Simulation-Optimization Model for Dokan Reservoir System Operation

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Received : 28/12/2016
Accepted : 24/05/2017
DOI Link: https://doi.org/10.17656/sjes.10053

Abstract

Reservoir operation system is the essential part of water resources management, and each reservoir has a special policy for operation. Simulation and optimization are two different techniques for the operating process of any reservoir. Combined simulation-optimization (S-O) model as a new technique in recent years to minimize the deficit in hydropower generation and irrigation demand has been developed for Dokan reservoir system in Kurdistan Region, Iraq. The model combines the Simulink and genetic algorithm (GA) as techniques for simulation and optimization respectively. For comparison, one traditional simulation model based on the standard operating policy (SOP) and two optimization models using nonlinear programming (NLP) and discrete differential dynamic programming (DDDP) optimization methods was developed. In the present study, three performance evaluation criteria, namely; reliability, resiliency and vulnerability have been used for comparing and evaluating the developed models.

The proposed models were run over a period of 54 years using monthly time step interval, i.e. 648 months starting from Jan-1958 to Dec-2011. The results reveal that the SOP model (Model-I) has serious deficit events in minimum downstream demands, although, it has a higher reliability in the irrigation demand (0.94). In addition, the other models; NLP, DDDP and S-O by considering weight factors (w_1=0.2) and (w_2=0.8)almost have the same reliability, 0.90, 0.90 and 0.91 respectively. Furthermore, the results show a low resilience for NLP model and a high vulnerability for S-O modelwhich causes higher severity of failure events. Moreover, for the operation period from 1995 to 2011, the annual productions of hydropower are 1280, 1339, 1344and 1296 MW by increasing of 24.9, 30.64, 31.16 and 26.46 % more than the actual hydropower production (1025 MW) for SOP, NLP, DDDP and S-O models respectively.

Finally, the conclusions present that the DDDP optimization model provides high reliability as well as more power generation at the same time. The model can be more easily applied to solve the nonlinear and multi objective problems with less computational time.

Key Words : Reservoir operation, Optimization, Simulation, Genetic algorithm, Dokan reservoir, Linear programming, Dynamic programming.

1. Introduction

Reservoir operation system is the vital part of water resources management and operation of the reservoir includes assigning the available water for different uses, whereas reducing the risks of water deficits or flooding damages. It is usually accepted using two different techniques such as simulation and optimization in the operating process of reservoir systems that involve multiple purposes such as water supply for irrigation, domestic use, industrial, hydropower generation, flood control, etc. The optimization is choosing the best solution among a number of possible alternatives while the simulation is representing the system behavior and better understanding of it. Different optimization methods have been implemented in an attempt to increase the efficiency of reservoir operation [1]. Some of these techniques utilize for optimization like Linear Programming (LP); Nonlinear Programming (NLP); Dynamic Programming (DP); Stochastic Dynamic Programming (SDP); Genetic Algorithms (GA)and Experimental Programming such as Fuzzy Logic, Neural Networks, etc. These methods provide operation strategies for reservoir releases according to the current reservoir level, water de mands, hydrological conditions, and the time during the year.

Linear programming has been successfully applied in the studies of single, multi-purpose reservoir systems. Grygier & Stedinger, (1985) [2] used the successive linear programming (SLP) model and combination of linear programming with dynamic programming (LP-DP) to optimize the operation of multi-reservoir hydro-systems. Dynamic programming is among earliest methods applied to the reservoir operation problems. Karamouz & Houck, (1982) [3] proposed deterministic dynamic programming to generate reservoir system operating rules and tested in 48 cases. Furthermore, an incremental dynamic programming (IDP) model for optimizing the long-term operations of a large number of real-world reservoir systems were suggested by Bayazit & Duranyildiz, (1987) [4]. Moreover, genetic algorithm (GA) is applied for estimating operating policies of reservoir systems used for different purposed by some researchers [5] and [6]. Despite, the development and increasing use of optimization methods, simulation models stay in practice as a pronounced approach for reservoir operation planning and management studies [7]. In the recent years, the combination of simulation and optimization (S-O) have been used as a new technique in reservoir systems operation. Ngo, et al., (2007) [8] by applying the optimization and simulation techniques together showed that the optimized rule curves using the shuffled complex evolution (SCE) algorithm, significantly, improve the reservoir performance. Furthermore, Dhar & Datta, (2008) [9] developed a linked simulation–optimization method to take the optimal operation policy of a single objective reservoir to regulate the downstream water quality requirements.

The Dokan reservoir is one of the main sources of water for drinking, irrigation and power generation in Kurdistan Region, Iraq, especially for the governorates of Kirkuk, Sulaimani and Salahadin. Several studies have been carried out to simulate and optimize the operation of this reservoir. Rashid, et al., (2007) [10] developed an explicit stochastic optimization model based on dynamic programming for long-term operation of Dokan reservoir. Furthermore, Ahmed, et al., (2013) [11] showed that the linear programming of a full optimization model provides more accurate representation of Dokan reservoir system behavior than the simplified optimization (yield model). The most important purpose of this study is to derive an optimal operation policy for allocating water to all downstream demands (agricultural, domestic, industrial and environmental) and providing more hydropower production at the same time with regarding the deficits minimization in irrigation and hydropower demands for Dokan reservoir system. Therefore, a combined simulation-optimization (S-O) model as a new technique in recent years has been developed to fill the main gap in the application of this technique for reservoir operation in Iraq, especially for Dokan reservoir. The model combines the simulation and genetic algorithm (GA) as technique for optimization. Furthermore, for comparison, one traditional simulation model based on standard operating policy (SOP) and two optimization models using nonlinear programming (NLP) and discrete differential dynamic programming (DDDP) has been developed for Dokan reservoir system operation.

2. Study Area and Used Data

2.1. Study Area Characteristics

Dokan dam is one of the big dams in Iraq, which is built in 1959 on the Lesser Zab river it is located about approximately 295 km north of Baghdad and 67 km north-west of Sulaimani city, Kurdistan Region, Iraq. The dam site is located at Latitude 35°57'15" N and Longitude 44°57'10" E near to the city of Ranya, Kurdistan Region, Iraq as shown in Figure-1. The dam was constructed between 1954 and 1959 as a multipurpose dam to provide water for irrigation and hydroelectric power generation. In addition, it was constructed for the storage of excess water contained in the upstream parts of Lesser Zab river and its branches to take advantage of the water and launch when necessary in times of summer drought periods for areas south of the reservoir, which suffer from deficiencies, particularly for irrigation purposes such as the Hawijah, Kirkuk and Koya irrigation projects. The characteristics of Dokan dam and reservoir are tabulated in Table-1. The dam type is a concrete arch dam abutted by gravity monoliths, and the primary inflow is from the Lesser Zab river [12].

2.2. Used Data

Data collection and processing are the significant part of the first stage of building the reservoir operation models. Due to the high level of computerization and modem means of information spreading, the data collection is a simpler exercise in growth countries. However, in several countries, most of the data are still in the manuscript form and are distributed in various branches of a data collection agency [13]. Inflow to reservoirs is generally calculated at gaging stations placed on streams entering the rivers and reservoirs and other control points. In some of the reservoirs, the inflow is estimated by the water balance in the reservoir using the actual release records on an hourly or daily basis. In reservoir operation systems and modeling, it is preferable to have a long record of stream flows that includes worst-case scenarios of droughts and floods experienced during the historical record [14]. The inflow discharge of the reservoir is formed from numerous small rivers, which are the south-western tributary of upper Lesser Zab and the rivers are the following:

1. Sewail river which has two tributaries Shalar and Qislaja.
2. Joga soor river which has only one tributary called Mawakan.

These two tributaries, Sewail and Jaga soor combine together contributing Qala jolan river and drain to Lesser Zab river near the Iraq–Iranian border. There are several other small rivers at northern part of this watershed drain directly to Dokan reservoir such as; Hizob, Qashan, Dara-siw, Sulana and Zarawa [15].

In this study, from the available data in the Dokan dam directorate, monthly inflow discharges into Dokan reservoir of dam site gauge station over the period (1958-2011) were used for developing the simulation and optimization models as shown in Figure-2. The inflows data of Dokan dam gage station are obtained by operation balance, and hence the losses are implicitly included. The maximum and minimum values of inflow discharges are 1510 m3/s in March, 1988 and 9 m3/s in August and September, 2008 respectively. While, the average monthly multiannual data is about 186 m3/s.

Water conveyance for different sectors (domestic use, agriculture, industrial, environmental, etc.) is one of the important purposes of reservoir systems [14]. The Dokan reservoir is one of the main sources of water supply for domestic use of Kurdistan Region, Iraq, particularly to the provinces of Sulaimani, Kirkuk and Salahadin. For this purpose, water requirements are about 400000 m3/day for Sulaimani province [16] and 288000 m3/day for Kirkuk province [17]. In addition, the reservoir provides water for agriculture land about 730000 donum for Kirkuk, Hawija and Adhaim irrigation project [18] and [19]. Furthermore, Klesa irrigation project is a new project in Koya, Sulaimani, Kurdistan Region, Iraq that involving about 28000 donum of agriculture land [20].

Providing adequate water to protect the aquatic, biological, and aesthetic values of a stream and to preserve existing fishery is an important constraint in river–reservoir systems planning and operation. To calculate the minimum flow requirement, have some different methods are used in different countries. In this study to estimate environmental flow for Dokan reservoir, hydrological method which is uses daily or monthly flow to determine environmental flow has been used. It is can be used to calculate minimum flow in the stream with/without gauging station. Furthermore, can be applied easily in the planning stage of the water resources development project. Table-2 shows the water requirements for different uses in the downstream of Dokan reservoir.

Storage capacity is the most important physical characteristic of reservoirs and can be calculated at each level of water from the topographic map of the site [14].From the area-volume-elevation relationships, storage and surface area of water can be determined for any elevation of water surface in the reservoir above sea level. For Dokan reservoir, the following relationship between storage and elevation of water surface was derived from the available data by quadratic regression [21]:

$$h = -0.0000007 * S^2 + 0.0118 * S + 464.01 \qquad (1)$$

In which h is the elevation of water surface from sea level (m) and S is the storage volume in the reservoir (million m3).

One of the important aims of Dokan reservoir was to protect Baghdad city, the capital, and other major cities from flooding. During the flood season (September to April), the storage volume in the reservoir should be lowered below 6800 million m3 according to flood control operation rule as shown in Table-3 which displays the maximum allowable reservoir storage for different months throughout the year [19].

3. Methodology

The present study is an attempt towards the development of a mechanism for dealing with the operation problems within the Dokan reservoir system in Kurdistan Region, Iraq. The appropriate techniques for simulation and optimization of the reservoir operation were selected. The selected techniques include Nonlinear Programming (NLP), Discrete Differential Dynamic Programming (DDDP) and the Genetic Algorithm (GA) technique for optimization with Standard Operation Policy (SOP) for simulation. The basic and principle theories of these techniques related to reservoir simulation, optimization and combined simulation-optimization modelling, including data and information processing, objectives and constraints identification that depended in the present study are described in the following sections.

3.1. Reservoir Simulation with Standard Operating Policy (SOP)

Standard operating policy (SOP) trains to best meet the demand for each period based upon the availability of water in that period, and it is not based on or derived from any optimization process. According to this rule, if the total available water at a specific period is less than the demand, then all the available water is released. If the available water is more than the demand, however, less than the sum of demand and maximum storage capacity, then release is equal to the demand. On the other hand, if the available storage after meeting the demands exceeds the maximum storage capacity, excess water is released as spill from the reservoir [22]. The values of release, overflow discharge, and storage are determined as follow:

$$\left.\begin{array}{l} R(t) = D(t) \text{if} S(t) + Q(t) \geq D(t) \\ R(t) = S(t) + Q(t) \quad \text{otherwise} \end{array}\right\} \tag{2}$$

$$\left.\begin{array}{ll} O(t) = \big(S(t) + Q(t) - D(t)\big) - Smax(t) & \text{if positive} \\ O(t) = 0 & \text{otherwise} \end{array}\right\} \tag{3}$$

$$S(t+1) = S(t) + Q(t) - R(t) - O(t) \tag{4}$$

Where R(t), O(t), D(t), Q(t) are the release, overflow discharge, water demand, inflow discharge respectively during the time t, S(t) is the storage at the beginning of time t, S(t+1) is the storage at the end of time t and Smax(t) is the maximum storage at time t.

3.2. Nonlinear Optimization Technique

Non-linearity exists in various reservoir system operation problems due to complex relationships among different physical and hydrological variables or because of specific objectives being served by the system. Nonlinear programming (NLP) techniques are used to solve such class of problems [7]. In this study, the objective function is minimizing the deficit in the hydropower production and irrigation demand for Dokan reservoir, which is nonlinear function because of the hydroelectric power generation is a function of storage or head and discharge release. By considering the water supply, irrigation demands and water quality constraints, general objective function can be expressed as follows:

$$\text{Minimize} \sum_{t=1}^{n} \left(w_1 \big(PC - HP(t)\big)^2 + w_2 \big(D(t) - R(t)\big)^2 \right) \tag{5}$$

$$HP(t) = \frac{e.\gamma.R(t).H(t)}{1000} \tag{6}$$

Where PC is the maximum power capacity of turbines (400 MW), HP(t) is the hydropower generation (MW) at time t, H(t) is the average net head above turbines (m) at time t, e is the overall efficiency (0.8), γ is the specific weight of water (9810 N/m3), and w_1,w_2 are the weight factors for each objective function. The loss function of the release (LR) could be explained as follows [23]:

$$\left.\begin{array}{lll} \text{if } R(t) < D(t) & \text{then} & LR(t) = a\big(D(t) - R(t)\big)^2 \\ \text{if } R(t) > R_{max} & \text{then} & LR(t) = b\big(D(t) - R(t)\big)^2 \\ \text{if } D(t) \leq R(t) \leq R_{max} & \text{then} & LR(t) = 0 \end{array}\right\} \tag{7}$$

In which R_max is the maximum capacity of outlet turbines and a, b are constants that represent weighting factors to reflect the effect of violating the constraints concerning irrigation demand and flood control in the river, respectively; their values depend on the consideration of the decision maker.

3.3. Reservoir Operation Constraints

In the optimization of reservoir system operation, there are several constraints, which represent limitations on the behavior and performance of the system. Water balance in the reservoir must be preserved in all stages of optimization. The reservoir continuity equation is considered as the main constraint in this case. In the mass balance equation, any losses due to evaporation or seepage have been neglected for Dokan reservoir because the inflows data are obtained by operation balance, and thus the losses are implicitly included. In addition, release from the reservoir must be less than or equal to the downstream demands, while these demands equal to sum of irrigation, water supply and other demands (municipal, industrial, and hydropower generation), which can be written as:

$$R_{min} \leq R(t) \leq R_{max} \tag{8}$$

Where R_min is the minimum discharge release required for downstream demands (Mm3) and R_max is the maximum capacity of outlet turbines (Mm3). Moreover, the reservoir storage for any time period should not be greater than the maximum capacity of reservoir and less than dead storage of reservoir and expressed as:

$$S_{min} \leq S(t) \leq S_{max}(t) \tag{9}$$

Where S_min is the minimum storage of the reservoir (Mm3) and S_max (t) is the maximum capacity of the reservoir at time t (Mm3). Furthermore, the overflow constraint takes care of the spills as and when the storage in the reservoir exceeds the maximum capacity of the reservoir. The relevant constraint can be expressed as shown in equation (3). On the other hand, the power plants working in a specified range of water elevation in the reservoir; therefore, the level of water in the reservoir should be remained below maximum and above minimum water elevation and its written as:

$$H_{min} \le H(t) \le H_{max} \qquad (10)$$

Where H_min and H_max are the minimum and maximum net heads of water respectively, that can operate the turbines. Finally, the hydropower must be generated according to the demand during that period and should not be greater than the maximum required of hydropower (capacity of turbines) and this constraint written as:

$$HP(t) \le HP_{max} \qquad (11)$$

In which HP_{max}_max is the maximum capacity of turbines that installed at the reservoir hydropower station.

3.4. Discrete Differential Dynamic Programming (DDDP)

The discrete differential dynamic programming (DDDP) was used as the program for optimization of reservoir operation by [24]. The DDDP uses the concept of increments for state variables in an iterative procedure by which the DP recursive equation may be solved within a restricted set of quantized values of the state variables. It has all the required characteristics of the conventional dynamic programming computational procedure and it is need less computational time. The following steps are the procedure used in the discrete differential dynamic programming (DDDP) computations [25]:

1. Choose the initial trial trajectory $\bar{S}_i, (i = 1, 2, \ldots, N)$ and these state vector must satisfy the following equations:

$$S_i \in SS_i \qquad (12)$$

$$D_i \in DD_i \qquad (13)$$

Where SS_i is a set of admissible states of stage i and DD_i is a set of admissible decisions at stage i.

2. Select the maximum deviate (Δs) allowed from the initial trial trajectory, to define the corridor (C_j), then the state sub-domain (S_i) becomes:

$$S_i = \begin{cases} \bar{S}_i + \Delta s(i) \\ \bar{S}_i \\ \bar{S}_i - \Delta s(i) \end{cases} \qquad (14)$$

Use only state sub-domain in the next step which satisfy equations (12) and (13).

3. Use state sub-domain (S_i) to find the optimal total of the return (F_i^*) in corridor by using the dynamic programming (DP) recursive equation which is shown as below, then compute the optimal trajectory (S_i^*):

$$F_i(S_i) = \min Q_i(S_i, D_i) \qquad i = 1, 2, \ldots, N \qquad (15)$$

$$Q_i(S_i, D_i) = r_i(S_i, D_i) \qquad i = 1 \qquad (16)$$

$$Q_i(S_i, D_i) = r_i(S_i, D_i) + F_{i-1}(S_{i-1}) \qquad (17)$$

$$S_{i-1} = t_i(S_i, D_i) \qquad i = 2, 3, \ldots, N \qquad (18)$$

4. Let $F_{i-1}^* = F_i^*$ and $S_i = S_i^*$ then repeat steps (2) and (3).
5. If ($(F_i^* - F_{i-1}^*) > \lambda$) then go to step (4) or if ($(F_i^* - F_{i-1}^*) < \lambda$ and if $(\Delta s/S_{max}) > \gamma$ then $\Delta s = \Delta s/2$ and go back to step (4). If $(F_i^* - F_{i-1}^*) \le \lambda$ and if $(\Delta s/S_{max}) \le \gamma$ then stop iteration. Where λ and γ are the convergence parameters and have been used as $\gamma = 0.1$ and $\lambda = 0.001$.

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3.5. Combined Simulation-Optimization Approach

Simulation-optimization can be defined as the process of finding the best input variable values from among all possibilities without explicitly evaluating each possibility [26]. According to different authors, simulation-optimization is the most significant simulation technology in the last years. Simulation without optimization required extra time to simulate the model due to the availability of a large number of possible alternatives. Therefore, it is necessary use optimization approach not as a way to find the best solution, but to define a relatively small number of good alternatives that can later be tested, evaluated, and improved by means of simulation. Process of using optimization to decrease the large number of plans and policies to a few that can then be simulated and better evaluated is often called preliminary screening [27]. There are lots of methods suggested for simulation optimization. The Heuristic methods represent the latest developments in the field of direct search methods (requiring only function values) frequently used for simulation-optimization. The heuristic search algorithms provide good and reasonably fast results on a wide variety of problems. Authors mention at least a few important heuristic algorithms. These include genetic algorithms, evolutionary strategies, simulated annealing, simplex search and tabu search [26]. Simulation-optimization generally works as the following steps [28]:

1. An initial set of parameter values is selected, and one or more replication experiment is carried out with these values.
2. The results are obtained from the simulation runs, and then the optimization module chooses another parameter set to try.
3. The new values are set, and the next experiment set is run.
4. Steps 2 and 3 are repeated until either the algorithm is stopped manually or a set of defined finishing conditions are met.

In this study, the genetic algorithm is used for optimization in the combined simulation-optimization model. Genetic algorithms are random or probable optimization search methods used to determining the optimum values of the parameters or decision-variables of existing models [27]. This algorithm contains several iterations of the operation in each iteration (generation) creates populations that tend to obtain better results. The genetic algorithm process can end when there is no significant change in the values of the best solution that has been found. Usually, the genetic algorithm (GA) requires the following three heuristic processes [29] and more details can be found in [30] and [31]:

1. Random reproduction: the algorithm begins its search through a certain initial random point, known as population. Any member of the population that defines a solution for a given problem is called a chromosome. Chromosomes develop in iterations (generation). In genetic algorithm, a chromosome is consisting of several genes that change the parental features to the children.
2. Crossover: the crossover operator constitutes one or more chromosomes of parents to generate their children. Also, it is the most significant genetic operator. Evolutionary operators such as roulette wheel and selection process can be noted as the rule of parental selection for construction of next generation's population. According to this rule, each chromosome, based upon its fitness function value, distributes a particular surface area of the roulette wheel.
3. Mutation: the mutation operator can produce random changes in one or more genes in one or more chromosomes.

3.6. Reservoir Operation Policy Performance Criteria

One of the most significant stage in simulation and optimization model building of reservoir operation is evaluating the reservoir operation policy performance. The performance criteria or indices that aid the planner to classify the status of a system as satisfactory or unsatisfactory outputs should be defined [14]. There are three main criteria that used for evaluating the performance of reservoir operation systems and also useful to evaluate and rank different alternative plans or policies. These criteria are reliability, resilience, and vulnerability as described below:

1. Reliability

Reliability can also be defined as the probability of providing a specific percentage of water for demand in the given time period [32]. The reliability index for examining the reservoir operation system performance is calculated as follows:

$$\text{Rel} = \frac{\text{Number of months with standard supply}}{\text{Total number of months}} \quad (19)$$

2. Resilience

Resilience (Res) describes how quickly a system is likely to recover or bounce back from failure, once failure has occurred [32]. According to state [33] resilience is equal to the inverse of the mean value of the time that the system spends in an unsatisfactory state as shown below:

$$\text{Res} = \left[\frac{1}{M}\sum_{j=1}^{M} d(j)\right]^{-1} \quad (20)$$

In which, d(j) is the duration of the j^th failure event and M is the total number of failure events.

3. Vulnerability

Vulnerability (Vul) is defined as the severity of failure event and was simplified by [33] as the mean value of the deficit events. It is given as:

$$\text{Vul} = \frac{1}{M}\sum_{j=1}^{M} v(j) \quad (21)$$

Where v(j) represents the deficit volume of the failure event.

4. Models Building

In current study, models building includes developing three types of reservoir operating models and applying them to Dokan reservoir in Kurdistan Region, Iraq. The developed models are; simulation (SOP) model, optimization with two different methods (NLP, DDDP) models and combined simulation-optimization (S-O) model based upon the GA optimization technique. For this purpose, the MATLAB computer software was used for building the models based on the Simulink and Optimization toolboxes.

4.1. Model-I: Simulation Model

The simulation model is operated according to physical relation and a series of operation rules to simulate new situation and system behavior based a specified rule. The simulation model (Model-I) based on standard operation policy (SOP) was run over a period of 54 years, i.e. 648 months starting from January, 1958 to December, 2011, for which the historical data were available. The initial storage value was specified as the storage volume of January, 1958.The results of the simulation model were evaluated by computing various performance measures such as reliability, resilience and vulnerability. Figure-3 shows the simulation flowchart that developed for Dokan reservoir system based on SOP and executed by Simulink toolbox of MATLAB software.

4.2. Model-II: Optimization Models

4.2.1. Model–II-a: Nonlinear Programming Optimization Model

To apply the nonlinear programming optimization (NLP) model, several different values of weight factors, w_1, w_2 between 0 and 1 should be tested and then selected. In the present study, for analyzing the results of the developed models, three sets of weight factors have been selected as follows: set 1 (w_1=0.2 ,w_2=0.8), set 2 (w_1=0.5 ,w_2=0.5), and set 3 (w_1=0.8 ,w_2=0.2). In which w_1 represents the weight factor of first objective function (minimize the deficit in hydropower production) and w_2 represents the weight factor of the second objective function (minimize the deficit in irrigation demand). Also, many different values of a, and b in the loss function (LR) of irrigation demand were tested and there is no significant difference in the results of different values of a, and b. The solver (fmincon) inOptimization toolbox of MATLAB software is commonly used to solve nonlinear optimization problems, then the results are simulated by Simulink toolbox.

4.2.2. Model-II-b: DDDP Optimization Model

The DDDP optimization process method starts with an initial trial trajectory satisfying a specific set of initial and final conditions, and much time is spent to find the feasible initial trial trajectory, which is a difficult task, especially in a complex system. At the end of each iteration step a locally improved trajectory is obtained and used as the trial trajectory in the next step. In the present study, to apply the DDDP optimization model for Dokan reservoir operation process, the initial storage (2000 million m3) in January, 1958 and monthly inflow series during the past 54 years (January, 1958 to December, 2011) were used. The solution improvement for Dokan reservoir optimization had become very small after about 50 iterations and slight differences of convergences among each run were recognized after about 120 iterations. The optimum results of objective function were obtained at the iteration number 32.

As mentioned in the nonlinear optimization model (NLP), the optimum values of discharge releases that determined from DDDP model were utilized in the Simulink of MATLAB software to simulate the reservoir operation. The input data for the simulation model are inflow, elevation-storage relationship, downstream demands, physical characteristics of the reservoir and series of optimized discharge releases from DDDP model.

4.3. Model-III: Combined Simulation-Optimization Model

The combined simulation-optimization model uses a repetition process to generate inputs to the simulation model then the results would be used by the optimization model to search the optimal solution. The solution of the optimization model will lead to better or more appropriate input for the simulation model, and this repetition process continues so that the final optimal solution is achieved [29]. In the present study, the optimization model by applying genetic algorithm is linked to simulation model to develop the simulation-optimization (S-O) model. Obtaining optimum population size is very important in the applied of genetic algorithm. Therefore, different population size has been considered and a population size of 300 gives the optimum fitness value. Toward optimality have become very small after about 200 generations and there are slight differences of convergences among the runs after about 8000 generations. Therefore, a population size of 300 and a maximum generation number of 8000 have been chosen to run the S-O model.

The second important parameter for genetic operator chosen is crossover probability (pc). Its effect on the system performance was studied by varying the probability of crossover from 0.5 to 0.9 with an increment of 0.05 and adopting the obtained optimal population of 300. The results show that 0.5 is the optimum value for crossover probability, which takes the minimum fitness value. Furthermore, a mutation probability (pm) of 0.001 was selected and the total number of decision variables of the model is 648, which is equal to the dimension of the problem. The result obtained by the created genetic program is not always similar because of the difference in initial population, since the GA creates initial population randomly. Using MATLAB code for applying genetic algorithm provides full control on the genetic operations such as population, cross over and mutation, and also give more freedom in developing constraints and penalty methods. In the code, the initial population is generated randomly, and the user can specify the size of population. Moreover, real value coding is used, and the fitness function is evaluated by penalty methods. The selection process is done by a random selection method and single point crossover is carried out because it is easy to code in MATLAB software.

By running the model, for the parameter set in each trial, the simulation model is used to evaluate the performance of the system with respect to different objectives. Then, the parameter set is modified toward optimality by using the optimization algorithm. Flowchart of the S-O model for Dokan reservoir system is shown in Figure-4. The process is continued until the maximum number of generations or convergence in objective function space is satisfied.

5. Results and Discussion

The results that obtained in the present study by applying the developed models for operating the Dokan reservoir are viewed and discussed in details in the following sections. As well as, a comparative study based upon the results of the developed models has been carried out considering the irrigation water supply, performance evaluation, release through turbines, storage of reservoir, spillway release controlling and monthly hydropower generation and operation policies.

5.1. Discharge Release for Downstream Demands

The present study focuses on developing models that provide priorities for different sectors of demands with a manner that, first fulfilling domestic, industrial and environmental water demands, and then meeting irrigation demands. Figure-5 shows the discharge releases for Dokan reservoir system operation during the period (1958-2011). The results demonstrate that the system operation on the basis of simulation model (Model-I) has a significant difference from the other developed models to determine the optimum discharge release. Table-4 shows characteristics of discharge releases for downstream demands in the proposed models. The actual and models outputs of average monthly discharge releases for Dokan reservoir are presented in Figure-6. It is noted that for the actual operation state, the deficiency was occurred during the months of March to June because of the high discharge releases in summer months for power production. On the other hand, the simulation model (Model-I) shows more discharge releases during the flood season because the SOP aims to best meet the demand for each period based upon the water availability in that period. In this way, the shortage in irrigation demand is occurred during the dry season.

From the results, it is observed that the lowest level of discharge release for downstream of the reservoir was recorded in the simulation model (Model-I) because of the discharge release based on SOP method is depended on the current available water in the reservoir. Therefore, when the available water is less than the downstream demands do not save water in the reservoir for the months that has low inflow discharge, and it causes the increase in severity of failure events and extra discharge is released through spillway of the reservoir during the flood season. In addition, average discharge releases of the reservoir operation period are nearly equal for all the applied models and do not change for all different weighted factors of objectives. While, the minimum discharge changed with using different weights of objective functions, in a manner that the discharge release is decreased to the minimum level of downstream requirements, especially for the first year of reservoir operation, by increasing the value of weight factor for the power objective (w_1) in order to rise the water surface elevation in the reservoir to generate more hydropower. Furthermore, the outcomes of the developed models display that the discharge releases based on NLP (Model-II-a) and S-O (Model-III) models are very close, in contrast with the results of the DDDP (Model-II-b) model that lesser discharge is released to the downstream in order to remain the reservoir storage at a high level to generate more hydropower.

5.2. Performance Criteria of Reservoir System

According to the results of all the proposed models, water supply for domestic, industrial and environmental flow can be satisfied without any deficits in all 648 months, except the simulation (SOP) model (Model-I) has 10 months of shortage. On the other hand, the results reveal that the water allocated for the agricultural sector cannot satisfy all demands. Hence, the number of failure months in irrigation demand can be calculated based on Natural Resources Conservation Service (NRCS) practice to use the 80 percent of irrigation demand as a minimum criterion [34]. The calculated number of critical failure months and performance indices of discharge release by considering 80% supply of downstream agricultural demand in all months are shown in Table-5. The higher reliability for irrigation demand and risky deficit events in irrigation and water quality requirement was recorded in the simulation (SOP) model (Model-I). While, the reliabilities of irrigation demand based on optimization models (Model-II-a and Model-II-b) are very close, and the combined simulation-optimization (S-O) model (Model-III) provided more reliability and resilience than the optimization models. The reliability and resilience values are varying with the different weight factors of objective functions.

Irrigation reliability in the optimization models was decreased with increasing the weight factors of hydropower objective function and vice versa because of, increase the reliability of irrigation demand requires more discharge released for the downstream, and it is conflicting with the hydropower objectives that required less discharge release for the downstream to protect the water surface elevation at a high level in the reservoir. Furthermore, the maximum and minimum vulnerabilities were recorded in the simulation model (Model-I) and the NLP optimization model (Model-II-a) respectively, and this represents the severity of failure events for irrigation demand. By comparing the results of discharge releases for all the developed models with the actual discharge release for Dokan reservoir system, it is observed that the actual status has the most failure events in irrigation and minimum downstream requirements. Furthermore, high vulnerability was occurred in the actual operation status which increases the risk of deficiencies in irrigation, and water supplies demand.

5.3. Hydropower Generation

Table-6 shows the characteristics of hydropower generation of the developed models. From the results of developed models appeared that the average monthly hydropower generation in the DDDP optimization model (Model-II-b) is greater than the other models. While, the maximum power that can be produced was obtained in the SOP simulation model (Model-I). In other words, optimization process minimizes hydropower deficits, and it causes fewer reduction rates of power generation when compared to the deficits obtained with simulation based on the standard operating policies.

Figure-7 shows the monthly hydropower generation of the proposed models during the period (1958-2011). The results of applied models exhibit most numbers of months that power generation is halted (25 months) occurred in the SOP simulation model (Model-I) due to; the discharge release through turbines is less than the minimum discharge (50 m3/s) required for hydropower generation. While, for other models the number of failure months for power generation is rise directly with the increase the weight factor of hydropower generation objective function. In addition, the higher production of hydropower was generated during summer months (May to September). In other words, the production of hydropower is proportional with the downstream demands except for SOP simulation model (Model-I) which has a greater generated power during the winter season.

The average monthly hydropower generation of the proposed models for Dokan power station was observed throughout the period (1995-2011) as shown in the Figure-8. The figure demonstrates that the actual operation system has a lower power generation comparing to the results of the developed models, especially during the wet season and so on the lowest and highest power was produced during the months of April and August respectively. Moreover, considering the weight factors (w_1=0.8,w_2=0.2), the annual production of hydropower for the period (1995-2011) can be increased by 24.9, 30.64, 31.16 and

26.46% more than the actual hydropower production when the models, Model-I (SOP), Model-II-a (NLP), Model-II-b (DDDP) and Model-III (GA) are applied respectively. Hence, it can be said that the system operation with any of the proposed models is better than the actual operation of the reservoir system.

5.4. Elevation of Water Surface in the Reservoir

When the water level in the reservoir is below the minimum operating level, hydropower generation is halted. Monthly water elevation in the Dokan reservoir throughout the time period of operation is shown in Figure-9. In this figure, it can be noted that the reservoir has a lower water level during the first and last years of operation, due to climate changes and decreased inflow discharge in that periods. Moreover, the average monthly elevation of water surface in the reservoir is extracted from the results of 648 months for each model. It can be said that the average water levels in the reservoir are very close based on the two optimization models (Model-II-a, Model-II-b). On the other hand, the elevation of water surface in the reservoir for combined simulation-optimization (S-O) model (Model-III) is nearly (1.0) m below the water elevation of other models. This state appears the powerful of NLP and DDDP optimization methods to find the optimal solution for the objectives of this study. Monthly operation rule curves in terms of water elevation in Dokan reservoir for the proposed models are shown in Figure-10.

As it is clear from the results, the maximum elevations of water surface in Dokan reservoir are recorded during the month of May for the SOP simulation model. In contrast, from the results of other suggested models, the maximum elevations of water are occurred during the month of June. It means that, in the optimization methods, the maximum elevation of water in the reservoir is lagged one month in order to save more water in the reservoir for the months that have low inflow rate, i.e. months of the season of summer.

5.5. Sensitivity Analysis of Models

Sensitivity analysis is the technique used to describe how much model output values are affected by changes in model input values. It is the investigation of the importance of imprecision or uncertainty in model inputs in a decision-making or modelling process [27]. Usually water demand for different sectors in any particular month is varying from year to year caused by meteorological and climate changes as well as changes in crop patterns, irrigation practice, etc. In the present study, the series of downstream demands for Dokan reservoir throughout different years of operation (1958-2011) is not available. Therefore, to demonstrate the effect of varying demands along different years of reservoir operation on the outputs of developed models, the downstream demands were assumed to change randomly between 80-120% of the estimated downstream demands. For this purpose, the DDDP optimization (Model-II-b) model and combined simulation-optimization (S-O) model (Model-III) has been applied to get the discharge releases and power generation for variable demand status and then compared with the constant demand state. Table-7 represents the characteristics and performance criteria of discharge release based on variable and constant demand status for weight factors of w_1=0.2 and w_2=0.8.

The results of DDDP optimization model (Model-II-b) demonstrate that the discharge release at most times is directly changed with the same or less than the amount of varying downstream demands. In addition, the performance indices; reliability, resilience and vulnerability of discharge releases were decreased, compared to the constant demand status. While, the discharge releases for combined simulation-optimization (S-O) model (Model-III) for the variable demand state show there is a significant change compared with the constant demand state and a greater deficit in discharge releases as a result of vulnerability increasing. The series of discharge releases for variable and constant demand states for DDDP optimization (Model-II-b) and combined simulation-optimization (Model-III) models are shown in Figure-11 and Figure-12 respectively.

Furthermore, although some events of power failure (power production halted) were recorded in the results of the DDDP optimization model (Model-II-b), there is no significant change in the production of hydropower by using variable demands. Table-8 represents the characteristics of hydropower generation for variable and constant demand states for weight factors of w_1=0.2 and w_2=0.8. On the other hand, the maximum and average values of hydropower generation for variable demand state are reduced for combined simulation-optimization (S-O) model (Model-III). The patterns of power production throughout reservoir operation for variable demand state are shown in Figure-13 and Figure-14 for DDDP optimization (Model-II-b) and combined simulation-optimization (Model-III) models respectively.

6. Conclusions

In this study, combined simulation-optimization (S-O) model as a new technique that developed in recent years has been used for Dokan reservoir system in Kurdistan Region, Iraq. The model combines the Simulink and genetic algorithm (GA) as techniques for simulation and optimization respectively. The developed model was compared with the traditional simulation model based on the standard operating policy (SOP) and optimization models using nonlinear programming (NLP) and discrete differential dynamic programming (DDDP) optimization methods. The results demonstrate that the applied models can efficiently optimize the hydropower production and decrease the deficit in downstream irrigation demands for Dokan reservoir operation system. Based on hydropower generation results of the developed models during the period of 1995-2011 it has been found that the total annual hydropower generation between 1281 MW and 1345 MW with an increase about 25 % to 31 % more than the production of actual system operation, which is 1025 MW. Furthermore, the results appear that the reservoir operation with each of the suggested models can increase the reliability of irrigation demand from 0.66 of real operation of the reservoir to above 0.90.
Finally, by comparing the results of all implemented models shown that the operation of DDDP optimization model (Model-II-a) can produce more hydropower and has best solution to satisfy the downstream demands with less computational time to reach the optimal solution. The present study is recommended continue studying to develop the combined simulation-optimization model for Dokan reservoir system by using other techniques such as Tabu Search (TS), Simulated Annealing (SA), Evolutionary Strategies (ES), …, etc., which may improve the results.

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نموذج محاكاة -الأمثل لتشغيل نظام خزان دوكان

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المستخلص :
إن نظام تشغيل الخزانات هو جزء أساسي من إدارة موارد المياه وان كل خزان له سياسة خاصة للتشغيل . ان المحاكاة والأمثلية هما تقنيتان مختلفتان في عملية التشغيل لأي خزان . لذلك ، تهدف هذه الدراسة إلى تطوير نموذج محاكاة جنبا إلى جنب مع نموذج الأمثلية (S-O) كتقنية جديدة استخدمت في السنوات الأخيرة للحد من العجز في توليد الطاقة الكهرومائية والمتطلبات المائية للري في نظام خزان دوكان في إقليم كوردستان العراق . لقد تم تطوير هذا النموذج بالجمع بين الأداة (SIMULINK) والخوارزمية الجينية (GA) كتقنيتين للمحاكاة والأمثلية على التوالي . ولغرض المقارنة ، فقد تم بناء نموذج محاكاة تقليدية (نموذج I-استنادا إلى سياسة التشغيل القياسية (SOP) باستخدام أداة (SIMULINK)في برنامج MATLAB ونموذجين للأمثلية (نموذج II-a- ونموذج (II-b-باستخدام البرمجة غير الخطية (NLP) والبرمجة التفضيلية المنفصلة الديناميكية (DDDP) على التوالي . تم في هذه الدراسة ، استخدام ثلاثة معايير لتقييم الأداء؛ وهي الموثوقية(Reliability) ، والمرونة (Resiliency)والحساسية (Vulnerability) لمقارنة وتقييم الأداء للنماذج المستخدمة. تم تشغيل النماذج المقترحة باستخدام البيانات الشهرية لمدة 54 عاما ، أي 648 شهرا تبدأ من كانون الثاني 1958 إلى كانون الاول 2011 . وأشارت النتائج إلى أن النموذج) SOP نموذج (I-ذا هامش مخاطرة عالي في حساب العجز في متطلبات الحد الأدنى ، على الرغم من الدرجة العالية من الموثوقية في تجهيز متطلبات الري (0.94) . كما ان النماذج الأخرى؛ البرمجة غير الخطية (نموذج(II-a- ، البرمجة التفضيلية المنفصلة الديناميكية (نموذج- (II-bو (S-O) نموذج (III-ومن خلال استخدام المعاملات الوزنية (w1 = 0.2)و (w2 = 0.8) لديها تقريبا نفس الموثوقية للكهرباء والري ، 0.90 ، 0.90 و 0.91 على التوالي . علاوة على ذلك ، فقد بينت النتائج مرونة منخفضة لنموذج البرمجة غير الخطية (نموذج (II-a-ووجود حساسية شديدة لنموذج S-O)نموذج (III-الذي يتسبب بمخاطرة عالية لحدوث الفشل . وبالإضافة إلى ذلك ، وللفترة الممتدة 1995 – 2011 ، فان الإنتاج السنوي من الطاقة الكهرومائية هي 1280 ميغاواط ، 1339 ميغاواط ، 1344 ميغاواط و1296 ميغاواط بزيادة قدرها 24.9٪ ، 30.64٪ ، 31.16٪ و26.46٪ أكثر من إنتاج الطاقة الكهرومائية الفعلي (1025 ميغاواط) للنماذج) SOP نموذج(I- ، NLP)نموذج(II-a- ،) DDDPنموذج (II-bو S-O (نموذج (III-على التوالي.
وأخيرا ، فإن الاستنتاجات تشير إلى أن النموذج الأمثل هو DDDP (نموذج – II-b) حيث يوفر الموثوقية العالية ، فضلا عن المزيد من توليد الطاقة في نفس الوقت . يمكن تطبيق هذا النموذج بسهولة أكبر في حل المسائل غير الخطية ومتعددة الأغراض مع وقت قليل للحسابات .

الكلمات المفتاحية : تشغيل الخزانات ، الأمثلية ، المحاكاة ، الخوارزمية الجينية ، خزان دوكان ، البرمجة الخطية ، البرمجة الديناميكية .

Fig.1: Location of the Dokan dam and reservoir on Lesser Zab river in Kurdistan Region, Iraq.

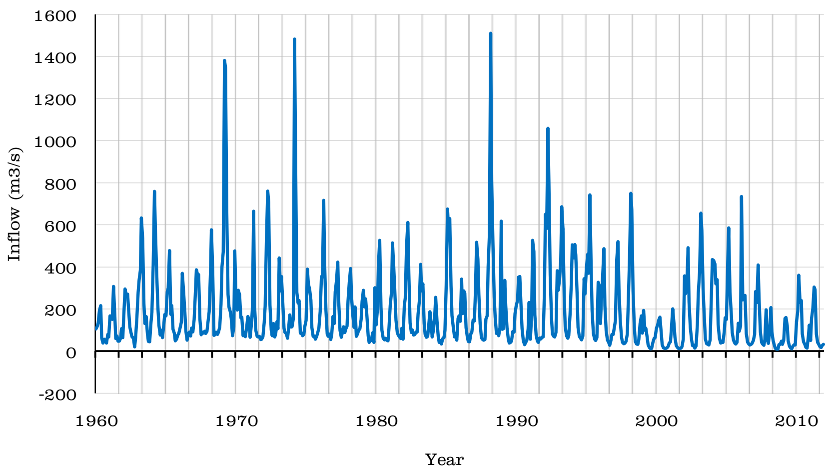

Fig.2: Monthly inflow discharges into Dokan reservoir for the period October, 1958 to September, 2011.

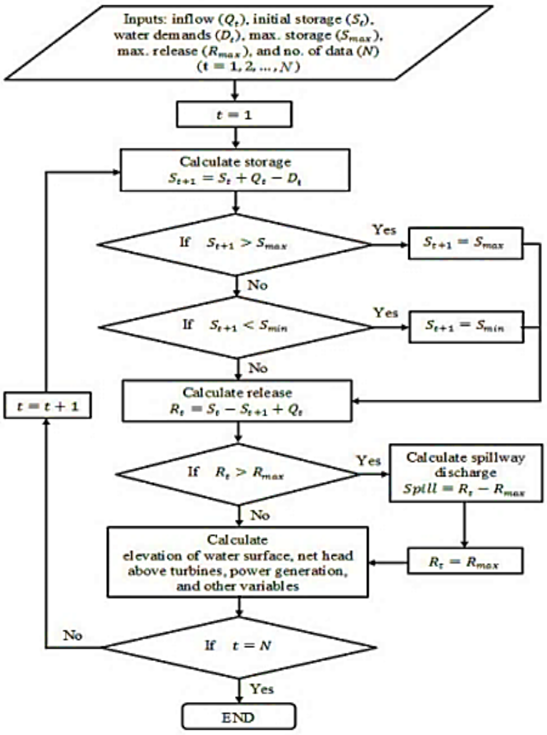

Fig.3: Flowchart of simulation with standard operating policy (SOP).

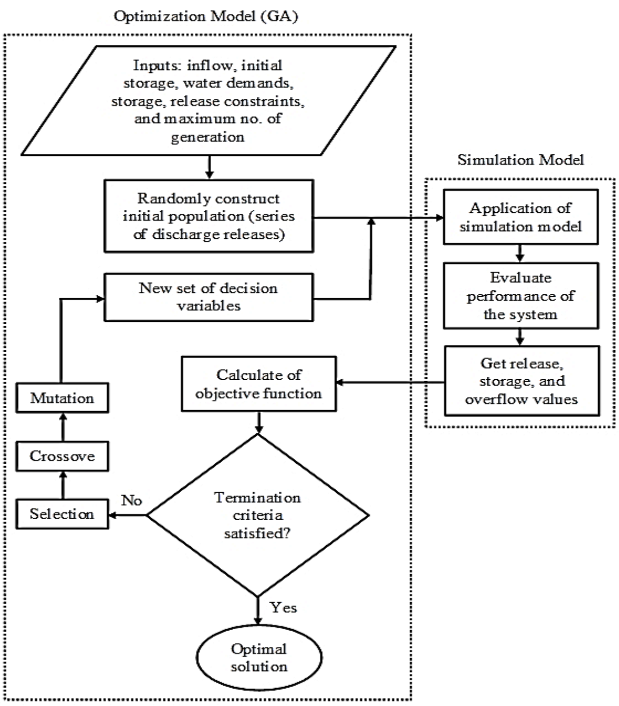

Fig.4: Flow chart of S-O model based on the genetic algorithm (GA).

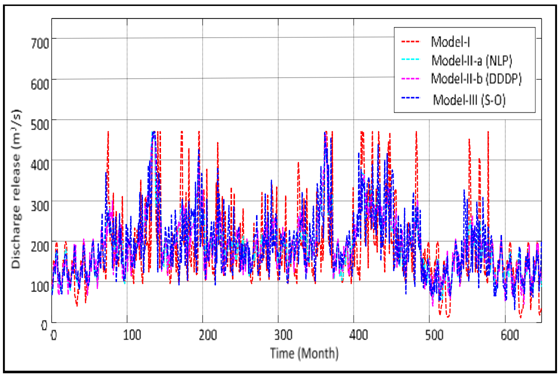

Fig.5: Models outputs of discharge release for Dokan reservoir during the period (1958-2011).

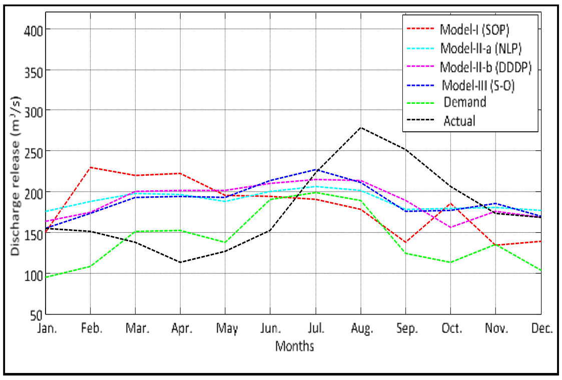

Fig.6: Actual and outputs of models of average monthly discharge release for Dokan reservoir.

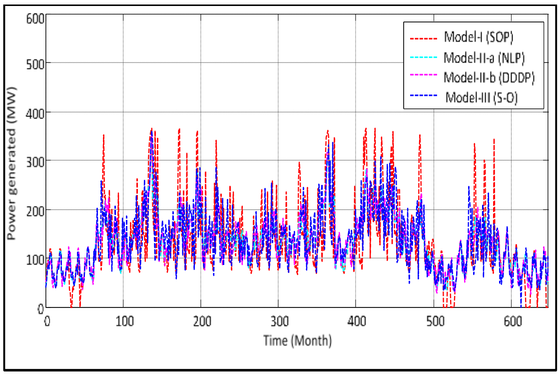

Fig.7: Monthly generated power of the proposed models for Dokan reservoir system during the period (1958-2011).

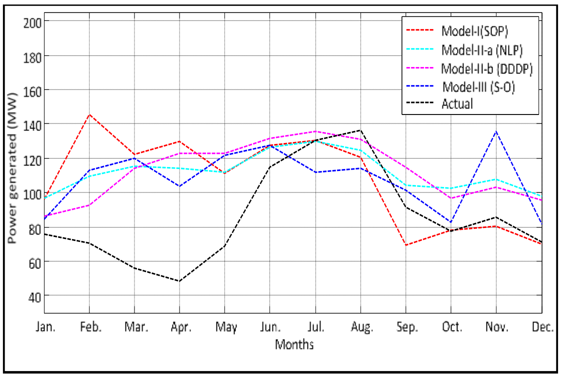

Fig.8: Average monthly power generation of the proposed models for Dokan reservoir system.

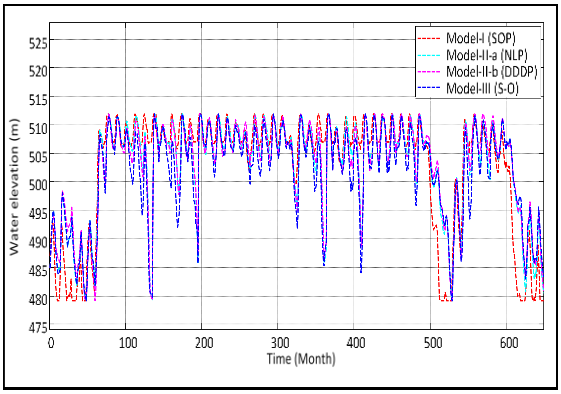

Fig.9: Monthly water surface elevation of the proposed models for Dokan reservoir system during the period (1958-2011).

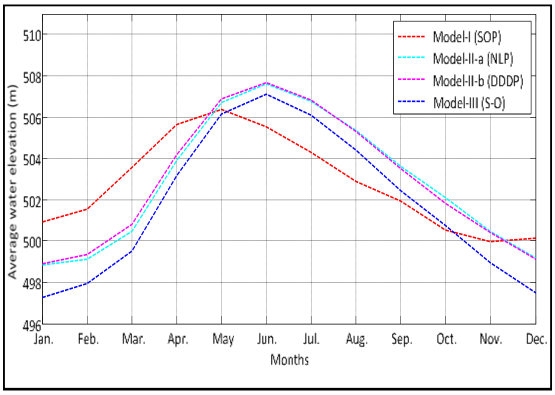

Fig.10: Average monthly water surface elevation of the proposed models for Dokan reservoir.

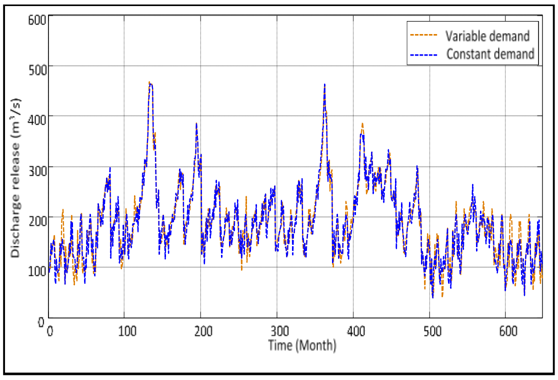

Fig.11: Discharge releases of DDDP optimization model (Model-II-b) for Dokan reservoir system during the period (1958-2011).

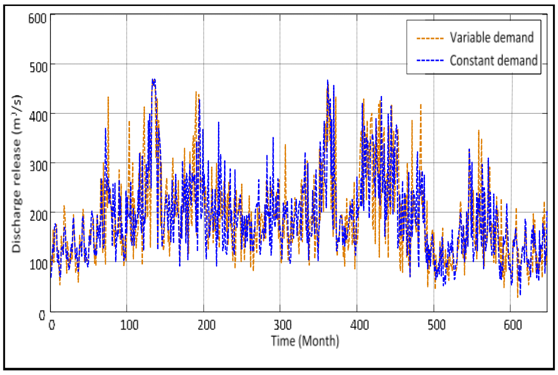

Fig.12: Discharge releases of simulation-optimization (S-O) model (Model-III) for Dokan reservoir system during the period (1958-2011).

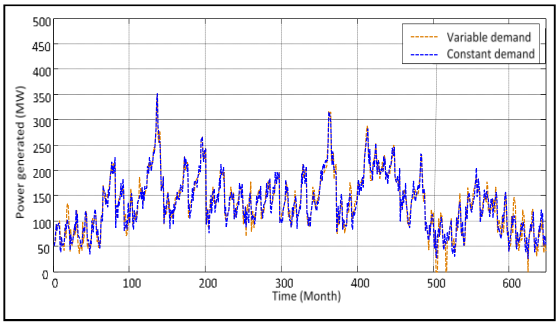

Fig.13: Power generation of DDDP optimization model (Model-II-b) for Dokan reservoir system during the period (1958-2011).

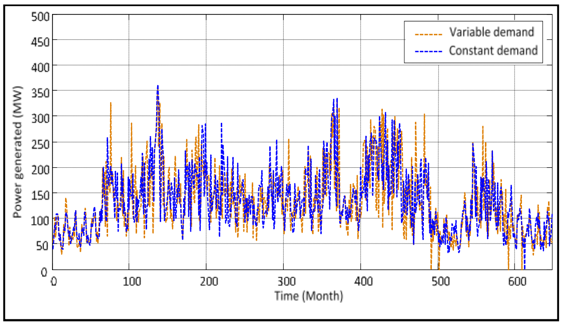

Fig.14: Power generation of simulation-optimization (S-O) model (Model-III) for Dokan reservoir system during the period (1958-2011).

Table 1 : Characteristics of dam and reservoir of Dokan.

Dam and Spillways		Reservoir	
Height	116 m	Capacity	6,970,000,000 m^3
Length	360 m	Active capacity	6,100,000,000 m^3
Crest width	6.2 m	Inactive capacity	790,000,000 m^3
Base width	34.3 m	Surface area at level 511 m	270 km^2
Crest elevation	516 m	Normal elevation	511 m
Type of spillway	Service: Tunnel Emergency: Bell-mouth	Maximum elevation	515 m
		Minimum hydropower operating level	479 m

Table 2 : Downstream water demands for different uses of Dokan reservoir.

Month	Irrigation Requirement (million m^3) Kirkuk, Hawija and Adhaim Projects	Klesa Project	Sulaimani Domestic Use (10^6 m^3)	Kirkuk Domestic Use (10^6 m^3)	Environmental Flow Requirement (10^6 m^3)	Total Water Demand (10^6 m^3)
January	184.81	0.12	12.4	8.93	40.18	246.44
February	202.95	0.80	11.6	8.35	37.58	261.28
March	326.76	3.16	12.4	8.93	40.18	391.43
April	316.22	7.19	12	8.64	38.88	382.93
May	286.59	8.94	12.4	8.93	40.18	357.04
June	409.54	7.98	12	8.64	38.88	477.04
July	444.61	8.58	12.4	8.93	40.18	514.70
August	417.83	9.85	12.4	8.93	40.18	489.19
September	243.65	8.56	12	8.64	38.88	311.73
October	227.66	5.26	12.4	8.93	40.18	294.43
November	274.75	3.40	12	8.64	38.88	337.67
December	206.24	0.51	12.4	8.93	40.18	268.26

Table 3 : Flood control operation rule of Dokan reservoir.

No.	Month	Storage (Month End) (10^6 m^3)	No.	Month	Storage (Month End) (10^6 m^3)
1	January	5320	7	July	6800
2	February	5320	8	August	6800
3	March	5870	9	September	5970
4	April	6580	10	October	5320
5	May	6800	11	November	5320
6	June	6800	12	December	5320

Table 4 : characteristics of discharge releases for downstream demands in the proposed models.

Models	w_1	w_2	Model-I (SOP)	Model-II-a (NLP)	Model-II-b (DDDP)	Model-III (S-O)
Maximum Discharge Release (m^3/s)	0.2	0.8	469.91	469.91	462.96	469.24
	0.5	0.5		469.91	462.96	469.77
	0.8	0.2		469.91	469.91	469.59
Average Discharge Release (m^3/s)	0.2	0.8	181.24	188.94	188.94	188.94
	0.5	0.5		188.94	188.94	188.93
	0.8	0.2		188.94	188.94	188.93
Minimum Discharge Release (m^3/s)	0.2	0.8	11.02	55.76	38.97	31.99
	0.5	0.5		49.75	38.26	37.54
	0.8	0.2		23.15	23.59	23.9

Table 5 : Performance criteria of proposed models for downstream discharge release.

Models	w_1	w_2	Actual	Model-I (SOP)	Model-II-a (NLP)	Model-II-b (DDDP)	Model-III (S-O)
No. of months with deficit in irrigation demand greater than 20%	0.2	0.8			67	62	59
	0.5	0.5	240	40	91	77	118
	0.8	0.2			104	101	149
Reliability	0.2	0.8			0.9	0.9	0.91
	0.5	0.5	0.63	0.94	0.86	0.88	0.82
	0.8	0.2			0.84	0.84	0.77
Resilience	0.2	0.8			0.19	0.47	0.58
	0.5	0.5	0.25	0.23	0.08	0.34	0.45
	0.8	0.2			0.05	0.04	0.5
Vulnerability (Mm^3)	0.2	0.8			25.88	45.29	59.33
	0.5	0.5	133.36	169.71	31.09	52.16	48.47
	0.8	0.2			68.1	70.85	88.43

Table 6 : Characteristics of hydropower generation of the proposed models.

Models	w_1	w_2	Model-I (SOP)	Model-II-a (NLP)	Model-II-b (DDDP)	Model-III (S-O)
Average monthly power produced(MW)	0.2	0.8		134.84	134.94	133.24
	0.5	0.5	130.85	135.93	135.92	134.79
	0.8	0.2		137.38	137.57	135.48
Maximum monthly power produced(MW)	0.2	0.8		346.84	351.5	361.2
	0.5	0.5	364.83	346.84	351.5	362.97
	0.8	0.2		346.84	342.83	363.04
Minimum monthly power produced(MW)	0.2	0.8		34.37	24.77	0
	0.5	0.5	0	0	0	0
	0.8	0.2		0	0	0
No. of months' power production halted	0.2	0.8		0	0	1
	0.5	0.5	25	1	9	5
	0.8	0.2		6	9	21

Table 7: Characteristics and performance criteria of discharge releases based on variable and constant demand states.

Models	Variable Demand		Constant Demand	
	Model-II-b (DDDP)	Model-III (S-O)	Model-II-b (DDDP)	Model-III (S-O)
Maximum discharge release (m^3/s)	467.46	467.03	462.96	469.24
Average discharge release (m^3/s)	188.94	188.91	188.94	188.94
Minimum discharge release (m^3/s)	38.97	28.41	38.97	31.99
Reliability	0.88	0.88	0.9	0.91
Resilience	0.3	0.61	0.47	0.58
Vulnerability (Mm^3)	32.05	64.53	45.29	59.33

Table 8: Characteristics of power generation for variable and constant demand states.

Models	Variable Demand		Constant Demand	
	Model-II-b (DDDP)	Model-III (S-O)	Model-II-b (DDDP)	Model-III (S-O)
Average monthly power produced (MW)	134.66	132.47	134.94	133.24
Maximum monthly power produced (MW)	351.5	355.8	351.5	361.2
Minimum monthly power produced (MW)	0	0	24.77	0
No. of months' power production halted	6	4	0	1