Phouthavanh Sorachampa; Nakorn Tippayawong; Kanchit Ngamsanroaj

Article

Optimizing multiple reservoir system operation for maximum hydroelectric power generation

Energy Reports

Provided in Cooperation with:
Elsevier

Suggested Citation: Phouthavanh Sorachampa; Nakorn Tippayawong; Kanchit Ngamsanroaj (2020) : Optimizing multiple reservoir system operation for maximum hydroelectric power generation, Energy Reports, ISSN 2352-4847, Elsevier, Amsterdam, Vol. 6, Iss. 2, pp. 67-75, https://doi.org/10.1016/j.egyr.2019.11.043

This Version is available at:
http://hdl.handle.net/10419/243859

Available online at www.sciencedirect.com
ScienceDirect
Energy Reports 6 (2020) 67–75
www.elsevier.com/locate/egyr

The 6th International Conference on Power and Energy Systems Engineering (CPESE 2019), 20–23 September 2019, Okinawa, Japan

Optimizing multiple reservoir system operation for maximum hydroelectric power generation

Phouthavanh Sorachampa[a], Nakorn Tippayawong[a,*], Kanchit Ngamsanroaj[b]

[a] Department of Mechanical Engineering, Chiang Mai University, Chiang Mai 50200, Thailand
[b] Electricity Generating Authority of Thailand, Sirikit Hydropower Plants, Uttaradit 53110, Thailand

Received 1 October 2019; accepted 22 November 2019

Abstract

Operational management of multiple reservoirs and hydropower plants based on Nam Ngum river basin near Vientiane, Laos PDR was investigated for optimal power generation. The system consists of three reservoirs namely Nam Ngum1, 2 and 5. Analysis of water balance, storage and discharge relationship for each reservoir was carried out using the HEC-ResSim 3.0 simulation software package. Historical monthly records of these reservoirs between 1975 to 2018 were used to derive representative dry, normal and wet years to be input for the simulation. Operational management of available water was optimized for maximum power generation based on particle swamp optimization technique. From the simulated results, it was possible that for a representative wet year, electricity production of Nam Ngum1 hydropower plant can be increased from 1217 to 1348 GWh/y, an increase of about 11%, compared to current operational practice. Total power production of all three reservoirs of 4380, 3816 and 3400 GWh/y could be increased to 4727, 3860, and 3426 GWh/y, respectively. The technique proved to be useful in the operation of reservoirs and hydropower plants.

Peer-review under responsibility of the scientific committee of the 6th International Conference on Power and Energy Systems Engineering (CPESE 2019).

Keywords: Multi-reservoirs; Hydropower; HEC-ResSim; Optimization; Renewable energy

1. Introduction

Nam Ngum river originates in Xieng Khouang of Laos PDR, with a total length of about 354 km. The catchment area of Nam Ngum river is 16,640 km^2. There are several existing and planned hydropower plants for Nam Ngum basin, with a total of four cascades (Nam Ngum1 to 4) on the main river, and one (Nam Ngum5) on an upstream tributary of Nam Ting river, shown in Fig. 1. At present, Nam Ngum1, 2 and 5 hydropower plants (HPPs) are in operation, while Nam Ngum3 and 4 HPPs are planned. The reservoir management of the existing three HPPs is of great interest. Several works have been done for reservoir and HPP operation in lower Mekong region and Laos

* Corresponding author.
E-mail address: n.tippayawong@yahoo.com (N. Tippayawong).

https://doi.org/10.1016/j.egyr.2019.11.043

Peer-review under responsibility of the scientific committee of the 6th International Conference on Power and Energy Systems Engineering (CPESE 2019).

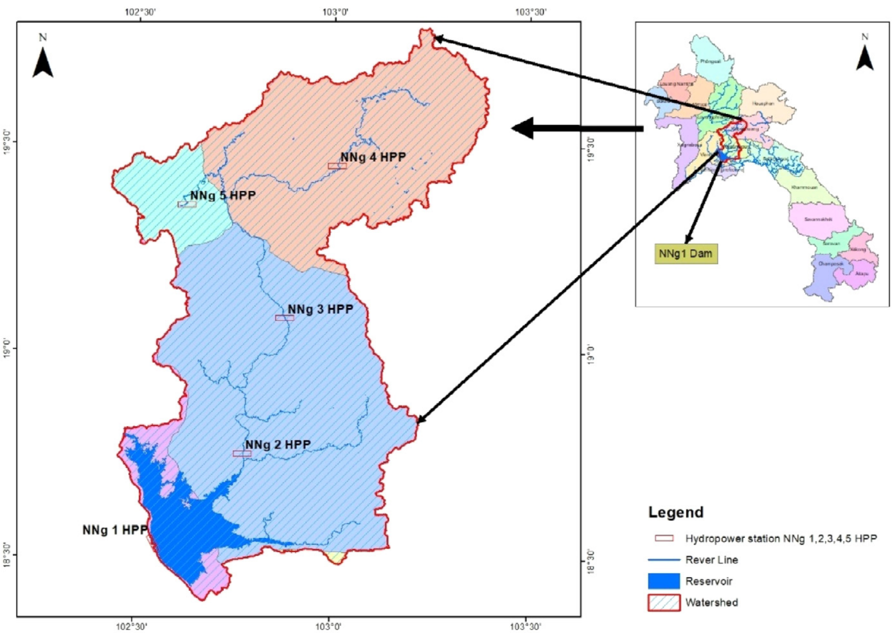


Fig. 1. Map of Nam Ngum river basin and locations of existing hydropower plants.

based on streamflow synthesis and reservoir regulation (SSARR) program to approximate the river flow and based on a public domain, general purpose software, the HEC-ResSim to simulate the reservoir operation [1–4].

Optimization algorithms have drawn significant attention from researchers and widely applied to reservoir system management [5,6]. Ming [7] studied the optimal operation of multi-reservoir system based-on cuckoo search to check if the new algorithm can solve complex reservoir operation optimization problems. Zhang et al. [8] adopted an improved particle swarm optimization (PSO) algorithm for the optimization of hydroelectric power scheduling in multi-reservoir systems. Fu et al. [9] reported on flood control capacity for a multi-reservoir system among the three reservoirs. The primary objectives were to see how the joint operation of multi-reservoir can reduce downstream overflow and boost hydroelectric power generation at the same time.

The main goals of HPP operation modeling works were to maximize the utilization of water resources and economic benefits, while the risk from flood should be kept minimum. So far, only a single HPP or two cascaded HPPs have been considered for hydropower plants in Laos. In this work, the reservoir operation of the three HPPs was considered. The simulation model was used to develop operational management for optimal power generation.

2. Methodology

2.1. Simulation procedure

In this study, simulation was used to develop guideline for HPP operation based on the multi-objective PSO technique to optimize electricity production. The software used in this study was the HEC-ResSim software, developed by the US Army Corps of Engineers. The Nam Ngum 1, 2 and 5 HPP have been in operation since 1971, 2011 and 2012, respectively. The following data can be collected, water inflows, water outflow, elevation level, and power production. Three cases of dry, normal and wet years were considered. Steps in the simulation is as follows.

Step 1: Define water inflow data into HEC-Decision Support System file.
Step 2: Create watershed in HEC-ResSim software by input river and stream (.dfx) file.
Step 3: Create a reservoir network in HEC-ResSim software.
Step 4: Variables setting and define the operation alternative.

Step 5: Check the simulation results. If the results do not satisfy and follow the objective function and constraints, the process will be returned to step 2.

Step 6: Use the calibration equations to indicate validity between the actual and the simulated results, if the differences are not within the predefined limit; it returns to step 3.

2.2. Hydrological model and plant performance

The software used for the reservoir simulation was the HEC-ResSim software. The governing equation is the water balance equation. Change in reservoir storage volume is dependent on water inflows and outflows, which are important to operate the electricity production and control flood. Fig. 2 illustrates the schematic depiction of the Nam Ngum 1, 2 and 5 reservoirs. It was noted that Nam Ngum 3 and 4 reservoirs are currently planned.

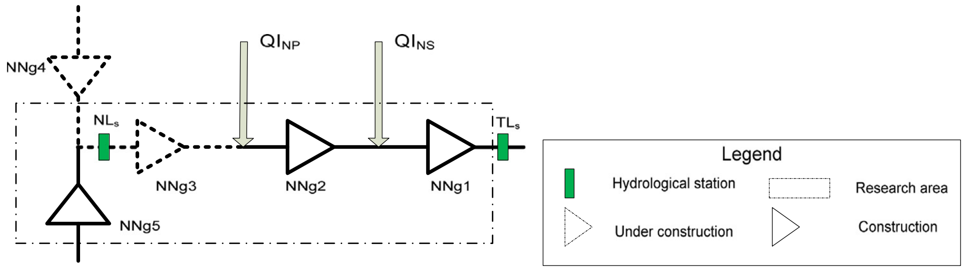


Fig. 2. Schematic representations of Nam Ngum1, 2 and 5 HPPs.

From the schematic, the equations for Nam Ngum 5 reservoir can be written as:

$$V_{5,t+1} = V_{5,t} + (I_{5,t} - Q_{5,d,t} - S_{5,t} + E_{5,t}) \tag{1}$$

The outflow of Nam Ngum 5 reservoir is the main inflow to Nam Ngum 2 reservoir. Therefore, the corresponding water balance equations are:

$$V_{2,t+1} = V_{2,t} + (I_{2,t} - Q_{2,d,t} - S_{2,t} + E_{2,t}) \tag{2}$$

$$I_{2,t} = L_t + Q_{5,d,t} \tag{3}$$

The outflow of Nam Ngum 2 reservoir is the main inflow to Nam Ngum 1 reservoir. Therefore, the corresponding water balance equations are described as:

$$V_{1,t+1} = V_{1,t} + (I_{1,t} - Q_{1,d,t} - S_{1,t} + E_{1,t}) \tag{4}$$

$$I_{1,t} = Lt + Q_{2,d,t} \tag{5}$$

where $V_{i,t}$ is the storage volume of reservoir i in period t, i = 1 for Nam Ngum1 reservoir, i = 2 for Nam Ngum2 reservoir and i = 3 for Nam Ngum5 reservoir; $I_{i,t}$ is the water inflow to reservoir i in period t; $L_{i,t}$ is the local water inflow of reservoir i in period t; Qi,t is the water release from above reservoir i in period t; $S_{i,t}$ is the spillway discharge of reservoir i in period t, and $E_{i,t}$ is the evaporation of reservoir i period t.

The maximum water discharge through turbine enables mechanical to electrical energy conversion as:

$$P_{i,t} = \rho\, \eta\, g\, h_t\, q_{i,t} \tag{6}$$

$$E = \max \sum_{t=1}^{n} \sum_{j=1}^{N}, P_{i,t} \Delta_t, \; n = T/\Delta t \tag{7}$$

where $P_{i,t}$ is the power of generator unit i in period t; E is the total power production; h_t is he gross head in period t; $q_{i,t}$ is the water released of unit i in period t; g is the gravitational acceleration and ρ is the water density.

2.3. Reservoir system optimization

The objective function determination is important for optimizing the electricity production. The study used multi-objective function to solve the issue. The multiple objectives include (1) the reservoir level must be reduced to near the dead water level, in order to preserve the reservoir for receiving the incoming water, (2) the maximal water discharge must be reduced during flood season, and (3) the water level of the reservoir must be near to the flood control level before the ending of the rainy season. These objective functions were to maximize the electricity production and control the release of large amounts of water downstream to prevent possibility of flood.

(a) Reduce the reservoir level: $F_1(x) = \min L_t, \quad t \in [1, T]$ (8)

(b) Reduce the peak discharge: $F_2(x) = \min\{\max Q_t\}, \ t \in [1, T]$ (9)

(c) Preserve the reservoir level is close to flood control level $F_3(x) = \min\{L_t - L_f\}$ (10)

where L_t is the reservoir level i in period t, i = 1 for Nam Ngum1 HPP and i = 2 for Nam Ngum2 HPP; Q_t is the outlet released of reservoir i in period t; L_f is the flood control level.

Explicit lower and upper bounds on reservoir release, gross head level, power generation and turbine discharge were assigned as;

(i) Reservoir level constraint: $L_{t,min} \le L_t \le L_{t,max}$ (11)

(ii) Gross head constraint: $H_{t,min} \le H_t \le H_{t,max}$ (12)

(iii) Power generation constraint: $P_{t,min} \le P_t \le P_{t,max}$ (13)

(iv) Turbine discharge constrain: $Q_{t,min} \le Q_t \le Q_{t,max}$ (14)

2.4. Validity of simulation result

The validity test was conducted to compare the simulated results and the actual data records to check if the software prediction was reliable [10, 11]. Indices used were:

a. Root mean square error
$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(X_{obs,i} - X_{model,i})^2}{n}} \tag{15}$$

where $X_{obs,i}$ is the actual recorded data i; $X_{model,i}$ is the simulated results of data i and n is the data number. When the value of RMSE equal to zero, the simulation is highly reliable.

b. Pearson correlation coefficient
$$r = \frac{\sum_{i=1}^{n}(x_i - \overline{x}) \cdot (y_i - \overline{y})}{\sum_{i=1}^{n}(x_i - \overline{x})^2 \cdot (y_i - \overline{y})^2} \tag{16}$$

where x_i, y_i are the actual data i and the simulated data i, respectively. $\overline{x}$, $\bar{y}$ are the average values of actual recorded data and simulated data. When $r^2 = 1$, the simulation result is highly reliable, and it should be more than 0.6.

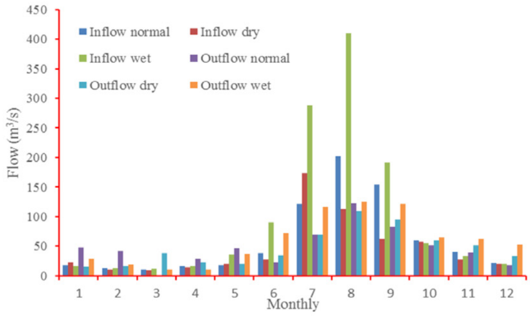
c. Efficiency index
$$\mathrm{EI} = 1 - \frac{\sum_{i=1}^{n}(X_{obs,i} - X_{model,i})^2}{\sum_{i=1}^{n}(X_{obs,i} - \overline{X_{obs}})^2} \tag{17}$$

where $X_{obs,i}$ is the actual recorded data i; $X_{model,i}$ is the simulated data i and $\overline{X_{obs}}$ is the average values of actual recorded data. When EI = 1, the simulation result is highly reliable, and it should be more than 0.7.

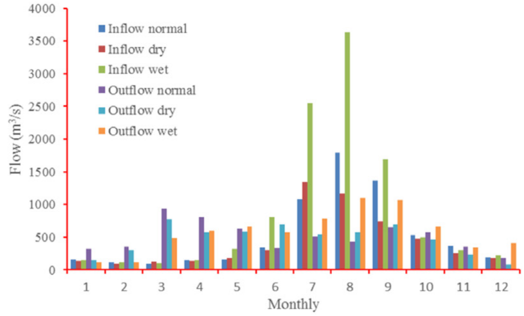
3. Results and discussion

3.1. Representative data and validation of simulation

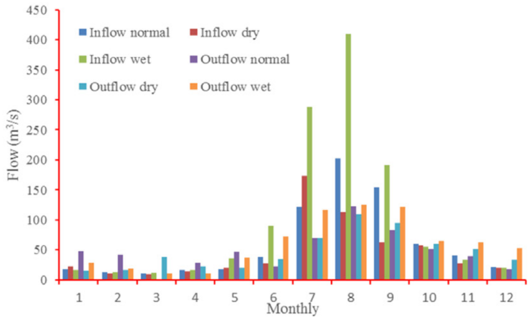
The water management strategy for optimal operation of Nam Ngum1, 2 and 5 reservoirs were solved using the multi-objective PSO technique. Three cases were considered whose water data of the year 2018, was used as the representative wet year, those of the year 2017 for the representative dry year, and those of the year 2014 for the



(a) Nam Ngum 1 hydropower plants;



(b) Nam Ngum 2 hydropower plants



(c) Nam Ngum 5 hydropower plants

Fig. 3. Representative yearly inflow and outflow data for Nam Ngum 1, 2 and 5 hydropower plants.

representative normal year, respectively. Monthly inflow and outflow data for the three reservoirs are summarized in Fig. 3.

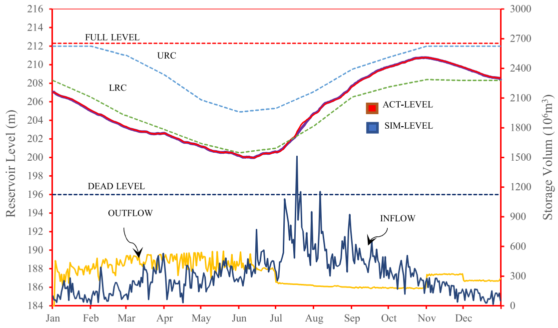
Initial simulation run was performed for all three reservoirs. The indices used were EI, r^2, and RMSE. The calibration output (the elevation and energy production) for Nam Ngum 1 HPP is shown as an example and summarized in Table 1 to show the comparison between the actual and simulation runs for all three cases. They were found to be acceptable.

Table 1. Calibrated simulation results of Nam Ngum 1 HPP against actual results.

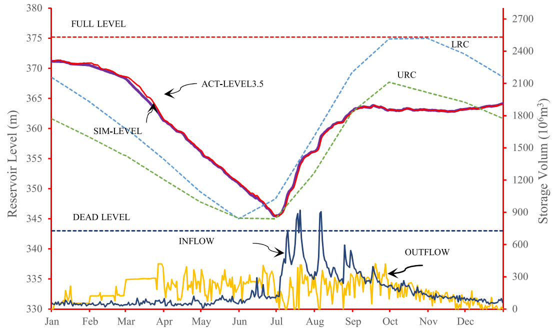
Case	Reservoir level			Energy		
	RMSE	r^2	EI	RMSE	r^2	EI
Normal	0.00	1.00	1.00	0.00	0.92	0.82
Dry	0.00	1.00	1.00	0.00	0.99	0.98
Wet	0.03	0.99	0.99	0.00	0.99	0.96

3.2. Optimized operation of reservoirs

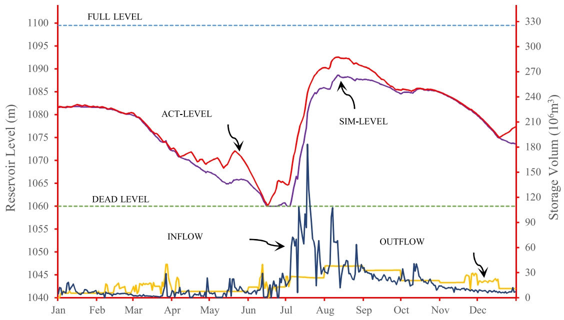
The actual regulation of the water level for Nam Ngum1, 2 and 5 HPPs against the simulated optimization model results are shown in Figs. 4–6. Generally, it was observed that the optimized operation curves showed similar pattern to the actual curves occurred in practice. In Fig. 4, the representative dry year was considered. Inflow and outflow of Nam Ngum 5 reservoir were smaller than Nam Ngum 2 reservoir, which in turn, smaller than half of Nam Ngum 1 reservoir. At the start of the year, the water levels of the Nam Ngum 5 and 2 reservoirs were 1081.6 m, and 371.18 m above sea level. The water level at the end of June was near the dead level to reserve the water storage volume in the coming rainy season. The water level of Nam Ngum 1 reservoir gradually increased from July to the highest operation level of 208.21 m above sea level in November. Similar pattern was observed for the water level of Nam



(a) Nam Ngum 1 hydropower plants

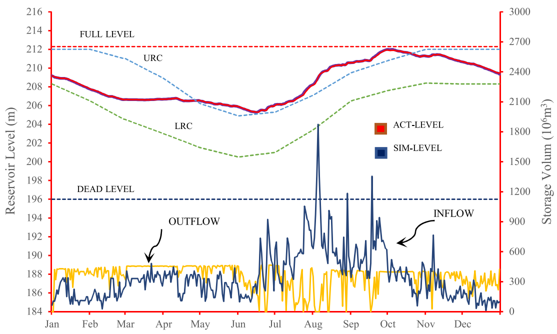


(b) Nam Ngum 2 hydropower plants

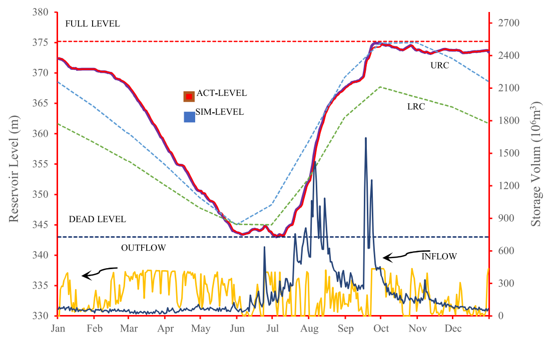


(c) Nam Ngum 5 hydropower plants

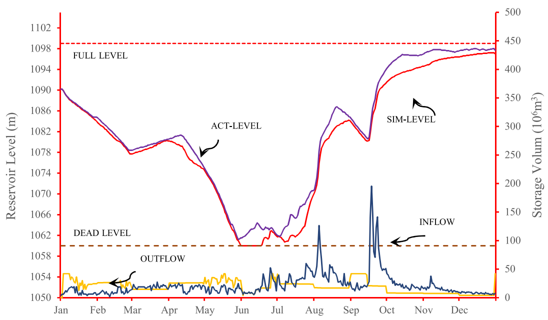
Fig. 4. Simulated optimization results of Nam Ngum1, 2 and 5 hydropower plants for **dry year** case.



(a) Nam Ngum 1 hydropower plants;

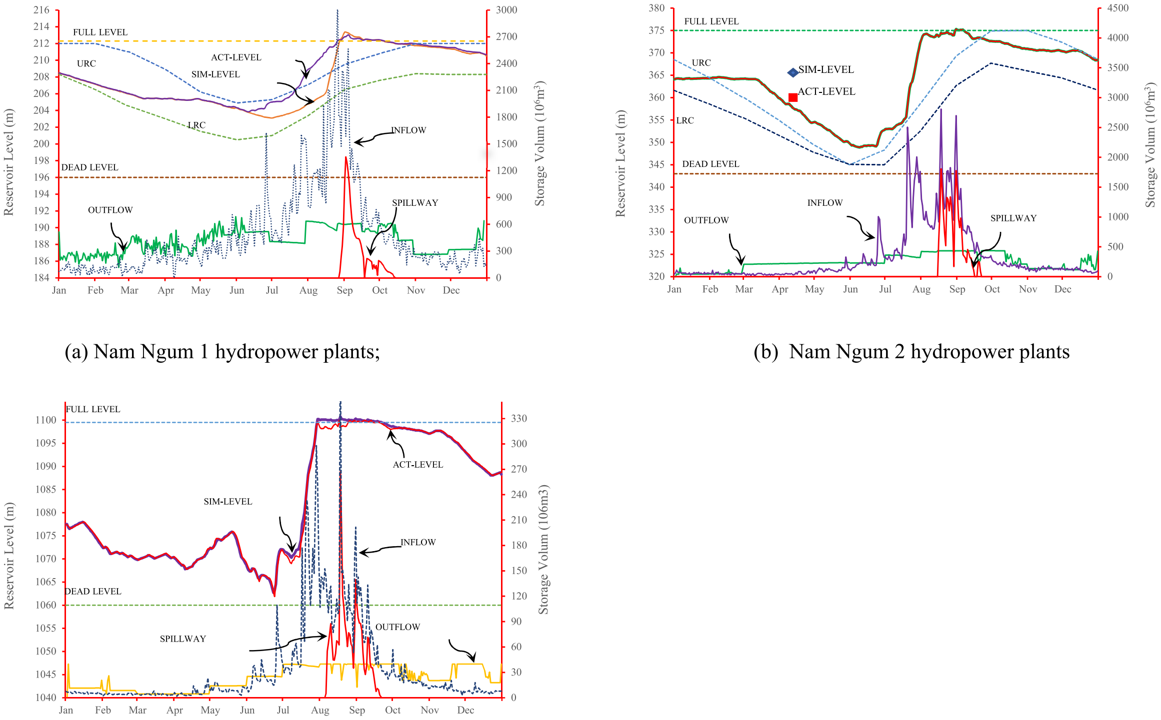


(b) Nam Ngum 2 hydropower plants



(c) Nam Ngum 5 hydropower plants

Fig. 5. Simulated optimization results of Nam Ngum1, 2 and 5 hydropower plants for **normal year** case.



(a) Nam Ngum 1 hydropower plants;

(b) Nam Ngum 2 hydropower plants

(c) Nam Ngum 5 hydropower plants

Fig. 6. Simulated optimization results of Nam Ngum1, 2 and 5 hydropower plants for **wet year** case.

Ngum 2 reservoir. Nam Ngum 5 reservoir level was found to decrease from January to the lowest operation level in June and reached the maximum of 1091.4 m to guarantee that the power demand was met. In comparison with the actual operation, average discharges of Nam Ngum1, 2 and 5 for simulated optimization scheme were slightly higher by 1.74, 0.34 and 1.31% per year, respectively. As a result, the optimized water level was lower than that in the actual operation.

For the representative normal year, the water management for Nam Ngum1, 2 and 5 HPPs is shown in Fig. 5(a), (b) and (c). It was shown that the water level of Nam Ngum 1 and 2 reservoirs were similar between the actual and optimized scheme. However, the water level of Nam Ngum 5 reservoir showed slight difference between the actual operation and the optimized simulation. Compared with the actual operation scheme, the optimized discharges of Nam Ngum1, 2 and 5 could be increased by 0.44, 2.23 and 0.96% per year, leading to lower water level of Nam Ngum 5 HPP.

In the representative wet year case, operation of Nam Ngum 1, 2 and 5 HPPs is shown in Fig. 6(a), (b) and (c). The optimal operation showed that the water volume of the spillway from Nam Ngum 1, 2 and 5 HPPs can be decreased from 2666, 2823, and 354 million m^3 per year to 1676, 2324, and 300 million m^3 per year, which equaled to about 60, 21, and 18% reduction, respectively. The direct benefit of this water control was an increase in the total electricity production from 4381 to 4732 GWh per year.

Table 2 summarizes benefits from the optimal reservoir operation, compared against the actual water management for the Nam Ngum 5, 2 and 1 reservoirs in the representative dry, normal and wet years. The cascade output power in the dry year were 402, 2087, and 913 GWh/y, respectively. With the optimal operation, the power production can have slight increases to 409, 2094, and 925 GWh/y, for Nam Ngum 5, 2 and 1 HPPs, respectively. Slight increase in power generation was also observed for the normal year. However, the largest increase of power production can be obtained in the wet year with lower spillway release for flood control downstream. The upfront gain of the water management was the improvement in hydroelectric power generation by about 10, 8.5, and 11%, for Nam Ngum 5, 2 and 1 HPPs, respectively, compared to the actual traditional operation.

Table 2. Summary of actual and optimal operation for Nam Ngum1, 2 and 5 HPPs.

Case		Nam Ngum 5 HPP				Nam Ngum 2 HPP				Nam Ngum 1 HPP			
		Start level (m)	Turbine release (10^6 m^3)	Energy (GWh/y)	Spillway release (10^6 m^3)	Start level (m)	Turbine release (10^6 m^3)	Energy (GWh/y)	Spillway release (10^6 m^3)	Start level (m)	Turbine release (10^6 m^3)	Energy (GWh/y)	Spillway release (10^6 m^3)
Dry	Actual	1081.6	572	402	0	371.18	5709	2087	0	207.05	9,645	913	0
	Optimal	1081.6	585	409	0	371.18	5711	2094	0	207.05	9,990	925	0
Normal	Actual	1090.2	602	417	0	372.37	6095	2253	0	209.17	11,004	1142	0
	Optimal	1090.2	609	421	0	372.37	6192	2293	0	209.17	11,030	1147	0
Wet	Actual	1077.5	721	508	354	364.12	6995	2656	2823	208.49	11,773	1217	2666
	Optimal	1077.5	793	557	300	364.12	7474	2822	2324	208.49	11,880	1353	1676

4. Concluding remark

In this paper, the multi-objective PSO technique has been adopted to optimize the multiple reservoir operation for maximum electricity production. The HPPs considered were Nam Ngum1, 2 and 5 reservoirs in central Laos PDR. Inflow data of the year 2014, 2017 and 2018 were used to represent the normal, dry and wet year cases. The multi-objective PSO technique was shown to enable increased power production for all cases considered. It was also shown that the water discharges through the spillway gates of all three reservoirs could be reduced. The obvious reward of the water control and management was to raise power generation, hence, earning of Nam Ngum1 HPP by over 10%, compared to the actual traditional operation. The method may be used to develop simple operational guideline for water management of another multiple reservoir system.

Acknowledgments

We wish to acknowledge the Electricité du Lao (EDL), Laos, the Electricity Generating Authority of Thailand (EGAT) and Chiang Mai University, Thailand for support of the research project.

References

[1] Rockwood DM. Application of streamflow synthesis and reservoir regulation SSARR program to the lower Mekong river. 2019, hydrologie.org/redbooks/a080/iahs_080_0329.pdf.
[2] Sounanthalath D, Promwungkwa A, Ngamsanroj K. HEC-ResSim model calibration for Nam Ngum 1 hydropower plant. In: presented at: 2013 Burapha university international conference. Chonburi, Thailand, 4-6 July.
[3] Bangsulin N, Promwungkwa A, Ngamsanroj K. Multi-reservoir operational management for optimal electricity production of Nam Khan 2 and 3 hydropower plants. In: presented at: 2016 ASAR international conference. Bhubaneswar, India, 3-4 December.
[4] Keophila V. Multi-objective optimization for flood control operation and electricity production of Nam Ngum 1 and 2 hydropower plants. J Thail Interdiscip Res 2019;13(5):58–66.
[5] Labadie JW. Optimal operation of multi-reservoir systems: state-of-the-art review. J Water Resour Plan Manage 2004;130(2):93–111.
[6] Chang J, Meng X, Wang Z, Wang X, Huang Q. Optimized cascade reservoir operation considering ice flood control and power generation. J Hydrol 2014;516:1042–51.
[7] Ming B. Optimal operation of multi-reservoir system based-on cuckoo search algorithm. Water Resour Manage 2015;29(15):5671–87.
[8] Zhang J, et al. Improve particle swarm optimization algorithm for multi-reservoir system operation. Water Sci Eng 2011;4(1):61–73.
[9] Fu X, et al. Allocation of flood control capacity for a multi-reservoir system located at the Yangtze river basin. Water Resour Manage 2014;28:4823–34.