OPTIMAL RESERVOIR OPERATION FOR HYDROPOWER GENERATION USING DIFFERENTIAL EVOLUTION ALGORITHM

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The reservoirs in India not only play a significant role in irrigation but also in power production. Hydropower reservoirs are very vital in supplying the high valued peak loads. However, hydropower reservoirs are often under constant scrutiny for diverting large quantity of water for power production, if the power production is not an incidental leading to conflict of interest. Hence, it is important to utilize the available water optimally among different purposes so that the multi-sectoral demands are satisfied. Optimizing a large-scale water resources system requires systematic study and the development of system analysis techniques, particularly soft computing techniques helps to achieve global optimum solution. In the present study, the Koyna hydropower reservoir in India is optimized for maximizing the power generation satisfying the monthly irrigation demands. The peculiar constraint of the system is the location of the powerhouses at different levels with different capacities and in the opposite direction of irrigation release. Thus, there is a need to optimally allocate the water to each powerhouse in addition to satisfying the irrigation demands. The Koyna reservoir operations are optimized using differential evolution (DE) algorithm for three different inflow conditions, representing wet, normal and dry scenarios. The results show that the power production from the system could be increased substantially besides meeting the irrigation demands. This study also shows that the differential evolution algorithm can be used for optimizing large-scale complex water resources systems.

Keywords: multi-purpose reservoir, optimization, hydropower generation, irrigation, differential evolution algorithm

Introduction

Reservoirs play a significant role in a country's economy through its multiple purposes such as irrigation, hydropower, navigation, flood control, etc. Among various purposes of a reservoir, hydropower is vital in supplying the high valued peak loads. However, hydropower reservoirs are often under constant scrutiny for diverting large quantity of water for power production, if the power production is not an incidental. Hence, it is important to utilize the available water optimally among the different purposes so that the multi-sectoral demands are satisfied. Thus, reservoirs serving multiple purposes are needed to be optimized for efficient operation and management.

Optimizing the operations of a multi-purpose reservoir requires a systematic study. Several optimization techniques from conventional to recent soft computing techniques had been developed and applied for optimizing reservoir operations. However, there is always a quest for new optimization technique for producing global optimal solutions. Among several soft computing techniques, differential evolution (DE) algorithm is one of the most recent global optimization technique developed by Storn and Price (1995). DE is a population-based technique that searches the global optimum using the randomly generated initial population (Price et al., 2005). The application of DE algorithm in water resources is relatively new and few studies can be found on optimal crop planning (Vasan and Raju, 2006; Pant et al., 2008; Adeyemo and Otieno, 2010). Apart from crop planning, DE has also been applied to hydropower optimization. Yin and Liu (2009) optimized the hydropower production using DE Algorithm. Regulwar et al. (2010) applied DE for the optimal operation of multipurpose reservoir in India with the objective of maximizing the hydropower production. Qin et al. (2010) proposed multi-objective cultured differential evolution (MOCDE) for reservoir flood control operation. Thus, the application of DE as a global optimization technique in water resources is wide and these studies show that it is also a robust technique in producing global optimal solution. In the present study, the DE algorithm is applied to optimize the hydropower production from the Koyna hydropower reservoir. The hydropower generation is evaluated for three different inflows representing the wet, normal and dry scenario of the reservoir. The irrigation demands are satisfied by considering it as a separate constraint.

Differential Evolution Algorithm

Storn and Price (1995) developed the differential evolution (DE) algorithm as an improved version of genetic algorithm (GA), a type of evolutionary algorithm (EA) for faster optimization (Price et al., 2005). The key parameters that controls the global search in DE are the population size (N_p), crossover factor (CR) and the mutation scale factor (F). Like other evolutionary algorithms, DE is also a population-based technique that evaluates the fitness of each vector (individual) in the population. The initial population is randomly generated within the specified upper (UB_j) and lower limits (LB_j) of the variables using the equation:

$$x_{i,j} = n_{i,j} \times (UB_j - LB_j) + LB_j \qquad i = 1, 2, \ldots, Np;\ j = 1, 2, \ldots, N_v \qquad (1)$$

Where $x_{i,j}$ is variable 'j' of the 'i^{th}' vector; N_p is the population size, $n_{i,j}$ is the uniformly distributed random number and N_v is the number of variables. Once the initial population is generated, the fitness of the each vector in the population is evaluated. Then the new population for the next generation is created using mutation and crossover operations in DE. In DE mutation, a scaled difference of two randomly selected vectors is added to the third vector in the population to generate a new intermediate vector. This is mathematically given as:

$$V_i = X_{r3} + F \times (X_{r1} - X_{r2}) \qquad i = 1, 2, \ldots, N_p; \quad r_1 \neq r_2 \neq r_3 \tag{2}$$

Where V_i is the new muted intermediate i^{th} vector in the population; X_{r1}, X_{r2}, *and* X_{r3} are the randomly selected vector from the old population and F is the scale factor. It is to be noted that the randomly selected vectors should not be of same index. Also, the scale factor ensures that the random vector does not duplicate the existing vector and shift the focus of the search from local to global (Price et al., 2005). This procedure is repeated until all the vectors in the population are muted. The DE mutation is carried out among the vectors of the population and the crossover is carried out between each variable of the vector in the population.

In DE crossover, a uniformly distributed random number (r_j) is generated, which will be compared with the crossover parameter '*CR*'. If the generated random number (r_j) is less than the *CR* value, then the variable from the intermediate vector is copied, else the variable in the old population is retained. This is mathematically given as:

$$U_{i,g} = u_{j,i,g} = \begin{cases} v_{j,i,g} & if \;\; r_j < CR \\ x_{j,i,g} & otherwise \end{cases} \tag{3}$$

Where r_j is the random number and *CR* is the crossover factor. Then a new trial population is generated by repeating this procedure for all the variables in the vector of the intermediate population. The fitness of each vector in the new trial population is estimated and then based on the fitness value, the new population for the next generation is created. If the fitness of the trial vector is lesser than the fitness of the old population, then the trail vector is selected for the next generation else the old vector will be retained. This selection process can be mathematically expressed as:

$$X_{i,g+1} = \begin{cases} U_{i,g} & if \;\; f(U_{i,g}) \leq f(X_{i,g}) \\ X_{i,g} & otherwise \end{cases} \tag{4}$$

The above procedure is continued until the termination criteria are satisfied. The termination criteria may be taken as the maximum number of generation or when there is no further improvement in the fitness value.

Study Area

The differential evolution (DE) algorithm is applied to Koyna Hydropower reservoir, Maharashtra, India for maximizing the hydropower production. The Koyna reservoir has three powerhouses developed in different stages, in which the two powerhouses are on the western side of the reservoir and third powerhouse is at the dam foot on the eastern side as shown in Fig. 1. The Koyna stage – I and stage – II are housed together with a capacity of 4 x 70 MW and 4 x 80 MW respectively (KHEP, 2005). For these two stages, the dam, headrace tunnel, surge well, pressure shafts and tailrace are common and henceforth referred as single powerhouse, PH I in the present study. The stage – IV, referred as PH II in the present study is 4 x 250 MW in capacity. Apart from power production, Koyna reservoir also serves irrigation on eastern side of the reservoir. Thus in order to utilize the head available in reservoir, the Koyna Dam Power House (KDPH) (henceforth referred as PH III in the present study) was constructed at the dam foot with an installed capacity of 2 x 20 MW to generate hydropower through irrigation releases. It can be observed that the major powerhouses are located on the western side of the reservoir and require huge quantity of water for operation. Thus, diversion of large quantity of water for power production towards the western side has resulted in dispute from the downstream stakeholders. Hence, the diversion of water towards the western side is limited to a certain quantity by the tribunal formulated to resolve this dispute (KWDT, 2010).

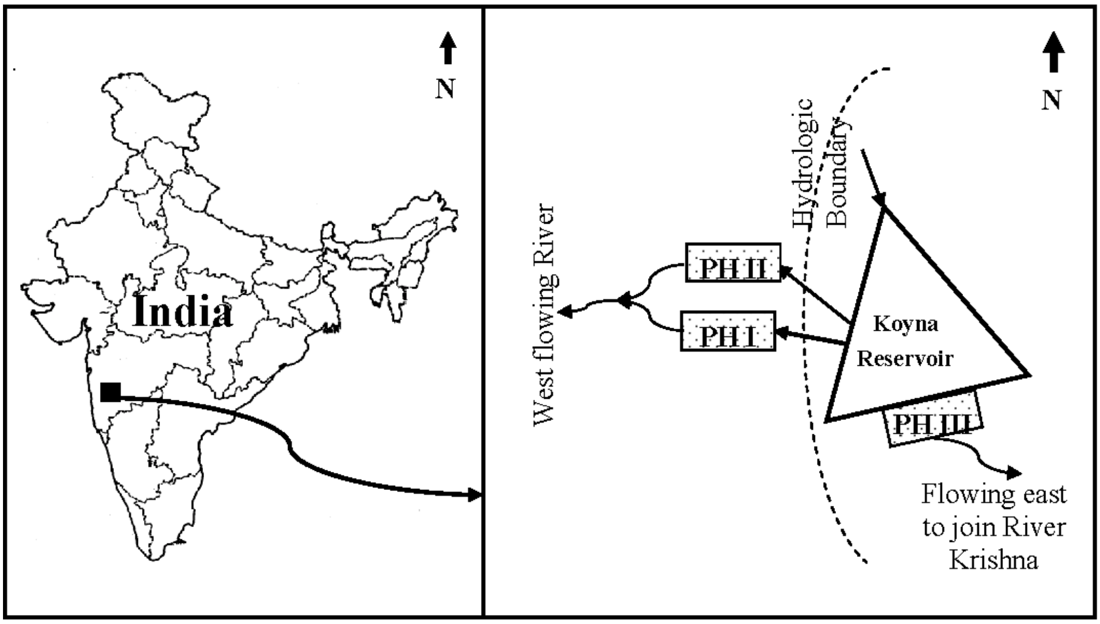

Figure 1: Location of the powerhouses of Koyna Reservoir

Hydropower Model

The objective of the present study is to maximize the power production from all the powerhouses of the Koyna reservoir and is expressed as:

$$\text{Max } Z = \sum_{t=1}^{12} \sum_{n=1}^{3} PH_{n,t} \qquad (5)$$

Where, $PH_{n,t}$ is the power produced from the powerhouse ‘n’ during the time period ‘t’ in terms of kWh. The above objective function is subjected to various constraints.

The other general constraints used in the study are :

Minimum drawdown level:

$$H_{n,t} \geq MDDL_{n,t} \qquad t = 1, 2 \ldots 12; n = 1, 2, 3 \qquad (6)$$

Maximum power production:

$$PH_{n,t} \leq P\,max_{n,t} \qquad t = 1, 2 \ldots 12; n = 1, 2, 3 \qquad (7)$$

Irrigation release constraint:

$$R_{3,t} \geq ID_t \qquad t = 1, 2 \ldots 12 \qquad (8)$$

Minimum and Maximum storage:

$$S_{min} \leq S_t \leq S_{max} \qquad t = 1, 2 \ldots 12 \qquad (9)$$

Water balance continuity constraint:

$$S_{(t+1)} = S_t + I_t - \sum_{n=1}^{3} R_{n,t} - O_t - E_t \qquad t = 1, 2 \ldots 12, n = 1, 2, 3 \qquad (10)$$

Overflow constraint:

$$O_t = S_{(t+1)} - S_{max} \qquad t = 1, 2 \ldots 12 \qquad (11)$$

$$O_t \geq 0 \qquad t = 1, 2 \ldots 12 \qquad (12)$$

where $H_{n,t}$ is the average head (m) in the reservoir for the powerhouse '*n*' during the time period '*t*'; $MDDL_{n,t}$ is the minimum drawdown level (m) for the powerhouse '*n*' during the time period '*t*'; $Pmax_{n,t}$ is the maximum generation capacity (kWh) for the powerhouse '*n*' during the time period '*t*'; $R_{3,t}$ is the irrigation release through PH III during the time period '*t*' (10^6 m^3); ID_t is the monthly irrigation demand for the time period '*t*'(10^6 m^3); S_{min} is the minimum storage of the reservoir (10^6 m^3); S_{max} is the maximum storage of the reservoir (10^6 m^3); S_t is the storage in the reservoir during the time period '*t*' (10^6 m^3); $S_{(t+1)}$ is the final storage in the reservoir during the time period '*t*' (10^6 m^3); I_t is the inflow into the reservoir during the time period '*t*'(10^6 m^3); $R_{n,t}$ is the release to the powerhouse '*n*' during the time period '*t*' (10^6 m^3); O_t is the overflow from the reservoir during the time period '*t*'(10^6 m^3) and E_t is the evaporation losses from the reservoir during the time period 't' (10^6 m^3).

Apart from these general constraints, Koyna reservoir is having one specific constraint. The diversion of huge quantity of water to the major powerhouses on western side of the reservoir has resulted in dispute. In order to ensure adequate water for irrigation on the eastern side of the reservoir and other downstream requirement, the western side diversion was restricted to certain limit by Krishna Water Dispute

Tribunal (KWDT, 2010). As per this constraint, diversion of large quantity of water to Western side for power production was restricted to 1912 x 10^6 m^3 and the total annual release for irrigation to 850 x 10^6 m^3. These constraints are given as:

$$\sum_{t=1}^{12}\sum_{n=1}^{2} R_{n,t} \leq R_{w,max} \tag{13}$$

$$\sum_{t=1}^{12} R_{3,t} \leq AID_{max} \tag{14}$$

Where, $R_{w,max}$ is the maximum water that can be diverted to the western side for power production and AID_{max} is the water to be released annually for irrigation to the eastern side.

Results and discussion

In the present study, the Koyna hydropower production is maximized along with satisfying the monthly irrigation demands using differential evolution algorithm. The above developed non-linear model is optimized for three different inflow scenarios, representing wet, normal and dry conditions. The wet inflow represents the 50% dependable inflow, the normal inflow represents the 75% dependable inflow and the dry inflow represents the 90% dependable inflow. The inflow dependability is estimated from 49 years of inflow data using Weibull's method. For each dependable inflow, the corresponding year starting month (June) storage observed in the reservoir is used as the initial storage in optimization. The '*DE/best/1/exp*' strategy DE is applied for optimization of all the scenarios. In this, '*best*' represents that the scaled difference is added to the best vector (X_{r3}) of the previous generation in mutation, '*1*' is vector difference and '*exp*' represents the exponential crossover. The DE parameters such as CR and F are fixed as 0.6 and 0.3 respectively by trial and error. For a population size of 250, the model is iterated for 1000 generations. The constraints in the model are handled using the penalty function method. The convergence of three inflow scenarios to optimal solution is shown in Fig. 2. From the figure, it is observed that initially all the inflow scenarios have resulted in sub-optimal solution. However, over the generation the DE finds the optimal solution and finally converges to the global solution with in 500 generations for all the inflow scenarios.

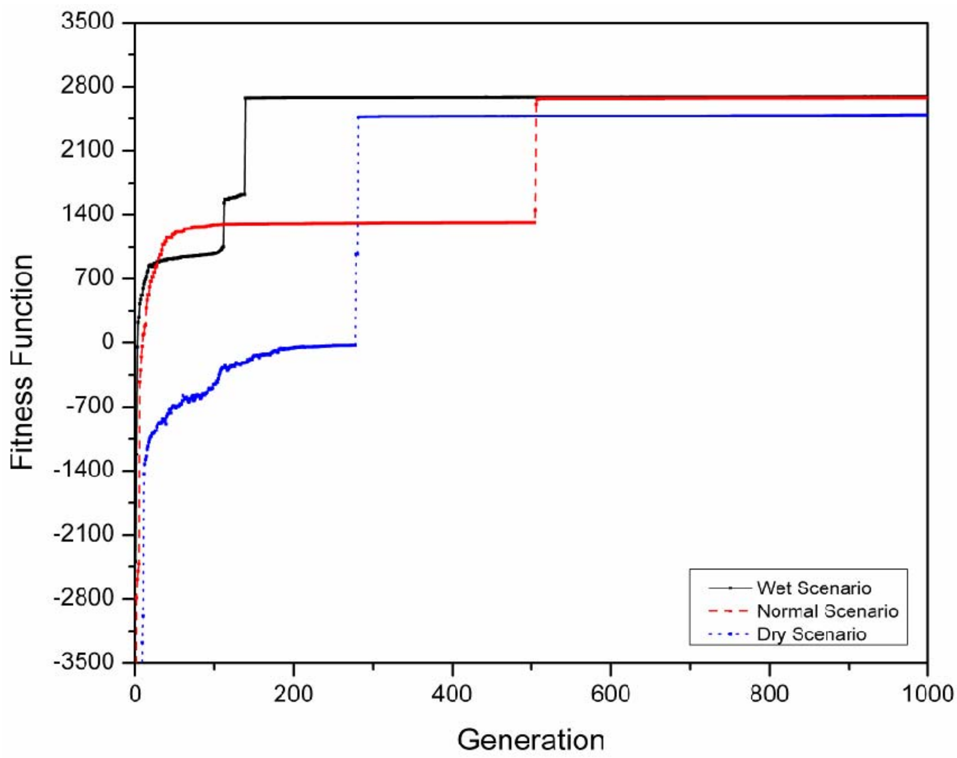

Figure 2: Convergence of DE to global optimum for different inflow scenarios

The wet inflow scenario has produced a maximum of 2686.71 x 10^6 kWh of hydropower. The normal inflow scenario has produced 2675.07 x 10^6 kWh and dry inflow scenario has produced 2494.31 x 10^6 kWh of hydropower. Even though the total releases to all the powerhouses and irrigation in the wet scenario and dry scenario are same, the power production varies slightly due to the variation in the monthly storage level and head available in the reservoir. However, the dry scenario has not released the total quantity due to less inflow in to the reservoir and the storage in the reservoir is always lesser than the wet and normal scenarios. This has lead to low head available in the reservoir for power production.

The monthly power production from various powerhouses for different inflow scenarios is given in Fig. 3. From the figure, it can be seen that the power production from PH I for all the inflow scenarios is almost constant and the variation is less. The power production from PH II various significantly for different inflow scenarios and hence the total annual power production varies among wet and dry inflow scenarios. This shows that the model releases a constant volume to PH I for all inflows and the variation in releases for PH II according to the inflow, which is having high capacity and net head. It is observed that during August, the power production from both PH I and PH II are significantly higher than other months due high inflow into the reservoir, particularly in wet inflow scenario. The power production from PH III is same for all inflow scenarios, which shows that the irrigation requirements are completely satisfied for all the three inflow scenarios and the power production is according to the irrigation release. Even though the total releases for dry inflow scenario is less than the specified limits, the model has satisfied the monthly irrigation demands. It is observed that the total monthly power production from all the powerhouses for normal inflow is higher during the non-monsoon season than wet and dry inflow scenarios. It is also seen that the total monthly power production for dry inflow scenario is higher during monsoon season than normal inflow scenario, however during non-monsoon season the production from normal inflow is higher.

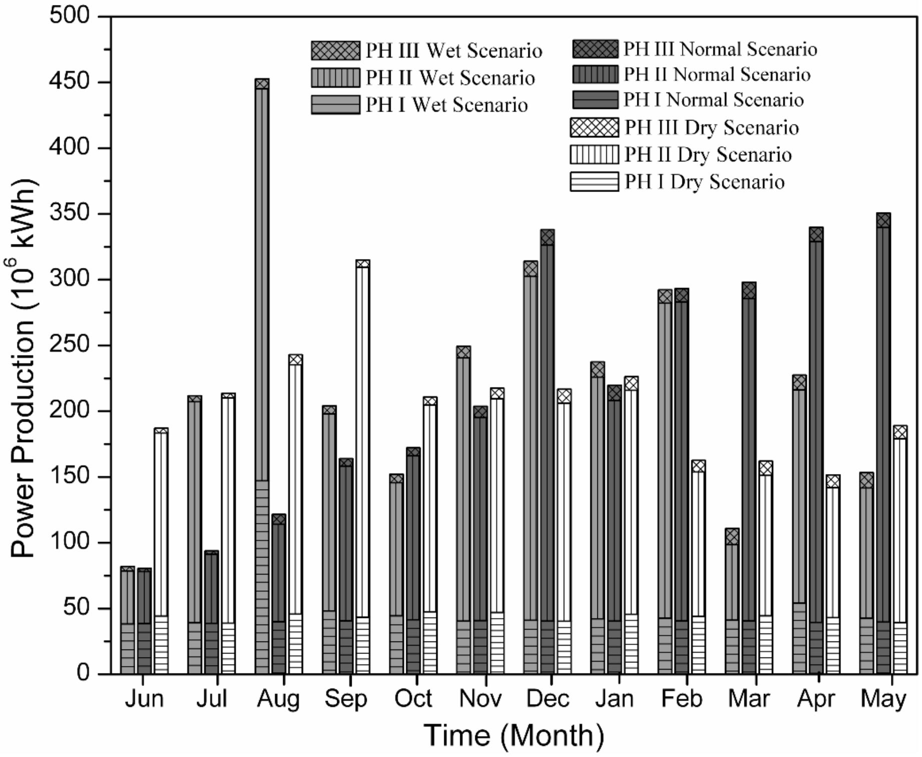

Figure 3: Monthly power production in various powerhouses for different inflow scenarios

The resulted end of month storage levels for different inflow scenarios are given in Fig. 4. From the figure, it is observed that the wet inflow has resulted in more storage than other inflow scenarios due to high inflow. In addition, only the wet inflow scenario has resulted in overflow during August and hence the power production in high in August. During the non-monsoon season, the variation in storage levels between wet and normal inflow scenarios are less. The dry inflow scenario has resulted in lesser storage and there is constant decrement in the storage during the non-monsoon seasons. This shows that the reservoir is completely dependent on monsoon inflow and during the non-monsoon season, the storage available in reservoir is used for power production. It is also observed that the final storage at the end of the time period (May) is higher than the initial storage used at the start of the time period (June) for wet and normal inflow. This is due to the restriction in releases to the powerhouses on the western side. This excess storage can be further utilized for power production by relaxing the restriction on releases towards western side.

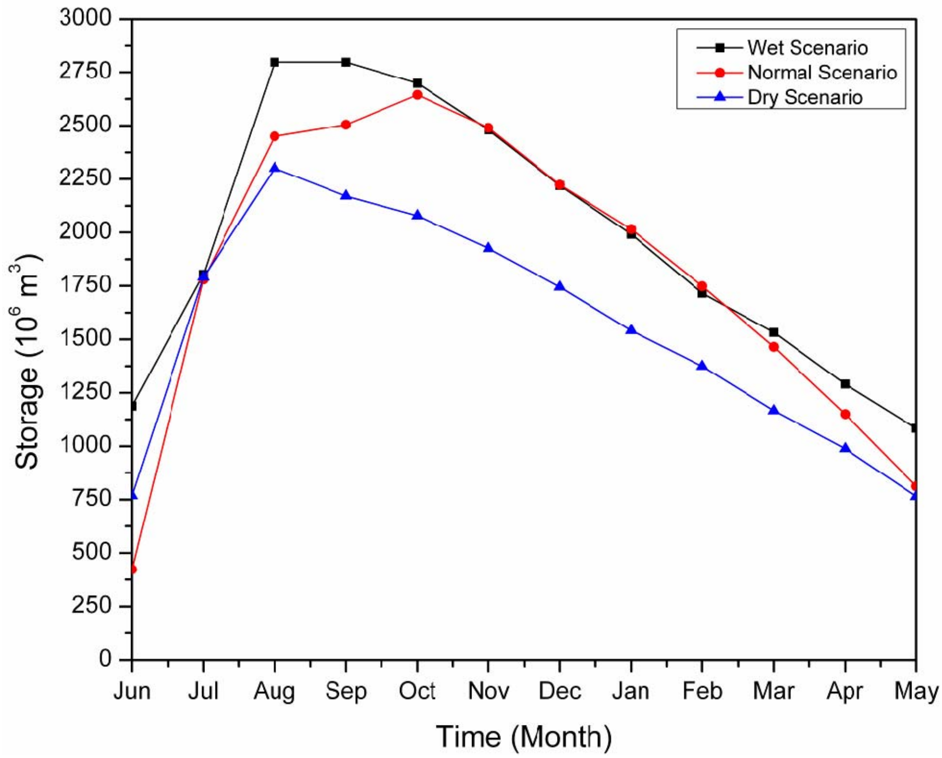

Figure 4: Resulted end of month storage for different inflow scenarios

Conclusion

In the present study, the hydropower production from Koyna reservoir is maximized satisfying the irrigation demands through a non-linear model solved using differential evolution algorithm. The DE algorithm has been applied for three inflow conditions representing wet, normal and dry scenarios. The global optimal results are obtained by iterating the DE algorithm for 1000 generations for a population size of 250, crossover factor of 0.6 and scale factor of 0.3. However, the DE algorithm reached the global optimal solution within 500 generation, which shows that the DE is quick and robust. The wet inflow scenario has resulted in higher power production. For both the wet and normal inflow scenarios the end of month storage levels are higher which shows that more power can be produced besides meeting the irrigation demands. This study also shows that the differential evolution algorithm can be used for optimizing large scale complex water resources systems.

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