

Chapter 6

Reservoir Optimization and Simulation Modeling: A Case Study

Abstract This chapter presents a combination of optimization (LINGO) and simulation (HEC-ReSim) models to determine monthly operating rules for the Zayandehrud reservoir system in Iran. Based on the optimized flow determined in the single-objective framework, system behavior was simulated over 47 years. The results show that optimizing the operation of Zayandehrud reservoir could increase its storage by 88.9 % as well as increase the reliability index of regulated water for all downstream demands by more than 10 %.

6.1 Introduction

A reservoir is a natural or artificial lake to storage water; it keeps the water level at a controlled level, and releases it regularly to supply downstream requirements. The most important applications of reservoirs are: flood control, agricultural and environmental water supply, domestic and industrial water supply, hydroelectric power generation, and recreational activities. However, due to increasing water demands across the world and difficulties in building new dams, it is important to enhance the efficiency of reservoir operation based on optimization analyses. In other words, we need to determine the appropriate operating policies to find the amount of water that should be released in different periods according to downstream needs. The major points that need to be considered in any reservoir optimization analysis are:

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1. Determine the main objective function in a reservoir optimization analysis (e.g., minimizing spills, maximizing releases, or minimize the cost to maximize benefits),
2. Obtain decision variables that should be optimized (e.g., water levels or releases),
3. Determine the constraints of the problem (e.g., inflows, outflows, dead storage) properly.

In general, various mathematical programming methods such as linear or nonlinear techniques are applied to optimize operation of reservoirs. However, regarding the uncertainties of hydrological and hydraulic variables, it is difficult to draw a solid operational program that controls all decision variables. It should be noted that each reservoir system includes a number of unique characteristics due to its particular geographic location, local climate conditions, and downstream requirements; and hence it needs to be studied individually.

Optimizing the operation of existing water resources and structures is of particular importance in arid and semi-arid countries such as Iran where water demand is on the rise. Because of the high geographical variability of rainfall in Iran, reservoir operation occupies an important place in the usage of water resources. An efficient approach to defining reservoir operation is to use optimization models in combination with simulation models (Ngo et al. 2007). The main advantage of simulation models is that they provide insight into how the real system might perform over time under varying conditions.

In this chapter the combination of optimization and simulation studies for long periods on ZayandehRud reservoir located in central part of Iran is presented. Many areas of Iran, in particular central regions, have recently been suffering draught, with large proportions of the country's crops and livestock perishing while it is difficult to supply the industrial and agricultural water demand. Thus, obtaining appropriate operation policies and scenarios can help managers with decision making to attain optimum allocation of water resources based on priorities and downstream demands. The main objectives of the ZayandehRud reservoir study regarding a monthly simulation–optimization model are:

1. To derive an optimal operational policy for assessing the amount of allocated water to all downstream demands (agricultural, domestic, industrial, and environmental) with regards to minimizing shortages, and
2. To simulate reservoir conditions using optimized data record of 47 years (1957–2003) for the Zayandehrud reservoir.

6.2 Optimization Analysis

Optimization or optimality is the expression that is referring to the study of minimizing or maximizing a real function by selecting the values of real or integer variables systematically from within an acceptable interval. This concept

essentially is used for improving the efficiency of system and gains the best available values of some objective function in the problem area. As described in previous chapters optimization problems can be divided into two fundamental parts: the objective function, and the set of constraints. The objective function describes the performance criteria of the system. Constraints describe the boundaries and restrictions under which the system or process is being analyzed. In general, constraints include physical characteristics of the reservoir system such as storage capacities, diversion or stream flow requirements for various purposes, and mass balance. An optimal solution is a set of values of the decision variables that satisfy the constraints and provides an optimal value of the objective function.

LINGO, one of the simplest tools commonly used to formulate, solve, and analyze different linear and non-linear optimization problems, has been applied as an optimization model throughout this study. LINGO is capable of modeling all systems (large or small) for linear or non-linear problems. It creates related groups for solving the problem in which these groups are determined based on the inherent defined problems such as discharge, precipitation, demand, time period, etc. Then, LINGO allows the placing of similar objects into a *set* and uses a single statement for all elements of a set. This model allows a user to quickly input model formulation, assess the correctness or appropriateness of the formulation based on the solution, quickly make minor modifications to the formulation, and repeat the process. Many researchers such as Bozorg Haddad et al. (2008) and Montazar et al. (2010) have applied LINGO to arrive at an optimal allocation plan of surface and ground water for various types of hydrosystems.

Application of optimization techniques to reservoir operation problems has been a major focus of water resource management for some time (for comprehensive surveys, see Wurbs 1993 and Labadie 2004). Bower et al. (1962) recommend two rules for determining releases over a specific period: a Standard Operation Policy (SOP) and a hedging rule. The SOP calls for a target release in each period, if possible. If insufficient water is available to meet the objective, the reservoir releases all the available water and becomes empty; if too much water is available, the reservoir can fill up and spill the excess water. Different optimization models include linear, nonlinear and dynamic programming, which have been used to recognize the hedging rules with respect to the economic return or other system products such as water supply reliability (Hashimoto et al. 1982; Shih and ReVelle 1995; Neelakantan and Pundarikanthan 1999; Shiau and Lee 2005). The linear-based models are still popular and effective tools in dealing with optimization problems (Rani and Moreira 2009). Linear Programming (LP) is concerned with solving problems where all relations among the variables include the constraints and the objective function, and that all underlying models of real-world processes are linear. Latif and James (1991) presented a linear programming-based conjunctive model and applied it to the Indus basin in Pakistan to maximize the net income of irrigators. Peralta et al. (1995) developed a linear programming-based simulation optimization model to obtain sustainable groundwater extractions over a period of five decades, under a conjunctive water use scenario. Shih and Revelle (1995) investigated a discrete hedging rule for water supply operation during

droughts and impending droughts by applying a mixed integer linear programming model. Devi et al. (2005) presented a linear programming model for optimal water allocation in a large river basin system. They applied the model to the trans-boundary Subernarekha River in India. Loucks and Beek (2005) introduced and compared various methods of water resource system optimization based on linear programming in the LINGO model. Sudha et al. (2007) studied the effects of optimization on the efficiency of water use in agriculture and highlighted what is needed for optimizing reservoir operation.

6.3 Simulation Analysis

One of the most efficient ways of analyzing water resource systems is applying simulation models. These models work based on physical relatives with a series of operational rules to simulate new conditions and system behavior under a specified policy. HEC's ResSim reservoir simulation program is a computer program applicable for hydrologic and hydraulics of reservoir system simulation. This model is also used for research in water resources management to survey the connection between decisions support system and GIS. HEC-ResSim developed by the United States Army Corps of Engineers (USACE) is the new extension of the HEC-5. This model is commonly used for simulation of flood control and conservation systems alternative analysis. HEC-ResSim, reservoir simulation program applies reservoir operation for critical state variables with operational investigation or variance purposes as constraints. The reservoir simulation models for flood control are generally defined based on single guide curves that cause for the creation of optimum realization of benefits (Timothy and Curran 2003). This program simulates reservoir operation, including all characteristics of a reservoir and channel routing downstream. The model also allows users to define alternatives and run simulations simultaneously to compare results. On this basis, HEC-ResSim as a simulation tool is able to manage drought situations where the objective is to access the impacts of different drought rules, their timing, and impacts to activate emergency measures. Computations can be performed, and the results are viewed within the simulation module. In this case, many problems require determination of the properties of the output of a system given the input and transfer function. When the transfer function is simple, the properties of the output can be obtained analytically. But when transfer function is complex, the derivation of the properties of output maybe difficult (Olani 2006). Hec-ResSim involves three main functions that are called modules and are briefly described as:

1. Watershed setup, contains system elements and basic geographic information,
2. Reservoir network, used to create a water resource network, and
3. Simulation module that performs, identifies, and manages outputs of simulation or optimization runs.

Each module has a unique purpose and an associated set of functions accessible through menus, toolbars, and schematic elements. HEC-ResSim allows the change of the background layer to show the physical layout of the system. i.e., it is possible to import an Arc GIS shape file of watershed into the HEC-ResSim and put in the background of program. Input data of HEC-ResSim include stream flow, demands (i.e., domestic, Industrial, agricultural withdrawals), power generation (if is available) and reservoir operations. Necessary data for reservoir operation includes providing adequate data of reservoir capacity, evaporation and diversions, capacity of spillway and elevation-volume curves. The main parts of ResSim program can be written as bellow:

1. Schematic which is a part of watershed module and include a schematic network of streams and rivers of watershed.
2. Module Elements to show different element in a network such as reservoirs, reaches, junctions, and diversions.
3. Operation Scheme that includes necessary criteria for reservoir release decisions.
4. Alternatives; this option allows to user to compare estimated results.
5. Analysis Tools to analyze the results of simulation and also preparing summary reports and HEC-DSSVue.

This model has been applied for simulating the history of events, especially for flood and drought periods (Hanbali 2004). Babazadeh et al. (2007) considered the performance of a storage dam by HEC-ResSim simulation model under various scenarios in present conditions and different periods considering sedimentation. Other researchers who have used this model for simulation are Olani (2006) and Klipsch (2003). The main computer programs for reservoir system modeling using simulation and optimization were reviewed by Ejeta and Mays (2002) and Wurbs (1993). Karamouz and Vasiliadis (1992) investigated a non-linear optimization model along with simulation model to analyze the long-term performance of a reservoir system. Reservoir simulation models for flood control are generally defined based on single rule curves that bring about optimized benefits (Timothy and Curran 2003).

6.4 Case Study

Water demands change from year to year and month to month. There are many physical, social, economic, and political reasons for these alternations. In recent years, significant climatic changes have been observed in many parts of the world, including more severe floods, greater precipitation, and even unusual droughts in many areas of the world. These changes have considerably influenced the water demands in many parts of the world including Iran that many regions of which are classified as arid ore semi arid. Iran has a variable climate and it has an arid

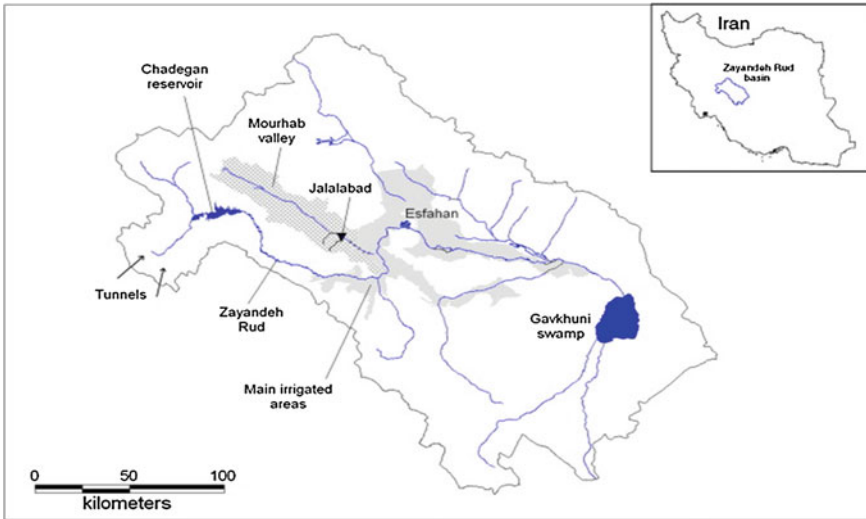


Fig. 6.1 The schematic view of ZayandehRud basin (Molle and Mamanpoush 2012)

climate in the central regions and most of the relatively scant annual precipitation falls from October through April and in some parts of the country, annual precipitation average is 25 cm (~ 8 in.) or less. Due to limited water resources, optimal operation of these resources is unavoidable. Latest estimates show, the demand for water in Iran will be 116.2 billion cubic meters in 2020 with a population of 100 millions where agriculture and fishery fields are the greatest water consumers (Babazadeh et al. 2007). Obviously, it is necessary to do more research toward storage and management of water resources to meet different demands in the country. In Iran, reservoirs are usually constructed to provide multiple purposes, such as irrigation, municipal and industrial water supply, and hydropower generation. Because of the high geographical variability of rainfall in the country, reservoir operation occupies an important position in the usage of water resources. So, understanding reservoir behavior and optimal release are crucial for envisaging drought period and maximizing the annual net benefit. The final output expected from water management studies is an optimization and simulation model that will be used to assess given situations and constraints.

The Basin of ZayandehRud River is located in the west central part of Iran and is the major water source for Isfahan Province. This river is one of the most important rivers of Iran and the largest river in Isfahan Province. It starts in the Zagros Mountains and flows 400 km eastward before ending in the Gavkhouni Marsh, a seasonal salt lake, in the south-east of Isfahan City (Fig. 6.1). It is important to note that the ZayandehRud reservoir also is known as Chadegan reservoir since it is located in Chadegan area.

The River basin has an area of 41,500 km², altitudes change from 3,974 to 1,466 m above mean sea level (msl), annual average rainfall (precipitation) is 130,



Fig. 6.2 The schematic view of ZayandehRud basin (Molle and Mamanpoush 2012)

Table 6.1 Physical characteristics of ZayandehRud dam

Characteristics	Description
Type of dam	Concrete arch dam
Elevation from foundation (m)	100
Crest length (m)	450
Type of spillways	Gated spillway
Reservoir gross capacity (MCM)	1,470
Min elevation of operation (MCM)	210
Effective capacity (MCM)	1,250
Regulated annual water (MCM)	1,200
Irrigated area (ha)	95,000
Area of reservoir (km ²)	4,130

and monthly average temperature range of 3–29 °C. Managing optimum operation of Zayandehrud Reservoir is unavoidable because of high limitations of available water resources and recently severe droughts in the province of Isfahan. The ZayandehRud Dam and its physical characteristics are shown in Fig. 6.2 and Table 6.1, respectively.

Isfahan is a generally arid region, with agriculture, industry, and municipalities all dependent on the river as an economical source of water that seems insufficient to meet the need for water. So, there are many transbasin diversions constructed from other basins which are delivering water to the reservoir. Since many years ago there has been severe shortage of water, an optimal exploitation from available water sources has become the most important and intricate problem in the Zayandehrud basin.

To deal with varying flow of the river, reservoirs have been built and inevitably the government has done several transbasin diversion projects such as; Koohrang 1, Koohrang 2, and Cheshme Langan with a total of 900 million cubic meters annual input has been implemented. Another transbasin diversion plan, the Koohrang 3 which is ongoing will have annual input of 250 MCM. The most important project of transferring water which is under study is called the Behesht Abad, consisting of, reservoir dam, tunnel with 5.5 m diameter and 65 km length with 1,100 MCM average annual input.

6.5 Optimization Model

The main objective of this study is to maximize the total reservoir release by considering domestic, industrial, and environmental aspects as major priorities over the planning horizon. Hence, the objective function of the problem can be written as follows:

$$\max Z = \sum_{i=1}^N R_i \quad (6.1)$$

where, R_i is the regulatory water release of the i th month and N is the planning horizon (total months of optimization, in this case $N = 564$).

It is important to note that Eq. 6.1 is used for single-objective optimization and solving it results in maximizing the dam's total regulatory water within 564 months. The general form of the intended linear optimization model can be written as:

$$F(x) = c_1x_1 + c_2x_2 + \dots + c_Nx_N = \underline{c}^T \underline{x} \quad (6.2)$$

where c_1, c_2, \dots, c_N , are real numbers, c^T is the transposed vector of vector c , and vectors c and x are defined as:

$$\underline{c} = \begin{bmatrix} c_1 \\ \vdots \\ c_N \end{bmatrix} \quad \text{and} \quad \underline{x} = \begin{bmatrix} x_1 \\ \vdots \\ x_N \end{bmatrix}$$

where x_1, x_2, \dots, x_N are the problem decision variables. So, Eq. 6.1 can be written as:

$$\max Z = \sum_{i=1}^N R_i = (R_1 + R_2 + \dots + R_N) = \underline{c}^T \underline{x} = K \quad (6.3)$$

The requirement values for each month of the period are constant and known, and hence, the second term of Eq. 6.3 is constant and its value is considered as K . Therefore, the amounts of coefficient matrixes and decision variable are as follows:

$$\underline{c} = \begin{bmatrix} +1 \\ \vdots \\ +1 \end{bmatrix} \quad \text{and} \quad \underline{x} = \underline{R} \begin{bmatrix} R_1 \\ \vdots \\ R_N \end{bmatrix}$$

As reservoir water balance must be preserved in all stages of optimization, the reservoir continuity equation is considered the main constraint in this case. The reservoir continuity equation can be written as:

$$S_{i+1} = S_i - R_i + I_i \quad i = 1, 2, \dots, N \quad (6.4)$$

where S_i is the reservoir volume in the month, S_{i+1} is the reservoir volume in the $(i + 1)$ th month, R_i is the released volume of water from the reservoir in the i th month, and I_i is the inflow to the reservoir in the i th month.

6.5.1 Boundary Conditions

1. Based on the policies of the Ministry of Energy of Iran, the priority demands in ZayandehRud basin are domestic, industrial and environmental, and should be fully supplied in the planning horizon. In other words, the minimum allowed release of the dam must supply the total needs of the mentioned priorities in each month. Equation 6.5 shows the boundary conditions in this case:

$$(D_I + D_E + D_D)_i \leq R_i \leq (D_I + D_E + D_D + D_A)_i \quad (6.5)$$

where D_I is the industry requirement, D_E is the environmental requirement, D_D is the domestic requirement, and D_A is the agricultural requirement.

Equation 6.5 demonstrates that the agricultural water demand will be sacrificed during shortage and all the water in this sector will be dedicated to other sectors to minimize priority deficiencies.

2. The maximum reservoir capacity equals 1,250 MCM and $0 \leq S_i \leq S_{\max}$.
3. The starting month for optimization is January and the Zayandehrud reservoir is almost half full in January of different years. So, it is assumed that the reservoir is half full at the beginning of optimization, or $S_1 = 580$ (MCM).

6.6 Finding Outlier Data

Outlier data means the data that are significantly higher or lower than normal range of time-series data. For extreme data that appear to be high or low outliers they can be tested with the Bulletin 17B detection procedure as follows. Based on long term optimization in this study (47 years), finding outlier data is necessary.

Table 6.2 Initial information for outlier test

Statistical parameters	Quantity
Mean	2.099
Standard deviation	0.337
Y_{oh}	3.158
Y_{ol}	1.041
n	564
k	3.138

1. Use the sample size (n) to obtain the value of the detection deviate K_0 (in this study, regarding to the 564 inflow data, K_0 is 3.148,
2. Compute the mean (\bar{Y}) and standard deviation (S_y) of the logarithms of the series data,
3. Compute the value of the detection criterion for high outliers (Y_{oh}):

$$Y_{oh} = \bar{Y} + K_0 S_y \quad (6.6)$$

4. Compare the logarithm of the extreme data being considered (Y_h) with the criterion (Y_{oh}). If $Y_h > Y_{oh}$, then the data can be considered a high outlier,
5. For low outlier data, compute the value of the detection criterion as follows.

$$Y_{ol} = \bar{Y} - K_0 S_y \quad (6.7)$$

6. Compare the algorithm of the extreme data being considered (Y_1) with the criterion (Y_{ol}). If $Y_1 < Y_{ol}$, then the data can be considered a low outlier. In this case, the coefficients and data are as follows (McCuen 2005).

For this example, Table 6.2 illustrates the initial information that is required for Bulletin 17B procedure.

Based on the initial information in Table 6.2, the outlier test was performed and the results are shown in Table 6.3. The results of outlier test show that there is no outlier data for ZayandehRud basin.

Table 6.3 Outlier test for inflow data to ZayandehRud reservoir

Rank	Inflow to ZayandehRud	Log of data	High outlier test	Low outlier test
1	82	1.913	No high outlier data	No low outlier data
2	93	1.968	No high outlier data	No low outlier data
3	140	2.146	No high outlier data	No low outlier data
4	301	2.478	No high outlier data	No low outlier data
5	286	2.456	No high outlier data	No low outlier data
6	228	2.357	No high outlier data	No low outlier data
7	157	2.195	No high outlier data	No low outlier data
8	92	1.963	No high outlier data	No low outlier data
9	52	1.716	No high outlier data	No low outlier data
10	48	1.681	No high outlier data	No low outlier data
11	57	1.755	No high outlier data	No low outlier data
12	104	2.017	No high outlier data	No low outlier data
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557	315.5242	2.499	No high outlier data	No low outlier data
558	206.4787	2.3148	No high outlier data	No low outlier data
559	138.0758	2.140	No high outlier data	No low outlier data
560	75.99744	1.880	No high outlier data	No low outlier data
561	44.21952	1.645	No high outlier data	No low outlier data
562	37.11744	1.569	No high outlier data	No low outlier data
563	43.23456	1.635	No high outlier data	No low outlier data
564	58.4496	1.766	No high outlier data	No low outlier data

6.7 Simulation by HEC-ResSim

Simulation of reservoir system by ResSim is based on utilizing physical information of the reservoir, importing inflow data and downstream demands. The steps of simulating process in this study can be summarized according to following steps:

1. Collecting necessary data and reservoir modeling,
The required data for the ZayandehRud reservoir has been collected from the administration for 47 water years (1957–2003).
2. Develop a schematic view of the watershed and create major parts of basin such as location of reservoir(s), junctions, and etc. shown in Fig. 6.3. Geo-referenced map files of the ZayandehRud basin (identified in step one) is used as schematic background of the model.
3. HEC-ResSim contains seven methods for routing streamflow (Coefficient, Muskingum, Muskingum-Cunge 8-pt Channel, Muskingum-Cunge Prismatic Channel, Modified Puls, SSARR, and Working R&D Routing), for flow routing in the main channel and major tributaries. As the study area is located in an arid climate, the effect of flooding is ignored.

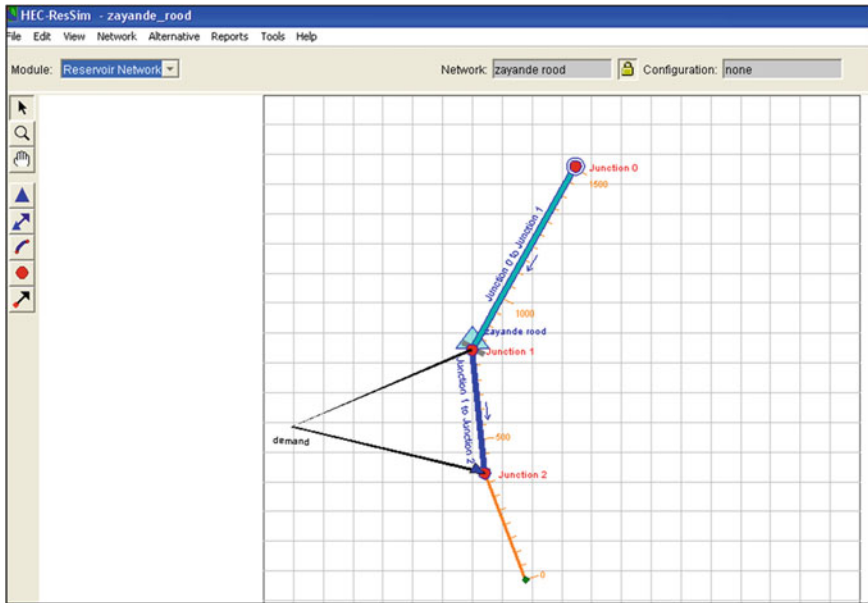


Fig. 6.3 Reservoir network modules of HEC-ResSim for ZayandehRud reservoir

4. Providing operational and physical data for any reservoirs in the watershed. The physical data of reservoir involves; the length and elevation of crest of dam, the capacities of outlet structures, pool storage definition of reservoir, etc.

During simulation by ResSim, various types of data should be applied in which they are classified as follows in this study:

1. Time-series data; monthly inflow to ZayandehRud reservoir is used for 47 years (1957–2003), and
2. Physical data include; elevation-storage-area of the ZayandehRud reservoir, reach between reservoir and sources of demands in downstream, outlet capacity curves for spillway, and junctions and diversions between the reach and demands (agricultural, environment, and industrial). The top and bottom elevations of the Zayandehrud reservoir are 2,060 and 2,005 m, respectively.

In addition, the following constraints are considered for desired case of study:

1. Evaporation of surface water,
2. The sediment profile of 50 years has been used at the beginning of the simulation period (administration of dam),
3. Simulation period is 47 years (1957–2003),
4. Operation policy is based on demands in downstream of reservoir, and
5. Based on the previous studies, the amount of seepage in the ZayandehRud reservoir is negligible, so, in this study it has been ignored.

Table 6.4 The values of current and new rule curve based on the optimized data

Month	New rule curve	Current rule curve
January	73	73
February	74	74
March	132	185
April	197	276
May	218	314
June	296	395
July	237	311
August	243	315
September	192	241
October	190	250
November	131	179
December	75	75

6.8 Study Results

6.8.1 Reservoir Operation Policy

Reservoir-river operation is based on specific policies that present practical guidelines for the amount of stored or released water from the reservoir to meet project requirements. A rule curve comprises static policies and practical guidelines to determine specific operation policies for downstream flow requirements and reservoir operation. In this study, LINGO 11.0 was applied for the single-objective optimization, and total releases were optimized by the model from 1957 to 2003.

After that, the optimized monthly averages of regulatory release were used to attain the new rule curve for ZayandehRud reservoir which will be used as a guideline for dam administration to find the best water allocation to downstream demand, and optimal water distribution to different sectors to minimize deficiency. Table 6.4 and Fig. 6.4 show the proposed and the new rule curves for different months of the year.

6.8.2 Operation Policy Performance

Evaluating reservoir operation policy performance is an important step in an optimization model. A major indicator is the reliability index (a), which was defined as the probability that the system output is satisfactory or the probability that the system will not fail in a given period. Reliability can also be defined as a probability of providing a specific percentage of water for demand in the given time period. Hashimoto et al. (1982) investigated reservoir operation system performance with a reliability index and presented Eq. 6.8:

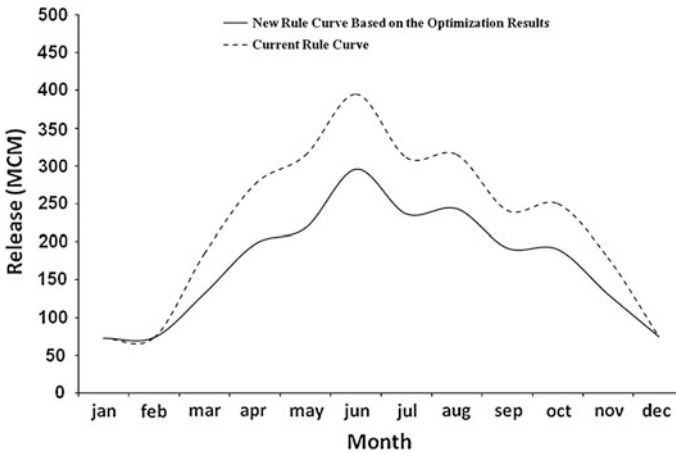


Fig. 6.4 The proposed and the new rule curve

Table 6.5 Reliability index for ZayandehRud reservoir

Reliable months		Percentage of reliable months (%)	
Opt.	Non-opt.	Opt.	Non-opt.
463	402	82.1	71.3

$$a = \frac{\text{The number of months with standard supply}}{\text{Total months}} \times 100 \tag{6.8}$$

Reliability analysis has shown that the reliability index of regulatory water increased 10.8 % for priority demands (Table 6.5).

6.8.3 Optimization Outcomes

The regulatory dam releases were evaluated by executing a simulation model for optimized and non-optimized conditions. The values of water elevation and storage volume before and after optimization analysis (from 1999 to 2001), as sample results, are presented in Tables 6.6 and 6.7. The trend of varying water elevation and water storage volume under optimization and non-optimization conditions also are shown in Figs. 6.5 and 6.6, respectively.

As the volumes of reservoir storage are 636.1 and 336.8 MCM for optimized- and non-optimized operation, respectively, the reservoir storage volume increased about 88.9 % under the optimized operation condition.

Increasing the average storage in the reservoir allows dam administrators to distribute water based on priorities and decrease deficiencies in draught seasons. Furthermore, optimization results signified that the reservoir is full for 33 months

Table 6.6 The variations of water elevation under optimized and non-optimized conditions in 1999–2001

Months	1999		2000		2001	
	Opt.	Non-opt.	Opt.	Non-opt.	Opt.	Non-opt.
January	2,009.7	2,009.7	2,009.5	2,009.5	2,014.7	2,014.7
February	2,009.8	2,009.8	2,010.1	2,010.1	2,016.4	2,016.4
March	2,013.3	2,011.4	2,012.9	2,010.2	2,019.5	2,017.4
April	2,024.2	2,018.1	2,016.7	2,009.6	2,027.3	2,021.3
May	2,027.3	2,014.5	2,016.3	2,009.5	2,032.9	2,022.3
June	2,020.6	2,009.5	2,010.0	2,009.5	2,031.6	2,013.1
July	2,009.8	2,009.5	2,009.5	2,009.5	2,024.7	2,009.5
August	2,009.5	2,009.5	2,009.5	2,009.5	2,012.9	2,009.5
September	2,009.5	2,009.5	2,009.5	2,009.5	2,009.5	2,009.5
October	2,009.5	2,009.5	2,009.5	2,009.5	2,009.5	2,009.5
November	2,009.5	2,009.5	2,009.5	2,009.5	2,009.5	2,009.5
December	2,009.5	2,009.5	2,010.8	2,010.8	2,009.5	2,009.5

Table 6.7 The variations of storage volume (MCM) under optimized and non-optimized conditions in 1999–2001

Months	1999		2000		2001	
	Opt.	Non-opt.	Opt.	Non-opt.	Opt.	Non-opt.
January	99.1	99.1	97.5	97.5	147.7	147.7
February	99.8	99.8	102.7	102.7	166.4	166.4
March	134.3	115.1	129.5	103.9	204.3	177.8
April	268.7	186.2	169.6	98.8	319.4	226.6
May	317.6	147.2	164.9	97.5	421.3	239.8
June	220.7	97.5	102.3	97.5	396.1	133.5
July	99.8	97.5	97.5	97.5	276.6	97.5
August	97.5	97.5	97.5	97.5	131.7	97.5
September	97.5	97.5	97.5	97.5	97.5	97.5
October	97.5	97.5	97.5	97.5	97.5	97.5
November	97.5	97.5	97.5	97.5	97.5	97.5
December	97.5	97.5	109.7	109.7	97.5	97.5

(5.9 %) and four months (0.7 %), and empty for 76 months (13.5 %) and 181 months (32.1 %) under optimized and non-optimized conditions, respectively (Table 6.8).

6.9 Discussions

As the Zayandehrud reservoir is located in a semi-desert area and the annual average precipitation in Esfahan Province is only 130 mm per year, there is a constant shortage in the Zayandehrud basin; and even with optimized operation,

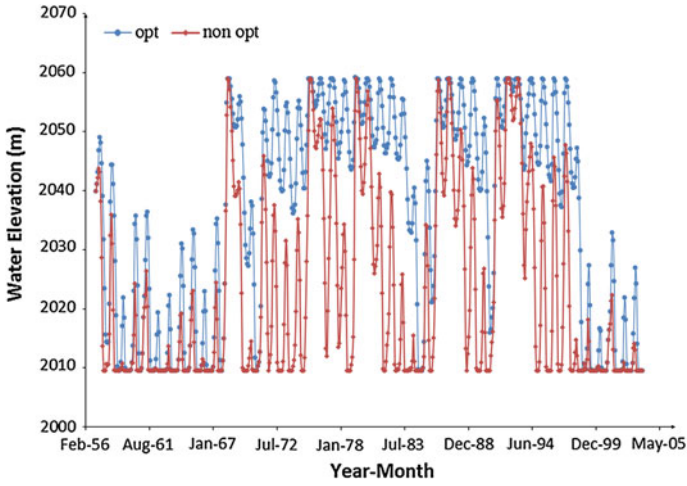


Fig. 6.5 Water elevations in optimized and non-optimized conditions

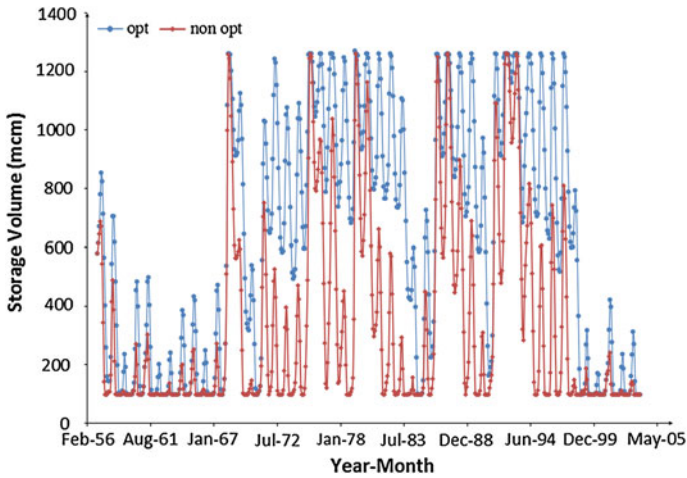


Fig. 6.6 Water storage volume in optimized and non-optimized conditions

Table 6.8 The number of months that reservoir is full or empty

	Opt.	Non-opt.
Number of months reservoir is full	33	4
Percentage that the reservoir is full (%)	5.9	0.7
Number of months reservoir is empty	76	181
Percentage that the reservoir is empty (%)	13.5	32.1

Table 6.9 The mean of regulated water in 47-year for total demands (MCM)

Months	Demands	Optimized	Non-optimized
January	73	69	67
February	74	72	72
March	185	136	178
April	276	219	271
May	314	255	303
June	395	302	335
July	311	225	232
August	315	209	186
September	241	149	116
October	250	138	110
November	179	106	95
December	75	70	68
Annual (sum)	2,688	1,952	2,033
Supply (percent)		72.6	75.7
Number of month with deficit		101	162
Reliability (%)		82.1	71.3

downstream needs cannot be completely accommodated. However, the important point is finding the best policy to allocate water between downstream demands using optimization analysis considering the priorities (drinking water, industrial and environmental).

Table 6.9 shows the total regulatory volume to supply downstream operation demand under both non-optimized and optimized operation conditions. The results demonstrate that the annual regulating volumes of the Zayandehrud dam are 2,033 MCM for non-optimized conditions, but decrease to 1,952 MCM under optimized operation. Under the optimized and non-optimized operating conditions on average, 72.6 and 75.7 % of downstream demand would be met, respectively. The results reveal that water allocated for the agricultural sector is sacrificed by getting distributed among other sectors in the optimization process, so the total release is reduced here. According to the results, about 70 % of downstream requirements were supplied under optimal and non-optimal conditions in different months of the 47 year period.

Figure 6.7 shows the average of the total regulatory volume under the non-optimized and optimized operating conditions in conjunction with total downstream demands. By considering 70 % supply of downstream demand in all months, there would be 101 months of shortage in optimized condition, while, there are 162 months of shortage under non-optimized conditions. It can be concluded that the reliability of system would be 82.1 and 71.3 % in the optimized and non-optimized conditions, respectively. Figure 6.8 shows the average of optimized and non-optimized regulatory volume for drinking, industrial and environmental purposes of ZayandehRud reservoir. The results demonstrate that the annual regulatory volume to meet the drinking, industrial and environmental needs under

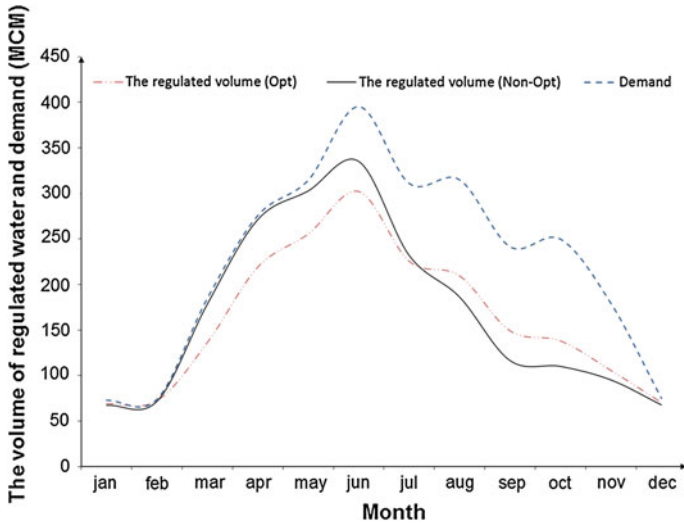


Fig. 6.7 Total downstream demands and the average of total regulatory volume

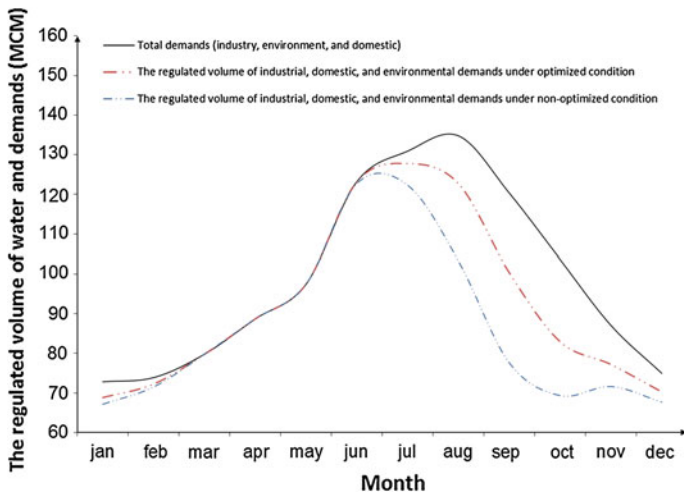


Fig. 6.8 Average of regulatory volume for drinking, industrial and environmental needs

non-optimized and optimized operational conditions are 1,039 and 111 MCM per year, respectively. On average, 93.6 and 87.5 % of the required water for domestic, industrial and environmental purposes was met under the optimized and non-optimized operating conditions, respectively. Although deficiency still exists under the optimized condition for all priorities and it is only 6.4 %; however,

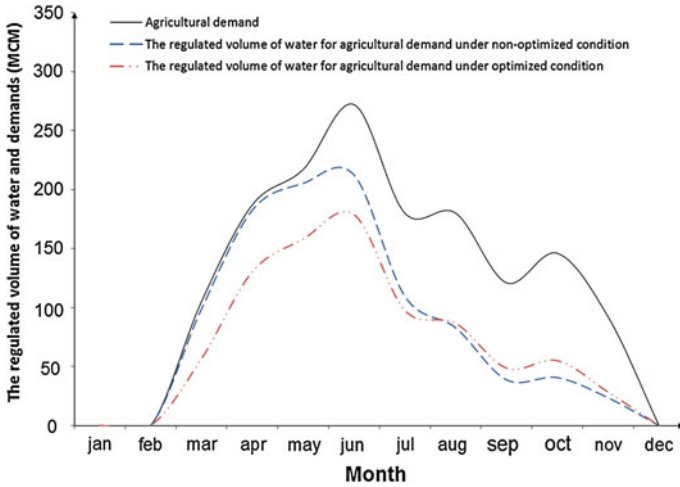


Fig. 6.9 The regulated volume of water for agricultural sector

under the non-optimized condition it is 12.5 %. This was overcome by the use of supplementary wells in the domestic and industrial water supply network and mostly applied during peak water requirement.

Furthermore, it can be observed that the Zayandehrud reservoir cannot supply the required needs of priorities for 99 and 206 months under optimized and non-optimized operating conditions, respectively. So, the reliability index is 82.4 and 63.5 % under optimized and standard operating conditions, correspondingly. In other words, under standard condition, 63.5 % of the water supply would be on the safe side, while in the optimal operating condition 82.4 % of the required water can be provided.

Finally, the achieved results revealed that the annual regulatory volume of the ZayandehRud dam to meet agricultural needs under non-optimized and optimized conditions were 994 and 840 MCM per year, respectively. The agricultural demand was supplied by 56 % under the optimized and 66.3 % under the non-optimized conditions. In other words, during the planting season, the agricultural sector would have faced 44 and 33.7 % deficit in irrigation supply in optimized and non-optimized operating conditions, respectively. Increased deficiency under the optimized condition is due to considering the lowest priority in the agricultural sector and allocating its water to other parts with higher priorities during shortage. The reliability indexes of agricultural water supply were 71.3 and 52.1 % under non-optimal and optimal operation conditions, correspondingly. These values demonstrate that the water allocated to the agricultural sector is sacrificed and distributed among other priorities (Fig. 6.9).

6.10 Conclusions

This chapter focused on the operation of the ZayandehRud reservoir using a combination of LINGO and HEC-ResSim optimization and simulation models. Study results prove that the applied methods can efficiently optimize the rule curves for operating the existing reservoir in a single-objective framework. In addition, optimizing resulted in increasing reservoir storage by about 88.9 %, increasing the time that the reservoir is full by about 5.2 %, and decreasing the time that the reservoir is empty by about 18.6 %. Although optimizing ZayandehRud reservoir results in a 3.1 % reduction of total supply, it also causes 10.8 % increased reliability index of regulatory water for all requirements. Furthermore, optimization resulted in an increase of 6.1 % of water supply and 19 % reliability index to supply priorities (drinking water, industrial and environmental).

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