Improvement of reservoir operation by hybrid optimization algorithm: case study of Huong Dien Reservoir, Vietnam

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Abstract An Improved Incremental Dynamic Programming (IDP) algorithm is developed in this study by combining IDP and Harmony Search (HS) to form HS-IDP for the initial procedure of generating decision variables. The developed hybrid algorithm (HS-IDP) and HS algorithm are simultaneously proposed for optimizing the reservoir operation to effectively solve a linear reservoir water balance equation and an objective function of benefit of Hydroelectrical Power (HP) to find optimal decision variables, taking into account water release or storage volume rates. The optimal reservoir operation (ORO) model is firstly applied for HuongDien (HD) hydroelectric dam of Hue Basin, Vietnam, downstream as it reaches Bo River where many critical problems have occurred such as water shortages and flooding inundations. This paper outlines how to reduce the impact of droughts and floods and to maximize the economic benefit through effective HD reservoir operation. The results indicated that the hybrid algorithm found the optimal decision variables having the highest HP benefit, while satisfying the specified constraints for reservoir and downstream safety.

Key words Optimization Reservoir Operation; Incremental Dynamic Programming (IDP); Harmony Search (HS); Huong Dien Reservoir; Hue-Vietnam

INTRODUCTION

Water is a vital factor for human life as well as for the socio-economic development of countries or river basins. Furthermore, developing hydropower is essential as a renewable source of electricity. It can replace other electricity production from gas, oil, and coal which then reduces carbon dioxide production. Hydropower dams have contributed to good economic and social benefits in Vietnam; however, there are still pressing issues which could be well-known to disadvantage hydropower construction. For instance, after two storms in September and November 2009, the Vietnamese Public showed concern about the release rates of water from hydropower dams that were the cause of flooding as well as contributing to the rapid increase of the high peak discharge (water level) in downstream rivers in which habitation was high. In particular, Huong Dien (HD) reservoir, where downstream there was damage to inhabitants from October to December in these floods and where there have been water shortages in the dry season from May to July.

Recently, many researchers have investigated the optimal condition of reservoir operation using different algorithms. Firstly, methods such as linear programming or dynamic programming formulation for finding the optimal operating schedule of a reservoir were applied successfully for a simplified reservoir (Yeh, 1985). Afterwards, the application of meta-heuristic techniques such as genetic algorithms (GAs) were used widely in many complex multi-objective problems related to the reservoir operation (Chang *et al.*, 2005). Moreover, Lason (1968) introduced the IDP, a successive approximation method, to overcome high dimensionality problems. Since, the IDP can tackle multiunit reservoir systems by taking a limited state space for every individual reservoir in the system (Nadalal & Bogradi, 2007). Furthermore, Janejira *et al.* (2007) combined the GAs and differential dynamic programming approach (called GA-DDDP). DDDP is known as a generalization of IDP to optimize the operation of multi-reservoir system. He stated that the hybrid GA-DDDP provided optimal solutions, converging into the same fitness values; however it required more computing time to obtain the precise results.

Moreover, Geem *et al.* (2001) and Kim *et al.* (2001) introduced a new meta-heuristic algorithm, which is originally inspired from a music improvisation process. It is a new meta-heuristic technique used to solve many different problems. In this case, Geem (2007) used the HS to find optimal scheduling of a multiple dam system with the modelling data. The HS model reached the global optimum while performing a sensitivity analysis of algorithm parameters, while the GAs required tedious sensitivity analysis.

In this research, the HS-IDP is a newly developed hybrid method and HS algorithm are used to obtain results for the optimization operation problem of the HD reservoir for finding the optimal monthly water release rates and storage volume at the end of month.

OPTIMIZATION ALGORITHMS

Harmony search

When a musician is improvising, he/she has three possible choices: (1) playing any famous tune exactly from his or her memory; (2) playing something similar to the famous tune (thus, adjusting the pitch slightly); or (3) composing new or random notes. For the first step, the HS randomly generates solution vectors equal to the number of Harmony Memory Size (HMS), and evaluates their fitness, afterward, stores them in Harmony Memory (HM):

$$[HM] = \left[\begin{array}{cccc|c} \mathrm{Re}_1^1 & \mathrm{Re}_2^1 & & \mathrm{Re}_N^1 & F(\mathrm{Re}^1, S^1, I^1, H^1, O^1, Ev^1, If^1) \\ \mathrm{Re}_1^2 & \mathrm{Re}_2^2 & & \mathrm{Re}_N^2 & F(\mathrm{Re}^2, S^2, I^2, H^2, O^2, Ev^2, If^2) \\ . & . & \cdots & . & . \\ . & . & & . & . \\ \mathrm{Re}_1^{HMS} & \mathrm{Re}_2^{HMS} & & \mathrm{Re}_N^{HMS} & F(\mathrm{Re}^{HMS}, S^{HMS}, I^{HMS}, H^{HMS}, O^{HMS}, Ev^{HMS}, If^{HMS}) \end{array}\right] \tag{1}$$

where N is the number of decision variables (for single reservoir, N = the number of time steps).

For the next step, a new harmony, ReNew is improvised as follows:

(a) Random Selection. For Re_i^{New}, the value can be randomly chosen out of value range ($\mathrm{Re}_i^{Min} \leq \mathrm{Re}_i^{New} \leq \mathrm{Re}_i^{Max}$) with a probability of (1-HMCR).

(b) Memory Consideration. Instead of the random selection, the value can be chosen from any pitches stored in HM with a probability of HMCR (harmony memory considering rate, 0 ≤ HMCR ≤ 1).

(c) Pitch Adjustment. PAR (0 ≤ PAR ≤ 1) stands for pitch adjusting rate.

$$\mathrm{Re}_i^{New} \leftarrow \begin{cases} \mathrm{Re}_i^{New} + \Delta \quad w.p\, HMCR \times PAR \times 0.5 \\ \mathrm{Re}_i^{New} - \Delta \quad w.p\, HMCR \times PAR \times 0.5 \\ \mathrm{Re}_i^{New} \quad randomize \quad w.p\, HMCR \times (1 - PAR) \end{cases} \tag{2}$$

Incremental Dynamic Programming

The general scheme of the IDP procedure is concisely presented in Fig. 1. The IDP uses the recursive equation of DP as equation (3) to search for an improved trajectory starting with an assumed feasible solution, which can be visualized as a trial trajectory. Then, the improved trajectory is sought within the pre-specified range as the "Temporal Memory". The computation cycle is completed when the search process has converged to the optimal trajectory according to a pre-specified convergence criterion. A trajectory is feasible if it satisfies all constraints.

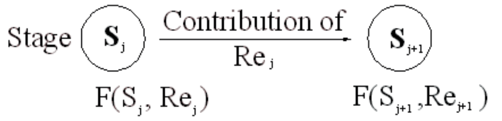

Fig. 1 Basic structure of dynamic programming.

For every state at stage j, the optimal policy is given by:

$$F_j^*\left(S_j^{New}, \mathrm{Re}_j^{New}\right) = \underset{\mathrm{Re}_j}{\mathrm{Max}}\left\{F_j\left(S_j^{New}, \mathrm{Re}_j^{New}\right) + F_j^*\left(S_{j+1}^{New}, \mathrm{Re}_{j+1}\right)\right\} \tag{3}$$

where S_j and Re_j are decision variables at the stage j (S_j has three states for next S_j^{New}: $S_j + \Delta$; $S_j - \Delta$; S_j). $F_j(S_j^{New}, Re_j^{New})$ is the cost or contribution of decision S_j^{New}& Re_j^{New} given at the actual stage, and $F_j^*(S_{j+1}^{New}, Re_{j+1})$ is the accumulated suboptimal cost (contribution for following stages j+1, j+2,…, N). For the stopping condition, the following equation is used:

$$(F_i - F_{i-1})/F_{i-1} \leq 0.0002 \tag{4}$$

where, F_i is the objective function's value for each evaluation, i = 1, 2, ..., m.

Hybrid HS-IDP

In the new approach, the hybrid HS-IDP is proposed to apply to optimization of reservoir operation. It operates by a combination of HS as the first step and IDP for the second step. The decision variable of HS is water release rate Re(j) (m^3s^{-1}) and the IDP is storage volume rate S(j) (hm^3). HS-IDP has two operating processes: First, HS generates a prescribed number of feasible solutions, then, the IDP uses the obtained solutions by the HS for the initial trajectories of the second stage. Figure 2 shows the flowchart and steps of the HS-IDP method having two main steps.

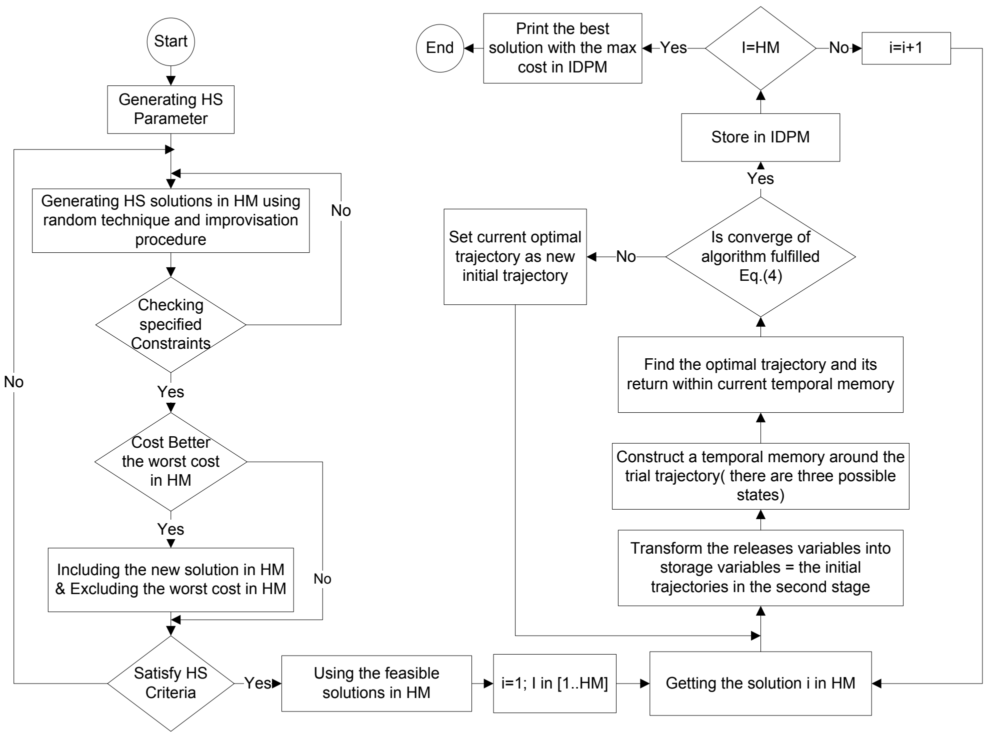

Fig. 2 Flowchart illustrates two operating stages including HS and IDP for the HS-IDP.

OPTIMIZATION OF RESERVOIR OPERATION MODEL

The hydroelectric plant uses water turbines to drive generators. In this problem, the target is to maximize the sum of multiplying the benefit of monthly HP generation with electricity prices. The formulation of fitness function HP benefit is defined as given in equations (5) and (6):

$$\text{Maximize } F = \sum_{j=1}^{T} E(j) \times p(j) \tag{5}$$

$$E(j) = 9.81 \times \eta \times Re(j) \times H(j) \times \Delta t/10^6 \text{ (Hydro-energy generation, in GWh)} \tag{6}$$

where F is HP benefit (million \$US.$year^{-1}$). $Re(j)$ is discrete monthly rate of water release during period j via turbines (m^3s^{-1}). $H(j)$ is head water level turbines during period $j = Z_{\text{water level}} - Z_{\text{turbines}}$ (m), $p(j)$ is price of energy during period j (cent/kWh), Δt is monthly time which is set to 732 (h). η is overall generation efficiency, which is set to 0.82, and j is values of 1, 2, …, 12 (representing the months for the period from October to September, respectively).

Imposed constraints

The goal is to optimize the fitness function, while complying with physical constraints given:

Release rate constraints: $23.61 \leq Re(j) + O(j) \leq 488.0$ ($m^3 s^{-1}$) (7)

where $Q_{max} = 488.0$ and $Q_{min} = 23.61$ ($m^3 s^{-1}$), are the maximum and minimum allowed discharges.

Storage volume constraints: $261.5 \leq S(j) \leq 882.5$ (hm^3) (8)

where $S_{max} = 882.5$ and $S_{min} = 261.5$ (hm^3), are the maximum and minimum allowed storage.

Overflow constraint for spillway:

$$O(j) = (S(j-1) + I(j) \times \Delta t) - S_{maxspillway} - Re(j) \times \Delta t \ \ (\mathrm{hm}^3) \tag{9}$$

where $O(j)$ (hm^3) is discrete monthly rate period of water release period j via spillways. And $S_{maxspillway}$ (hm^3) is maximum storage volume at peak spillways.

State transformation equation (Mass balance constraint): The relationship between the month to month storage is given by the linear reservoir water balance equation:

$$S(j) = S(j-1) + I(j) \times \Delta t - Ev(j) - If(j) - Re(j) \times \Delta t - O(j) \ \ (\mathrm{hm}^3) \tag{10}$$

where Ev(j) (hm^3) is monthly reservoir evaporation during period j. $I(j)$ (m^3s^{-1}) is monthly inflow to reservoir during period j. $If(j)$ (hm^3) is infiltration of reservoir during period j. $S(j-1)$ (hm^3) is storage volume at the period j. And $S(j)$ (hm^3) is storage volume at the end of each period j.

CASE STUDY

The developed ORO model was applied to the Huong Dien (HD) Reservoir, Bo River basin, located at Hue City, in the central region of Vietnam, which has a total basin area of 707 km^2. It is located from latitude 160°16′N to 160°45′N, and longitude 107°23′E to 107°55′E. Figure 3 shows the location of HD Dam and general features of the basin and Fig. 4 shows the connection of the study basin system with Huong River basin system.

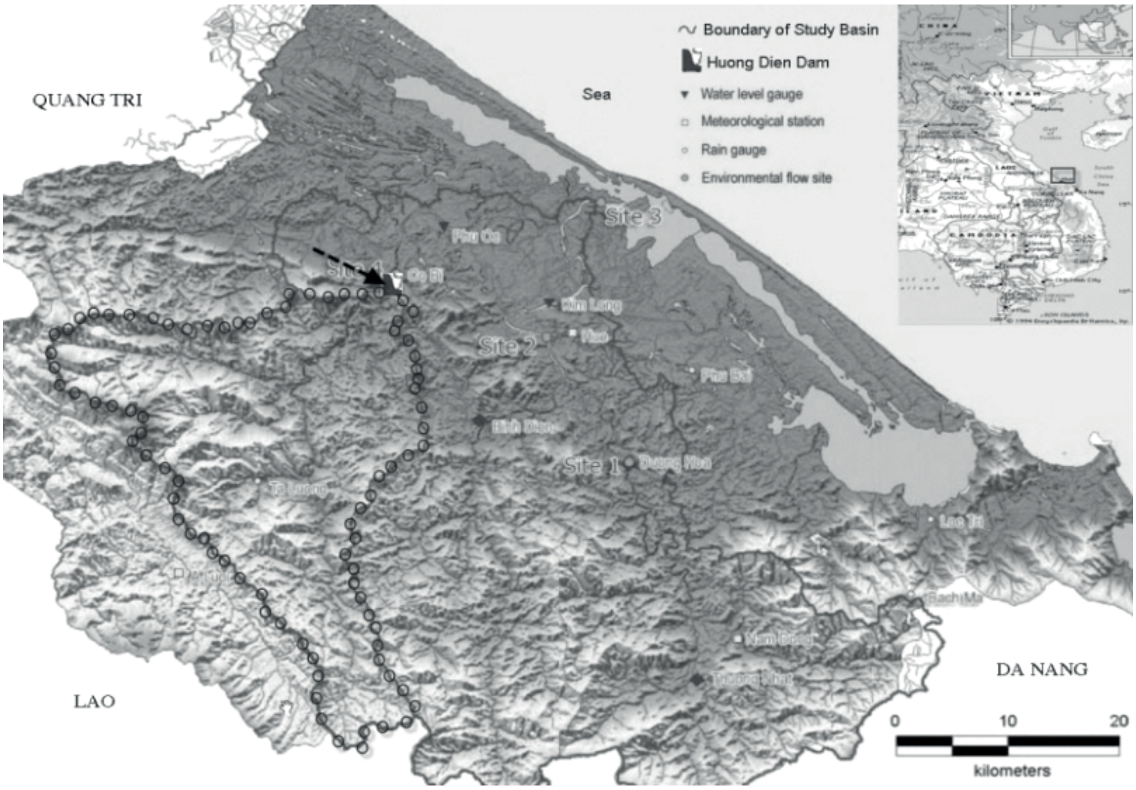

Fig. 3 Study basin (highlighted with -o-) in Hue Province, Vietnam. The arrow shows the location of the HD Dam (Picture is extracted from source NCCSAP, 2005).

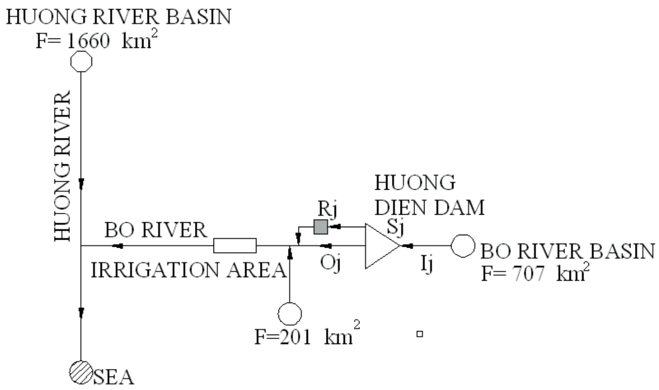

Fig. 4 Schematic of study system configuration.

Table 1 HD dam associated parameters (UCRHYDROPROJECT *et al.*, 2006).

Parameters	Quantity
Peak dam elevation	59.3 m
Downstream turbines elevation	2.12 m
Maximum storage volume	882.04 hm^3
Useful storage volume	822.5 hm^3
Installed capacity of power plant	54 MW
Mean HP capacity of previous study	226.31 GWh
Annual rainfall	3160 mm
Mean discharge of river	80.4 (m^3/s)
Mean annual temperature	25.1°C
Mean annual PE	79.4 mm

Table 2 Extracted values of average Inflow ($I(j)$-m^3 s^{-1}), Evaporation ($Ev(j)$-mm/month) and the price of electricity ($P(j)$-cent/KWh; following Vietnam electricity price 2004) for the HD Reservoir.

Month	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.
$I(j)$	155.7	220.0	114.2	79.3	19.9	19.8	20.5	31.6	27.2	11.8	61.4	108.0
$Ev(j)$	33.0	24.0	22.0	24.0	21.0	30.0	48.0	61.0	67.0	77.0	68.0	44.0
$P(j)$	3.7	3.7	3.7	3.7	4.0	4.0	4.0	4.0	4.0	3.7	3.7	3.7

* The authors used the meteorological dataset from 1977 to 2005 of Hue Province (2006) to derive the datasets above.

RESULTS AND DISCUSSION

The ORO model used the hybrid HS-IDP and the existing HS. The optimization results obtained from these two methods have been compared and given in tables and figures below. The initial parameters of the HS and those used in the ORO model were IDP: $\Delta = \pm 10^6$ m^3; HS: $\Delta = \pm 0.5$ (m^3 s^{-1}), HMCR = 0.92, HMS = 30 and PAR = 0.3. The problem was initialised using the HS for 5000 HP evaluations (function evaluation) as equation (5) to generate feasible initial solutions, then the optimization process continued for 250 000 HP evaluations using either the HS improvisation process or the IDP procedure by the developed hybrid method (HS-IDP). The optimization was carried out using five independent runs for each case. Table 3 shows the results by the two reported methods. For further clarification, Fig. 5 illustrates the convergence rate for the optimum solutions between the HS and HS-IDP. As can be seen from Fig. 5, the HS-IDP hybrid algorithm has found better solutions than the HS in terms of the resultant values and also has a faster convergence rate. Figure 6 demonstrates the optimal water level curves obtained by the two methods. The optimal decision variables value of the objective function found by the hybrid method when considering the average inflow derived from the datasets (1977–2005) was 243.27 (GWh), while from UCRHYDROPROJECT *et al.*(2006) the value of 226.31 (GWh) was obtained.

Table 3 Attained Statistical Evaluation Time, Number of HP Evaluations, the Highest HP and HP benefit. Indexes "1" and "2" stand for the HS and HS-IDP methods, respectively.

Algorithms	Evaluation Time (seconds)	Number of HP Evaluation	Highest HP (GWh)/year	Highest HP benefit (million $US)/year
(1)	111.85	255 000	241.26	9.188
(2)	175.687	255 000	243.27	9.233

The UCRHYDROPROJECT *et al.*, (2006) found HP of 226.31 (GWh) converted to benefit 8.68 (million $US).

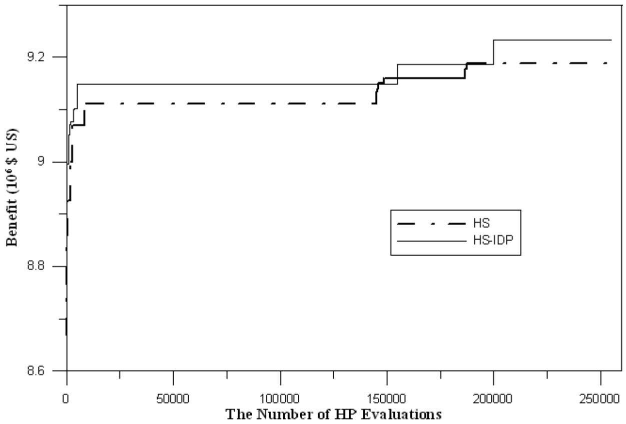

Fig. 5 Comparison of convergence rate for the HP benefits using the HS and HS-IDP.

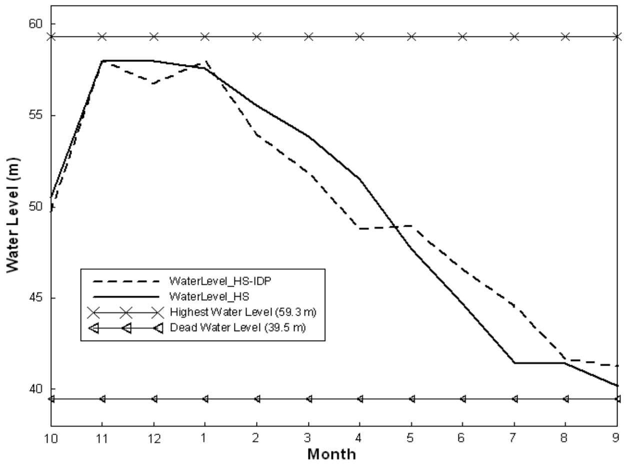

Fig. 6 Water level curves at the end of month(m) obtained using the HS and HS-IDP.

Table 4 Result of monthly water release rates (Re(j)-m^3/s) via turbines and storage volume rates (at the end of month) (S(j)-10^8 m^3). Indexes "1" and "2" stand for the HS and HS-IDP methods, respectively.

Month	1/Oct.	Oct	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.
Re(j) (1)		28.9	122.3	112.0	83.9	45.1	37.7	46.5	74.3	60.7	48.2	60.7	121.7
Re(j) (2)		38.1	113.0	134.8	51.5	80.5	43.9	54.2	30.6	52.7	35.5	98.5	116.2
S(j) (1)	2.62	5.93	8.23	8.23	8.12	7.47	6.96	6.23	5.06	4.14	3.14	3.13	2.74
S(j) (2)	2.62	5.69	8.23	7.85	8.23	6.99	6.35	5.40	5.44	4.72	4.11	3.21	3.08

The minimum water release rate of the optimal solution derived by the algorithms in drought periods was 30.6 (m^3s^{-1}) better than the allowed value of 23.61 (m^3s^{-1}). Similarly, the maximum discharges released downstream in a flood period were smaller at 200 (m^3s^{-1}), while the allowed value was 488(m^3s^{-1}), as shown in constraints (7) and (8) and Table 4.

CONCLUSIONS

The HS and HS-IDP performed the optimization task with less CPU time compared to the GAs used for other reservoir problems (Hashemi *et al.*, 2008). From the results obtained, the HD reservoir should be operated by storing water monthly with values close to the optimal water level trajectories shown in Fig. 6, or storage volume rates and water release rates, as in Table 4. The current study showed good results for optimal HD reservoir operation. The hybrid HS-IDP algorithm found a better solution than the HS algorithm having the same number of HP evaluations based on the HP benefit criterion. Therefore these results may be used in reservoir operation to reduce the impact of floods and droughts for the HD basin and enhance HP benefits.

The results concluded that the highest HP is not only dependent on the water release rates, it was also affected by the monthly water level (storage volume) and monthly electricity cost. The water storage for the optimal solutions at the end of September was much higher than the lowest limited volume leading to surplus water saved for the next year and other demands. The algorithms proposed were flexible and can be applied to solve optimization of any reservoir operation.

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