi-reservoir system, a discharge that is 10% larger than the 50-year return period flood discharge (i.e. 1670 m^3/s) is assumed to flow into the Yusufeli Dam reservoir regularly throughout a whole month, (i.e. for 30 days). The corresponding monthly water volume is calculated as 4328 hm^3 and the maximum observed inflow in the historical inflow time series is replaced by this amount in the optimization model input data. The operation studies of the multi-reservoir system are carried out to protect downstream of Artvin HPP from discharges exceeding 50-year return period flood discharge.

Finally, in Scenario 4, the cascade system is assumed to work as a pumped-storage system for Yusufeli and Artvin HPPs. In other words, it is allowed to transfer water from each downstream reservoir to the one immediately at its upstream. The assumption is that, the turbines of Arkun and Yusufeli HPPs are capable of pumping as well and when the energy prices are low, the water is pumped from the lower reservoir to the upper reservoir. Then, water is released back and utilized energy generation during the peak-hours. Although, the amount of energy consumed during pumping of water is higher than the energy generated from the pumped water (losses in the transition structures and the turbine and pump efficiencies are some of the reasons) additional revenue may be obtained due to the time-based differences observed in energy prices. The mass balance equations for the related reservoirs are reorganized regarding the water volume used for pumped-storage system.

6.3. Models for the Scenarios

In this section, the models of the scenarios are introduced. Firstly a basic model is given and then for each scenario the differences from the basic model are presented.

6.3.1. Basic Model

In Section 5.2.1, the multi-reservoir system composed of Arkun, Yusufeli and Artvin HPPs is modelled and the total average annual energy generation (TAE) is maximized through reservoir operation studies. This model is considered as the basic model in this chapter. The objective function and its components of the basic model are already given through Equations (5.1) and (5.9).

The mathematical model of the basic model is again presented in this section. The sets, scalars, parameters, and variables are introduced below for the basic model. The models for the remaining scenarios are explained by contrasting them with the basic model.

Sets:

t (month)	:	Time step ($t \in T = \{1,2,3,\ldots,228\}$)
i	:	Hydropower plant ($i \in K = \{1,2,3\}$)

Scalars:

n	:	The number of years in the operation period

Parameters:

$Smin_i$ (hm³)	:	Minimum level of reservoir storage for HPP i

$Smax_i$ (hm³) : Maximum level of reservoir storage for HPP i

S_{0i} (hm³) : Initial reservoir storage for HPP i

Rw_i (hm³) : Minimum water release as environmental flow for HPP i

$Qmin_i$ (m³/s) : Minimum turbine discharge for HPP i

Qd_i (m³/s) : The design discharge of HPP i

I_{ti} (hm³) : Water volume entering the reservoir naturally for power plant i, in month t

Variables:

IA_{ti} (hm³) : Actual water volume entering the reservoir for power plant i in month t

S_{ti} (hm³) : The reservoir water volume at the end of month t for HPP i

$Savg_{ti}$ (hm³) : The average reservoir storage for month t

O_{ti} (hm³) : The amount of water released in month t (summation of spilled water and water used for energy generation)

R_{ti} (hm³) : The water released as environmental flow in month t

Q_{ti} (m³/s) : Discharge passing through the turbines for energy generation in month t

Model Constraints:

$$IA_{ti} = R_{ti-1} + O_{ti-1} + I_{ti} - I_{ti-1} \qquad t \in T \; and \; i \in K \; for \; i > 1 \tag{6.1}$$

$$IA_{ti} = I_{ti} \qquad t \in T \; and \; i \in K \; for \; i = 1 \tag{6.2}$$

$$S_{ti} = S_{t-1i} + IA_{ti} - R_{ti} - O_{ti}, \; t \in T \; and \; i \in K \tag{6.3}$$

$$Smin_i \leq S_{ti} \leq Smax_i, \; t \in T \; and \; i \in K \tag{6.4}$$

$$R_{ti} \geq Rw_i, \; t \in T \; and \; i \in K \tag{6.5}$$

$$S_{0i} = S_{Ti}, (\equiv S_{0i} = S_{228i}) \tag{6.6}$$

$$Qmin_i \leq Q_{ti} \leq Qd_i, t \in T \ and \ i \in K \tag{6.7}$$

$$S_{ti} = S_{t+12i}, \ 0 < t < 217 \ and \ i \in K \tag{6.8}$$

Equations (6.1) and (6.2) are for the estimation of actual water volume amount to the reservoir area of hydropower plant i, (6.3) is the continuity equation, (6.4) limits the end-of-month reservoir storages in accordance with the physical limitations of the reservoir, (6.5) sets a lower bound on the released water volume for environmental requirements, (6.6) forces the initial and final storage levels of the simulation period to be the same (initial reservoir levels are assumed to be at their maximum levels). Equation (6.7) is used if optimum dynamic discharges are used and discharges are limited by the design discharge and finally (6.8) is used for the derivation of rule curve (RCStrict).

6.3.2. Model for Scenario 1

According to Scenario 1, municipal water supply objective is added to the multi-reservoir system (see Figure 6.1). The objective functions are the same with the basic model. The differences from the basic model are presented below.

The additional scalars and variables for Scenario 1 are as follow:

Parameters:

Pop_i	:	The population of the city where the need for Municipal water arises
$Usage_i$ (lt/capita)	:	Municipal water demand per capita

Variables:

Dr_{ti} (hm³)	:	The water volume released from HPP i, for municipal water supply purpose in month t

Municipal water demand is added to the continuity equation and Equation (6.3) of the basic model is replaced by the following.

$$S_{ti} = S_{t-1i} + IA_{ti} - R_{ti} - O_{ti} - Dr_{ti}, \; t \in T \; and \; i \in K \quad (6.9)$$

where Dr_{ti} (hm³) is estimated as follow:

$$Dr_{ti} = 30 \times Pop_i \times Usage_i / 10^9 \quad (6.10)$$

Note that the municipal water demand is only valid for Arkun Dam.

6.3.3. Model for Scenario 2

In this scenario, the purpose of irrigation water supply is added to the multi-reservoir system together in addition to municipal water supply (see Figure 6.1). It is assumed that it is not strictly required to meet 100% of the irrigation demand for every month throughout the planning horizon (i.e., simulation period). Some percentage of the irrigation water demand must strictly be met. For the remaining part, not meeting the demand is discouraged with a penalty term in the objective function. Note that the penalty value is a scalar selected by the decision maker. If the penalty of violation is high, then the model tries to meet the demand as much as possible. The energy equation of the basic model, Equation (5.3), is replaced by the following equation:

$$E_{ti} = Hnet_{ti} \times Q_{ti} \times \mu_{ti} \times \gamma \times Tm_{ti} - Penalty \times Hnet_{ti} \times Def_{ti} \times \frac{10^6}{3600} \times \mu_{ti} \times g$$
$$t \in T \; and \; i \in K \quad (6.11)$$

where, $Penalty$ is a scalar value selected by the decision maker considering the amount of allowance for not meeting the irrigation water demand. For instance, if the $Penalty$ value is chosen as two, two times of the energy generated by using the allocated water for irrigation will be deducted from the total energy generation so that usage of the irrigation water for energy generation is likely to be curbed.Def_{ti} (hm³) is the amount between the real demand for irrigation (Irr_{ti}, hm³) and the actual water allocated for irrigation ($IrrR_{ti}$, hm³):

$$Def_{ti} = Irr_{ti} - IrrR_{ti} \quad (6.12)$$

The penalty function in the energy generation for irrigation purpose decrease the real amount of energy generation, therefore the real energy generation should be estimated excluding the penalty function. However, the objective should be estimated with the energy equation including the penalty function.

The additional scalars, parameters and variables added to the basic model for Scenario 2 are as follow:

Scalars:

$Perc$	:	The coefficient used to determine the minimum amount of irrigation water demand that must be met
$Penalty$	:	The coefficient used to determine the amount of allowance for not meeting the irrigation water demand

Parameters:

Pop_i	:	The population of the city where need for Municipal water
$Usage_i$ (lt/capita)	:	Municipal water usage per capita
Irr_{ti} (hm³)	:	The irrigation water requirement that is met from HPP *i*, in month *t*

Variables:

Dr_{ti} (hm³)	:	The water volume released from HPP i, for Municipal water requirements in month *t*
$IrrR_{ti}$ (hm³)	:	The actual water volume released from HPP i, for Municipal water requirements in month *t*

The released water for irrigation water is added to the current continuity equation and Equation (6.3) of the basic model is replaced by the following equation.

$$S_{ti} = S_{t-1i} + IA_{ti} - R_{ti} - O_{ti} - Dr_{ti} - IrrR_{ti}, \ t \in T \ and \ i \in K \tag{6.13}$$

The actual water allocated for the irrigation ($IrrR_{ti}$, hm³), can be limited as follow:

$$Perc \times Irr_{ti} \leq IrrR_{ti} \leq Irr_{ti} \tag{6.14}$$

The irrigation water demand is only taken into account for Yusufeli Dam's reservoir.

6.3.4. Model for Scenario 3

According to Scenario 3, the purpose of flood control is added to the multi-reservoir system together with municipal and irrigation water supply purposes (see Figure 6.1). The objective function is reorganized as done for Scenario 2. The additional scalars, parameters and variables for Scenario 3 are as follow:

Scalars:

$Perc$	:	The coefficient used to determine the minimum amount of irrigation water demand that must be met
$Penalty$	:	The coefficient used to determine the amount of allowance for not meeting the irrigation water demand

Parameters:

Pop_i	:	The population of the city where need for Municipal water
$Usage_i$ (lt/capita)	:	Municipal water usage per capita
$Flood_i$	:	The maximum flood discharge limitation
Irr_{ti} (hm³)	:	The irrigation water requirement that is met from HPP i, in month *t*

Variables:

Dr_{ti} (hm³)	:	The water volume released from HPP *i*, for Municipal water requirements in month *t*
$IrrR_{ti}$ (hm³)	:	The actual water volume released from HPP *i*, for Municipal water requirements in month *t*

The continuity equation for Scenario 2 is valid for this Scenario as well and Equation (6.3) of the basic model is replaced by the following equation.

$$S_{ti} = S_{t-1i} + IA_{ti} - R_{ti} - O_{ti} - Dr_{ti} - IrrR_{ti}, \ t \in T \ and \ i \in K \qquad (6.15)$$

The estimation of Dr_{ti} (hm³) and the limitations for $IrrR_{ti}$ (hm³) are given in Equation (6.12) and (6.14), respectively. The additional constraint for flood control is added to the basic model as follow:

$$(O_{ti} + R_{ti})\times 10^6/(30\times 24\times 3600) \leq Flood_i \quad (6.16)$$

Equation (6.16) is only valid for Artvin HPP. However all HPPs are responsible from flood mitigation purpose because the Arkun and Yusufeli is located in the upstream of Artvin HPP.

6.3.5. Model for Scenario 4

In Scenario 4, the cascade system composed of Arkun, Yusufeli and Artvin Dams are treated as a pumped-storage system. In this scenario, municipal and irrigation water supply and flood mitigation purposes are not considered (see Figure 6.1). The objective of basic model is maximization of total average annual energy generation, but maximization of the average annual net revenue is considered for the pumped-storage system (i.e. Scenario 4). The cost for the energy consumption during pumping is subtracted from the revenue obtained from monthly energy generation. Then the estimated average annual net revenue is tried to be maximized for the whole system.

In the following, the objective function, maximization of the average annual net revenue, is explained.

Objective: Maximization of the average annual net revenue (NR)

$$NR = \sum_{i=1}^{i=K} AER_i - AERPump_i \quad (6.17)$$

where K denotes the total number of plants (in our study, $K = 3$), AER_i is the average annual revenue of hydropower plant *i*, and estimated as follows:

$$AER_i = \frac{\sum_{t=1}^{12xn} ER_i}{n} \quad (6.18)$$

n is the total number of years in the simulation period and $t \in T = \{1,2,3, \dots, 12\times n\}$, ER_{ti} is the revenue in month t (TL) for plant i, and estimated as:

$$ER_{ti} = E_{ti} \times P_{ti}, t \in T \text{ and } i \in K \qquad (6.19)$$

P_{ti} is the representative price of electricity for month t (TL/kWh) which is a function of the duration of energy generation within a day, $Tm_{ti}/30$: The estimation of representative price for each month is explained in Chapter 4.

$$P_{ti} = f_1(Tm_{ti}/30), t \in T \qquad (6.20)$$

where Tm_{ti} is the duration of energy generation in month t (hr). Note Tm_{ti} depends on energy generation E_{ti}, and $Tm_{ti}/30$ is the duration of energy generation in a day and f_1 defines the equation obtained from the relationship between the energy unit price and the duration (see Chapter 4).

In Equation (6.18), $AERPump_i$ is the total cost of energy consumption during pumping to the upstream reservoir for power plant i, and estimated as follow:

$$AERPump_i = \frac{\sum_{t=1}^{12xn} ERPump_{ti}}{n} \qquad (6.21)$$

n is the total number of years in the simulation period and $t \in T = \{1,2,3, \dots, 12\times n\}$, $ERPump_i$ (TL) is the monthly cost of energy consumption (for month t) during pumping to the upstream reservoir for power plant i, and estimated as follow:

$$ERPump_i = PPump_{ti}(TdP_{ti})\times Epump_{ti} \qquad (6.22)$$

$PPump_{ti}$ is the representative unit cost of energy for month t (TL/kWh) which is a function of the duration of energy consumption within a day, $TmP_{ti}/30$:

$$PPump_{ti} = f_2(TmP_{ti}/30), t \in T \qquad (6.23)$$

where TmP_{ti} is the duration of energy consumption in month t (hr). Note TmP_{ti} depends on energy consumption $EPump_{ti}$, and $TmP_{ti}/30$ is the duration of energy consumption in a day. The estimation of the representative unit cost for energy consumption is based on the assumption that, pumping is carried out when the energy prices are minimum as the exact opposite of the estimation of representative price for energy generation revenue. The procedure for the estimation of the representative price for pumping can be summarized as follows:

i) The average of hourly electricity prices formed in the market in month t are calculated;

ii) Average hourly electricity prices in month, t are sorted from the lowest to the highest;

iii) An average of lowest electricity prices corresponding to all possible durations of energy generation within a day is calculated.

iv) The data obtained in one step before is graphed and an equation is derived for the best fitted curve for this data (see Figure 6.2).

v) The average daily duration for energy consumption is estimated and the related representative unit cost for pumping is estimated from the equation derived (In Equation (6.23) f_2 represents this equation) for the corresponding month.

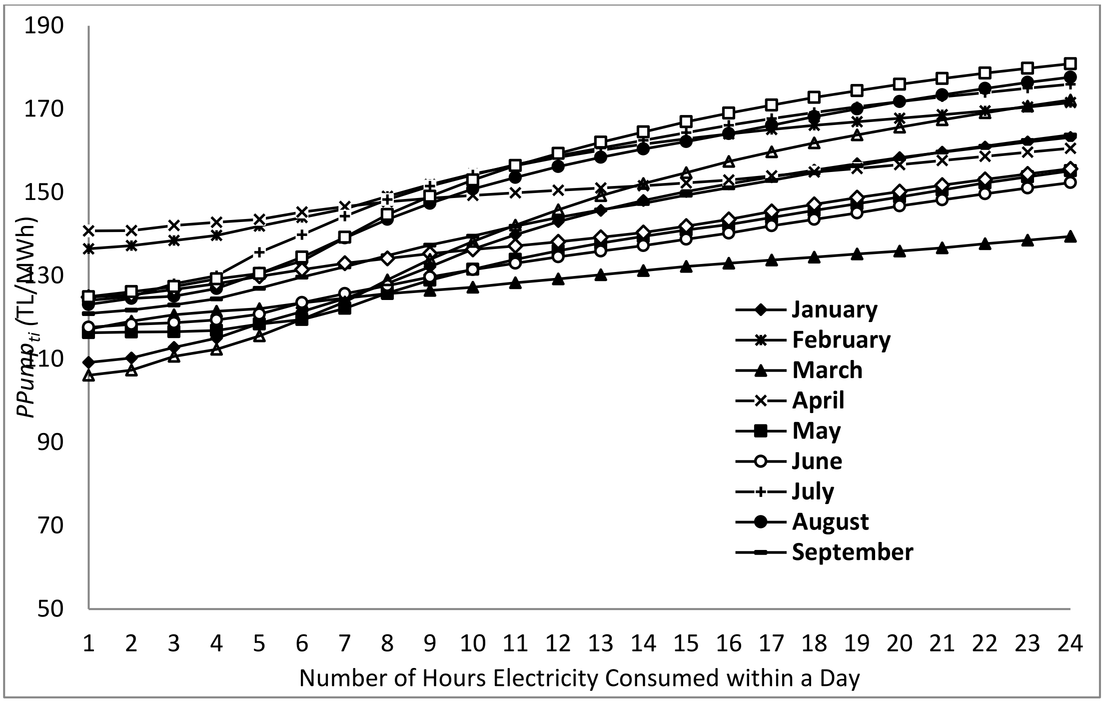


Figure 6.2. Representative Unit Cost with respect to the Duration of Electricity Consumption in a Day (PMUM, 2015)

For example, the minimum electricity price is valid for the energy consumption for pumping, when the duration of pumping is equal to one hour; and for two hour pumping, the unit cost of energy consumption is estimated as the average of the lowest and second lowest electricity price. In other words, the estimation of representative unit cost for pumping is the just opposite of the estimation of representative unit price for revenue. In this study, representative unit cost for energy consumption is estimated using electricity prices belong to the year 2014, for the accordance with the estimation of revenue.

$EPump_{ti}$ is the energy consumption during month *t*, for power plant *i*, and estimated as follow:

$$EPump_{ti} = \frac{(H_{ti}+hlP_{ti})\times QP_{ti}\times TmP_{ti}\times g}{\mu P_{ti}} \tag{6.24}$$

where H_{ti} is the gross head (m) and estimated as in Equation (5.5), QP_{ti} is the discharge passing through the turbine (m^3/s) during pumping, TmP_{ti}, is the duration of energy consumption for pumping (hr), μ_{ti} is the efficiency for pump (it is assumed that turbine efficiency curve is same for pumped-storage system (GE Energy, 2016) in month t for the hydropower plant i, and γ is the specific weight of the water (9.81 kN/m^3).The head loss through the tunnel and the penstock during pumping in month t, hlP_{ti} (m) is estimated using:

$$hlP_{ti} = Kl_i \frac{\left(\frac{QP_{ti}}{\pi Dl_i{}^2/4}\right)^2}{2g} + Kp_i \frac{\left(\frac{QP_{ti}}{\pi Dp_i{}^2/4}\right)^2}{2g}, \quad t \in T \; and \; i \in K \tag{6.25}$$

where Kl_i and Kp_i are the summations of coefficients for head losses that occur through the tunnel and the penstock, respectively, Dl_i and Dp_i are the diameters of the tunnel and the penstock (m), respectively, and g is the gravitational acceleration (m/s^2). The efficiency of the pump in month t, μ_{ti}, is expressed as:

$$\mu P_{ti} = f_3\left(\frac{Q_{Pti}}{Qd_i}\right), \quad t \in T \; and \; i \in K \tag{6.26}$$

where Qd_i is the design discharge of the turbine (m^3/s). In Equation (6.26) f_3 defines an efficiency curve, which provides the relation between QP_{ti}/Qd_i and the efficiency of the pump.

The duration of energy consumption for pumping in month t, TmP_{ti} is calculated using:

$$TmP_{ti} = \frac{\min(OPump_{ti}, Omax_i) \times 10^6}{3600 \times Q_{ti}}, t \in T \; and \; i \in K \tag{6.27}$$

where $Omax_i$ is the maximum amount of water that can be pumped within a month (i.e. if pump works with the design discharge for 720 hours) (hm^3), $OPump_{ti}$ is the total amount of water pumped from the downstream reservoir to the reservoir of HPP i, during the month t.

The additional variables used in Scenario 4 are as follow:

Variables:

$OPump_{ti}$ (hm³)	:	The water volume pumped by HPP i, from the downstream reservoir to the reservoir of HPP i, in month t
QP_{ti} (m³/s)	:	The discharge passing through the turbine (m³/s) during pumping
TmP_{ti} (hour)	:	The duration of energy consumption for pumping in month t

The water volume used for pumped-storage is considered in the continuity equation and Equation (6.3) of the basic model is replaced by the following equation.

$$S_{ti} = S_{t-1i} + IA_{ti} - R_{ti} - O_{ti} - OPump_{t(i-1)} + OPump_{ti}, t \in T \text{ and } i \in K \quad (6.28)$$

The additional constraints are added to the basic model:

$$Qmin_i \leq QP_{ti} \leq Qd_i \quad (6.29)$$

$$TmP_{ti} + Tm_{ti} \leq 720 \quad (6.30)$$

In Equation (6.29), the discharge used for pumping by HPP i in month t, is restricted by the minimum discharge and design discharge. In Equation (6.30), the summation of the duration for energy generation and the duration for energy consumption for pumping is limited to 720 hours (the duration of a month).

6.4. Discussion of Results

In this study, effects of multiple purposes are investigated and the results are compared with those of the multi-reservoir system which has only energy generation purpose. As done in Chapter 4 and 5, CONOPT Solver of GAMS Software is used to solve the models, and optimum solutions are found in 30 seconds. Rule Curve Strict policy is adopted and optimal dynamic discharge is assumed in all the models.

The results are evaluated in two parts. First, solutions obtained for Scenarios 1, 2, and 3 are compared with the single-purpose multi-reservoir system. Then, the solutions obtained from Scenario 4 (the pumped-storage system), are compared with the multi-reservoir system without pumping.

6.3.1. Comparison of Scenarios 1, 2 and 3 with Single Purpose Case

The current multi-reservoir system having only energy generation purpose is already analyzed under maximization of energy objective in Chapter 5. In addition to this objective, municipal and irrigation water supply and flood control purposes are taken into consideration in Scenarios 1, 2, and 3. In Scenario 2, the actual water allocated for irrigation is assumed to be decreased at most to half of the actual demand ($Perc$: 0.50). On the other hand, $Penalty$ value is chosen as two. Finally, flood control purpose is added to the multi-reservoir system and all dams are assumed to be responsible for the flood mitigation. In Table 6.1, optimum energy generations for single purpose case and different scenarios are given.

Table 6.1 Optimum Energy Generations for Single Purpose (i.e. Energy Generation) and Scenarios 1, 2, and 3 (GWh)

HPP	Single Purpose: Energy Generation	Scenario 1	Scenario 2	Scenario 3
Arkun	768.84	735.32	735.32	735.32
Yusufeli	1832.22	1796.90	1642.10	1642.10
Artvin	1040.22	1020.60	938.62	938.62
Total	3641.28	3552.82	3316.04	3316.04

As seen in Table 6.1, addition of municipal water supply purpose to Arkun Dam decreases energy generation with 2.43%. On the other hand, when both municipal and irrigation water supply purposes are added to the multi-reservoir system simultaneously, the energy generation decreases at an amount of 8.93%. The municipal water demand is taken as 72 hm^3 (6.0 hm^3 per month throughout the whole year), whereas irrigation water demand is taken as 300 hm³ (100 hm³ per month for July, August and September). These values explain the reason of the significant effect of irrigation water demand in energy generation. Energy generation does not change when the flood control purpose is added to the multi-reservoir system. This shows that the flood control is already achieved as long as the proposed rule curves for Scenario 2 are considered. Rule curves belonging to Scenarios 1, 2 3 and the single purpose multi-reservoir system are given in Figures 6.3, 6.4, and 6.5 for Arkun, Yusufeli and Artvin HPPs, respectively.

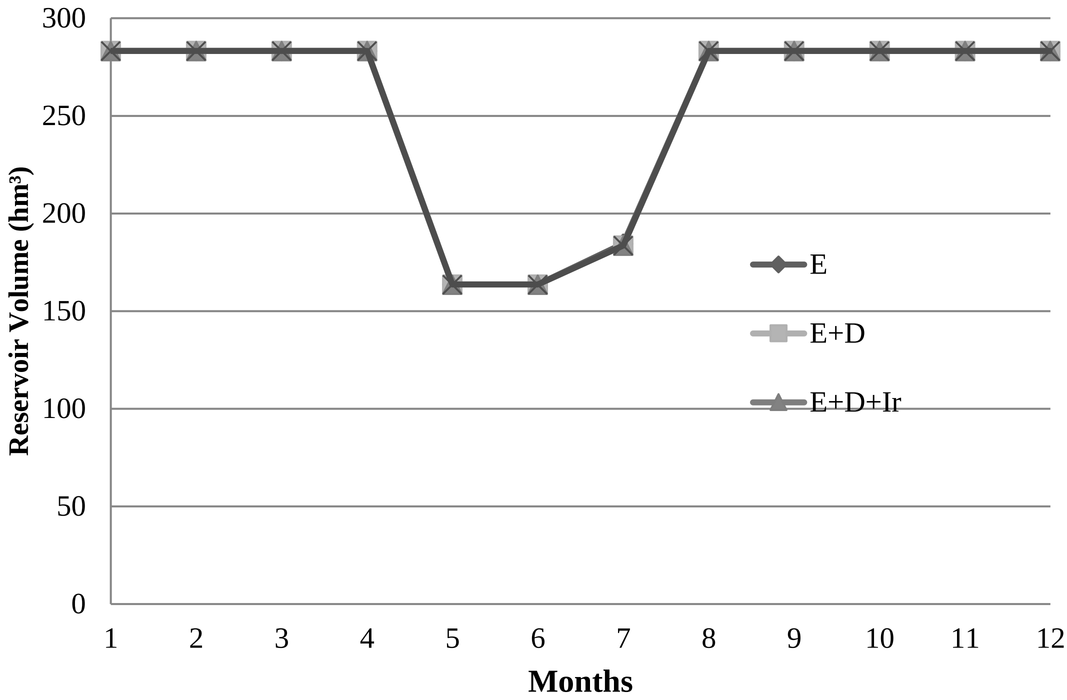


Figure 6.3 Rule Curve Solutions for Arkun HPP (E: Energy Purpose; D: Municipal Water Purpose; Ir: Irrigation Water Purpose; F: Flood Control Purpose)

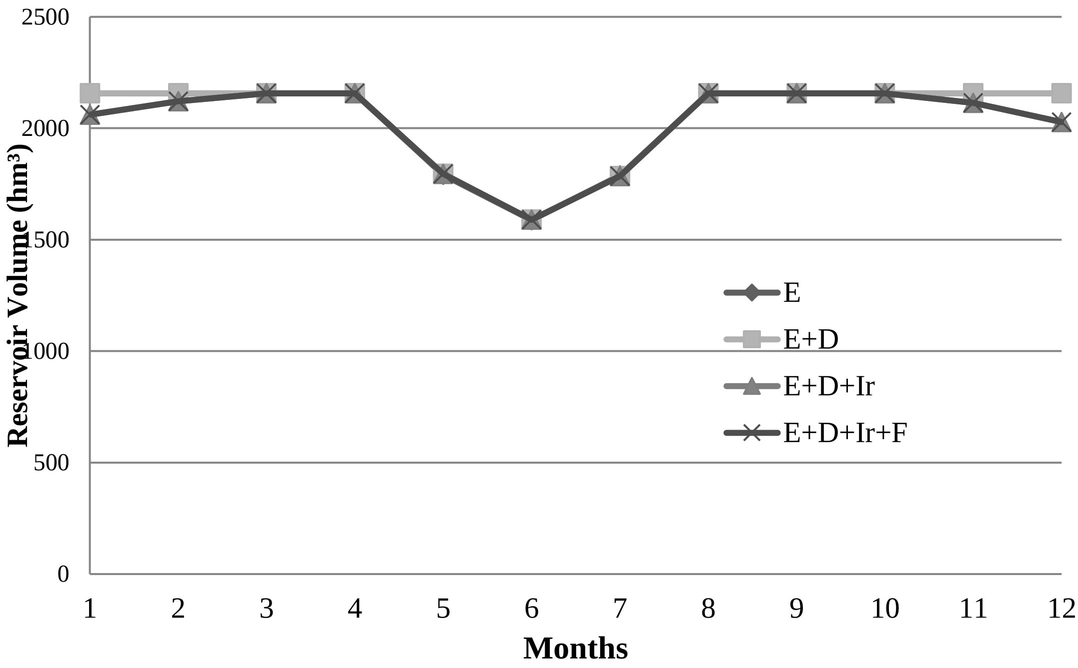


Figure 6.4 Rule Curve Solutions for Yusufeli HPP (E: Energy Purpose; D: Municipal Water Purpose; Ir: Irrigation Water Purpose; F: Flood Control Purpose)

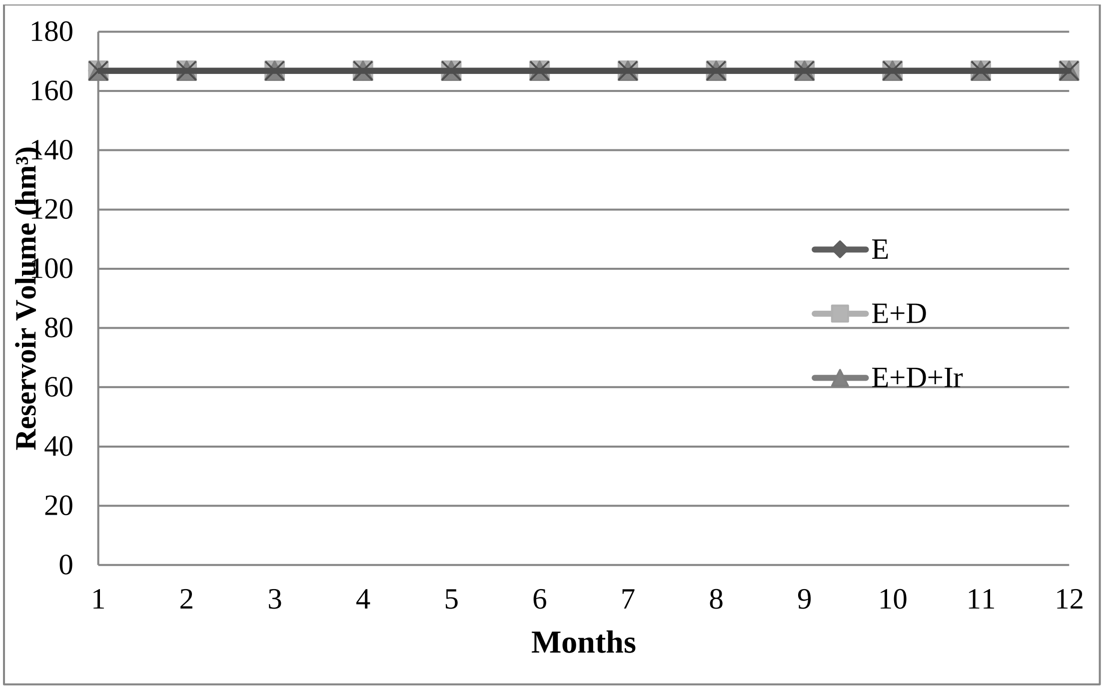


Figure 6.5 Rule Curve Solutions for Artvin HPP (E: Energy Purpose; D: Municipal Water Purpose; Ir: Irrigation Water Purpose; F: Flood Control Purpose)

When the rule curves are compared, it is seen that for Scenario 1, all rule curves remain the same compared to the basic model. The reason is municipal water

demand being very small compared to the total inflow coming to the reservoirs of HPPs (see Chapter 3). Municipal water demand can easily be met from Arkun reservoir without affecting the rule curves generated for maximization of energy generation. For Scenario 2, the release for irrigation water does not seem to affect the rule curves of Arkun and Artvin HPPs. On the other hand, for Yusufeli HPP, there are small changes for August, September and October (see Figure 6.4). In order to meet the irrigation demand in July, August and September (see Figure 6.4), water inflow to the reservoir of Yusufeli Dam is not enough most of the time and the remaining water is met from the reservoir itself. Therefore reservoir level is decreased in August and September to meet the irrigation demand, and then it is raised to its maximum level after a few months to obtain maximum energy potential.
In the previous studies, it is observed for Yusufeli HPP that, the reservoir level is decreased before the wet periods to keep extra water for the future energy generation. This situation can also be seen in this study. Therefore, for Scenario 3, the flood control can easily be provided due to this descent in reservoir level of Yusufeli HPP and it is not required to change reservoir operation policy for Scenario 3.

6.3.2. Comparison of with and without Pumped-Storage Systems

Pump storage version of the cascade system is considered in Scenario 4. In this scenario, it is assumed that the three reservoirs are connected through pumps which allow transfer of water from downstream to upstream reservoir. The average annual net revenue belonging to the multi-reservoir system is to be maximized for the pumped-storage system. The results obtained from Scenario 4 are given in Table 6.2. Energy generation values of Scenario 4 (GWh), the energy consumption during pumping (GWh), energy revenue and energy cost for pumping and the estimated net revenues for both objective functions (i.e. maximization of average annual energy generation and maximization of average annual revenue) are presented in Table 6.2 for comparison purposes.

Table 6.2 Results for Scenario 4

	Without Pumped-Storage				With Pumped-Storage System					
Objective	Maximization of Energy		Maximization of Revenue		Maximization of Revenue					
	Energy (GWh)	Revenue (10^6 TL)	Energy (GWh)	Revenue (10^6 TL)	Energy (GWh)	Energy Consumption for Pumped-Storage (GWh)	Net Energy (GWh)	Revenue (10^6 TL)	Energy Consumption cost (10^6 TL)	Net Revenue (10^6 TL)
Arkun	768.84	135.01	758.11	134.96	934.72	227.61	707.11	167.76	28.49	139.27
Yusufeli	1832.22	319.93	1794.00	329.07	2451.60	793.39	1658.21	446.20	101.47	344.73
Artvin	1040.22	182.02	1040.10	191.21	1038.30	0.00	1038.30	189.91	0.00	189.91
Total	***3641.28***	***636.96***	***3592.21***	***655.24***	***4424.62***	***1021.00***	***3403.62***	***803.87***	***129.96***	***673.91***

As seen in Table 6.2, total net energy generation under the objective of maximization of energy generation (3641.30 GWh for without pumped-storage) decreases at an amount of 6.53% when pumped-storage is used at the multi-reservoir system (i.e. the net energy generation with pumped-storage system becomes 3403.62 GWh). This is expected, since pumped-storage systems do not generate extra energy, rather they consume energy. On the other hand, the net revenue of the pumped-storage system (673.91 million TL) increases at an amount of 2.85% compared to the value obtained from maximization of revenue objective without pumped-storage system (655.24 million TL). As can be seen, net revenue increases although net energy generation decreases. The reason is that, the HPPs pump water when the energy prices are very low, generally during the night, and they generate energy in peak hours during which the energy prices are highest, generally during day time. Therefore extra revenue can be gained by the price difference between night and day. The extra investment cost due to pumped-storage system is not considered in this study, to evaluate feasibility of the pumped-storage system a benefit-cost analysis need to be carried out. For this specific system, the gain in net revenue is about 19 million TL; the final decision should be based on results of the benefit-cost analysis.

The rule curves are given in Figure 6.5, 6.6 and 6.7 for Arkun, Yusufeli and Artvin HPPs, respectively. The rule curves are considerably different under pumped-storage compared to those under the absence of pumped-storage system. This is the case when objectives of maximization energy generation and maximization of revenue are taken into consideration for the non-pumped-storage system. For Arkun and Yusufeli

HPPs, the rule curve under pump-storage lies between the rule curves of the non-pumped-storage system when maximization of energy generation and revenue are the objective functions, respectively (see Figure 6.6 and Figure 6.7). For Artvin HPP, the obtained rule curves are same under both pumped-storage and non-pumped-storage system, and for both energy and revenue objectives. The active storage volume belonging to the reservoir of Artvin HPP is relatively small and the head is much more important in terms of energy generation. Therefore, it is logical that the reservoir level is kept at its maximum level for all scenarios (see Figure 6.8).

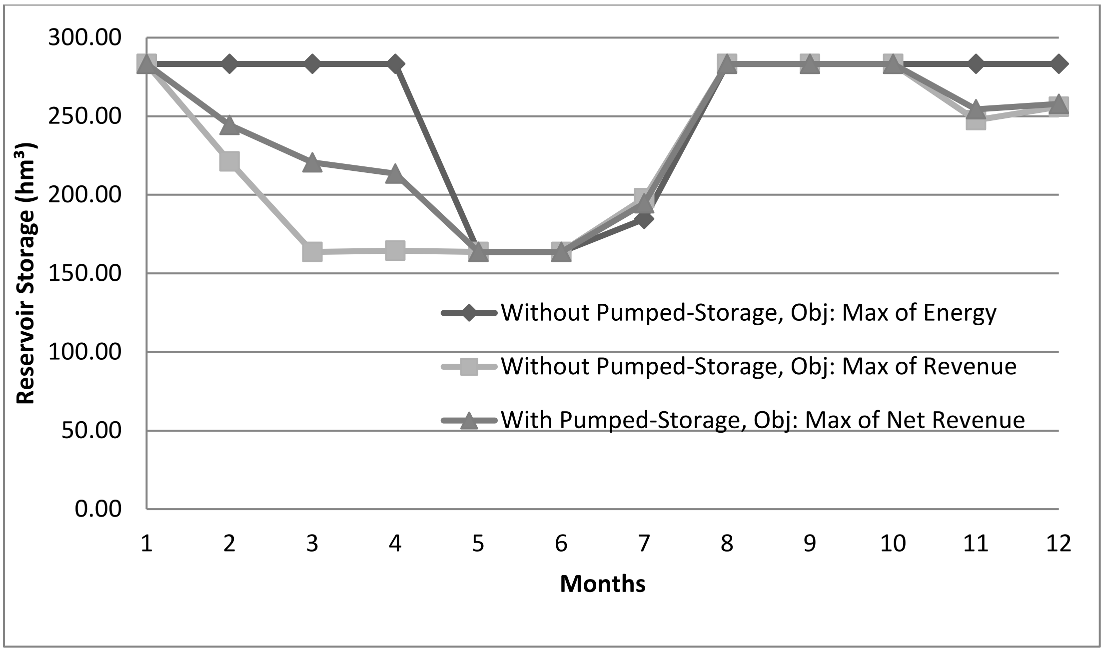


Figure 6.6 Rule Curve Solutions for Arkun HPP under Three Models

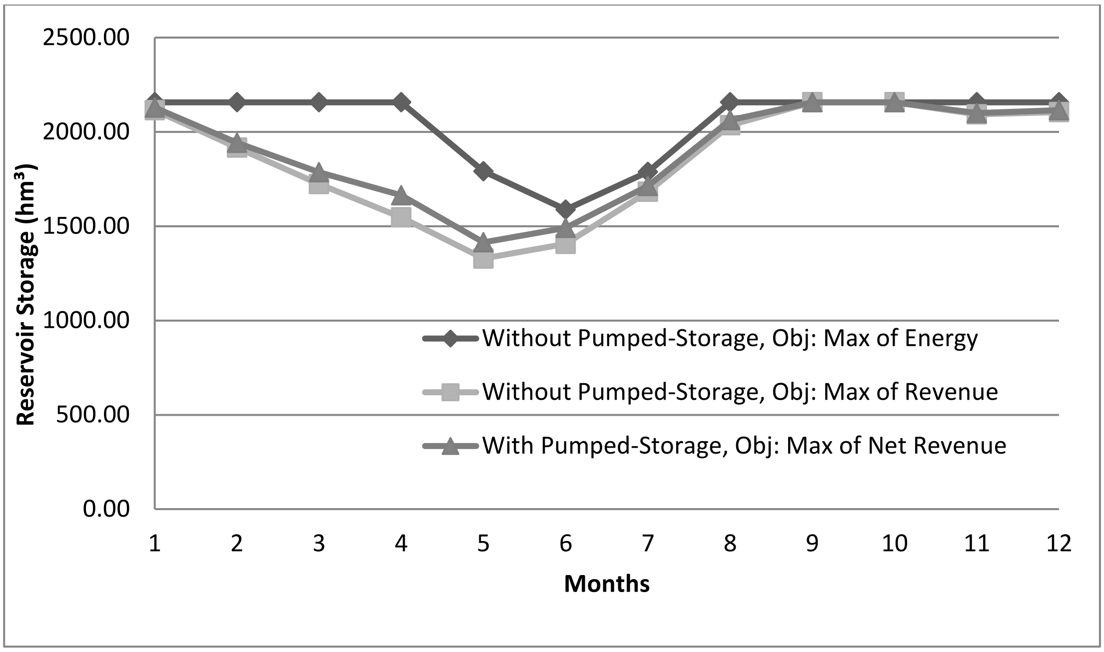


Figure 6.7 Rule Curve Solutions for Yusufeli HPP under Three Models

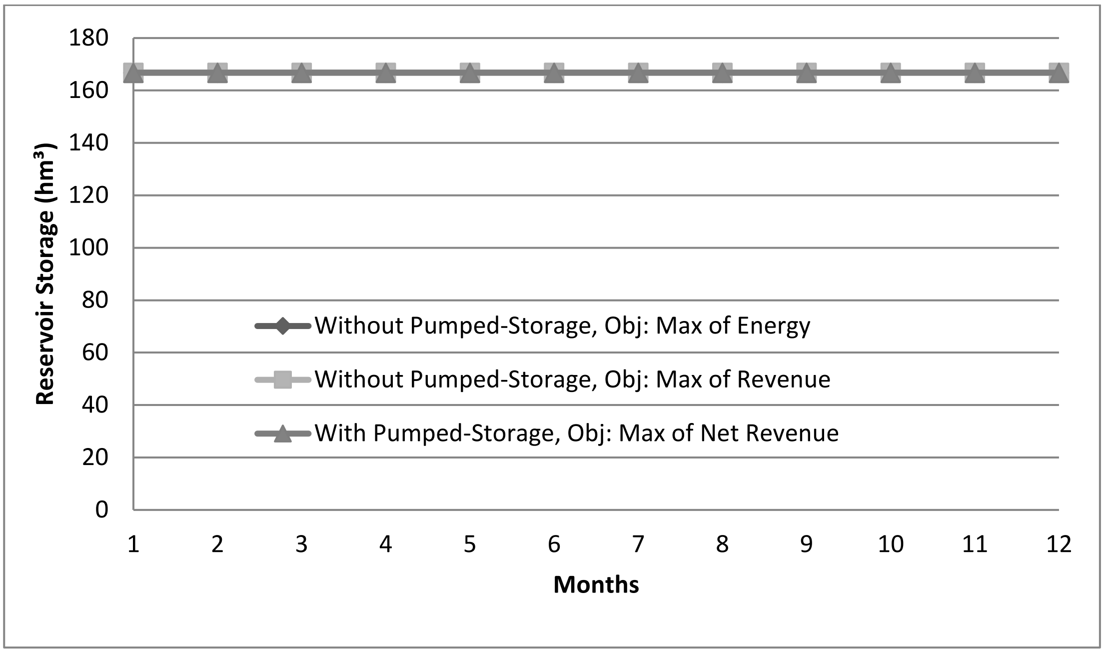


Figure 6.8 Rule Curve Solutions for Artvin HPP under Three Models

6.3.2.1. Evaluation of Pumped-Storage System under Fixed Price Assumption

In this study, for Scenario 4, the energy revenue and cost are estimated using hourly energy prices. However, integration of hourly prices into the model is not an easy task and it is not commonly used by the private sector in evaluating hydropower system benefits. Alternatively, a fixed electricity price is assumed in estimating energy revenue and cost. In this section, model results, when hourly prices and selected fixed prices are used, are compared.

Fixed prices for energy cost and revenue for each month are determined as follows: energy generated can be sold at a fixed price, which is the average of the 6 hours when the prices are highest in that month, and conversely, the energy required for pumping can be bought at a fixed price, which is the average of the 6 hours when the prices are lowest in that month. Therefore, for each month, two fixed prices (total 2x12=24 prices) are estimated. The results obtained under fixed price assumption are given in Table 6.3.

In Table 6.3, it is seen that when the buying and selling prices of electricity are assumed to be fixed, the net revenue increases by an amount of 6.67% compared to that of the without pumped-storage system (728.39 million TL proportioned to 682.83 million TL). Note that under variable price assumption (i.e. hourly electricity prices are used), the net revenue increase due to pumped-storage were only 2.85%. In addition, the obtained net revenue for fixed prices is 8.08% higher than that of hourly prices (728.39 million TL for fixed price assumption and 673.91 million TL for hourly prices). These results show that, considering fixed prices may lead over-estimation of the revenue and system planners may take wrong decisions about pumped-storage systems. Pumped-storage system may be evaluated as being more profitable than it actually is. Therefore, realistic evaluation of the system requires estimation of energy revenue and consumption using hourly energy prices.

Table 6.3 Results for Scenario 4 under Fixed Prices

Without Pumped-Storage					With Pumped-Storage System					
Objective	Maximization of Energy		Maximization of Revenue		Maximization of Revenue					
	Energy (GWh)	Revenue (10^6 TL)	Energy (GWh)	Revenue (10^6 TL)	Energy (GWh)	Energy Consumption for Pump-Storage (GWh)	Net Energy (GWh)	Revenue (10^6 TL)	Energy Consumption cost (10^6 TL)	Net Revenue (10^6 TL)
Arkun	768.84	135.01	757.85	141.32	1161.70	524.21	637.49	218.81	66.95	151.86
Yusufeli	1832.22	319.93	1798.80	343.09	3134.70	1607.90	1526.80	589.00	206.90	382.10
Artvin	1040.22	182.02	1041.60	198.42	1039.90	0.00	1039.90	194.43	0.00	194.43
Total	***3641.28***	***636.96***	***3598.25***	***682.83***	***5336.30***	***2132.11***	***3204.19***	***1002.24***	***273.85***	***728.39***

CHAPTER 7

CONCLUSION

In this thesis, reservoir operation strategies are developed for single-reservoir and multi-reservoir HPPs. A real-life case study is used to demonstrate the methodology proposed. The operation strategies obtained from the mathematical models are applied to the multi-reservoir system composed of Arkun, Yusufeli and Artvin HPPs. The studies carried out in this thesis can be categorized into three groups.

In the first part of the thesis (Chapter 4), a single purpose single reservoir system (Yusufeli HPP) is investigated and four different types of rule curves are developed under two objectives, maximization of average annual energy generation and maximization of average annual revenue. In the second part (Chapter 5), a cascade-type multi-reservoir system with single purpose of energy generation that is more representative of the real situation is investigated. In this study, decentralized management and integrated management of the cascade system are compared under again the objectives of maximization of average annual energy and average annual revenue. In addition, nonlinear mathematical models which are set up considering net profit maximization objective are used to determine HPPs' optimum installed capacities. Finally, hypothetical multi-purpose (i.e. municipal water supply, irrigation and flood control in addition to energy generation) scenarios for the multi-reservoir system are investigated (Chapter 6). Maximization of energy generation and maximization of net revenue are selected as two objective functions for the multi-purpose multi-reservoir system. In this chapter a final analysis for the pumped-storage version of the cascade system is carried out.

The important results and findings obtained in Chapter 4, where a single purpose single reservoir system is investigated, are given below:

- The naive policy, **RCFixed**, which fixes the reservoir storage level over time, deteriorated the objective function values as much as 6% for this case study. The reason is that the fluctuation in the mean inflow values throughout the year is better exploited by the **RCStrict** and **RCGuidance** rule curves in contrast to this naive policy. On the other hand, **RCStrict** and **RCGuidance** have limited success in responding to the fluctuations in inflows over the years compared to **RCDynamic** which can perfectly adapt to the fluctuations in inflow throughout the simulation period by dynamically varying the storage levels. This flexibility resulted in a potential improvement of **RCDynamic** by 2.5% in the objective function values for this case study. However, **RCDynamic** does not yield an applicable policy for future real-time operation of the reservoir.

- Under the revenue maximization objective, long-term planning horizon with hourly electricity price variations is coupled when generating the rule curves. Under both objectives (maximization of average annual energy generation and maximization of average annual revenue) the reservoir level is decreased just before the wet period. When the objective is the maximization of revenue, water is turbined for an extended number of months and in increased amounts compared to those obtained under the maximization of energy objective. This is due to the fact that the mean monthly electricity prices tend to be higher during the dry period since the contribution of hydropower to the overall energy supply decreases. It is concluded that ignoring the change in the rule curve with respect to different objectives may result in losses of resource and benefit. It is also emphasized that electricity price variations (hourly, daily and monthly variations) should be taken into account for realistic revenue estimation.

The important results and findings obtained in Chapter 5, where a single purpose multi-reservoir system is investigated, are given below:

- For this case study, when energy generations obtained from integrated and separate systems are compared, it is seen that the value obtained under the integrated system is slightly higher (0.11%) than that obtained under the separate system. Thus, optimization of the integrated system is slightly more effective than optimizing individual HPPs separately. The cascade system considered here is composed of only three consecutive HPPs, as the system gets larger (i.e. more HPPs are added to the system) it is expected to have larger benefits.

- It is shown by the optimum installed capacity determination studies that integrated basin management results in higher net profits (up to +0.5%) with smaller installed capacities (-2.0%). In other words, if the cascade system is studied as an integrated system, higher net profits with lower initial investments can be obtained. It is concluded that optimization studies should be performed by considering integrated management for multi-reservoir systems in the planning stage to obtain higher benefits.

The important results and findings obtained in Chapter 6, where multi-purpose multi-reservoir systems are investigated, are given below:

- Municipal water supply and irrigation purposes cause a reduction in the energy generation and revenue (Scenario 1 and 2). This is an expected result, because water is drawn from Arkun and Yusufeli HPP’s reservoirs to meet water demands.

- For the scenario including flood control purpose (Scenario 3), rule curves, total energy generation and total revenue do not change with respect to Scenario 2 (which includes energy generation, municipal water supply and irrigation purposes). The reason of this situation is considered to be flood control’s provision in the rule curves which are obtained for Yusufeli Dam’s reservoir (which has higher active reservoir volume than that of Artvin HPP) under Scenario 2. Although the critic region is assumed to be located at the downstream part of Artvin HPP, the flood control is ensured by Yusufeli Dam without any loss in the energy and revenue amounts. If, Artvin HPP was forced to mitigate the flood great amount of losses both in energy and revenue would be expected. These results demonstrate that when integrated basin management is implemented, the optimization model identifies and uses the most suitable reservoir to mitigate the flood. This results in mitigation of the flood without sacrificing benefits of energy generation or water supply for other purposes such as municipal water supply or irrigation.

- In Scenario 4, in which the pumped-storage case is considered for the multi-reservoir system, the net revenue increased by 2.85% compared to that of the current system without pumped-storage. Hourly price fluctuations within the day results in a minor increase in the net revenue. Head losses (formed through the transmission structures) and the pump efficiency increase the energy consumption during pumping and this increase results in higher costs. However, it should be noted that as the energy price difference between peak and off-peak hours in a day increases overall net revenue will increase in a pumped-storage system.

Recommendations for Future Studies

In this thesis, single-reservoir and multi-reservoir systems are considered under objectives such as maximization of average annual energy generation and maximization of average annual revenue. However, all these objectives are studied disjointly in this thesis. In future studies, multi-objective optimization models can be developed and overall system performance can be investigated. For example, maximization of energy generation and revenue objectives can be considered simultaneously. Moreover, some objectives which are not considered in the scope of this thesis like maximization of firm energy generation can also be investigated in the future studies considering single-reservoir and multi-reservoir systems.

In the studies carried out for the determination of optimum installed capacity (Chapter 5), constant unit prices are utilized for the estimation of the installed capacity costs. Instead of using constant unit prices, a more detailed economic analysis can be carried out for the estimation of costs in future studies.

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PUBLICATIONS

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2. Ak, M., Yanmaz, A.M., and Kentel, E. (2014) "A comparative study on energy income estimation: A case study in Turkey," Renewable and Sustainable Energy Reviews, 38, 700-705.

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