Optimal Operation of Two Cascading Reservoir System for Maximizing Hydropower Generation Based on Particle Swarm Algorithm

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Abstract—**Hydropower is one of the most significant renewable energy resources, especially for mountainous countries like Laos PDR. Expansion and development of many hydropower projects in the country have presented a challenge to the operation of multiple reservoir system. Nam Ngum river was the focus of this work, where there are two or more cascading reservoirs. Optimal operation of such system is of interest, with the main goal of maximizing power generation. A multi-objective Particle Swarm Optimization (PSO) was adopted in this study, applying to two cascading reservoirs of Nam Ngum 1 and 2 hydropower plants. It was demonstrated that increases in hydroelectric power generation could be realized for all cases of normal, dry and wet years, compared to the traditional actual operation of the hydropower plant system. Similar approach may be adopted to assess opportunities in other water management problems.**

Index Terms—**hydroelectricity, renewable energy, multiple reservoir management, optimization, power engineering**

I. Introduction

Fossil fuel resources have increasingly become scarce owing to continual rise in energy demand. Renewable energy can play a major leading role in this situation. Hydropower has been viewed as one of the most important renewable energy sources. It is the only clean and sustainable energy source that is commercially proven in a very large scale [1], [2]. Globally, electricity generation from hydropower represents a significant fraction. For a mountainous country like Laos PDR, hydropower is the major contributor. There have been expansion of existing hydropower plants and construction of new projects. So, operation of multiple reservoir system has become a challenge [3], [4].

The dominant objective of reservoir system operation is usually to optimize water releases from the reservoirs or storage volume in order to achieve desired objectives such as maximizing hydropower generation or minimizing risk of flood, and operation costs. Adoption of these practice is a must for hydropower plant operators to do, based on the past and present conditions of the reservoir storage and inflow [2], [5], [6]. Reservoir operation is classified as a dynamic optimization type of problem. It is non-linear and complex. Research works on optimal operation of hydropower systems have been ongoing for several decades and usually based on computational programming, artificial intelligence and population-based algorithms [7], [8]. Particle Swarm Optimization (PSO) is one of the most popular among modern artificial intelligence techniques. It has been widely applied to solve the problem of optimal hydropower operation [9].

In the present work, PSO was adopted and applied to an optimization challenge in operation of two cascading reservoirs, Nam Ngum 1 and 2 in central Laos PDR for three different (dry, normal and wet) representative years. Results were presented and compared between the actual and optimized operation.

II. Methodology

A. Problem Formulation

The multiple reservoir system comprises cascaded hydropower stations and dams. Optimization of this system operation is about how best to utilize the restricted water resource over the planned duration. Mathematically, they can be expressed as

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$$E = \max \sum_{t=1}^{n} \sum_{j=1}^{N} P_{i,t}\ \Delta_t ,\quad n = T/\Delta t \tag{1}$$

$$P_{i,t} = C_i\ q_{i,t} \tag{2}$$

where E is the total electricity production; $P_{i,t}$ is the power of i^{th} generator unit in the t^{th} period; C_i is the generation coefficient for each power station.

The multiple objective functions were to maximize the electricity production and control the release of large amounts of water downstream to prevent possibility of flood. They included

a) Reduce the reservoir level

$$F_1(x) = \min L_t,\ t \in [1, T] \tag{3}$$

b) Reduce the peak discharge

$$F_2(x) = \min \{\max Q_t\},\ t \in [1, T] \tag{4}$$

c) Preserve the reservoir level is close to flood control level

$$F_3(x) = \min \{L_t - L_f\} \tag{5}$$

where L_t and Q_t are the i^{th} reservoir level and the outlet released in the t^{th} period; L_f is the flood control level.

Those reservoirs have many requirements to meet during their practical operation. These constraints are;

(i) The water balance equation for the hydropower Network

$$V_{i,\,t+1} = V_{i,t} + [I_{i,t} - Q_{1,d,\,t} - S_{i,t} - L_{i,t} + \sum(Q_{1,t} + S_k)] \tag{6}$$

where $V_{i,t}$, $I_{i,t}$, $Q_{i,t}$, $S_{i,t}$ and $E_{i,t}$ are the storage volume, the inflow, the discharge, the spillway discharge and the net loss due to evaporation and precipitation of the i^{th} reservoir in the t^{th} period. $Q_{k,t}$ and S_k are the upstream plant's discharge and spillway discharge.

(ii) Reservoir level limits:

$$L_{t,min} \le L_t \le L_{t,max} \tag{7}$$

(iii) Gross head limits:

$$H_{t,min} \le H_t \le H_{t,max} \tag{8}$$

(iv) Power generation limits:

$$P_{t,min} \le P_t \le P_{t,max} \tag{9}$$

(v) Turbine discharge limits:

$$Q_{t,min} \le Q_t \le Q_{t,max} \tag{10}$$

B. Case Study

A case study of Nam Ngum 1 and 2 reservoirs in Laos PDR, shown in Fig. 1 and Fig. 2, was considered. The Nam Ngum reservoirs are located in the mainstream of Nam Ngum river. Nam Ngum 1 hydropower station has a storage capacity of 7,030 x $10^6 m^3$ and 37 m of a net head. While Nam Ngum 2 station has a storage capacity of 4,886 x 10^6 m^3 and 151 m of net head. Other technical data is summarized in Table I.

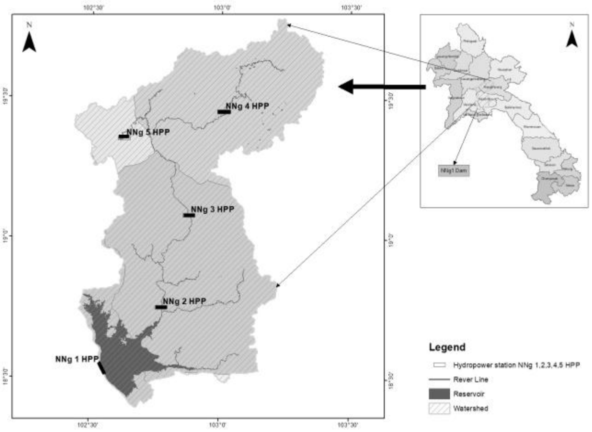


Figure 1. Locations of Nam Ngum 1 and 2 hydropower stations.

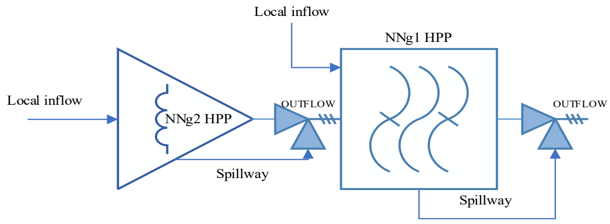


Figure 2. Two cascaded reservoir hydropower system.

TABLE I. THE TECHNICAL DATA OF NNG1 ANG NNG2 HPPS

Description	Units	1	2
Reservoir			
Catchment Area	km^2	8,460	5,640
Average Annual Inflow	$10^6 m^3$	382	6,305
Maximum Flood Level	m	213	378.75
Full Supply Level	m	212.3	375
Reservoir Area at MFL	km^2	370	107
Storage at MFL	$10^6 m^3$	7,030	4,886
Dead Level	m	196	345
Storage at MOL	$10^6 m^3$	2,330	2,269
Dam			
Dam Type		CGD	CFRD
Crest Level	m	215	381
Crest Length	m	468	485
Dam Height	m	75	181
Spillway			
Type		Radial Gate	
Design Flood	m^3/s	3,800	11,910
Crest Level	m	202.5	359
Number	Sets	4	3
Size	m	12.5x10	15 x16.90

C. Simulation Procedure and Scenarios

The software HEC-ResSim was used for the reservoir simulation. PSO technique was also applied to optimize hydroelectric power generation. Historical data were analyzed, and three cases of representative dry, normal and wet years were used. The simulation procedure is shown schematically in Fig. 3.

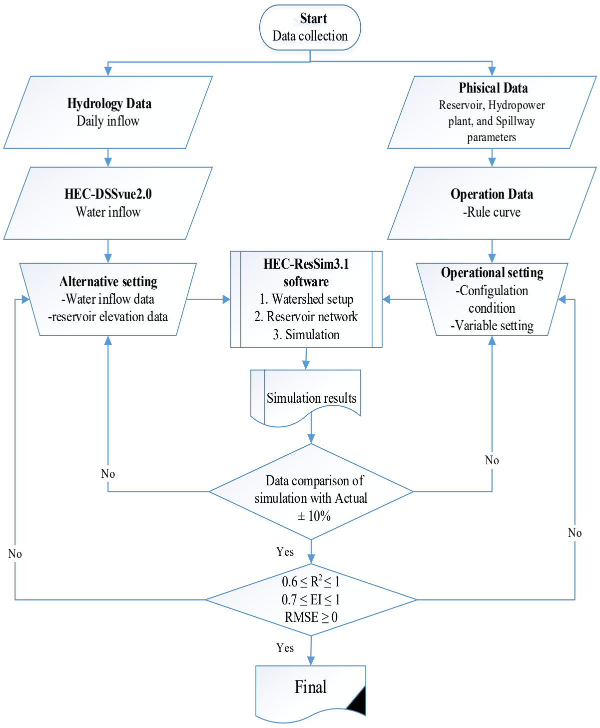
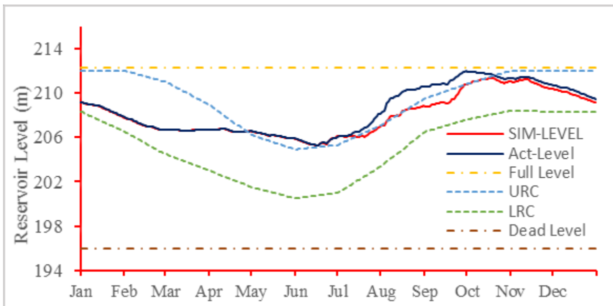


Figure 3. Reservoir simulation procedure using the HEC-ResSim.

III. RESULTS AND DISCUSSION

The simulation runs can yield the best results in reservoir operation optimization utilizing the PSO algorithm. Fig. 4 to Fig. 9 shows the simulated results of temporal reservoir levels in the representative year against actual operation previously executed, along the rule curves. Inflow and outflow data were also plotted along each graph. Overall, it can be seen that the simulated optimal operation curves have similar character to the rule curves
used in practice.

In the normal year (Fig. 4 and Fig. 5), from January to June, the operational curves went lower so as to prepare the reservoir storage for the rainy season the curves showed higher level to retain large volume of water for later to avoid the water shortage if drought occurs. Nam Ngum 2 level tended to stay near to the dead level so as to generate a lot of power. Meanwhile, Nam Ngum 1 tended to stay within the upper bound of the rule curve limit because large volume was saved for subsequent power production all year round.



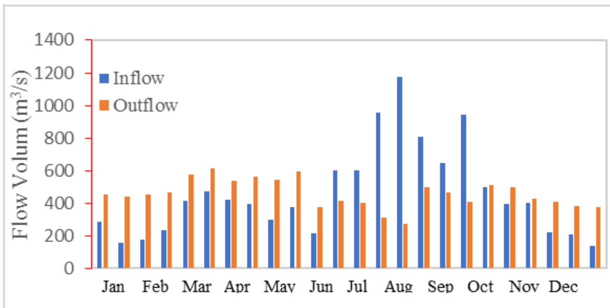
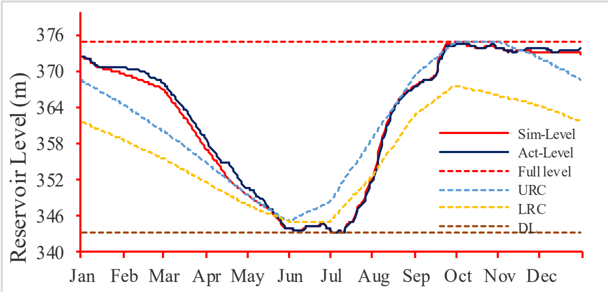


Figure 4. Simulated results of optimal Nam Ngum 1 plant operation for normal year case.



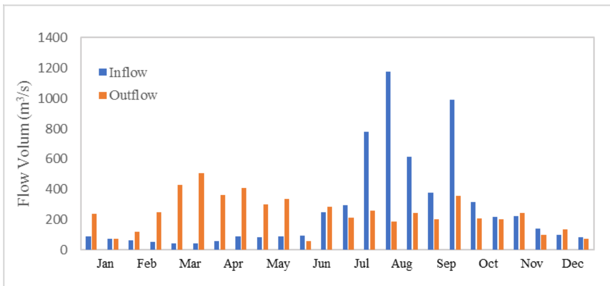
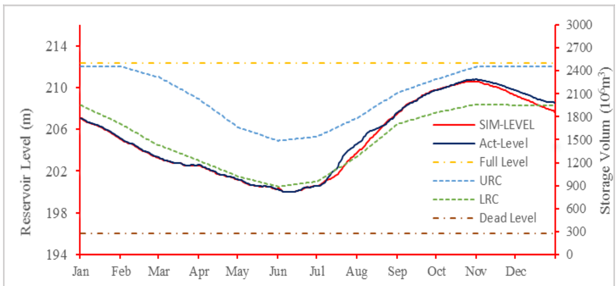


Figure 5. Simulated results of optimal Nam Ngum 2 plant operation for normal year case.



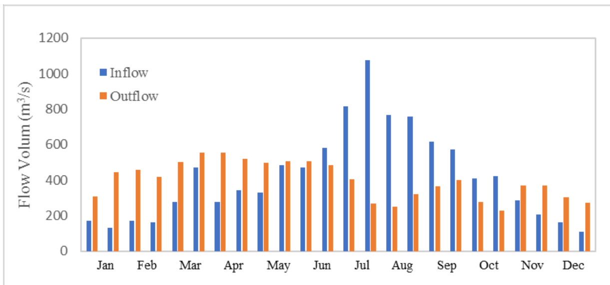


Figure 6. Simulated results of optimal Nam Ngum 1 plant operation for dry year case.

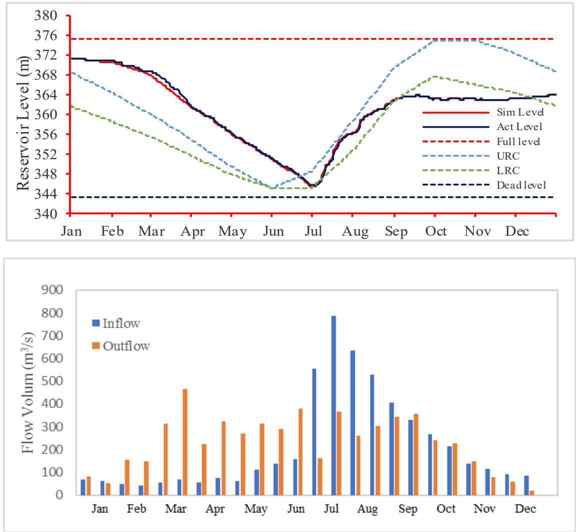


Figure 7. Simulated results of optimal Nam Ngum 2 plant operation for dry year case.

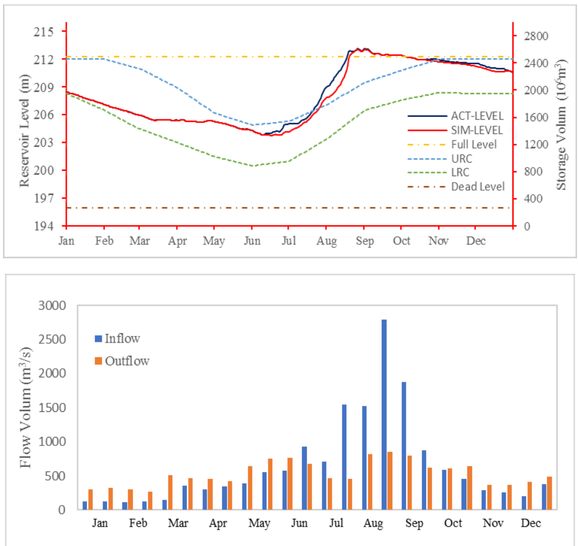


Figure 8. Simulated results of optimal Nam Ngum 1 plant operation for wet year case.

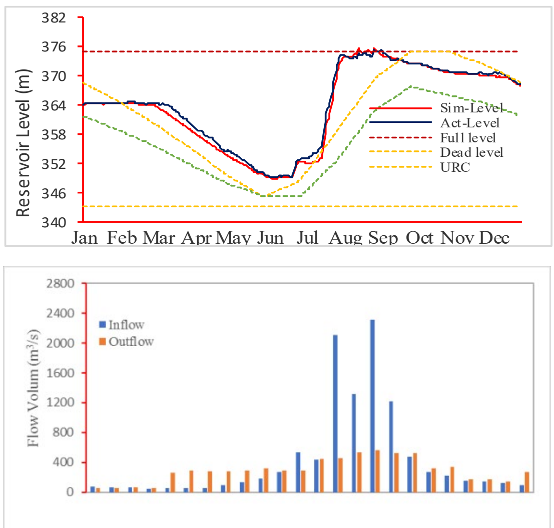


Figure 9. Simulated results of optimal Nam Ngum 2 plant operation for wet year case.

TABLE II. SUMMARY OPTIMAL OPERATION FOR NAM NGUM 1 HYDROPOWER STATION

case		Start level (m)	Turbine release (10^6 m^3)	Energy (GWh/y)	Spillway release (10^6 m^3)
Dry	Actual	207.05	9,572	974	0.00
	Optimal	207.05	9,602	977	0.00
Normal	Actual	209.17	10,995	1,143	0.00
	Optimal	209.17	12,246	1,267	0.00
Wet	Actual	208.49	11,880	1,222	3,444
	Optimal	208.49	12,776	1,299	2,992

TABLE III. SUMMARY OPTIMAL OPERATION FOR NAM NGUM 2 HYDROPOWER STATION

case		Start level (m)	Turbine release (10^6 m^3)	Energy (GWh/y)	Spillway release (10^6 m^3)
Dry	Actual	371.18	5,583	2,139	0.00
	Optimal	371.18	5,582	2,140	0.00
Normal	Actual	372.37	5,803	2,246	0.00
	Optimal	372.37	5,874	2,280	0.00
Wet	Actual	364.12	6,834	2,669	3,028
	Optimal	364.12	7,035	2,743	2,739

In the dry year (Fig. 6 and Fig. 7), similar patterns were observed. But, the difference to the normal year was that the water discharges from both hydropower stations were smaller and the water levels were delayed. The operation curves appeared to be nearer to the lower bound of the rule curves. This was to limit the water supply and save water for use.

In the wet year (Fig. 8 and Fig. 9), water inflows were more than twice as high, compared to the normal and dry years, while the outflows increased a little bit. It can be seen that the water levels were near to or exceeded the upper bound of the rule curves. This was to prevent or minimize the risk of flood downstream of Nam Ngum 1 hydropower stations.

It was noted here that the water supply curves were derived from historical and long-term data of weather and rainfalls. For all cases, it was clear that optimal operation could be obtained, and it can offer improvement in terms of water management and power generation. Slight differences in the reservoir water level were observed between the optimal and the actual operation, especially during the normal and wet years.

Table II and Table III summarize possible benefits from optimal operation for both Nam Ngum 1 and 2 hydropower stations. Water releases through the turbine could be increased, and the spillway release during the wet year could be minimized. Annual energy production could be increased up to 11 and 3% for Nam Ngum 1 and 2 hydropower plants, respectively.

IV. CONCLUSION

Optimal management of water resources or reservoir operation is a complex and non-linear optimization problem. In this work, PSO algorithm was adopted and applied to a real and large-scale two cascaded reservoir system in Nam Ngum river as a case study. Simulation was based on the HEC-ResSim software. Historical inflow data were analyzed and used to derive the representative normal, dry and wet year cases. The PSO appeared to offer an accurate and fast approach in managing the multiple reservoir system operation. From the simulated optimal results, up to 11 and 3% increase in power generation could be realized. This simulation approach and the PSO technique seemed to be useful and may be employed to develop a simple operational guideline for hydropower plant operators.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

PS: Investigation, Formal Analysis, Writing – original draft, NT: Conceptualization, Supervision, Methodology, Writing – revising and final draft, KN: Resources, Supervision, Methodology

REFERENCES

[1] Y. Ibrahim, "Hydropower for sustainable water and energy development," *Renewable and Sustainable Energy Reviews*, vol. 14, pp. 462-469, 2010.

[2] R. Zhang, J. Zhou, S. Ouyang, X. Wang, and H. Zhang, "Optimal operation of multi-reservoir system by multi-elite guide particle swarm optimization," *International Journal of Electrical Power & Energy Systems*, vol. 48, pp. 58-68, 2013.

[3] V. Keophila, A. Promwungkwa, and K. Ngamsanroaj, "Effectiveness of cascades reservoir for flood control operation and electricity production in Nam Ngum river," *Journal of Physics: Conference Series*, vol. 1175, no. 012276, 2019.

[4] V. Keophila, "Multi-objective optimization for flood control operation and electricity production of Nam Ngum 1 and 2 hydropower plants," *J. Thai Inter. Res.*, vol. 13, no. 58, 2019.

[5] B. Asadieh and A. Afshar, "Optimization of water-supply and hydropower reservoir operation using the chatged system search algorithm," *Hydrology*, vol. 6, no. 5, 2019.

[6] J. Chu, C. Zhang, G. Fu, Y. Li, and H. Zhou, "Improving multi-objective reservoir operation with sensitivity-informed dimension reduction," *Hydrology and Earth System Sciences*, vol. 19, pp. 3557-3570, 2015.

[7] A. Mosavi, M. Salimi, S. F. Ardabili, T. Rabczuk, S. Shamshirband, and A. R. Varkonyi-Koczy, "State of the art of machine learning models in energy systems, a systematic review," *Energies*, vol. 12, no. 7, pp. 1-42, 2019.

[8] A. Ahmad, A. El-Shafie, S. F. M. Razali, and Z. S. Mohamad, "Reservoir optimization in water resources: A review," *Water Resources Management*, vol. 28, pp. 3391-3405, 2014.

[9] J. Zhang, Z. Wu, C. Cheng, and S. Zhang, "Improved particle swarm optimization algorithm for multi-reservoir system operation," *Water Science and Engineering*, vol. 4, pp. 61-74, 2011.

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