

# Energy Management and Regression Analysis With Risky Inflow Data From the Basin in Multi-reservoir Systems

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## Research Article

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# Abstract

In a multi-reservoir system, the stochastic nature of basin data resulting from rainfall introduces risk into water management operations. Effective management that accounts for these risks can obtain maximum benefits for the system. This study presents a description of a multi-reservoir water resources system with hydroelectric power plants, utilizing the energy optimization model developed by OPAN in 2007. Specifically, the model was applied to reservoirs located successively on the Lower Kızılırmak River in the Kızılırmak Basin, with the objective function being the maximization of firm power and total energy. The study considered three scenarios: deterministic, probabilistic, and risky, with probabilities of inflows from the basin being determined for the latter. Monthly inflows with determined probabilities were used to obtain data for the risky case. Optimum operating levels were determined based on this data to maximize firm power and total energy. The values obtained from the optimization were then used in multivariate regression analysis using the Statistical Package for Social Scientists (SPSS), a statistical analysis program. The analysis explored the effects of monthly operating levels in the reservoirs, the amount of inflow released from the spillway, the amount of inflow released for energy production, the monthly average inflow to the reservoirs, and firm power values on energy production.

## 1 INTRODUCTION

Water resources play a crucial role in sustaining human life and supporting social and economic development. Effective management of these resources is essential for improving the quality of life and ensuring sustainable development. However, the increasing impacts of population growth, climate change, and social and environmental factors are posing new challenges for water resources management, making it increasingly complex. Uncontrolled water use and growing demand can lead to water scarcity, which can have significant consequences for human life and development. The management of water resources can be carried out on both short-term and long-term bases. In short-term operations, uncertainties are often ignored and considered deterministic, with the primary goal being to maximize benefits by operating reservoirs in the most efficient manner possible.

The effective use of reservoir systems has become increasingly important, given their multifaceted purposes, which include hydroelectric power generation, irrigation, flood and drought control, recreation, and natural life protection. Reservoir system planning considers the evolving water demands over time to ensure the system's performance meets current needs. In the operation of reservoirs, the goal is to maximize benefits and minimize costs, subject to constraints and equilibrium equations (Rani and Moreira 2009).

System analysis provides an optimal solution for the development of water resources. This approach involves creating a mathematical model that includes the system's objective function and constraints, which is then solved using optimization methods. Commonly used methods for water resources planning include linear programming, dynamic programming, simulation, queuing theory, and nonlinear mathematical programming models. Although dynamic programming's mathematical formulation may seem complex, it is readily applicable to systems (Tai 1984). Dynamic programming is the most appropriate approach for solving multi-stage or multi-period problems where the problem parameters that require a series of interconnected decisions change from stage to stage. The dynamic programming approach breaks down the main problem into subprograms, or stages, each of which requires a decision. The optimal solution is found by combining the results obtained at each stage according to the purpose determined for each stage. Dynamic programming is divided into deterministic and stochastic approaches. In deterministic dynamic programming, the future state is entirely determined by the current state and policy. In a multi-stage decision process, the process is deterministic if all external factors affecting the decision are fully known. Given the uncertainties arising from climate change, various stochastic models have been developed (Tai 1984).

Energy production in reservoirs plays a crucial role in meeting the growing energy demands worldwide. Accurate estimation and correlation of energy production are vital for optimal energy planning. This study focuses on the energy optimization model developed by OPAN in 2007 for long-term planning in a multi-reservoir system. The Lower Kızılırmak River in the Kızılırmak Basin was chosen for the model application. The objective of the model was to maximize energy production. The study analyzed three cases, including deterministic, probabilistic, and risky cases. During the analysis, the model aimed to maximize firm power and obtain minimum operating levels using monthly inflows during the dry period. Firm power was used as a constraint, and the model aimed to maximize total energy using monthly average inflow values. The study used the results to perform multivariate regression analysis on energy production with five independent variables. These variables included monthly operating levels at the reservoirs, the amount of inflow released from the spillway, the amount of inflow released

for energy production, monthly average inflows to the reservoirs, and firm power values. The study compared the results of deterministic and risky case analyses.

## 2 DESCRIPTION OF THE SYSTEM

A multi-purpose and multi-reservoir water resources system can be defined on a stream. The variables related to the operation of reservoir  $i$  at time  $t$  are showed in Fig. 1.

In multi-purpose and multi-reservoir systems, the time period is divided into stages. Each stage represents a period, and the total number of periods in a year represents a cycle. In the system, the amount of water stored in the reservoir is considered as the state variable, while the amount of water released from the reservoir for energy production is regarded as the decision variable. The water balance relationship of the reservoirs at time  $t$  can be showed in Eq. (1):

$$S_{i,t+1} - S_{i,t} = F_{i,t} + Q_{i-1,t} + R_{i-1,t} - Q_{i,t} - R_{i,t} - E_{i,t} \quad (1)$$

where,  $S_{i,t}$  is the amount of water stored in reservoir  $i$  at time  $t$ ;  $F_{i,t}$  is the amount of inflow from the basin of reservoir  $i$  at time  $t$ ;  $Q_{i,t}$  is the amount of inflow released for energy production from reservoir  $i$  at time  $t$ ;  $R_{i,t}$  is the amount of inflow released from the spillway of reservoir  $i$  at time  $t$ ;  $E_{i,t}$  is evaporation loss of reservoir  $i$  at time  $t$  (Opan 2007).

The amount of water stored in the reservoirs in the system, as shown in Eq. (2) with their maximum and minimum storage capacities, the inflows to be released from the reservoirs can be limited as shown in Equations (3) and (4);

$$S_i^{\text{Min}} \leq S_{i,t} \leq S_i^{\text{Max}}$$

2

$$0 \leq Q_{i,t} \leq Q_i^{\text{Max}}$$

3

$$0 \leq R_{i,t} \leq R_i^{\text{Max}}$$

4

The average power obtained in reservoir  $i$  at time  $t$  is shown in Eq. (5);

$$P_{i,t} = k_i \cdot Q_{i,t} \cdot h_{i,t} \quad (5)$$

where  $k_i$  is the energy production coefficient;  $h_{i,t}$  is average net head at reservoir  $i$  in time  $t$ .

The installed capacity of the hydroelectric power plant should not be exceeded by the power generated from the inflow released in each reservoir for energy production.  $P_{k_i}$  shown in Eq. (6) is the installed power for reservoir  $i$ ;

$$P_{i,t} \leq P_{k_i}$$

6

The inflow ( $F$ ) from the basin is subject to its own probability. The amount of water stored ( $S$ ), inflows released for energy production ( $Q$ ), and inflows released from the spillway ( $R$ ) are all variables that are affected by this probability. In this study,  $F$  was considered as stochastic because it is a natural event. The probabilities obtained from the analysis were used to identify the risky cases of inflows from the basin.

The other variables, on the other hand, are values that are affected by this probability as produced by the authors. Each variable has a probability assigned to it which is equal to the probability assigned to  $F_{i,t}$ . The system is managed according to  $F_{i,t}$ , and the probability that carries the main probability is  $F_{i,t}$ . Each monthly flow has its own statistical feature, which manages the other variables with the statistical feature taken that month. There is no stochasticity in the objective function. The stochasticity here is affected by the value taken and an energy production is realized with the probability assigned to  $F$ .

### 3 THE ENERGY OPTIMIZATION

Dynamic programming is a powerful tool for optimizing multi-stage decisions, and it has been successfully applied in various fields, including reservoir operation. The method works by breaking down the problem into smaller stages and finding the optimal decision at each stage. In dynamic programming, the computation also increases exponentially as the number of state variables increases. In 2007, Opan developed the optimal energy operation optimization model and software for multi-reservoir systems, using the successive approximation dynamic programming technique for long-term planning. The energy optimization model and software developed by OPAN in 2007 will be used in this study. The purpose of the successive approximation dynamic programming method is to decompose a dynamic programming problem with multiple decision variables into dynamic programming problems, each of which has a single decision variable. It is to solve the main problem by considering the decision variables one by one. The advantage of this method is to reduce both computation time and computer memory requirements by reducing an  $(n)$  dimensional dynamic programming problem to a set of one-dimensional problems (Opan 2007).

Shim et al. (2002), have applied successive approximation dynamic programming for real-time flood control enterprises in the Han Basin. Yi et al.(2003), have applied successive approximation dynamic programming to assist in planning hourly optimal hydropower units in the Lower Colorado River Dam System.

Labadie (2004), has included multi-reservoir optimization studies in him technical report. He has explained explicit and implicit stochastic optimization, real-time optimization with prediction method, heuristic programming methods. Labadie stated that the gap between modeling technologies and general model use will narrow, adding that this will take time.

De Ladurantaye et al.(2009), have analyzed deterministic and stochastic models for maximizing profits from selling electricity generated in reservoirs.

Jaafar (2014), combined simulation and stochastic dynamic programming model and applied it to the Qarawn reservoir in Lebanon with the aim of energy production. Fayaed et al.(2019), applied stochastic dynamic programming and artificial neural network model to St. Langat reservoir in Malasia. They have carried out water resources management in relation to uncertain parameters such as inflow to the reservoir and evaporation.

Reservoirs were constructed for various purposes such as hydroelectric power generation, irrigation, flood and drought control, and recreation. In this study, four reservoirs were selected for energy production purposes. Selected systems aim to maximize the energy production. The objective function consists of two stages. In the first stage, monthly drought inflows were utilized to maximize reliable power and monthly minimum operating levels were determined. The objective function is shown in Eq. (7);

$$\max P_f = \max \left[ \min \sum_{i=1}^N P_{i,t} \right] \quad (7)$$

where, the minimum one among the total power values obtained for the t time of the system is assigned as the maximized firm power value. In the second stage of the objective function, the maximized firm power is used as a constraint in the same model, the total energy is maximized with the monthly average inflows and the monthly normal operating levels are determined. The maximum energy production formulation is shown in Eq. (8);

$$\text{Max.} \left[ \sum_{t=1}^{KM} \sum_{i=1}^M P_{i,t} \right]$$

8

In line with the targeted objective function, iteration processes are repeated until the steady state is reached for the optimal operating policy.

## 4 APPLICATION AREA

In the Kızılırmak basin, a multi-reservoir water resources system located successively on the main branch of the Lower Kızılırmak River was chosen for application. Kızılırmak, which is the longest river in Turkey with a length of 1,151 km, discharges the waters of an area of 78,180 km<sup>2</sup> into the Black Sea. The Kızılırmak Basin, which is the second largest basin in Turkey after the Fırat(Euphrates) River, is located in the eastern part of Central Anatolia. The river takes its name from the red coloration of the red colored sandy clayey sediment at the bottom of the stream bed in the Kızıldağ region of Sivas.

The total precipitation area of the Kızılırmak Basin is 78,646 km<sup>2</sup>, with an annual average precipitation height of 446 mm and an annual average flow of 164.15 m<sup>3</sup>/s. The basin experiences dry summers, with precipitation occurring primarily during the winter and spring periods. The Central Anatolia region, where the basin is located, is known for its intense droughts due to its continental climate, characterized by hot and dry summers and cold and snowy winters. The average air temperature in the region is 13.7°C, and the annual precipitation ranges between 300–800 mm. The Kızılırmak River, which is the second largest river in Turkey's water storage area after the Fırat River, has an irregular regime due to its dependence on rain and snow waters (Çakmak 2002, Balcanlı et al. 2012). Figure 2 shows a schematic view of the Kızılırmak Basin, while Fig. 3 illustrates the reservoirs located on the Lower Kızılırmak River in the Kızılırmak Basin that were studied in this research.

There are many reservoirs on the river. Among the reservoirs used in the study, Obruk was built for energy and irrigation purposes, Boyabat and Altinkaya were built for energy purposes, and Derbent was built for energy, irrigation and flood protection purposes. The characteristic features of these reservoirs are given in Table 1.

Table 1  
Characteristics of reservoirs (Alemdar 2019)

| Reservoirs                                       | Obruk    | Boyabat | Altinkaya | Derbent        |
|--------------------------------------------------|----------|---------|-----------|----------------|
| Rainfall Area (km <sup>2</sup> )                 | 58077    | 64724   | 75165     | 75166          |
| Objective                                        | Irr.+En. | Energy  | Energy    | Irr.+En.+Flood |
| Installed Power (MW)                             | 211      | 528     | 703       | 56             |
| Dam Height (m)                                   | 125      | 195     | 195       | 33             |
| Maximum operational level (m)                    | 512      | 330     | 190       | 59,5           |
| Minimum operational level (m)                    | 506      | 305     | 160       | 54             |
| Maximum Volume (10 <sup>6</sup> m <sup>3</sup> ) | 661      | 3557    | 5763      | 212,55         |
| Minimum Volume (10 <sup>6</sup> m <sup>3</sup> ) | 524      | 2147    | 2871      | 164            |
| Tailwater Elevation (m)                          | 446      | 192,9   | 61        | 33,7           |
| Spillway Capacity (m <sup>3</sup> / sn)          | 5000     | 9300    | 9250      | 11800          |
| Energy Production Capacity (m <sup>3</sup> / sn) | 343,0    | 413,2   | 584,8     | 232,9          |
| Monthly Maximum Inflow (m <sup>3</sup> /sn)      | 33,35    | 230,84  | 300,68    | 260,91         |
| Monthly Minimum Inflow ( m <sup>3</sup> /sn )    | 0,39     | 15,91   | 43,03     | 70,67          |
| Monthly Mean Inflow (m <sup>3</sup> /sn )        | 12,24    | 86,36   | 113,28    | 116,34         |

## 5 RESULTS FROM MODELS

The study considered three scenarios: deterministic, probabilistic, and risky. For each reservoir, the average monthly inflow data was calculated, and the values below the monthly average were used to determine the probabilities of these values approaching the monthly average inflow. The probability of not happening, or the risk case, was then determined by subtracting the probability value from 1.

To begin the analysis, the study aimed to maximize firm power by obtaining monthly minimum operating levels using the monthly inflow values of the dry period for each case. The inflow observation values from 1990 to 2011 in the Lower Kızılırmak basin were then transferred to the reservoir axes and arranged as 10<sup>7</sup> m<sup>3</sup> (Alemdar 2019). The total inflows during this time period were evaluated, and the year 2008 was identified as the dry period. Table 2 provides the monthly inflow values for the reservoirs during the dry period, which spanned from October to September.

Table 2  
Dry period monthly inflows

| Reservoirs | Dry period monthly inflows (10 <sup>7</sup> m <sup>3</sup> ) |    |    |   |   |   |    |    |   |   |    |    |
|------------|--------------------------------------------------------------|----|----|---|---|---|----|----|---|---|----|----|
| Obruk      | 22                                                           | 29 | 17 | 3 | 5 | 4 | 19 | 8  | 1 | 2 | 19 | 15 |
| Boyabat    | 24                                                           | 31 | 18 | 3 | 5 | 4 | 21 | 8  | 1 | 3 | 20 | 17 |
| Altinkaya  | 29                                                           | 37 | 22 | 4 | 6 | 5 | 25 | 10 | 1 | 3 | 25 | 20 |
| Derbent    | 29                                                           | 37 | 22 | 4 | 6 | 5 | 25 | 10 | 1 | 3 | 25 | 20 |

The values below the monthly average inflow data were determined and the probabilities of these values approaching the monthly average inflow was calculated. Probabilistic and risky dry period inflows were obtained by decreasing the dry period inflows with probability values. Obtained the probabilistic and risky case dry period inflows are shown in Table 3 and Table 4.

Table 3  
Probabilistic case dry period monthly inflows

| Reservoirs | Probabilistic case dry period monthly inflows ( $10^7 \text{ m}^3$ ) |    |    |    |    |    |    |    |    |    |    |    |
|------------|----------------------------------------------------------------------|----|----|----|----|----|----|----|----|----|----|----|
| Obruk      | 10                                                                   | 13 | 10 | 15 | 17 | 17 | 15 | 13 | 15 | 13 | 9  | 8  |
| Boyabat    | 11                                                                   | 13 | 11 | 16 | 19 | 19 | 16 | 14 | 16 | 14 | 10 | 8  |
| Altinkaya  | 13                                                                   | 16 | 13 | 19 | 23 | 23 | 19 | 17 | 19 | 17 | 12 | 10 |
| Derbent    | 13                                                                   | 16 | 13 | 19 | 23 | 23 | 19 | 17 | 19 | 17 | 12 | 10 |

Table 4  
Risky case dry period monthly inflows

| Reservoirs | Risky case dry period monthly inflows ( $10^7 \text{ m}^3$ ) |    |    |    |    |    |    |    |    |   |    |    |
|------------|--------------------------------------------------------------|----|----|----|----|----|----|----|----|---|----|----|
| Obruk      | 35                                                           | 34 | 28 | 12 | 10 | 12 | 17 | 13 | 10 | 7 | 21 | 27 |
| Boyabat    | 37                                                           | 37 | 30 | 13 | 10 | 13 | 19 | 14 | 11 | 8 | 22 | 30 |
| Altinkaya  | 45                                                           | 44 | 37 | 16 | 12 | 15 | 23 | 17 | 13 | 9 | 27 | 35 |
| Derbent    | 45                                                           | 44 | 37 | 16 | 12 | 15 | 23 | 17 | 13 | 9 | 27 | 35 |

As a result of the operation that maximizes the firm power, the monthly minimum operation level of the Obruk Reservoir in Fig. 4, the monthly minimum operation level of the Boyabat Reservoir in the Fig. 5, the monthly minimum operation level of the Altinkaya Reservoir in the Fig. 6, the monthly minimum operation level of the Derbent Reservoir in the Fig. 7, the monthly total power values of the dry period are shown in Fig. 8. Boyabat Reservoir, which has the largest useful storage according to the monthly minimum operating levels, is effective in maximizing the firm power.

To maximize the total energy, the model used monthly average inflows and firm power values during the dry period as constraints to obtain monthly normal operating levels. Inflow observation values from the Lower Kızılırmak Basin between 1990 and 2011 were transferred to the reservoir axes, and monthly average inflow values were calculated using this data (Alemdar 2019). The resulting monthly average inflow values for each reservoir are presented in Table 5.

Table 5  
Average monthly inflows of reservoirs

| Reservoirs | Average monthly inflows ( $10^7 \text{ m}^3$ ) |    |    |    |    |    |    |    |    |    |    |    |
|------------|------------------------------------------------|----|----|----|----|----|----|----|----|----|----|----|
| Obruk      | 45                                             | 47 | 38 | 27 | 27 | 29 | 32 | 26 | 25 | 20 | 30 | 35 |
| Boyabat    | 48                                             | 50 | 41 | 29 | 29 | 32 | 35 | 28 | 27 | 22 | 32 | 38 |
| Altinkaya  | 58                                             | 60 | 50 | 35 | 35 | 38 | 42 | 34 | 32 | 26 | 39 | 45 |
| Derbent    | 58                                             | 60 | 50 | 35 | 35 | 38 | 42 | 34 | 32 | 26 | 39 | 45 |

The values below the monthly average inflow data were determined and the probabilities of these values approaching the monthly average inflow was calculated. As a result of subtracting the probability value from 1, the probability of not

happening, that is, the risk case, was determined. Probabilistic and risky case monthly average inflow values were obtained by decreasing the monthly average inflow values with probability values. The obtained probabilistic and risky case monthly average inflow values are shown in Table 6 and Table 7.

Table 6  
Probabilistic case monthly average inflows

| Reservoirs | Probabilistic case monthly average inflows ( $10^7 \text{ m}^3$ ) |    |    |    |    |    |    |    |    |    |    |    |
|------------|-------------------------------------------------------------------|----|----|----|----|----|----|----|----|----|----|----|
| Obruk      | 10                                                                | 13 | 10 | 15 | 17 | 17 | 15 | 13 | 15 | 13 | 9  | 8  |
| Boyabat    | 11                                                                | 13 | 11 | 16 | 19 | 19 | 16 | 14 | 16 | 14 | 10 | 8  |
| Altinkaya  | 13                                                                | 16 | 13 | 19 | 23 | 23 | 19 | 17 | 19 | 17 | 12 | 10 |
| Derbent    | 13                                                                | 16 | 13 | 19 | 23 | 23 | 19 | 17 | 19 | 17 | 12 | 10 |

Table 7  
Risky case monthly average inflows

| Reservoirs | Risky case monthly average inflows ( $10^7 \text{ m}^3$ ) |    |    |    |    |    |    |    |    |   |    |    |
|------------|-----------------------------------------------------------|----|----|----|----|----|----|----|----|---|----|----|
| Obruk      | 35                                                        | 34 | 28 | 12 | 10 | 12 | 17 | 13 | 10 | 7 | 21 | 27 |
| Boyabat    | 37                                                        | 37 | 30 | 13 | 10 | 13 | 19 | 14 | 11 | 8 | 22 | 30 |
| Altinkaya  | 45                                                        | 44 | 37 | 16 | 12 | 15 | 23 | 17 | 13 | 9 | 27 | 35 |
| Derbent    | 45                                                        | 44 | 37 | 16 | 12 | 15 | 23 | 17 | 13 | 9 | 27 | 35 |

As a result of the total energy being maximized, the monthly normal operating levels of Obruk Reservoir in Fig. 9, the monthly normal operating levels of Boyabat Reservoir in Fig. 10, the monthly normal operating levels of Altinkaya Reservoir in Fig. 11, the monthly normal operating levels of Derbent Reservoir in Fig. 12, the monthly total power values of the reservoirs are shown in Fig. 13. Boyabat Reservoir is effective in maximizing the total energy according to normal operating levels. When the monthly inflows from the basin to the reservoirs are met at the monthly normal operating levels, all the inflows released from the reservoirs are released for energy production.

As a result of the optimization, multivariate regression analysis was performed. The relationship between the monthly operating levels in the reservoirs, the amount of inflow released from the spillway, the amount of inflow released for energy production, the monthly average inflow in the reservoirs, firm power values and energy production were examined.

## 6 STATISTICAL ANALYSIS

The relationship between dependent and independent variables is determined by multiple regression analysis. In the analysis, dependent variable  $Y$  and independent variables  $X_1, X_2, X_3, \dots, X_k$  are shown in Eq. (9);

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \dots + \beta_k X_k + \varepsilon \quad (9)$$

where, when  $\beta_0$  is  $X = 0$ , the value of the dependent variable (cutoff point),  $\beta_1$  is regression coefficient,  $\varepsilon$  indicates the error term.

The regression coefficient shows the average change that a one unit change in the independent variable will cause in the dependent variable. The error term is the difference between the actual value of the dependent variable and the value estimated from the model. The aim is that there is no difference between the actual value and the estimated value, or the difference is minimal. The coefficient of determination ( $R^2$ ) gives the rate at which the change in the dependent variable

is explained by the independent variables. If the coefficient is close to one, it can be interpreted that a large part of the change in the dependent variable can be explained by the independent variable (Tranmer et al. 2020).

Bernard et al. (2007), examined the change in energy demand models with multivariate regression by applying the Monte Carlo simulation method. Malley (2011), examined the connection between water scarcity and hydroelectric energy caused by climate change in the Mtera reservoir, which provides half of the hydroelectricity need. He stated that climate change is the main cause of water scarcity for hydroelectric power generation. He concluded that there is an increase in the average annual water supply for electricity generation in the reservoir with the increase in the variability in annual rainfall. Özkan (2016), performed a regression analysis with the factors affecting energy efficiency. Danladi and Yunusa (2019), analyzed the relationship between inflows and outflows with rainfall, temperature and evaporation variables using SPSS for energy production at Jabba Dam.

Rahardjo et al. (2021), performed a multivariate regression analysis in SPSS to examine the effects of rainfall intensity and water height on the energy efficiency of Kracak Hydroelectric Power Plant. They stated that rainfall intensity and water height have a positive effect on increasing energy efficiency.

In the regression analysis, deterministic and risky case was evaluated. Multivariate regression analysis was performed using the statistical analysis program SPSS on energy production with five independent variables. Monthly operating levels in the reservoirs, the amount of inflow released from the spillway, the amount of inflow released for energy production, monthly average inflow to the reservoirs, firm power values were used as independent variables.

## 6.1 Deterministic Case

Correlation coefficients ( $r$ ) between energy production and independent variables from deterministic case regression analysis with SPSS program and their significance were determined and given in Table 8.

Table 8  
Correlation Coefficient and Significances

|                     |                 | Energy | Operating Level | Released Energy | Avg. Inflow | Spillway Inflow | Firm Power |
|---------------------|-----------------|--------|-----------------|-----------------|-------------|-----------------|------------|
| Pearson Correlation | Energy          | 1,000  | ,928            | ,822            | ,374        | -,467           | ,621       |
|                     | Operating Level | ,928   | 1,000           | ,671            | ,120        | -,528           | ,479       |
|                     | Released Energy | ,822   | ,671            | 1,000           | ,661        | ,021            | ,591       |
|                     | Avg. Inflow     | ,374   | ,120            | ,661            | 1,000       | ,443            | ,411       |
|                     | Spillway Inflow | -,467  | -,528           | ,021            | ,443        | 1,000           | -,189      |
|                     | Firm Power      | ,621   | ,479            | ,591            | ,411        | -,189           | 1,000      |
| Sig. (1-tailed)     | Energy          | .      | ,000            | ,000            | ,004        | ,000            | ,000       |
|                     | Operating Level | ,000   | .               | ,000            | ,208        | ,000            | ,000       |
|                     | Released Energy | ,000   | ,000            | .               | ,000        | ,444            | ,000       |
|                     | Avg. Inflow     | ,004   | ,208            | ,000            | .           | ,001            | ,002       |
|                     | Spillway Inflow | ,000   | ,000            | ,444            | ,001        | .               | ,100       |
|                     | Firm Power      | ,000   | ,000            | ,000            | ,002        | ,100            | .          |

The correlation coefficient ( $r$ ) is expressed with numerical values ranging from  $-1$  to  $+1$  and shows the direction and strength of the relationship between the variables. The negative value of the coefficient indicates that the relationship between the variables is inversely proportional; positive values indicate that the relationship is directly proportional (Durmuş et al. 2011).

According to the correlation coefficients in Table 8, there is a positive relationship between the monthly operating level of the reservoirs ( $r = 0.928$ ), the inflow released for energy production ( $r = 0.822$ ), firm power ( $r = 0.621$ ) and monthly average inflow ( $r = 0.374$ ) and energy production. There is a negative relationship between the inflow released from the spillway ( $r = -0.467$ ) and energy production. 86% of energy production can be explained by the change in monthly operating levels in reservoirs. The explanatory power of the deterministic case model, how much of the change in the dependent variable can be explained by the independent variables have been determined, and the model summary is shown in Table 9.

Table 9  
Model Summary

| Model | R                 | R Square | Adjusted R Square | Std. Error of the Estimate |
|-------|-------------------|----------|-------------------|----------------------------|
| 1     | ,990 <sup>a</sup> | ,981     | ,978              | 24,95397                   |

When the  $R$  and  $R^2$  values are examined in Table 9, it is understood that the explanatory power of the model is high. As a result of the regression analysis, the model; the inflow released from the spillway, the inflow released for energy generation, monthly average inflow, monthly operating level and firm power explain 98.1% of the variance. In the deterministic case, it can be said that the energy production in reservoirs is shaped by these factors at a rate of 98.1%.

Table 10  
Analysis of Variance

| Model |            | Sum of Squares | df | Mean Square | F       | Sig.              |
|-------|------------|----------------|----|-------------|---------|-------------------|
| 1     | Regression | 1319650,737    | 5  | 263930,147  | 423,848 | ,000 <sup>b</sup> |
|       | Residual   | 26153,430      | 42 | 622,701     |         |                   |
|       | Total      | 1345804,167    | 47 |             |         |                   |

According to analysis of variance in Table 10, the  $H_0$  hypothesis is rejected since the F value is 423.85 and  $\rho$  (sig.) is 0.000. The result shows that the regression model created is statistically significant. It is possible to explain the energy variable in reservoirs with at least one of the inflow released from the spillway, the inflow released for energy production, the monthly average inflow, the operating level and the firm power values. The regression coefficients used for the deterministic case regression equation, their significance, the relationship between the dependent variable and the independent variables were determined and the regression coefficients are given in Table 11.

Table 11  
Deterministic Case Regression Coefficients

| Model                         |                 | Unstandardized Coefficients |            | Standardized Coefficients | t      | Sig. | 95,0% Confidence Interval for B |             | Collinearity Statistics |       |
|-------------------------------|-----------------|-----------------------------|------------|---------------------------|--------|------|---------------------------------|-------------|-------------------------|-------|
|                               |                 | B                           | Std. Error | Beta                      |        |      | Lower Bound                     | Upper Bound | Tolerance               | VIF   |
| 1                             | (Constant)      | -123,669                    | 16,158     |                           | -7,654 | ,000 | -156,277                        | -91,061     |                         |       |
|                               | Operating Level | ,391                        | ,033       | ,527                      | 11,843 | ,000 | ,324                            | ,457        | ,234                    | 4,275 |
|                               | Released Energy | 1,658                       | ,271       | ,307                      | 6,127  | ,000 | 1,112                           | 2,204       | ,285                    | 4,418 |
|                               | Avg. Inflow     | 3,585                       | ,629       | ,213                      | 5,698  | ,000 | 2,315                           | 4,854       | ,331                    | 3,018 |
|                               | Spillway Inflow | -1,223                      | ,148       | -,280                     | -8,247 | ,000 | -1,523                          | -,924       | ,401                    | 2,496 |
|                               | Firm Power      | ,068                        | ,041       | ,047                      | 1,648  | ,017 | -,015                           | ,151        | ,580                    | 1,724 |
| a. Dependent Variable: Energy |                 |                             |            |                           |        |      |                                 |             |                         |       |

The regression formula obtained as a result of the regression analysis is shown in Eq. (10);

$$\text{Energy production} = -123,67 + ((0,391 * \text{operating level}) + (1,658 * \text{inflow released for energy production}) + (3,585 * \text{monthly average inflow}) + (-1,223 * \text{inflow released from spillway}) + (0,068 * \text{firm power})) \quad (10)$$

According to the regression coefficients in Table 11, the B values show the relationship between the energy produced and each forecast variable. (positive or negative) B values show the extent to which each prediction variable affects the dependent variable when the effect of all other prediction values is held constant. The standard B values indicate how much a standard deviation change in the forecast variable will cause a change in the dependent variable.

According to the Table 11, the operating level, the inflow released for energy production, the monthly average inflow and the firm power have a positive effect on the energy production, while the inflow released from the spillway has a negative

effect. The monthly average inflow variable is the factor that has the most effect on energy production among the coefficients.

Variance Inflation Factor (VIF) is used to test whether there is a multicollinearity between the explanatory variables. The high value of the VIF coefficient increases the variance of the regression coefficients and causes misinterpretation of the effects of the independent variables on the dependent variable. In this case, the regression model becomes invalid (Özdamar 2011).

As a result of the analysis, the variables are statistically significant because  $p \text{ (sig.)} < 0.05$ . VIF is in the desired range.

## 6.2 Risky Case

Correlation coefficients (r) and significance between energy production and independent variables were determined from the risky case regression analysis and are given in Table 12.

Table 12  
Correlation Coefficient and Significances

| Risky Case          |                 | Energy | Operating Level | Released Energy | Avg.Inflow | Spillway Inflow | Firm Power |
|---------------------|-----------------|--------|-----------------|-----------------|------------|-----------------|------------|
| Pearson Correlation | Energy          | 1,000  | ,787            | ,641            | ,384       | -,177           | ,648       |
|                     | Operating Level | ,787   | 1,000           | ,233            | ,065       | -,273           | ,411       |
|                     | Released Energy | ,641   | ,233            | 1,000           | ,540       | ,230            | ,471       |
|                     | Avg.Inflow      | ,384   | ,065            | ,540            | 1,000      | ,473            | ,385       |
|                     | Spillway Inflow | -,177  | -,273           | ,230            | ,473       | 1,000           | -,044      |
|                     | Firm Power      | ,648   | ,411            | ,471            | ,385       | -,044           | 1,000      |
| Sig. (1-tailed)     | Energy          | .      | ,000            | ,000            | ,004       | ,115            | ,000       |
|                     | Operating Level | ,000   | .               | ,056            | ,331       | ,030            | ,002       |
|                     | Released Energy | ,000   | ,056            | .               | ,000       | ,058            | ,000       |
|                     | Avg.Inflow      | ,004   | ,331            | ,000            | .          | ,000            | ,003       |
|                     | Spillway Inflow | ,115   | ,030            | ,444            | ,000       | .               | ,383       |
|                     | Firm Power      | ,000   | ,000            | ,000            | ,003       | ,383            | .          |

According to the correlation coefficients in Table 12, there is a positive relationship between the risky case reservoirs monthly operating level ( $r = 0.787$ ), the risky case inflow released for energy production ( $r = 0.641$ ), the risky case firm power ( $r = 0.648$ ) and the risky case monthly average inflow ( $r = 0.384$ ) and the risky case energy production. There is a negative relationship between the inflow released from the spillway ( $r = -0.177$ ) and energy production. 62% of risky case energy production can be explained by the change in monthly operating levels in risky case reservoirs. The explanatory power of the risky case model, how much of the change in the dependent variable can be explained by the independent variables have been determined, and the summary of the model is given in Table 13.

Table 13  
Model Summary

| Model | R                 | R Square | Adjusted R Square | Std. Error of the Estimate |
|-------|-------------------|----------|-------------------|----------------------------|
| 1     | ,946 <sup>a</sup> | ,895     | ,883              | 38,70701                   |

When the R and R<sup>2</sup> values are examined in Table 13, it is understood that the explanatory power of the model is high. As a result of the regression analysis, the model's; risky case the inflow released from spillway, risky case inflow released for energy production, the risky case monthly average inflow, the risky case monthly operating level and the risky case firm power explain 89.5% of the variance. In the risky case, it can be said that the energy production in reservoirs is shaped depending on these factors at a rate of 89.5%.

Table 14  
Analysis of Variance

| Model (Risky Case) | Sum of Squares | df | Mean Square | F      | Sig.              |
|--------------------|----------------|----|-------------|--------|-------------------|
| 1 Regression       | 537638,958     | 5  | 107527,792  | 71,770 | ,000 <sup>b</sup> |
| Residual           | 62925,765      | 42 | 1498,232    |        |                   |
| Total              | 600564,722     | 47 |             |        |                   |

According to analysis of variance in Table 14, the H<sub>0</sub> hypothesis is rejected since the F value is 71,770 and p (sig.) is 0.000. It gives the result that the created regression model is statistically significant. It is possible to explain the risky case energy variable in reservoirs with at least one of the risky case inflow released from spillway, risky case inflow released for energy production, risky case monthly average inflow, risky case operation level and risky case firm power values. The regression coefficients used for the risky case regression equation, their significance, the relationship between the dependent variable and the independent variables were determined and the regression coefficients are shown in Table 15.

Table 15  
Risky Case Regression Coefficients

| Model (Risky Case) | Unstandardized Coefficients |            | Standardized Coefficients | t      | Sig. | 95,0% Confidence Interval for B |             | Collinearity Statistics |       |
|--------------------|-----------------------------|------------|---------------------------|--------|------|---------------------------------|-------------|-------------------------|-------|
|                    | B                           | Std. Error | Beta                      |        |      | Lower Bound                     | Upper Bound | Tolerance               | VIF   |
| 1 (Constant)       | -62,579                     | 15,038     |                           | -4,161 | ,000 | -92,926                         | -32,231     |                         |       |
| Operating Level    | ,285                        | ,029       | ,573                      | 9,940  | ,000 | ,227                            | ,343        | ,751                    | 1,331 |
| Released Inflow    | 1,622                       | ,268       | ,386                      | 6,046  | ,000 | 1,081                           | 2,163       | ,613                    | 1,630 |
| Spillway Inflow    | -,997                       | ,345       | -,178                     | -2,891 | ,006 | -1,694                          | -,301       | ,660                    | 1,514 |
| Average Inflow     | 1,574                       | ,670       | ,161                      | 2,349  | ,024 | ,222                            | 2,926       | ,534                    | 1,873 |
| Firm Power         | ,198                        | ,078       | ,161                      | 2,556  | ,014 | ,042                            | ,355        | ,630                    | 1,588 |

a. Dependent Variable: Risky state energy

The risky case regression formula obtained as a result of the regression analysis is shown in Eq. (11);

$$\text{Energy production} = -62,579 + ((0,285 * \text{risky case operating level}) + (1,622 * \text{risky case inflow released for energy production}) + (1,574 * \text{risky case monthly average inflow}) + (-0,997 * \text{risky case inflow released from spillway}) + (0,198 * \text{risky case firm power})) \quad (11)$$

According to the Table 15, risky case operation level, risky case inflow released for energy production, risky case monthly average inflow and risky case firm power have a positive effect on energy production, while risky case inflow released from the spillway has a negative effect. Among the coefficients, the factor that has the most effect on risky case energy production is the inflow released for risky case energy production. As a result of the analysis, the variables are statistically significant because  $p \text{ (sig.)} < 0.05$ . VIF is in the desired range.

## 7 CONCLUSIONS

In this study, the energy optimization model developed by OPAN in 2007 for long-term planning in the multi-reservoir system was applied to the reservoirs located successively on the Lower Kızılırmak River in the Kızılırmak Basin. Multivariate regression analysis was performed on energy production with five independent obtained from the optimization results.

The optimization results showed that the reservoir with the largest storage is effective in maximizing firm power and total energy when looking at the operating levels. Moreover, the firm power and average power obtained from the deterministic case operating model were greater than those obtained from the risky case dynamic programming model. This is because the monthly average inflow values in the risky case are reduced inflow data with probability, whereas the power values in the deterministic case were found to be larger. Optimum operation was provided by comparing the power values obtained monthly in the programming.

The regression analysis performed as a result of optimization shows that the  $R^2$  value is close to one, indicating that a large portion of the deterministic and risky energy production dependent variable can be explained by independent variables. When examining the  $R^2$  value of the model in the deterministic case, it is observed that the explanatory power is higher compared to the risky case, as it is found to be larger.

The results also showed that the operating level, the inflow released for energy production, the average monthly inflow, and firm power had a positive effect on energy production in both deterministic and risky cases, while the inflow released from the spillway had a negative effect. The correlation coefficients indicated a positive and strong relationship between the monthly operating level in reservoirs and energy production in both cases, while a negative relationship was observed between the inflow released from the spillway and energy production. This means that there would be a decrease in the energy production value as the inflow value released from the spillway increases. It was concluded that the deterministic case model with a higher coefficient according to the correlation ( $r$ ) and determination coefficients ( $R^2$ ) was better.

In future studies, it would be useful to evaluate whether an increase in energy production in reservoirs can be achieved by applying different operating policies. Additionally, the feasibility of statistical estimates on energy production can be checked by applying different methods.

## Declarations

### ACKNOWLEDGMENT

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The authors have no relevant financial or non-financial interests to disclose.

### Author Contributions

Material preparation, data collection and analysis, manuscript preparation, review and editing: E. Bacaksız; dynamic programming model analysis, review: M. Opan; review and editing: Z.E. Kara, M. Karadeniz

### Ethical Approval

The authors declare that the manuscript has not been published to other journals.

### Consent to Participate

All authors gave consent to participate in this study.

### Consent to Publish

All authors gave consent to publish this manuscript.

### Availability of Data and Materials

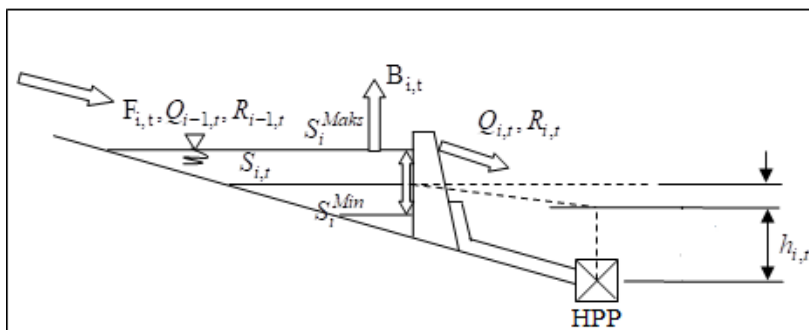
Available from the corresponding author on request.

## References

1. Alemdar F (2019) Energy Optimization of Successive Dams in the Lower Kızılırmak Basin, Master Thesis, Sakarya University, Institute of Science, Sakarya, 20–21
2. Balcanlı ÜG, Dikbaş F, Baran T (2012) Entropy Method in Drought Analysis. VII. National Hydrology Congress, Süleyman Demirel University, Isparta, 26–27 Eylül 2012
3. Bernard T, Idoud N, Khalah L, Ye'lou C (2007) Finite Sample Multivariate Structural Change Tests With Application To Energy Demand Models. J Econ 141:1219–1244
4. Çakmak B (2002) Evaluation of Irrigation System Performance in Kızılırmak Basin Irrigation Unions. KSÜ J Sci Eng 5(2):130–141
5. Danladi N, Yunusa MB (2019) Effect of Weather Variables on Reservoir Inflow for Hydroelectric Power Generation in Jebba Dam, Nigeria. 2nd School of Physical Sciences Biennial International Conference, Nigeria, 24–28 June 2019
6. De Ladurantaye D, Gendreau M, Potvin JY (2009) Optimizing Profits from Hydroelectricity Production. Comput Oper Res 36:499–529
7. Durmuş B, Yurtkoru ES, Çinko M (2011) Data Analysis with SPSS in Social Sciences, 4th Edition, Beta Publishing, 143
8. Fayaed SS, Fiyadh SS, Khai WJ, Ahmad AN, Afan HA, Ibrahim KR, Fai CM, Koting S, Mohd NS, Jaafar WZ, Hin LS (2019) Improving Dam and Reservoir Operation Rules Using Stochastic Dynamic Programming and Artificial Neural Network Integration Model. J Sustain 11:5367. 10.3390/su11195367

9. International Commission on Great Dams Turkish National Committee, Dams in Turkey, 1st edition, DSI Foundation, Ankara (2014)
10. Jaafar HH (2014) Maximizing Hydropower Production From Reservoirs: The Case Study Of Markaba, Lebanese Science Journal, 15(2)
11. Labadie JW (2004) Optimal Operation of Multi-Reservoir Systems: State-Of-The-Art Review. J Water Resources Planning and Management 130(2):93–111
12. Malley ZJU (2011) Climate Change and Water Resources for Energy Generation in Tanzania. World Renewable Energy Congress, Sweden, 8–13 May 2011
13. Opan M (2007) Multiobjective Optimal Operation in Multiple Reservoir Systems, PhD Thesis, Kocaeli University, Institute of Science, Kocaeli, 232690
14. Opan M (2007) Energy Optimization with Successive Approximation Dynamic Programming in Long-Term Planning in Multi-Reservoir Systems, Ministry of Culture and Tourism of the Republic of Turkey, Registration no: 2022/7840, Registration date: 27.12.2022, Production date: 13.09.2007
15. Özdamar K (2011) Statistical Data Analysis with Package Programs. Kaan Bookstore, Istanbul
16. Özkan G (2016) Economic Effects of Regulatory Reforms on the Turkish Energy Market, Master Thesis, Kırıkkale University, Kırıkkale
17. Rani D, Moreira MM (2010) Simulation-Optimization Modeling: A Survey and Potential Application in Reservoir. Water Resour Manage 24:11071138. <http://dx.doi.org/10.1007/s11269-009-9488-0>
18. Rahardjo A, Suyitno SM, Gunawan W, Wijayanta RP, Mahir (2021) and Sakirah The Effects of Rain Intensity and Water Elevation with Energy Productivity of Kracak Hydro Power Plant, Bogor Regency – West Java, Journal of Physics:Conference Series, 2111. doi:10.1088/1742-6596/2111/1/012044
19. Shim K-C, Fontane D, Labadie J (2002) Spatial decision support system for integrated river basin flood control. J Water Resources Planning and Management 128(3):190–201
20. Tai F (1984) “Optimization of Operating Procedures for Multi-Reservoir System Under Stochastic Inflows”, Master Thesis, Manitoba University, Canada
21. Tranmer M, Murphy J, Elliot M, ve Pampaka M (2020) Multiple linear regression (2nd Edition). Cathie Marsh Institute Working Paper. Access Address: <https://hummedia.manchester.ac.uk/institutes/cmist/archivepublications/workingpapers/2020/2020-1-multiple-linear-regression.pdf>
22. Yi J, Labadie J, Stitt S (2003) Dynamic optimal unit commitment and loading in hydropower systems. J Water Resources Planning and Management 129(5):388–398

## Figures



Variables related to the operation of reservoir i for time t (Opan 2007)



Figure 2

Schematic view of the Kızılırmak Basin (DSI 2014)

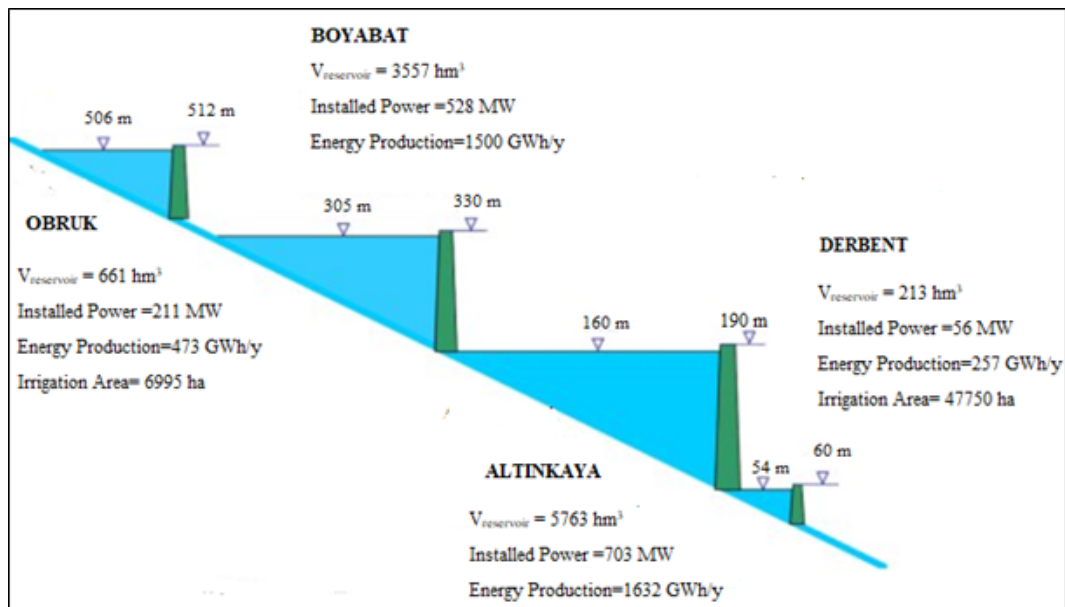


Figure 3

Reservoirs on the Lower Kızılırmak River in the Kızılırmak Basin (DSI 2014)

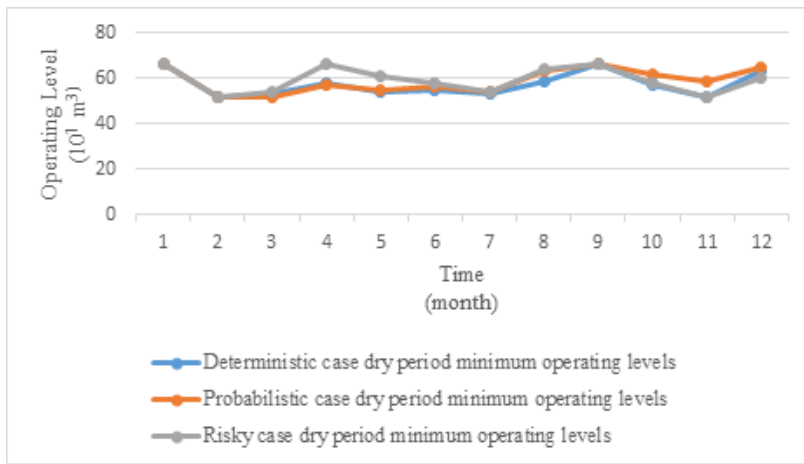


**Figure 4**

Obruk Reservoir monthly minimum operating levels

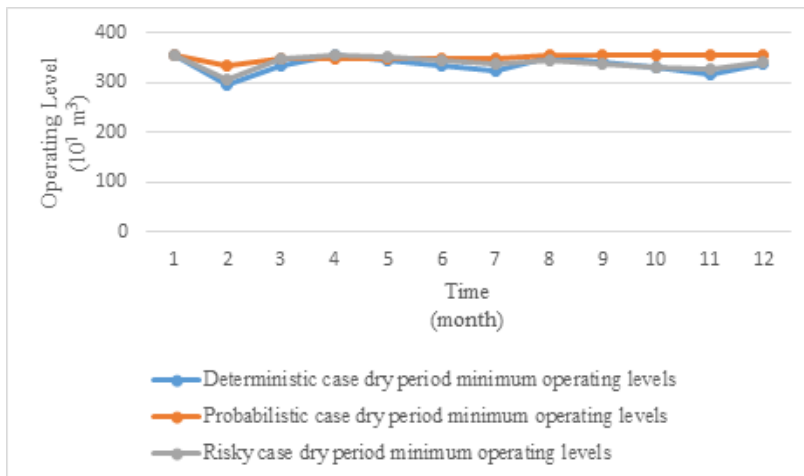


**Figure 5**

Boyabat Reservoir monthly minimum operating levels

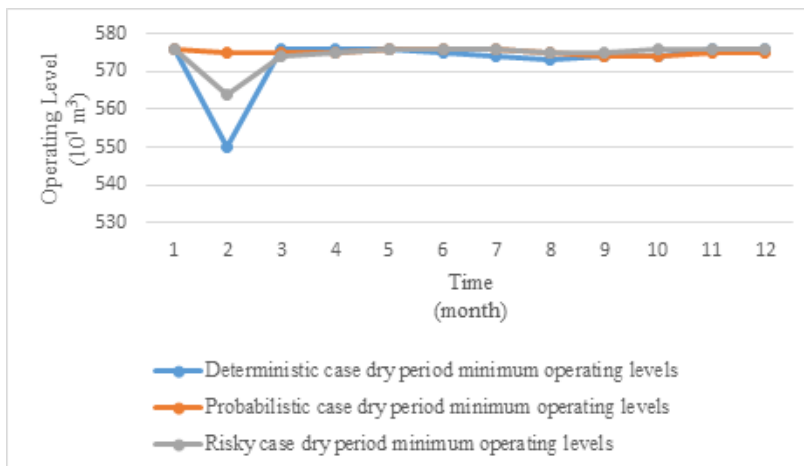


**Figure 6**

Altinkaya Reservoir monthly minimum operating levels

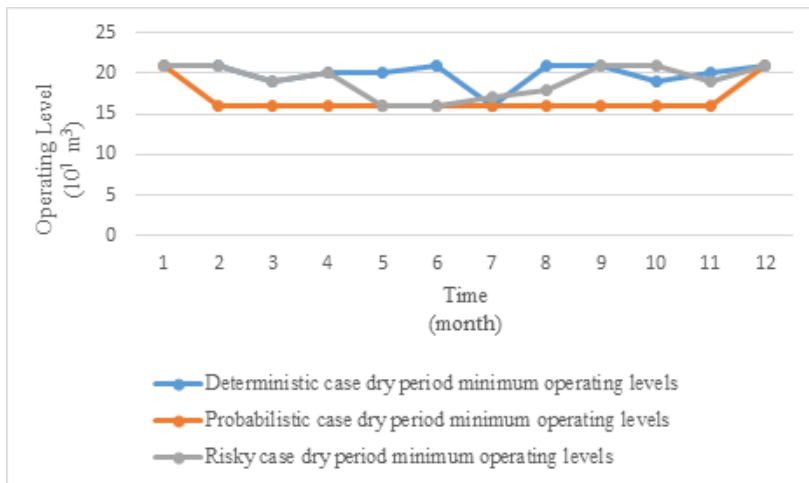


**Figure 7**

Derbent Reservoir monthly minimum operating levels

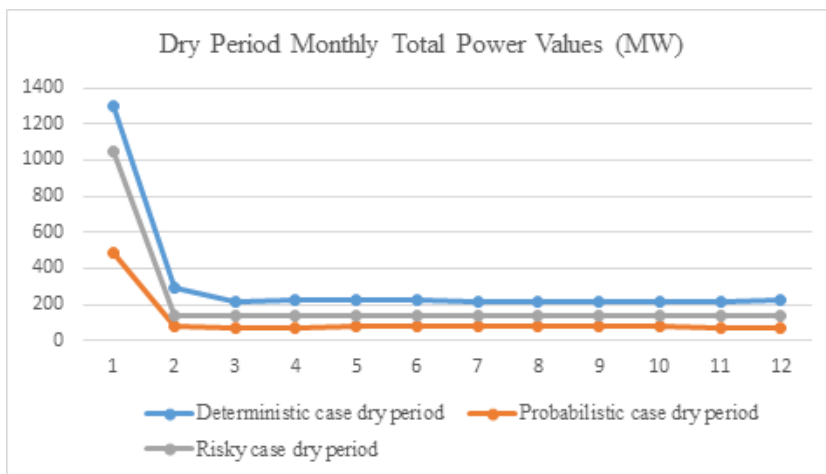


**Figure 8**

Dry period monthly total power values

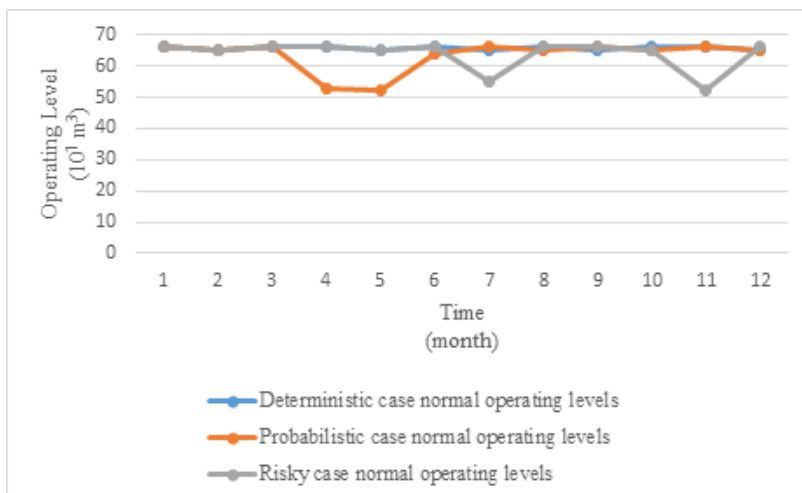


**Figure 9**

Obruk Reservoir monthly normal operating levels

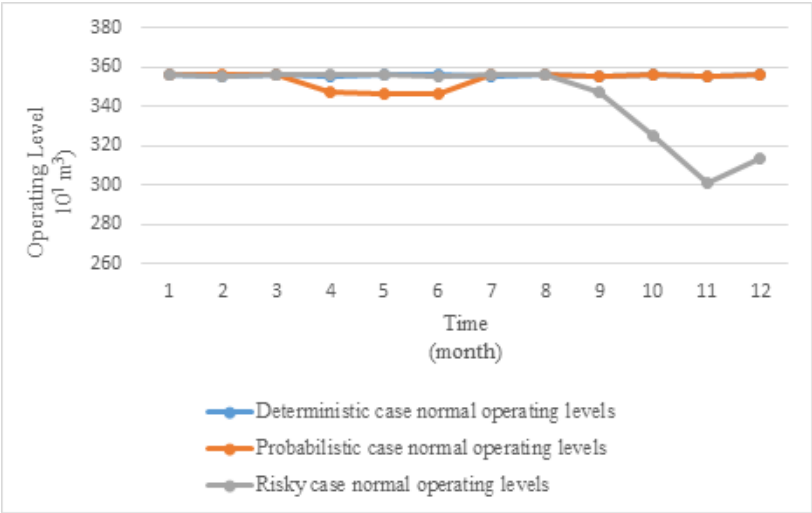


Figure 10

Boyabat Reservoir monthly normal operating levels

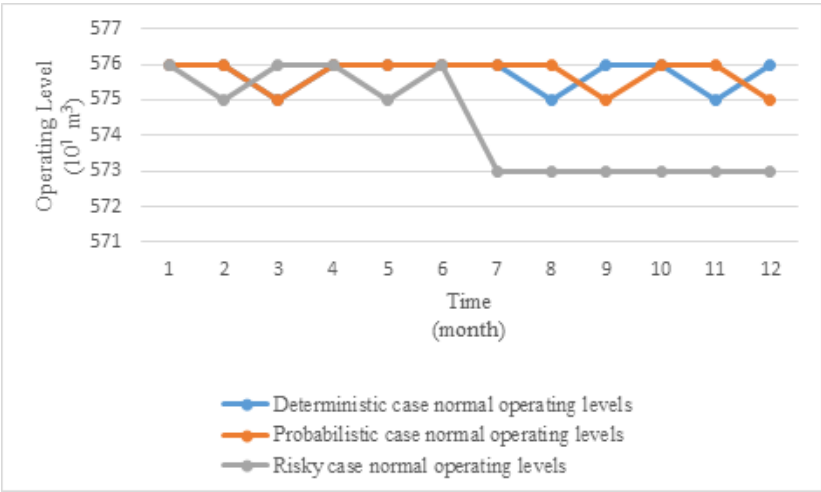


Figure 11

Altinkaya Reservoir monthly normal operating levels

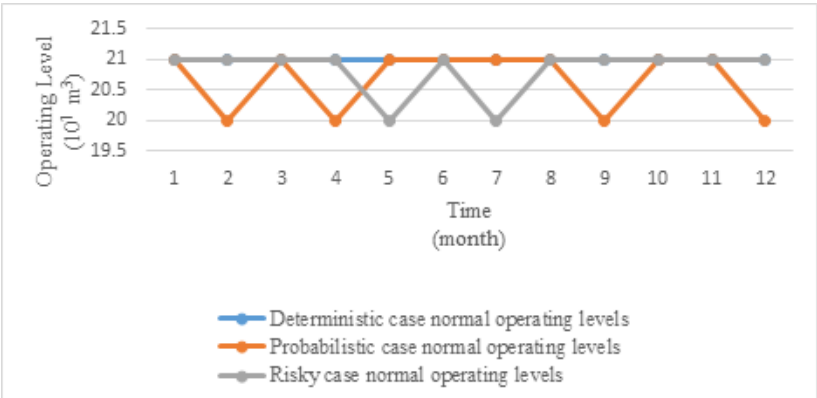


Figure 12

Derbent Reservoir monthly normal operating levels

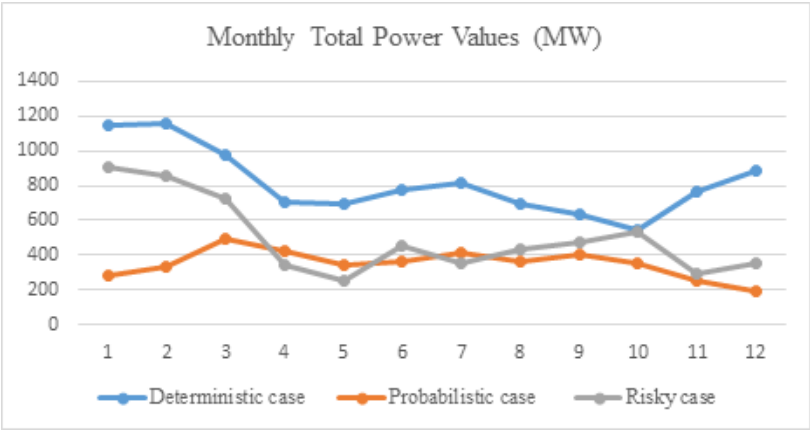


Figure 13

Monthly total power values