

Optimal utilization of DEZ dam reservoir considering drinking water demand by dynamic programming technique

Karan Asadipooya, Rohoolla Kolbadi nezhad

M.sc, civil engineering, kish international branch, Islamic azad university, kish, Iran.

M.sc, civil engineering, kish international branch, Islamic azad university, kish, Iran.

Abstract

One of the elements of water resources management is optimal operation of country dam's reservoirs as the main sources of surface water. Usually in the operation of reservoir drinking water the main goal is to minimize the downstream requirements differences and improve released water. In this study, dynamic programming backward-based approach is used to determine water release value to optimize the operation of DEZ Dam Reservoir. The data analysis process is dynamically addressed on the MATLAB programming environment and using software such as Excel spreadsheets. In order to solve reservoir operation problem, stored values at the end of period t is intended as a decision variable. According to problem definition, the possibility to change this variable in the range of (830, 3340) is available. Meanwhile, obtained solutions accuracy as well as objective function value depends on discretization of decision variables. Initially, in order to display the model sufficiency, operation is considered for 5 years, 20 years and 40 year with interval length of 251 units and objective function value is obtained as 1.13, 6.85 and 14.82 for 5, 20 and 40 year operations, respectively. Finally, to assess dynamic programming method performance in solving optimal operation of reservoirs problem, corresponding results are compared with recent conventional meta-heuristic methods results and their performance are presented.

Keywords: operation of dam's reservoirs, optimization, drinking water, dynamic programming, DEZ dam

1. Introduction

Generally, adoption of different goals in the analysis of reservoir systems may cause various models realization of these systems. The main objective of these models is to regulate and evaluate different designs schemes in order to meet watery concerns and requirements. Moreover, engineering conventional models that have been used in reservoir were based on simulation and optimization models and their combinations. The principle of optimization models is to minimize or maximize an objective function that includes a number of decision variables and constraints (Daghighi et al., 2017). In other words, these models will automatically search for the most optimal decision variables values so that all constraints satisfy. The purpose of simulation models are to improve the design and operation policy. These models predict the behavior of their systems according to variables values specified by user (Nahvi et al., 2017).

In fact, optimization refers to determining values of decision variables for minimization or maximization of objective function. The simplest type of optimization problems is linear type that can be easily solved with linear methods and we defiantly accept optimal solution. But in nonlinear problems finding the optimal solution is not easily possible and finding optimal solution among the countless feasible solutions would be complicated and time-intensive. Therefore, several approaches such as meta-heuristic techniques include ant colony, genetics, PSO has emerged so that each of them are intended to find fastest way to reach the optimal solution. Dynamic programming can also be used as a method for solving optimization problems. One of the novel methods in optimization is dynamic programming (DP) that will be used in this study to optimize reservoir operation.

The optimal operation of dam's reservoirs has been favorable interest of researchers for several years and various optimization methods have been applied to this problem in order to find the optimal solution. So far, optimal utilization of DEZ dam reservoir rarely has been studied especially with regard to dynamic conditions (variable) for downstream outcomes and requirements in which in this research dynamic optimization algorithm (DP) is applied for DEZ dam reservoir operation taking into account all parameters variations.

In general, drinking and hydropower reservoir operation is examined. In this study, the optimal operation of DEZ reservoir drinking water will be conducted using dynamic programming. The decision variables to optimize reservoir operation are water flow output that these variables must be optimized during operation process. Meanwhile, constraints in this problem are defined in four categories:

A) Continuity equation satisfaction: in all phases of operation optimization of reservoir mass balance equation must be satisfied between input and output values and reservoir storage volume.

B) Reservoir storage volume: moreover, in all phases of operation optimizing of reservoir, storage volume should be between the minimum and maximum values.

C) Reservoir output: optimized output per period should be limited between minimum and maximum values.

The objective function considered is minimization of total damage resulting from demand and output repository difference where damage due to water release from system is defined as a function of system output dam difference respect to downstream demand.

Various models have been proposed for optimum utilization of the reservoir. Furthermore, deterministic and non-deterministic models as well as hybrid models have all been recruited to contribute human forces to exploit the natural water resources. Meanwhile, regarding to uncertainties exit in a reservoir input such as rainfall, melting snow and ice, or drought researchers are looking forward to develop a sufficient model to minimize unexpected damage despite all problems constraints.

Both deterministic and probabilistic dynamic programming model are being applied for the production of reservoir operation policies so that in deterministic model a series of definite input (historical or synthetic) are used to determine the policies of exploitation while in probabilistic type a statistical expression is demonstrated for occurrence of water flow.

In preparing monthly and annual operational rules of the reservoir using deterministic optimization model, a certain dynamic programming algorithm is used to predict reservoir inlet. Moreover, objective function defined

as minimizing the damages resulting from the operation in a specified time period that is considered as a function of output.

In probabilistic planning method the inclination is toward this direction that finally existed uncertainties can be more effectively involved in the decision-making process. In the most basic models uncertainty is not considered as an important factors in predictions process because to predict based on a time series mainly no analysis was adopted to determine the uncertainty. While the optimization models must ensure a level of uncertainty to determine future flow conditions and therefore it is necessary to apply an appropriate process with sufficient accuracy to register the predicted values. Therefore, probability of transmission from one location to the next one could be applied in the category of probabilistic dynamic model taking into account the uncertainty in predicting using Markov chain model. In mentioned model flow predictions for the next month, the real input in current month and the reservoir volume at the beginning of the month are used as situational variables.

The diverse and abundant examples of these optimization models are presented in which these techniques and their combination are utilized in operation models to improve and prepared policies of reservoir output flow. In this content, dynamic programming is one of the most practical techniques that recently are used for system modeling exploitation of reservoirs. Principally, dynamic programming is applicable for problem and final status planning in which temporal or spatial modes of system are considered.

A review of previous research:

In the first studies, Daniel (1981) and AE (1985) claim that dynamic programming methods are more suitable among different methods used in reservoir management issues. Moreover, applications of dynamic programming to analyze water resources have been reviewed by Yankowitz (1982). Moreover, several optimizer approaches have been proposed to exploit the reservoir such as hybrid simulator- optimizer methods. In addition, WerbZ et al (1985) and Siminovic (1992) proposed hybrid simulator- optimizer methods to exploit the reservoir. Yang and Reed (1999) provided DP model for hydroelectric system in New Zealand that could successfully produce electricity as well as optimized water release in tow reservoir system. Johnson et al utilized stochastic dynamic programming considering uncertainties of reservoir input level. Then Russell and Campbell (1996) applied a fuzzy model for solving a multi-objective problem and different parameters governing on dams. Furthermore, neural networks, fuzzy theory and stochastic processes are used to manage the dam reservoirs from 2000 until 2004 (Mousavi and Karamouz, 2004) and (Tylman et al., 2002). In addition, Daniel and others have different attitudes towards water resources that are classified into four categories: Linear programming, dynamic programming, nonlinear programming, and simulation-based techniques.

Due to this fact that generally different objectives are followed in water resources management many mentioned models are considered objectives such as drinking water and arable land supply, power generation, flood control, etc.(Daniel et al., Kahane et al).

Firstly, Mayes (1946) and Little, Brown (1995) before full explanation of dynamic programming model developed by Bellman (1957) adopted ideas about the step programming algorithm for operation of reservoir (Yankowitz, 1982). Similar ideas were adopted by Hall, Havel and Rafe from 1963-1966 which eventually Yang (1967) introduced a definite programming model with limited time horizon limit for a reservoir. From early 1980s, several studies have been conducted mainly as a case study so that the purpose of these schemes were to determine the optimal utilization policies for limited or unlimited period's intervals (Bellman, Kahal and Daniel).

Subsequently, several related studies have been conducted in Iran including Amerian (2003) presented dynamic programming model to provide optimal utilization of Bukan reservoir. Moreover, Momeni and Rezai (2008) have obtained Aras dam reservoir operation model using dynamic programming. In this study, it is assumed that river monthly discharge process is treat as Markov-based model so they used transition probability matrix between different states of flow and have achieved suitable results. Also, Moradi et al (2010) used a combination of dynamic programming and ANFIS method in Jiroft dam operation model. Moreover, Mihankhah et al (2011) also used and analyzed dynamic programming in the exploitation of water resources and Anvari (2013) has been undertaken a performance comparison of dynamic programming and nonlinear programming in zayandeh-rud dam.

Materials and methods

Dynamic programming:

In computer science, dynamic programming is an optimization method that is utilized for a set of temporal backtrack algorithms where sub-problems are called repeatedly. This method was introduced in 1953 by mathematician Richard Bellman. Dynamic programming is a well-known method in Mathematics and Computer Science that is used for developing optimized algorithms so that a similar sub-problem execution will be removed. Indeed, dynamic optimization method is based on the principle of optimality and this approach is feasible only in cases where this principle is permissible.

The principle of optimality contains the optimal solution of all sub-problems which refers to optimal problem solving. In other words, problem must be derived in such a way that finding the optimal solution may provide optimal solutions for all sub-problems. For example, to find the shortest path between two cities, the path between the origin and each node that is in the optimum route will be the most efficient path between these two cities. Optimality principle will be acceptable in a case, if an optimal solution for a particular sample of problem always contain the optimum solution for all sub-samples. Two general conditions are expressed to apply the principle of optimality in the problem: 1. objective function must be additive respect to decision variables and (2) objective function must be integer able respect to decision variables at every stage. Therefore, in order to utilize dynamic programming, optimization problem must satisfy conditions so that the most important of them are optimal infrastructure and sub-problems overlapping.

Using optimal infrastructure implies that problem is decoupled into small sub-problems and find the optimal solution for each of them and optimal solution of main problem will be obtained by deploying together these partial optimal solutions. For example, when solving the problem of finding shortest path from one vertex of a graph to other vertex, we can obtain the shortest path to the destination of all adjacent vertices and utilize them as general solution. In general, problem solving with this method consists of three steps: 1. problem decomposition into smaller parts 2. Solving these sub-problems through decoupling them recursively and (3) using partial solutions for realization of a general solution.

On the other hand, it may be said that problem includes overlap sub-problems if we could decouple problem into smaller sub-problems so that each solution may be used multiple times during the resolution process. However, dynamic programming helps to calculate each of these solutions only once time and the process of solving will not be incurred duplication costs. For example, in the Fibonacci sequence to calculate the fourth number of sequence we need to know the third number. Moreover, to calculate fifth number we need to be informed the third number. If in such a situation we want to count sixth number of Fibonacci sequence, in this calculation we must be informed the fourth and number. If we decide to calculate the fourth and fifth numbers subsequently during calculating each of these values, we may need the third number value and we should calculate it again. To avoid this multiple calculation dynamic programming algorithms usually use backward and forward procedures.

In backward or top-down approach, problem is decomposed into several sub-problems and each sub problem solutions after calculating are stored somewhere. In the next steps whenever this solution were needed, the solution is read from memory. This process is a combination of recursive algorithm and storage in the memory. But in forward or bottom-up approach, all desired sub-problems will be solved from small to large and solution will be used immediately for the next calculation and the calculation process continues to achieve the required sub problem (which is actually our main problem). Obviously, in this case using a recursive algorithm is not necessary.

In normal mode, backward approach needs to solve the recursive function and recalculating all stages before it to calculate the optimal solution for each stage. But as a practical approach, in most cases simultaneously with the calculation of an optimal solution, data selected in each sub-problem can be stored in a table to not recalculate this information. The idea of this method is to remember in a recursive algorithm. In this method, a table containing sub-problems solutions will be hold while the control structure to fill the table is similar to a recursive algorithm.

A recursive algorithm with the ability to remember, will assigns an element for each sub-problem solution. Each element in the table is initialized such that show still has not been assigned a value. When during running time sub-problem is called for the first time, its solution is calculated and stored in the table. In the next time when treated with sub-problem, the amount stored in the table is simply returned. In the present study, this method is

used to find optimum solutions. Without having to use memorization techniques, recursive algorithm is executed normally in exponentially time because it solves sub-problems over and over again.

Main components of a dynamic programming model include:

1. Convert it into several sub-problems, 2. Recognition of variables vector 3- identification of decision variables vector 4- system transfer function and finally solving any problem at any stage by solving a recursive equation.

The advantages of this method can be mentioned as following: Benefiting from a smart search algorithm in comparison with full search, a search-based methods and encompass properties without the need for continuity and derivative of a function, including capabilities to solve nonlinear problems, deriving issues of uncertainty and risk in these methods compared to gradients-based is extremely easier, it will be more efficient in higher constrained problems; Finally, it should be noted that the as search space is smaller, it will be more efficient.

But application of this method also has disadvantages that has limited it efficiency such as including less degree of Generality and in large scale systems with high dimension will cause memory problems.

DEZ dam specifications:

The DEZ dam is an arch dam on the DEZ River in the southwestern province of Khuzestan, Iran which is known as country's largest dams (Akram et al., 2013). The reservoir volume was estimated to be 2510 million cubic meters and average inlet water into reservoir of this dam during 40 years of operation was equal to 5303 million cubic meters. According to reservoir volume, maximum and minimum values of water supply for duration of operation were 3340 and 830 million cubic meters, respectively. Moreover, amounts of the monthly release water into downstream for minimum and maximum mode were 0 and 1,000 million cubic meters, respectively.

This dam is especially a concrete hydropower dam that is located about 26 km (16 mi) north of Andimeshk (Figure 1) and its reservoir helps irrigate up to 80,500 ha (199,000 acres) of downstream farmlands. Moreover, the 40-year-old outcomes of DEZ River is available monthly.

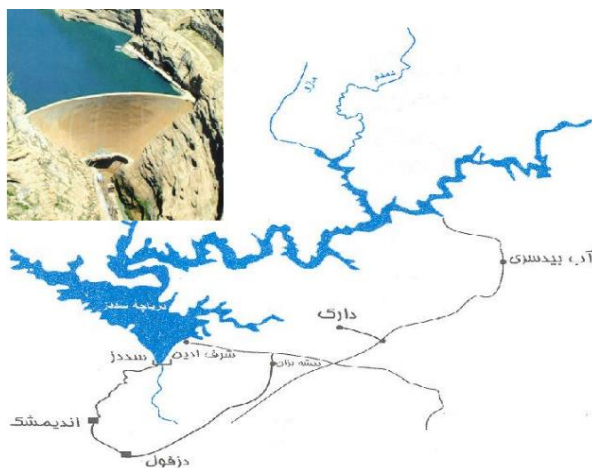


Figure 1 dose of double-arch concrete dam and its geographical location.

Problem Definition:

Usually in drinking water operation of the reservoir, the main goal is to minimize the differences downstream requirements and amount of water released. The drinking water operation of reservoirs is defined as following problem:

$$\text{Min TSD} = \frac{\sum_{t=1}^N (D_t - R_t)^2}{D_{\max}^2} \quad (1)$$

Taking into account the following constraints:

$$S_{t+1} = S_t + Q_t - R_t \quad (2)$$

$$S_{\min} \leq S_t \leq S_{\max}(3)$$

$$R_{\min} \leq R_t \leq R_{\max}(4)$$

Where in mentioned equations:

D_t : is downstream requirements during time interval t

R_t : released water into downstream during time interval t

$D_{\max}$: Maximum downstream requirements during the period of operation

Q_t : The river flows shedding into reservoir

$S_{\min}$: Minimum allowed value of reservoir water storage

$S_{\max}$: Maximum allowed reservoir water storage

$R_{\min}$: Minimum allowable level of water released

$R_{\max}$: Maximum allowable level of water released

Equation 1 defines the objective function. Equation (2) represents the water balance equation in the reservoir. Equations (3) and (4) are store water and released water of reservoir constraints, respectively.

Dynamic programming model structure:

In this study, to determine amounts of released water to optimize the operation of DEZ dam Reservoir, dynamic programming backward-based approach is used. Recursive function used is as follows:

$$F(s_t, Q_t) = \min\{F(s_{t+1}, Q_{t+1}) + TSD_{\min}\}(5)$$

As it is noted, DP model is a discrete model. Hence, the reservoir capacity has been discretized from 830 million cubic meters to 3340 cubic meters into 11 levels in order that we can decide what level of saving is preferable to per month. In cases where the volume of water saved and inserted is over 3340 we are forced to overflow the additional water flows. Continuity equation of water per month is defined as follows:

$$I_t + S_t - S_{t+1} - R_t = 0(6)$$

Where I_t is amount of water inlet into reservoir per month, S_t is water storage of reservoir in t -th month and S_{t+1} is amount of reservoir storage water in the next month and R_t is amount of water released which in highly filled month it encompasses overflow water. Meanwhile, model constraints are defined as follows:

$$830 > S_t > 3340 (MCM) (7)$$

$$0 \leq R_t \leq 1000(MCM)(8)$$

$$S_1, S_{12} = 1320 (MCM)(9)$$

Planning and Analysis:

In order to solve reservoir operation problem, the amount of reserve at the end of period t is intended as a decision variable. According to problem definition, this variable may possibly varies in the range of (830 and 3340). Moreover, results accuracy as well as objective function value depends on how discretized the decision variables. In order to display model efficiency, 5-year, 20-year and 40-year operations is examined taking into account the length of the interval as 251 units.

Results and discussion

Results obtained:

After analysis, the objective function value is determined as 1.13, 6.85 and 14.82 for 5, 20 and 40 years operation, respectively. Meanwhile, figures 2 to 4 demonstrate water released values for different periods during various operation intervals.

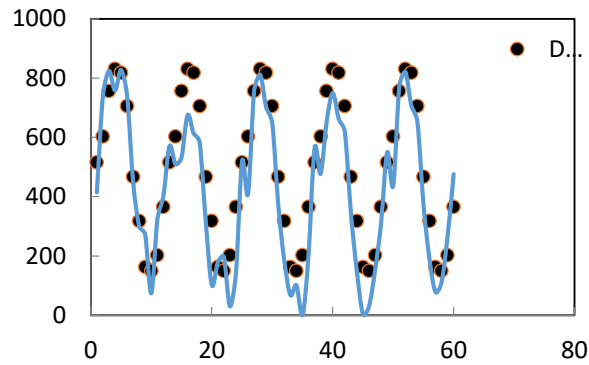


Figure 2. The release values in operation for 5 years.

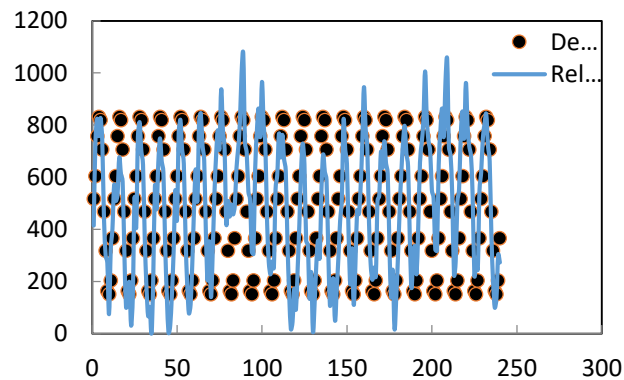
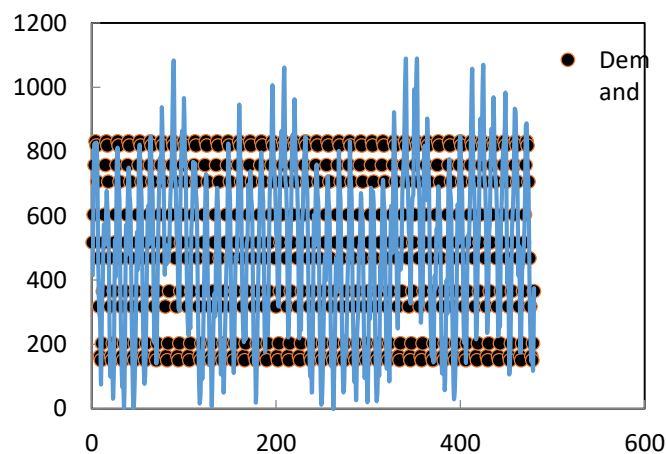


Figure 3. The release values in operation for 20 years.

Figure 4. The release values in operation for 40 years.



Sensitivity analysis respect to discretization intervals:

As previously mentioned, it is possible to improve problem solving accuracy by changing the range of decision variables discretization. In order to examine objective function variation respect to decision variables, objective function is calculated for different values of discretization intervals and shown in Table 1. Moreover, corresponding values and their variation are shown in Figures 5 to 7.

Table 1. Objective function variation by changing discretization intervals length.

Cost function value				discretization intervals length of decision variables (stored)
Operation for 40 years	Operation for 20 years	Operation for 5 years		
14.82	6.85	1,12756		251
10.67	4.805	0.6542		62.75
10.437	4.689	0.6882		10

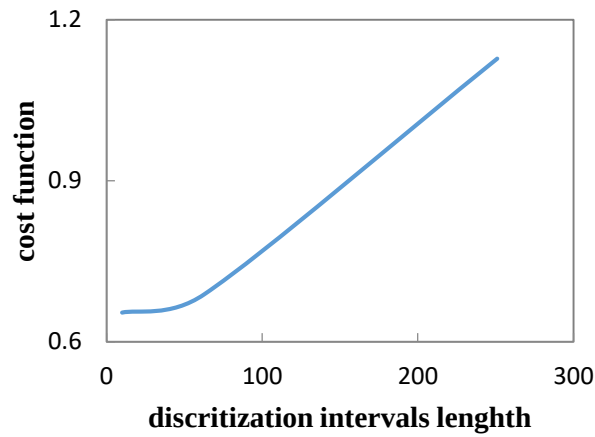


Figure 5. The objective function variation with discretization intervals during operation for 5 years.

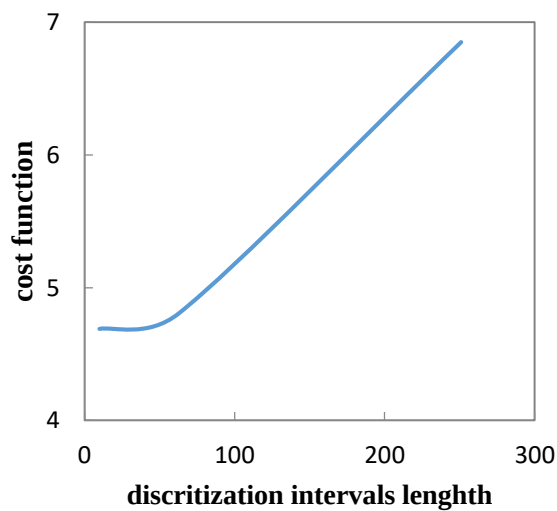


Figure 6. The objective function variation with discretization intervals during operation for 20 years.

Table 2. Comparison of minimum cost obtained during 5 years, 20 years and 40 years and comparison of presented DP models with CA, GA, PSO, ACO models that have been conducted by other researchers (Afshar and Moieni, 2008).

model	Months	Total cost	Computing time
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		period	(s)	
Dynamic Programming		60	1/13 E + 00	1/36
		240	6/85 E + 00	4/10
		480	1/48 E + 01	8/97
Non-penalized cellular automata		60	8/46 E-01	0.1
		240	4/83 E + 00	0.1
		480	1/06 E + 01	0.1
Penalized cellular automata		60	7/32 E-01	0.1
		240	4/80 E + 00	0.1
		480	1/06 E + 01	0.1
Genetic algorithm (Swarm/Colony size = 100)		60	8/44 E-01	3.5
		240	7/85 E + 01	14
		480	1/06 E + 04	27
Particle Swarm Optimization (Swarm/Colony size = 100)		60	2/86 E + 00	5.5
		240	4/95 E + 02	23
		480	1/87 E + 04	46
Ant Colony Optimization (Swarm/Colony size = 100)		60	8/54 E-01	30
		240	1/48 E + 01	121
		480	3/11 E + 02	244

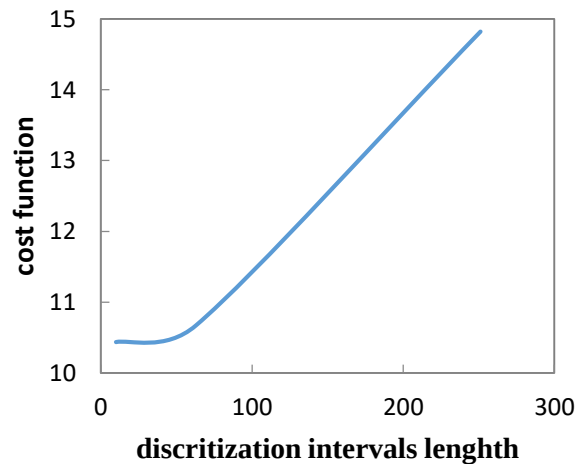


Figure 7. The objective function variation with discretization intervals during operation for 40 years.

According to figures 5 to 7 it can be seen that as length of the discretization interval is decreased, solutions accuracy will be increased and the minimum value of objective function is realized which means better solution is achieved however, in this case more computing time and cost should be spent. The results of this analyzes showed that interval length of 50 or smaller range will result most accurate solution of objective function and as this length is greater than 50, the minimum objective function is greater. According to this problem, most accurate solution of objective function at discretization intervals less than 50 will be equal to 0.6882, 4.689 and 10.437 for 5, 20 and 40 years, respectively.

Comparison of dynamic programming with heuristic methods:

In recent years application of heuristic methods for solving optimization problems has grown dramatically. The main reason for this generic popularity is due to generality of these methods in solving various optimization

problems as well as simplicity in implementation. The most common and most powerful heuristic methods are genetic algorithm (GA), ant colony optimization (ACO) and particle swarm optimization (PSO) algorithms. To evaluate the performance of dynamic programming method within optimal operation of reservoirs problem, obtained results of this method are expressed with cellular- automata, genetic algorithms, PSO and ACS in Table 2 that presented the end of paper. As can be seen from the table, dynamic programming method results are better than conventional heuristic techniques. However, the computational cost is rather than cellular automata (CA) methods, but it can be seen that this calculation times is less than famous heuristic techniques such as ACO, GA and PSO. It should be noted despite all the advantages of this method compared to heuristic techniques, it significantly requires to store as much data volume and as a consequence we have serious challenges with the big data problems. Moreover, the comparison made to better results analysis are presented in Figures 8 to 13.

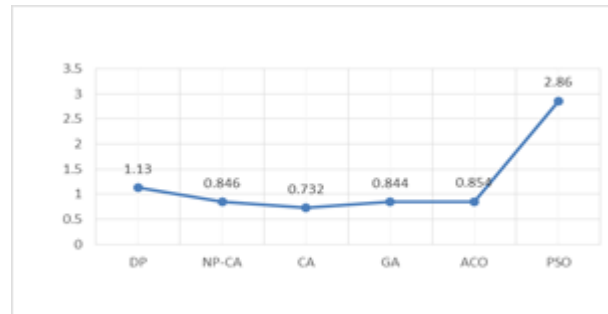


Figure 8. Comparison the value of objective function in DP with other methods in the period of 5 years.



Figure 9. Comparison analysis time in DP with other methods in the period of 5 years

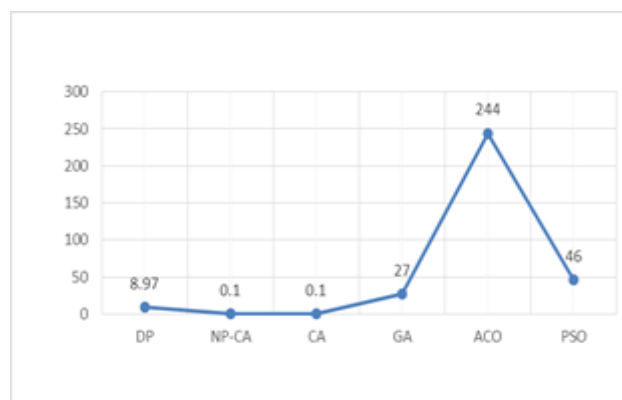


Figure 10. Comparison the value of objective function in DP with other methods in the period of 20 years.



Figure 11. Comparison analysis time in DP with other methods in the period of 20 years.

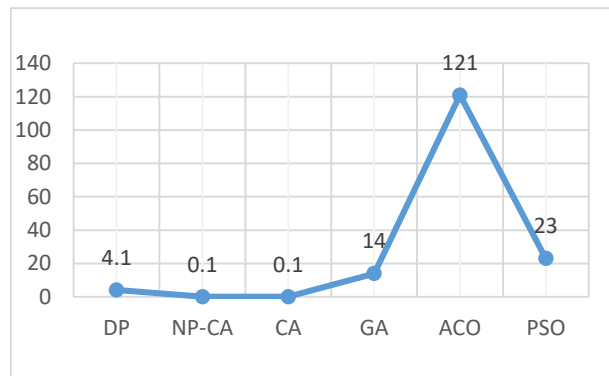


Figure 12. Comparison the value of objective function in DP with other methods in the period of 40 years.

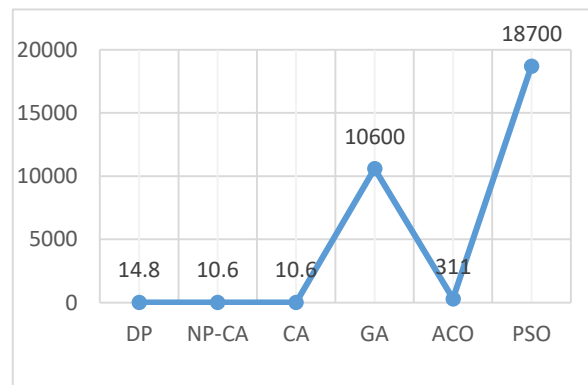


Figure 13. Comparison analysis time in DP with other methods in the period of 40 years.

Conclusion

In order to solve reservoir operation problem, the amount of reserve at the end of period t is intended as a decision variable. According to problem definition, this variable may possibly varies in the range of (830 and 3340). Moreover, results accuracy as well as objective function value depends on how discretized the decision variables. In order to display model efficiency, 5-year, 20-year and 40-year operations is examined taking into account the length of the interval as 251 units. As it is noted, DP model is a discrete model. Hence, the reservoir capacity has been discretized from 830 million cubic meters to 3340 cubic meters into 11 levels in order that we can decide what level of saving is preferable to per month.

After analysis, the objective function value is determined as 1.13, 6.85 and 14.82 for 5, 20 and 40 years operation, respectively. Since, this interval length of discretization impact on model response, a sensitivity

analysis is performed on the number of discretization levels. The results of this analyzes showed that interval length of 50 or smaller range will result most accurate solution of objective function and as this length is greater than 50, the minimum objective function is greater. According to this problem, most accurate solution of objective function at discretization intervals less than 50 will be equal to 0.6882, 4.689 and 10.437 for 5, 20 and 40 years, respectively.

Finally, to assess the dynamic programming performance within optimal operation of reservoirs problem, corresponding results in 11 discretization levels are compared with conventional meta-heuristic methods for solving optimization problems and the results are presented. According to presented results except CA method, dynamic programming results encompassed superior performance in terms of speed (calculation time) and response accuracy replies (objective function) than other meta-heuristic techniques. However, if the interval length of discretization is less in DP method, objective function solution may be equal to CA approach and only its analysis time-consumptions will be enhanced further.

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