Optimizing Reservoir Operation – A Case Study of Dokan Reservoir, Kurdistan Region, Iraq

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ABSTRACT

There has been renewed interest in optimization of reservoir operation for efficient planning and management of water resources. Generally, reservoir operation is based on empirical procedures, including rule curves to a certain range and subjective findings by the operation managers. This study is aimed to design the reservoir operation rule curve, based on optimization principles. The study has been conducted at Dokan Reservoir, which is fed by Lesser Zaab River at Dokan. The reservoir is mainly intended to meet irrigation demands, hydropower generation and flood control. The study proposes opportunity for changing traditional reservoir operation to optimized strategies and taking advantages of the Optimization technique is used to find the optimal solutions and based on that the optimized rule curves are developed for various scenarios of water demand, with different initial conditions rapid development in computational techniques. Dynamic Programming.

INTRODUCTION

Reservoir operation is meant to develop a strategy to fill reservoir during wet season in such a way that it ensures meeting downstream water demands, flood mitigation and dam safety. The objectives of reservoir operation are generally conflicting because water storage reduces the capacity for flood wave mitigation and affects downstream releases to meet the water demands including irrigation, hydropower and environment, etc. It is common in reservoir operation that fulfilment of one objective affects the other. It necessitates to define reservoir operation in such a way that the conflicting objectives should have minimum effects on each other.

One of the way is to devise reservoir operation strategy following optimization principles. (Louks et al., 2005) provide a variety of optimization techniques for water resources planning and management including reservoir operation and capacity expansion.

In general, the optimization techniques can be grouped into the conventional linear, nonlinear, dynamic programming and the emerging evolutionary computations. The conventional optimization techniques are still in practice and are applied extensively in water resources management problems for better solutions. (Rani and Moreira, 2009) stated that the advantage of Linear Programming is its versatility for large water systems, convergence to global optima and supported by many software packages. However, reservoir operation simulation may contain nonlinear
elements in the objective function constrained by reservoir capacity, pump and demand in nonlinear form. Common nonlinear programming methods are sequential linear programming (Barros et al., 2003), sequential quadratic programming (Finardi et al., 2005), method of multipliers (Fawal et al., 2007) and generalization of reduced gradient method (Peng and Buras, 2000). Stochastic Dynamic Programming (SDP) is another popular optimization method for reservoir operation optimization. (Alaya et al., 2003) studied reservoir optimization by using SDP and applied in Nebhana Reservoir. (Labadie, 2004) presented Dynamic Programming Successive Approximation (DPSA), Incremental Dynamic Programming (IDP) and Discrete Differential Dynamic Programming (DDDP) to manage the dimensionality problem in Dynamic Programming. The emerging group of optimization algorithms comes from computational intelligence which is named as Evolutionary Computations (EC). (Rani and Moreira, 2009) reported that the evolutionary algorithms such as Genetic Algorithm, Simulated Annealing, Tabu Search, Particle Swarm Optimization and Honey Bees Mating Optimization are efficient tools to deal with nonlinear and multi-objective analysis and they can be linked with simulation models. (Chuntian, 1999) applied a fuzzy dynamic programming model for real time operation of multiple reservoirs for flood management. (Chaves and Kojiri, 2007) developed Stochastic Fuzzy Neural Network Model to optimize the operation of Barra Bonita Reservoir in Brazil and concluded that it produced better results. (Ahmad et al., 2014) provides an extensive review of contemporary optimization techniques applied for reservoir operation including conventional optimization simulation techniques as well as some advanced algorithms like Artificial Bee Colony (ABC) and Gravitational Search Algorithm (GSA). (Celeste and Billib, 2009) investigated the advantages and disadvantages of these optimization techniques. They compared ISO, ESO and Parameterization-Simulation-Optimization (PSO) optimization methods. They conclude that, in general, PSO and ESO produce better results, but the choice of any method depends upon the type of problem and the water system to be optimized. (FANG et al., 2014) proposed a simulation-optimization model of reservoir operation based on target storage curves, where they used improved particle swap optimization (IPSO) to optimize key points of water diversion curves, the hedging rule curves and target multi-reservoir water supply system located in Liaoning Province China, including a water supply project. They concluded that the proposed operating rules are suitable for complex system. The storage allocation rule based on target storage curves shows an improved performance with regard to system storage distribution. (Jahanpour et al., 2014) developed a web-based application for optimization of single reservoir operation. They emphasized the application of computer optimization modelling tools to provide information for their rational operating decisions. Recent improvements in high-speed computers and internet encourage researches to become familiar with and use of modern techniques and tools more frequently. This article presents and tests a set of operational objectives to optimally operate a single reservoir using a web-based platform. All practitioners can use WBA to share their data, findings, and models while simultaneously solving their reservoir operation problems. (Rashid et al., 2007) developed Stochastic Dynamic Programming (SDP) model for Dokan Reservoir and suggested optimal decisions (ending storage levels) as a function of unregulated inflows. This study is aimed at to improve the Dokan Reservoir’s operation by devising a steady state optimized policy. The policy suggests reservoir’s improved operation rule curve
based on steady state policy to meet the multipurpose reservoir functions.

MATERIALS AND METHODS

Study Area

Study was conducted at Dokan Reservoir, which is located on the Lesser Zaab River about 65 km northwest of Sulaimaniyah City. The reservoir is impounded by Dokan Dam, which was commissioned in 1959. Reservoir’s total design capacity at normal operation level (Elevation 511.00 Above Mean Sea Level (AMSL)) of 6.87 Billion Cubic Meters (BCM) and live storage of 6.14 BCM. Minimum drawdown level is 469 m AMSL. There are five hydropower generation turbines with total installed capacity of the reservoir is 400 Mega Watts (MW), whose installation was completed in 1979. It need 550 m$^3$/s discharge at 95 m head to produce the power at maximum capacity. It is a multipurpose reservoir primarily for irrigation and then for hydropower and flood control. Figure 1 presents reservoir control rule curve (SMEC, 2006)

Data Collection

Lesser Zaab River inflow data at Dokan Dam were collected for last 22 years (1993-2014) from Dokan Dam Authority. Data on reservoir releases and water levels were collected for last five years, whereas the last 5 years data were collected for releases, reservoir water levels and hydropower generation. Downstream water demand data were not available, so the average releases have been considered as bench mark for the downstream water demands. Table 1 provides average monthly inflows to the reservoir for a period of 1993 to 2003 (high flow years) and releases for a period of 2010 to 2015.

| Month   | Inflows (BCM) | Releases (BCM) | Storage Target (BCM) |
|---------|---------------|----------------|----------------------|
| October | 0.146         | 0.190          | 5.392                |
| November | 0.484        | 0.223          | 4.545                |
| December | 0.458         | 0.223          | 4.545                |
| January | 0.905         | 0.165          | 4.545                |
| February | 1.100         | 0.184          | 4.545                |
| March   | 1.451         | 0.164          | 5.135                |
| April   | 1.677         | 0.178          | 5.660                |
| May     | 0.984         | 0.216          | 6.545                |
| June    | 0.438         | 0.341          | 7.207                |
| July    | 0.201         | 0.534          | 7.207                |
| August  | 0.139         | 0.575          | 6.868                |
| September | 0.123       | 0.287          | 5.941                |

Dynamic Programming Optimization

Dynamic Programming Optimization (DPO) technique is used in this study adopted from (Louks et al., 2005). Reservoir is mainly meant to meet downstream irrigation water demands, hydropower generation and flood mitigation. Generally, it is not be possible to meet all these objectives by affecting each other. DPO helps to devise reservoir operation strategy by minimizing the effects of one objective on the other by minimize a weighted sum of squared deviations from each of these targets. The weights reflect the relative importance of meeting each target in each season t. Dokan Reservoir’s live storage capacity of 6.14 BCM, is divided into 13 units from 0 to 6 for modelling purposes. Initial storage, $S_0$, can assume any value from 0 to 6 BCM with an interval of 0.3 for all periods t.

Storage volume continuity equation is given as:

$$S_t + Q_t + R_t - L_t(S_t, S_{t+1}) = S_{t+1} \ldots \ldots \ldots \ldots \ldots \ldots \ldots \ldots 1$$
where $Q_t$ is mean inflow, $L_t(S_t, S_{t+1})$ the evaporation and seepage losses, and $R_t$ the release or discharge from the reservoir. The hydrologic year is divided into 12 time periods (months), $t$. Overall four scenarios are simulated as Business as Usual (BAU), Flood Mitigation (FM), Hydropower generation during peak energy demand period (HP-PD) and hydropower generation in all seasons (HP-AS) and increase in downstream future water demands increase by 10%. Table 2 presents the weights associated with each scenario in different time of the year.

Table 2. Weights associated with different scenarios

| Month | BAU | Flood Mitigation | HP-PD | HP-AS | Demand 110% |
|-------|-----|------------------|-------|-------|-------------|
| Oct   | 1   | 0                | 0     | 0     | 0           |
| Nov   | 1   | 0                | 0     | 0     | 1           |
| Dec   | 1   | 0                | 1     | 0     | 0           |
| Jan   | 1   | 0                | 0     | 0     | 1           |
| Feb   | 1   | 0                | 0     | 1     | 0           |
| Mar   | 1   | 0                | 0     | 0     | 1           |
| Apr   | 1   | 0                | 0     | 0     | 1           |
| May   | 1   | 0                | 0     | 0     | 1           |
| Jun   | 1   | 0                | 0     | 1     | 0           |
| Jul   | 1   | 0                | 0     | 0     | 1           |
| Aug   | 1   | 0                | 0     | 1     | 0           |
| Sep   | 1   | 0                | 0     | 0     | 1           |
| Oct   | 1   | 0                | 0     | 0     | 1           |
| Nov   | 1   | 0                | 0     | 0     | 1           |
| Dec   | 1   | 0                | 0     | 0     | 1           |

The objective is to minimize the sum of total weighted squared deviations, $TSD_t$, over all seasons $t$ from now on into the future:

Minimize $\sum_t TSD_t$ ..............................................2

where,

$$TSD_t = w_s t (TS_t^2 - S_t)^2 + (TS_t^R - S_{t+1})^2 + w_f S_t [(ES_t)^2 + (ES_{t+1})^2] + wr_t [DR_t^2] ......3$$

In the above equation, when $t = 13$, the last period of the year, $t+1 = 1$, is the first period in the following year. Each $ES_t$ is the storage volume in excess of the flood storage target volume, $TS_t^F$. Each $DR_t$ is the difference between the actual release, $R_t$, and the target release $TR_t$, when the release is less than the target. The excess storage, $ES_t$ at the beginning of each season $t$ can be defined by the constraint:

$$S_t \leq TS_t^F + ES_t .......4$$

for periods $t = 1$ and 2, and the deficit release, $DR_t$, during period $t$ can be defined by the constraint:

$$R_t \geq TR_t - DR_t .......5$$

This constraint applies for all periods $t$.

The first component of the right side of Equation 3 defines the weighted squared deviations from storage target, $TSR_t$, at the beginning and end of season $t$. The weights $w_s$ associated with the storage component of the objective. The second component of Equation 3 is for flood control. It defines the weighted squared deviations associated with storage volumes in excess of the flood control target volume, $TSF_t$, at the beginning and end of the flood season, period $t+1$. Finally, the last component of Equation 3 defines the weighted squared deficit deviations from a release target, $TR_t$.

This minimum sum of weighted squared deviations for all $n$ remaining seasons $t$ is equal to:

$$F_t^n (S_t, Q_t) = \min \sum TSD_t (S_t, R_t, S_{t+1}) ......6$$

over all feasible values of $R_t$, where

$$S_{t+1} = S_t + Q_t - R_t - L_t (S_t, S_{t+1}) .........7$$

and $S_t \leq K$, the carrying capacity of the reservoir.

The policy which is required to be derived is called a steady-state policy. Such a policy assumes the reservoir will be operating for a
relatively long time with the same objectives. This steady-state policy can be found by first assuming that at some time all future benefits, losses or penalties, \( F_t^0(S_t, Q_t) \), will be 0. A steady-state policy will occur if the inflows, \( Q_t \), and objectives, \( TSD_t(S_t, R_t, S_{t+1}) \), remain the same from year to year. This steady-state policy is independent of the assumption that the operation will end at some point.

At each stage, or season, the release \( R_t \) or equivalently the final storage volume \( S_{t+1} \), are calculated that minimizes

\[
F_t^n(S_t, Q_t) = \text{Minimize}\{TSD_t(S_t, R_t, S_{t+1}) + F_{t+1}^{n-1}(S_{t+1}, Q_{t+1})\} \text{ for all } 0 \leq S_t \leq 6
\]

\[\ldots\ldots.8\]

The decision-variable can either be the release, \( R_t \), or the final storage volume, \( S_{t+1} \). If the decision-variable is the release, then the constraints on that release \( R_t \) are:

\[
R_t \leq S_t + Q_t - L_t(S_t, S_{t+1}) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.9
\]

\[
R_t \geq S_t + Q_t - L_t(S_t, S_{t+1}) - 6 \quad \ldots\ldots\ldots\ldots.10
\]

and

\[
S_{t+1} = S_t + Q_t - L_t(S_t, S_{t+1}) \quad \ldots\ldots\ldots\ldots.11
\]

If the decision-variable is the final storage volume, the constraints on that final storage volume \( S_{t+1} \) are:

\[
0 \leq S_{t+1} \leq 6
\]

\[
S_{t+1} \leq S_t + Q_t - L_t(S_t, S_{t+1}) \quad \ldots\ldots\ldots\ldots.12
\]

and

\[
R_t = S_t + Q_t - S_{t+1} - L_t(S_t, S_{t+1}) \quad \ldots\ldots\ldots\ldots.13
\]

The policy differs over each state, and over each different season, but not from year to year for any specified state and season. We have reached a steady-state policy. If we kept on computing the release and final storage policies for preceding seasons, we would get the same results.

**RESULTS**

Five scenarios are modelled as Business as Usual (BAU), Flood Mitigation (FM), hydropower generation during peak demand period (HP-PD), which are from December to February and June to August, then hydropower generation in all seasons (all months) (HP-AS) and finally downstream water demand increase by 10%. The reservoir operation rule curves are provided for two initial conditions as empty and half-filled reservoir at the beginning of hydrologic year. The steady state policies achieved by modelling are presented in the following sections:

**Business as Usual (BAU)**

BAU follows the design storage curve and ignores other parameters. Optimized releases and storage volumes are given in the Figure 2a and 2b for two initial conditions as zero and half live storage at the beginning of hydrologic year, in the month of October, respectively. Figures present optimal releases, optimal storages as well as design storage according to rule curve and average releases by the dam authorities in the last five years.

![Fig. 2a. Suggested reservoir operation under BAU scenario for zero initial live storage.](image1)

![Fig. 2b. Suggested reservoir operation under BAU scenario for half initial live storage.](image2)
Flood Mitigation (FM)

Flood mitigation is one of the important objectives of reservoir. In the last section, the weightage was given only to storage. In flood mitigation scenario, in the first three months the weightage is given to keep the space for flood storage in the reservoir, in order to mitigate flood peaks. Flood mitigation modelling produces the same results as given under BAU Scenario.

Hydropower Generation in Peak Energy Demand Periods (HP-PD)

Hydropower needs are increasing in the region, which puts pressure on energy sector to produce more sustainable energy. Hydropower generation data show that at Dokan Dam the power generation is directly related to water releases from the reservoir. Therefore, in this scenario, the weightage is given for releases during the peak energy demand months, which are, December to February and then June to August. In other months the weightage is given to storage. Figure 3a and 3b present the hydropower generation in peak demand period.

[Figure 3a. Suggested reservoir operation under HP-PD Scenario with zero initial storage.]

[Figure 3b. Suggested reservoir operation under HP-PD Scenario with half initial storage.]

Hydropower Generation in All Seasons (HP-AS)

In this scenario, the weightage is given for releases to all seasons (months) for hydropower generation. Figure 4a and 4b present the releases and storage volumes for the hydropower generation in all seasons.

[Figure 4a. Suggested reservoir operation under HP-AS Scenario with zero live storage.]

[Figure 4b. Suggested reservoir operation under HP-AS Scenario with half live storage.]
Increase in Future Water Demands (D10%)

In order to manage the future increase in water demands, a scenario with 10% water demand increase is simulated and the optimized rule curve is presented in the Figure 5a and 5b with two different initial conditions.

![Fig. 5a. Suggested reservoir operation under 10% increase in water demand with zero initial storage.](image)

![Fig. 5b. Suggested reservoir operation under 10% increase in water demands with half initial storage.](image)

Quantifying the Error

In order to obtain steady state reservoir operation policy, the difference between optimized storage or releases in two consecutive time steps should be zero. It means, the same storage and releases are proposed in two consecutive years. Figure 6 presents the analysis of errors, different between $S_t - S_{t+1}$ and $R_t - R_{t+1}$.

![Fig. 6. Errors in optimized storage and releases for two consecutive years.](image)

DISCUSSION

It can be seen in the Figure 6 that error in last two years become zero, which is an indication of achieving steady state policy. Scenarios simulated for different objectives of the reservoir operation suggest different releases and storage volumes as presented in the last section. Weightage given to different scenarios can be seen in Table 2. In general, the reservoir does not seem sufficient to fill the reservoir up to full capacity and meeting the downstream demands simultaneously.

In BAU scenario it can be observed that the optimized storage curve closely match the design storage curve. In HP-PD scenario, the high amount of releases can be seen in the peak demand energy demand months, whereas comparatively low releases are suggested in other months. The storage target in this scenario cannot be met. In HP-AS scenario, the time distribution of suggested releases are different than in the HP-PD scenario. Almost same trend in water releases can be seen in increased demand scenario. These comparisons are shown in Figures 7a to 8b.
Fig. 7a. Optimized storage volumes for zero initial live storage conditions.

Fig. 7b. Optimized releases for zero initial live storage conditions.

Fig. 8a. Optimized storage for initial half live storage conditions.

Fig. 8b. Optimized releases for initial half live storage conditions.

CONCLUSIONS

In this study, the Dokan Reservoir’s operation has been suggest based on Dynamic Programming Optimization technique on monthly basis. The DP technique solves the discrete optimization problem by minimizing the weighted sum of total squared deviations (TSD). A steady state operation policy is adopted when the error between two consecutive time steps become zero. Although the reservoir was mainly impounded to meet the irrigation water demands. However, growing energy crisis in the region and contribution of hydropower cannot be ignored. Keeping in view these pressing demands, a variety of scenarios has been modelled keeping in view the priorities for reservoir operation. Furthermore, the modelling has been performed for two initial live storage conditions as empty reservoir and half-filled reservoir at the beginning of the hydrologic year, which is start of the October month. The scenarios consist of BAU, FM, HP-PD, HP-AS and 10% increase in future water demand. Based on these scenarios, the study proposes the optimized storages and releases on monthly basis by having minimum effects on other objectives of the reservoir. Figures 7a to 8b present the optimized storages and releases for all the scenarios discussed above. Since downstream water demands are assumed to be equivalent to average releases, the optimized storage and release curves may change when the real data on downstream water demands are used.

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