Optimal Monthly Reservoir Operation to Maximize the Hydropower Generation

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Abstract: Reservoir operation is complex engineering problem due to non-linear, stochastic and non-convex in nature. This paper presents a robust and effective metaheuristic algorithm namely, Jaya algorithm (JA) to obtain optimal montly reservoir operation to maximize the hydropower generation. The advantage of JA is; it does not require any algorithm specific controlling parameters, it only requires the common controlling parameters such as number of iteration and population size. JA has been applied to Ukai reservoir, India. The results were compared with Invasive Weed Optimization (IWO) and Differential Evolution (DE). Based on the results it is found that JA is an effective and alternative method to solve reservoir operation.

Keywords: Reservoir operation; Optimization; Hydropower Generation; Jaya algorithm.

1. Introduction

Due to their non-linear objective function and constraints, the optimization of hydropower reservoirs is complex (Jothiprakash и Arunkumar 2013). However several traditional techniques for optimizing hydropower systems had been developed and implemented in the past decade. Linear programming (LP), non-linear programming (NLP) and dynamic programming (DP) are the traditional methods used in reservoir operation. Despite the effectiveness of these methods, it has its own drawback. For example, LP requires linear objective function and constraints, DP is cursed by dimensionality, and NLP cannot efficiently solve the non-convex issue (Hosseini-Moghari и съавт. 2015). Many heuristic and metaheuristic algorithms have lately been suggested for this purpose. Although the optimal global solution is not always guaranteed, it offers excellent results in an adequate calculation time (Kumar и Reddy 2006).

Evolutionary algorithms have been gaining interest among scientists over the previous few centuries. Various algorithms were used to solve the issue of the reservoir operation. Nagesh Kumar and Janga Reddy (2007) used particle swarm optimization (PSO) reservoirs to maximize hydropower generation and irrigation deficiencies. Bozorg Haddad et al. (2008) studied single and multi reserovir design operation of hydropower reservoir using honey- bee mating optimization (HBMO) algorithm. Azizipour et al. (2016) used the invasive weed optimization (IWO) algorithm to study optimal hydropower operation of the reservoir system and found that IWO is more efficient and effective than PSO and genetic algorithm (GA). Ming et al. (2015) used cuckoo search (CS) to operate the multi-reservoir scheme of Wujiang in China and compared the outcomes with GA and PSO. CS has been noted to have exceeded GA and PSO.

There are few limitations to the existing algorithms. Evolutionary algorithms have two parameter types: first, common parameters, i.e. population size and a number of iterations, and second, individual algorithm-specific parameters. Such as, GA required mutation parameters, crossover parameters and reproduction parameters. PSO used internal parameters like social and cognitive parameters and inertia weight. differential evolution (DE) used crossover rate and scaling factor. Artifical bee colony (ABC) necessitate the number of employed bees, scout bees and onlookers. Such parameters are referred to as algorithm-specific parameters and are different for different algorithms. Improper selection of these parameters affect the algorithm's overall efficiency. Apart, other algorithms used in hydropower operations have their own parameters, such as cuckoo search, bat algorithm, ant colony optimization, weed optimization, etc.

Jaya algorithm (JA) has been used in this research to overcome these algorithms specific parameters. JA is very recently developed by Venkata Rao (2016). The algorithm always attempts to approach achievement (i.e. achieving the highest solution) and attempts to prevent failure (i.e. moving away from the worst solution). Rao et al. (2017) used JA to optimize the procedures of modern machining and the outcome showed improved efficiency. Huang et al. (2018) used JA to solve the problem of maximum power point tracking, and the findings demonstrated faster convergence and improved efficiency. Kumar and Yadav (2018) used JA to optimize the multi-reservoir operations and better performance was achieved. Kumar and Yadav (2019) introduced the elitist JA to solve optimal crop pattern.

In view of JA's success in addressing various field and water resource problems, this paper applied to optimization of hydropower reservoirs in order to maximize power generation. A high storage in the reservoir is required to produce more energy to increase hydropower output. JA resutls were compared with the Invasive Weed Optimization (IWO) and Differential Evolution (DE) algorithms. The section below describes methods and materials.

2. Materials and Methods

Jaya algorithm (JA) work on the principal to get closer to the better solution by avoiding the failure. The following are the steps to be followed in order to run the algorithm.

i) The first step is similar to the other random search algorithm, i.e., deciding the population size and the number of iteration. The initial solutions are generated randomly between the upper and lower bounds of the variables.

ii) Identify the best and worst alternative on the population list. If $X_{j,k,i}$ is the j^{th} variable (i.e. j=1, 2,…..,m), of the k^{th} candidate (i.e. population size, k=1,2…..,n) of the i^{th} iteration. Where m is the number of design variables, and n is the number of candidate solutions.

iii) The modified solution is expressed as per the Eq. (1).

$$X_{new,j,k,i} = X_{j,k,i} + r_{1,j,i}\,(X_{j,best,i} - |X_{j,k,i}|) - r_{2,j,i}\,(X_{j,worst,i} - |X_{j,k,i}|) \qquad (1)$$

Where, $X_{j,best,i}$ is the best solution and $X_{j,worst,i}$ is the worst solution. $X_{new,j,k,i}$ is the new updates variable, $r_{1,j,i}$ and $r_{2,j,i}$ are the two random numbers produced between [0,1]. The term "$r_{1,j,i}\ (X_{j,best,i} - |X_{j,k,i}|)$" enables the solution to move towards the best solution and the term "$r_{2,j,i}\,(X_{j,worst,i} - |X_{j,k,i}|)$" enables the solution to prevent the worst solution.

iv) The objective function obtained from $X_{new,j,k,i}$ and $X_{j,k,i}$ is compared. The better function value obtained by the particular candidate is selected. The same process is considered for all the k^{th} candidate in the population. The accepted candidates and the corresponding functional values become the input to the next iteration. This completes one iteration. The cycle stops when the maximum generation number is reached, otherwise repeat itself.

3. Study Area Description and Data Collection

Ukai dam, built across the Tapi River in 1972, is situated at $21^0$14' 53.52" N and 73^0 35' 21.84" E. Tapi River is India's west-flowing interstate river that flows through major regions of Maharashtra and part of Madhya Pradesh and exits the Khambhat Gulf of Gujarat state. Tapi river's complete length is 724 km and has a catchment region of 65.145 km^2. The primary aim of the dam is irrigation, generate electricity and regulate the flood. Figure 1 shows the study area index map. There are three channel networks supplying water for irrigation. The first canal directly diverts from the Ukai dam, i.e. Ukai left bank main canal (ULBMC). The other two canals are diverted from the Kakrapar weir, 29 km downstream of the dam, i.e. Kakrapar left bank main canal (KLBMC) and Kakrapar right bank mail canal (KRBMC). Later KRBMC split into Kakrapar right bank main canal (KRBMC) and Ukai Right bank main canal (URBMC). The dam releases are used in the generation of electricity. Table 1 demonstrates the basin's silent characteristics.

Table 1. Silent features of the basin

Features	Readings
Geographical Location	72°33' to 78°17' E longitude 2009' N to 220 N latitude
Temperature	Maximum: 37.170 centigrade Minimum: 19.730 centigrade
Average Rainfall	820.07 mm
Highest Elevation	1556
Area	65145 Sq. km
State in the basin	Maharashtra, Madhya Pradesh, and Gujarat
Number of irrigation projects	Major -13, Medium -68
No of watersheds	100
No of villages	9443
Top of Dam	111.252 m
Type of spillway	Radial
Road width on the spillway	6.706 m

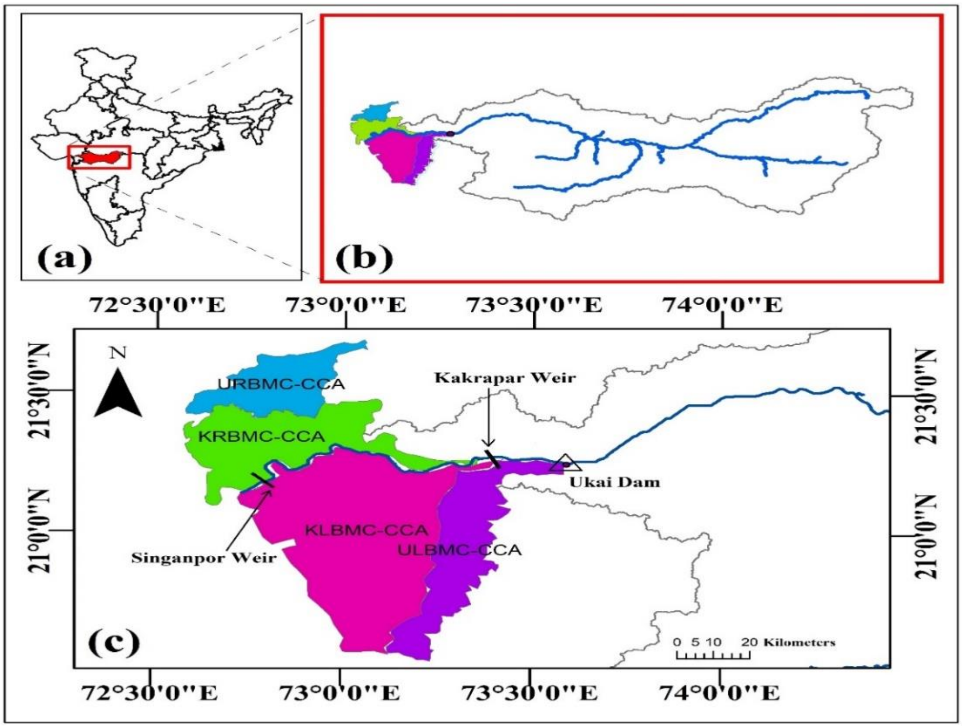

Figure 1. Study area index map

The data needed for this study were gathered from the Ukai left bank division and Surat irrigation circle. The information for the assessment were monthly Tapi river inflow (1972 to 2016), monthly Ukai reservoir levels (1972 to 2016), Ukai reservoir storage (1972 to 2016), Power house discharge (1976 to 2016), all CCA irrigation requirements, channel releases (1976 to 2016), evaporation rate (1972 to 2016), reservoir areas (1972 to 2016), domestic requirements, industrial requirements and water quality requirements (1990 to 2016).

4. Mathematical Model Formulation

The objective of the study is Maximize the annual hydropower generation

$$Maximize\ P = \\ = \sum_{t=1}^{12} 2725 * \eta * \left(\left(R_{1,t} + IR_{1,t} + IR_{2,t} \right) * \ H_{1,t} \right) + \sum_{t=1}^{12} 2725 * \eta \\ * \left(\left(IR_{3,t} \right) * \ H_{2,t} \right) \tag{2}$$

where, P is the total annual power generation in kilowatt-hour (kWh). η is the overall power plant efficiency, $R_{1,t}$ is the river bed turbine release in Mm^3 in period t. $H_{1,t}$ and $H_{2,t}$ are the net head on the river bed turbines and Ukai left bank main canal during period t. $IR_{1,t}$, $IR_{2,t}$ and $IR_{3,t}$ are the irrigation released for the Ukai left bank main canal (ULBMC), Kakrapar left bank main canal (KLBMC) and Kakrapar right bank mail canal (KRBMC), respectively in period $t = 1, 2, \ldots \ldots 12$, in Mm^3. The objectives are subjective to the following constraints:

Continuity constraints

$$S_{t+1} = S_t + I_t - \left(R_{1,t} + IR_{1,t} + IR_{2,t} + IR_{3,t} \right) - E_t - Ovf_t \tag{3}$$

Where, S_t is the active reservoir storage in Mm^3 at the beginning of period t, S_{t+1} is the reservoir storage in Mm^3 during period $t+1$, I_t is the Ukai reservoir inflow in Mm^3 during the period t, E_t is the evaporation losses during period t in Mm^3, Ovf_t is the overflow from the reservoir during period t in Mm^3.

Evaporation constraints

The evaporation losses are calculated as per Eq. (4).

$$E_t = \frac{E_{v,t}}{1000} * \frac{A_t + A_{t+1}}{2} \tag{4}$$

Where, $E_{v,t}$ is the evaporation from the reservoir during period t in mm, A_t and A_{t+1} are the reservoir areas at the beginning of the period t and t+1, respectively, in $10^6\ m^2$.

Storage constraints

$$S_{min} \leq S_t \leq S_{max} \tag{5}$$

Where, S_{min} and S_{max} are the minimum and maximize storage capacity according to the rule curve during period t in Mm^3.

Maximum power production constraints

The power production needs to be lower equal than the maximum power production capacity, at any time period t = 1,2 ….12.

$$2725 * \eta * \left(\left(\mathrm{R}_{1,t} + \mathrm{IR}_{\mathrm{KLBMC,t}} + \mathrm{IR}_{\mathrm{K,U,RBMC,t}} \right) * \ \mathrm{H}_{1,t} \right) \leq \ \mathrm{P}_{1,t,max} \tag{6}$$

$$2725 * \eta * \left(\left(\mathrm{IR}_{\mathrm{ULBMC,t}} \right) * \ \mathrm{H}_{2,t} \right) \leq \ \mathrm{P}_{2,t,max} \tag{7}$$

where, $P_{1,t,max}$ and $P_{2,t,max}$ are the maximum power produced by river bed turbines and ukai left bank turbines, respectively during the period t in kWh. H_t is represented with the head and storage relationship using Eq. (8).

$$H_t = c_1 + c_2 * S_t + c_3 * {S_t}^2 + c_4 * {S_t}^3 + c_5 * {S_t}^4 \quad (8)$$

where c_1, c_2, c_3, c_4 and c_4 are the constant coefficients of the storage height equation.

Canal Capacity constraints

$$IR_{1,t} \leq C_{1,t,max} \quad (9)$$

$$IR_{2,t} \leq C_{2,t,max} \quad (10)$$

$$IR_{3,t} \leq C_{3,t,max} \quad (11)$$

where, $C_{1,t,max}$, $C_{2,t,max}$ and $C_{3,t,max}$ are the maximum canal carrying capacities in ULBMC, KLBMC and KRBMC, respectively in period $t = 1, 2, \ldots \ldots 12$, in Mm^3.

Overflow constraints

$$Ovf_t \geq S_t + I_t - \left(R_{1,t} + IR_{1,t} + IR_{2,t} + IR_{3,t}\right) - E_t - S_{max} \quad (12)$$

Where, $Ovf_t > 0$, S_{max} is the maximum storage capacity observed in Mm^3.

Irrigation demands

$$D_{1,t,min} \leq IR_{1,t} \leq D_{1,t,max} \quad (13)$$

$$D_{2,t,min} \leq IR_{2,t} \leq D_{2,t,max} \quad (14)$$

$$D_{3,t,min} \leq IR_{3,t} \leq D_{3,t,max} \quad (15)$$

Where, $D_{1,t,min}$ and $D_{1,t,max}$ are the minimum and maximum irrigation demands for ULBMC, respectively; $D_{2,t,min}$ and $D_{2,t,max}$ are the minimum and maximum irrigation demands for KLBMC, respectively; $D_{3,t,min}$ and $D_{3,t,max}$ are the minimum and maximum irrigation demands for K&ULBMC, respectively, in time period t.

Water Quality Requirements

$$R_{1,t} \geq DR_{min,t} \quad (16)$$

Where, $DR_{min,t}$ is the minimum downstream release in the river to meet domestic, industrial and water quality requirement during period t in Mm^3.

5. Results and Discussion

Model Application and Parameters

A reservoir operating model has been created in this research to maximize the hydropower generation. The model uses the 75% dependable inflow. The 75% dependable inflow was computed using the Weibull formula based on available historical monthly reservoir inflow data (Subramanya 2013). All algorithms were coded with MATLAB R2014b software. Common control parameters such as number of iterations 10000 and population size (i.e. 25, 50, 75, and 100) were used to check the efficiency of algorithms over 10 separate runs. It has been observed that all algorithms performed better for population size 50. The internal parameters in DE, i.e. the lower and upper scaling factors were taken as 0.2 and 0.8, respectively, and the CR crossover probability was taken as 0.2. Internal parameters of IWO such as minimum and maximum seed number i.e. S_{min} and S_{max} were taken as 0 and 3, the non-linear modulation index (a) was taken as 2, initial SD $(\sigma_{initial})$ and final SD (σ_{final}) were taken as 0.6 and 0.001. The penalty is applied to the reservoirs to fulfil the reservoir storage constraint. The penalty parameter g(n) = 5, the penalty function $p_{(m,t)(c)}$ and c is the constraint. The features of the penalty are demonstrated in Eq. (17) and (18) respectively.

$$\text{If } f(p_{(m,t)(c)}) == 0, \text{ then } penalty\ function = 0 \tag{17}$$

$$\text{Else if } f(p_{(m,t)(c)}) \neq 0, \text{ then } penalty\ function = g(n) * abs\left(f(p_{(m,t)(c)})\right)^2 \tag{18}$$

Analysis of hydropower generation

In order to maximize the production of hydropower, a high level of storage in the reservoir is needed to generate more energy. Table 2 shows the 10 different run objective function values of JA, DE, and IWO. Comparing the best optimal solution, JA and DE achieved a better hydropower generation of 1723.50 $M\ kWh$ compared to IWO with an optimum hydropower generation of 1566.52 $M\ kWh$. When comparing the mean optimal solution, DE performed better with the average generation of hydropower compared to JA and IWO. The IWO progressed very slowly compared to JA and DE. When the IWO algorithm is run for 100,000 iterations, the near-optimal solution has been achieved as 1645.15 $M\ kWh$.

Table 2. Optimal solution obtained by different algorithm for model-2 in (M kWh)

Sr No.	JA	DE	IWO
1	1723.50	1723.50	1566.52
2	1711.14	1723.50	1534.72
3	1723.50	1723.50	1514.60
4	1723.50	1723.50	1509.23
5	1721.41	1723.50	1524.20
6	1723.50	1723.50	1499.64
7	1723.50	1723.50	1498.39
8	1723.50	1723.50	1490.39
9	1719.08	1723.50	1565.73
10	1723.50	1723.50	1525.65
Best	1723.50	1723.50	1566.52
Worst	1711.14	1723.50	1490.39
Mean	1721.62	1723.50	1522.91
Standard Deviation	3.96	0.00	26.54

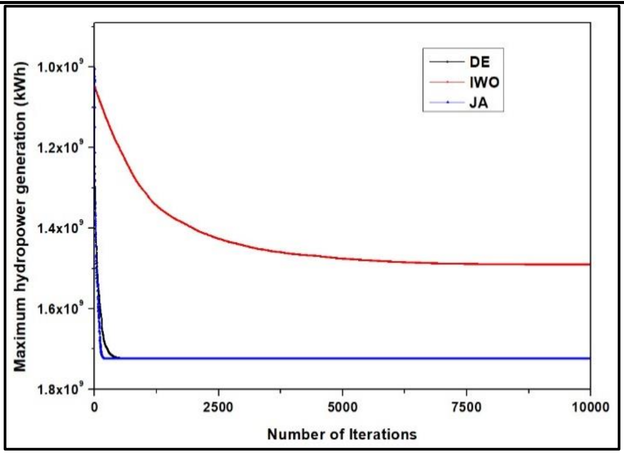

Figure 2. Convergence of the different algorithms

Convergence plot by different algorithm

The convergence rates of the model-2 for various algorithms upto 10,000 iterations are shown in Figure 2. It was noted that to obtain the optimum solution, JA convergence rate was faster than DE and IWO. The rate of IWO convergence was very slow. The IWO convergence rate for 100,000 iterations is shown in Figure 3. It was found that around 100,000 iterations IWO was able to obtain near optimal solution, i.e. 1645.15 $M\ kWh$.

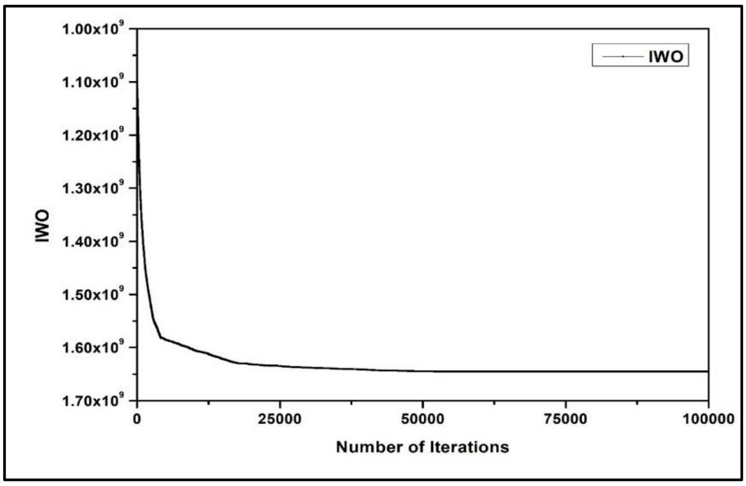

Figure 3. Convergence of the IWO algorithm

6. Conclusions

This paper applied to optimization of hydropower reservoirs in order to maximize power generation. This has been implemented over the Ukai reservoir. The Jaya algorithm was used and the results were compared with Differential Evolution and invasive weed optimization. The findings indicate that JA and DE achieved the best optimal solution compared IWO. While comparing the mean optimal solution, DE performed better than JA and IWO. It was noted that to obtain the optimum solution, JA convergence rate was faster than DE and IWO. Based on the results, JA is found to be an effective and alternative way to solve the reservoir operation.

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