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Multi-objective optimization for flood control operation and electricity production of Nam Ngum 1 and 2 hydropower plants

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Abstract

The aim of this paper was to study multi-objective optimization for flood control and electricity production. The hydropower plants are Nam Ngum 1 and 2, which are large size hydropower plants in central Laos. The optimal operation required scheduling to minimized flood risk and maximized electricity production. In order to attain this optimal operation, a multi-objective optimization for minimizing flood damage, but maximizing electricity production are put to action. The theories involved are streamflow synthesis and reservoir regulation algorithm (SSARR), as well as multi-objective particle swarm optimization algorithm (MOPSO). The software for simulating is HEC-ResSim. The cases studies used inflow data of year 2011 and medium-term inflow forecasting between July-December 2017, which used IBM SPSS Statistics base on ARIMA Method (Auto Regressive Integrated Moving Average). The inflow recorded data is 41 years for input the prediction. The simulation results demonstrate the decrease in spillway release of both hydropower plants is decreased cause the decrease of flood from seven-zero days. Direct benefit of water control is the increase of electricity production of NNG1 HPP from 1,140 to 1,231 GWh/year, which increase of 7.93% compared to conventional operation. The forecasting result is show percentage error is in acceptable range.

Keywords: flood control operation, electricity production, multi-objective optimization technique

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1. Introduction

Nam Ngum River are of the main river in Laos, It originates in the mountain located in Xiengkhouang province, northern Lao region. Nam Ngum River connects with Nam Lik River at the Vientiane province and connects to Mekong River in the Vientiane capital city with approximately 354 km long, it covering of basin 16,800 square km see in figure 1. The Nam Ngum River plays an important role in Laos's economic development because it has potential for electricity production, On occasion flood occur in the downstream area. Therefore, hydropower plants were constructed on this river such as Nam Ngum 1 built in 1971 and Nam Ngum 2 built in 2010. The requirement for optimal operation of both hydropower plants includes scheduling power production despite flood risking and maximizing electricity generation. Also medium-term inflow forecasting is important to the reservoir operation. In order to balance these objective, the multi-objective optimization technique, and HEC-ResSim software were used in this study.

NNG 2 HPP is located in Vientiane province, central part of Laos about 90 km north from Vientiane Capital City. Total capacity is 615 MW, annual electricity production is 2,310 GWh. Transmission line of NNG 2 HPP is connected to the Thai power grid at Udon 2 substation in Udone Thani province, Thailand. This hydropower plant is operated and managed by Nam Ngum 2 Power Company Limited, adjusting to the load demand from EGAT, Thailand. [1]

NNG 1 HPP from located downstream of NNG 2 HPP about 35 km across the reservoir. Total capacity is 155 MW, annual electricity production is 1,025 GWh. Transmission line of NNG 1 HPP is connected to the power grid at Phontong substation in Vientiane capital, Lao PDR. The NNG 1 HPP is operated and managed by EDL-Generation Public Company. The technical data of both power plant are shown below. [2]

In recent years, many researchers have presented the methods and principle for flood control operation and electricity production. The multi-objective optimization of reservoir flood control operation was researched by S. Wang, et al. [3], which used multi-objective particle

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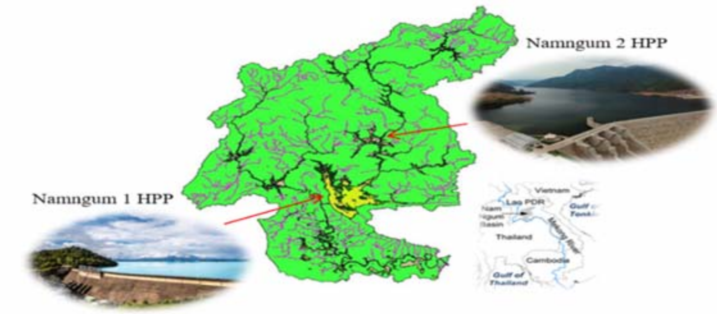


Figure 1 Location of Nam Ngum 1 and 2 hydropower plants

Table 1 Principal features of NNG1 and 2 HPPs.

Description	**Units**	**NNG 1 HPP**	**NNG 2 HPP**
		Reservoir	
Catchment Area	km^2	8,460	5,640
Average Annual Inflow	MCM	382.00	6,305
Maximum Flood Level	m.MSL	213.00	378.75
Full Supply Level	m.MSL	212.30	375.00
Reservoir Area at MFL	km^2	370	107
Storage at MFL	MCM	7,030	4,886
Dead Level	m.MSL	196.00	345.00
Storage at MOL	MCM	2,330.00	2,269.00
		Dam	
Dam Type		CGD	CFRD
Crest Level	m.MSL	215.00	381.00
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	masl	202.50	359.00
Number	Sets	4	3
Size	m	12.5 x 10	15.00 x16.90

swarm optimization (MOPSO) algorithm. The objectives are to minimize the water level for the dam safety and upstream, to minimize water discharge for reducing downstream damage and to save water for dry season. The short-term operation of flood management was studied by U Gokcen, et al. [4], the purpose of the study is to maximize water supply, and flood mitigation downstream. Software used was HEC-ResSim and RTC-Tools package of Deltares for simulating the reservoir operation, based on water balance equation and dynamic system for the optimization approach. M. Hosseini, et al. [5] had been studied multi-objective optimization model for the flood control operation. The idea is to select control point for reducing flood damage downstream and to maximize electricity production. The theory in this paper is the multi-objective particle swarm optimization algorithm. The study used VENSIM software to simulate reservoir operation for flood control, based on dynamic programming. The flood mitigation operation of multi- reservoir was researched by O. Prakah, et al. [6]. The goal is to minimize the volume of water flow at a control point, to mitigate flood at the control point and to maximize electricity generation. The theory is non-dominated sorting genetic algorithm-II (NSGA-II). A. Jung Min, et al. [7] had studied the evaluation of dam and weirs operation for water resource management, which considered water supply capacity, electricity production and flood damage at downstream.

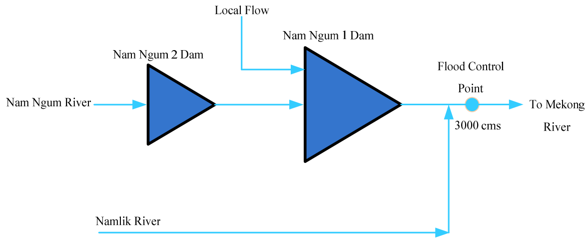


Figure 2 Schematic representations of NNG 1 and 2 HPPs

Software used is Streamflow Synthesis and Reservoir Regulation (SSARR) model to estimate the natural flow and HEC-ResSim for simulating the reservoir operation.

2. Objectives

To optimized flood control operation and electricity production of Nam Ngum 1 and 2 Hydropower plants by using multi-objective optimization technique.

3. Methods

3.1 Multi-objective optimization

The objective function determination important for optimizing flood control and electricity production. The study uses multi-objective function to solve the problem. Multi-objective considers three objective functions such as (1) minimize the highest reservoir level in the operation, (2) minimize the peak discharge, and (3) after the rainy season, reservoir level is close to flood control level. These objective functions is for maximizing the electricity production, but reducing flood day in the downstream area. [3, 9]

1) Minimize the highest reservoir level

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

2) Minimize the peak discharge

$$F_2(x) = \min\{\max Q_t\},\qquad t \in [1, T] \tag{2}$$

3) After rainy season, reservoir level is close to flood control level

$$F_3(x) = \min\left|Z_t - Z_{cnt}\right| \tag{3}$$

Where Z_t is the reservoir level i in t period, i=1 for NNG1 HPP and i=2 for NNG2 HPP; Q_t is the outlet released of reservoir i in t period; Z_{cnt} is the flood control level.

The maximum water release passes turbine converts the mechanical energy to electrical energy as below:

$$P_{i,t} = \rho\, \eta\, g\, H_t\, Q_{i,t} \tag{4}$$

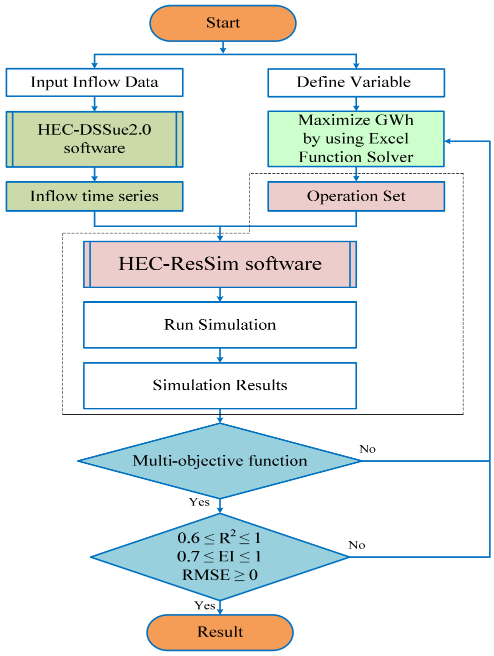


Figure 3 Flowchart of simulation model

$$E = \max \sum_{t=1}^{n}\sum_{j=1}^{N} P_{i,t}\ \Delta_t\,,\quad n = T/\Delta t \tag{5}$$

Where $P_{i,t}$ is the Power of generator unit i in t period; E is the total electricity production; H_t is he gross head in t period; $Q_{i,t}$ is the water released of unit i in t period; g is the gravitational acceleration (m/s^2) and ρ is the water density (~ 1000 kg/m^3).

3.2 Reservoir Operational Management

The HEC-ResSim software was used in this study, which is developed by US Army Corps of Engineers. The software is used for the reservoir simulation. The main equation in the software is water balance equation, which important to operate the flood control and electricity production. The changing of storage volume depends on the inflow and the outflow, which are the variables in the equation. Fig 2 shows the schematic representation of the NNG1 and 2 reservoir. [9, 11]

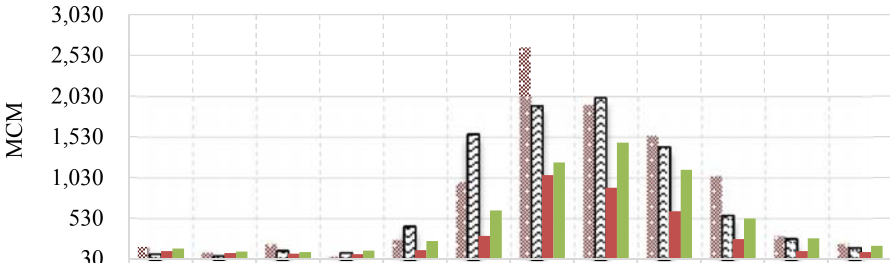
From the schematic, we can be written the equations as the following: In that

$$V_{2,t+1} = V_{2,t} + (I_{2,t} - Q_{2,outflow,t}) \tag{6}$$

$$Q_{2,outflow,t} = Q_{2,t} + S_{2,t} + E_{2,t} + B_{2,t} \tag{7}$$

The outflow of NNG2 HPP is main inflow to NNG1 HPP. Therefore, water balance equation can be written as. In that

$$V_{1,t+1} = V_{1,t} + (I_{1,t} - Q_{1,outflow,t}) \tag{8}$$



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1981	178	112	219	64	269	978	2,62	1,92	1,54	1,05	316	222
2011	94	72	137	111	436	1567	1914	2012	1411	571	283	172
Dry	125	103	93	87	137	312	1,05	904	614	273	126	114
Normal	156	119	115	131	251	624	1,21	1,45	1,12	527	282	190

Figure 4 Inflow data of NNG2 HPP

$$Q_{1,outflow,t} = Q_{1,t} + S_{1,t} + E_{1,t} \quad (9)$$

$$I_{1,t} = L_t + Q_{2,outflow,t} \text{ or} \quad (10)$$

Where $V_{i,t}$ is the storage volume of reservoir i in t period i = 1 for NNG1 HPP and i = 2 for NNG2 HPP; $I_{i,t}$ is the water inflow of reservoir i in t period; $L_{i,t}$ is the water inflow of reservoir i in t period; $S_{i,t}$ is the spillway discharge of HPP in t period; $E_{i,t}$ is the evaporation of reservoir i in t period, and $B_{i,t}$ is the button outlet of reservoir i in t period.

Downstream flow constraint

$$\min \sum_{t=1}^{n} (Q_{1,outflow,t} + V_t) \geq 200 \text{ cms} \quad (11)$$

Where v_t is the local flow at the downstream in t period.

The 200 cubic meters per second (cms) is the minimum water flow at downstream control point in the actual recorded data. Which this value is for retaining the ecosystem, irrigation and water supply in the dry season.

Reservoir level constraint: $Z_{t,min} \leq Z_t \leq Z_{t,max}$ (12)

Gross head constraint: $H_{t,min} \leq H_t \leq H_{t,max}$ (13)

Power generation constraint: $P_{t,min} \leq P_t \leq P_{t,max}$ (14)

Turbine discharge constraint: $Q_{t,min} \leq Q_t \leq Q_{t,max}$ (15)

3.3 Calibration equation

The calibration equation is to compare the simulation results and the actual recorded data for reliability of the software, which follows the each equation as below. [8]

1) **Root mean square error (RMSE)**

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n} (X_{obs,i} - X_{model,i})^2}{n}} \quad (16)$$

Which value of RMSE equal zero, the simulation is highly reliable.

Where $X_{obs,i}$ is the actual recorded data i; $X_{model,i}$ is the simulation results data i and n is the data number.

2) **Pearson correlation coefficient (r)**

$$r = \frac{\sum_{i=1}^{n} (x_i - \bar{x}) \cdot (y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n} (x_i - \bar{x})^2 \cdot \sum_{i=1}^{n} (y_i - \bar{y})^2}} \quad (17)$$

r^2 = 1 the simulation result is highly reliable and it should be more than 0.6.

Where xi, yi are the actual recorded data i and the simulation results data i, respectively. $\bar{x}$, $\bar{y}$ are the average values of actual recorded data and simulation results data.

3) **Efficiency index (EI)**

$$EI = 1 - \frac{\sum_{i=1}^{n} (X_{obs,i} - X_{model,i})^2}{\sum_{i=1}^{n} (X_{obs,i} - \overline{X}_{obs})^2} \quad (18)$$

EI = 1 the simulation result is high reliable and it should be more than 0.7.

Where $X_{obs,i}$ is the actual recorded data i; $X_{model,i}$ is the simulation results data i and $\overline{X}_{obs}$ is the average values of actual recorded data.

Table 2 Downstream flow results in rainy season.

Item	Sum Flow	Max Flow	Flood
	MCM	cms	Days
Actual	1,379,246	3,527	7
Before Optimize (Case B)	1,369,776	3,743	7
Optimize only NNG 1 HPP (Case 1)	1,285,177	3,072	1
Optimize NNG 1 and 2 HPPs (Case 2)	1,286,109	2,917	0

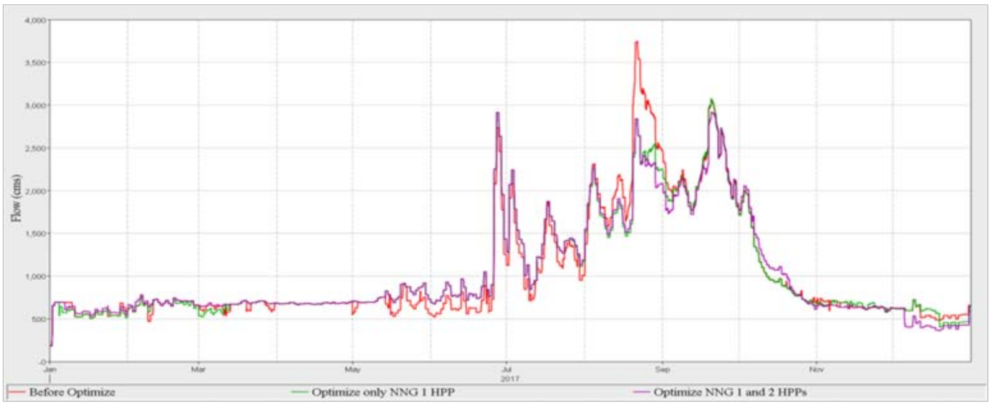


Figure 5 Downstream flow curve of each cases

3.4 Methodology

The study uses multi-objective optimization technique to optimize flood control operation and electricity production. The simulation results should follow the multi-objective function as well as respond all constraints. In addition, it should be under the limited value of calibration equation. This methodology is a pattern of Multi-Objective Particle Swarm Optimization Algorithm, which is used in the study. The methodology of simulation is shown in Figure 3.

Step 1: Define variable in simulation model, the variable is water release.

Step 2: Use function solver in Microsoft Visual Basic for application to optimize the water release. After that it was inputted to the HEC-ResSim for simulating.

Step 3: 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 4: Use the calibration equation for checking the percentage error between the actual data and simulation results, if the percentage error is not under the limited value, the process will be returned to step 2.

4. Input Data for Simulation Model

Inflow data collection of NNG2 HPP is 62 years between 1954-2016. The inflow volume is higher than 7401 MCM per year, which is defined as wet year. The NNG1 HPP have been operated the power generation between 1971 to present. Which counted for 45 years, as well as the data can be collected and summarized such as rainfall, water inflow, outflow, elevation level, and electricity production. [1, 2]

5. Results and Discussion

The multi-objective optimization technique was applied to two case studies, namely, NNG1 and NNG 2 HPPs, which consists two studies cases. The case one is used the water inflow of year 2011. The case two is used medium-term water inflow forecasting between July to December 2017.

1) Case one considered two operation scenarios such as (1) only NNG1 HPP was optimized and NNG2 HPP was operated under the same convention of year 2011. (2) Both hydropower plants were optimized. The results of both scenario are accepted and followed the multi-objective function such as the flooding days in downstream area was reduced from seven to one day and one to zero day, respectively. The downstream flow must be under 3000 cubic meter per second (cms).

The NNG1 HPP simulation results showed that water volume of spillway decreased from 2,826 to 1,654 MCM per year, which equals 79.06% as compared to the case B. Direct benefit of water control is the increase of electricity production from 1,140 to 1,231 GWh per year, which is 7.93% as compared to the case B. The summary shown in table 3.

Table 3 Generation results of NNG 1 and 2 HPPs.

Item	NNG 2 HPP				NNG 1 HPP			
	Energy (GWh)	**Turbine release (MCM)**	**Spillway release (MCM)**	**Level of end year (masl)**	**Energy (GWh)**	**Turbine release (MCM)**	**Spillway release (MCM)**	**Level of end year (masl)**
Case B	3,025	7,512	1,109	370.65	1,140	11,662	2,826	209.02
Case 1	3,025	7,512	1,109	370.65	1,213	12,698	1,769	209.09
Case 2	3,290	8,380	232	370.82	1,231	12,721	1,654	209.33

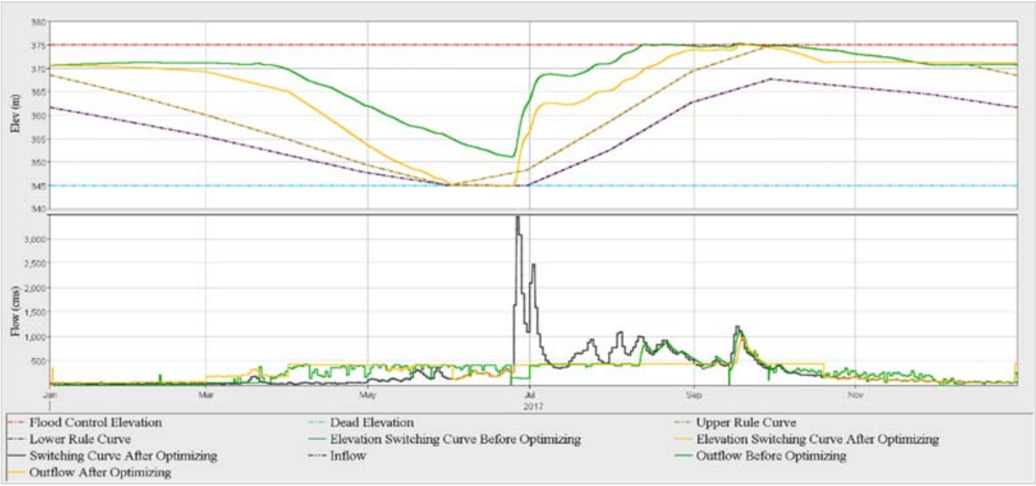


Figure 6 Switching operation curve of NNG 2 HPP

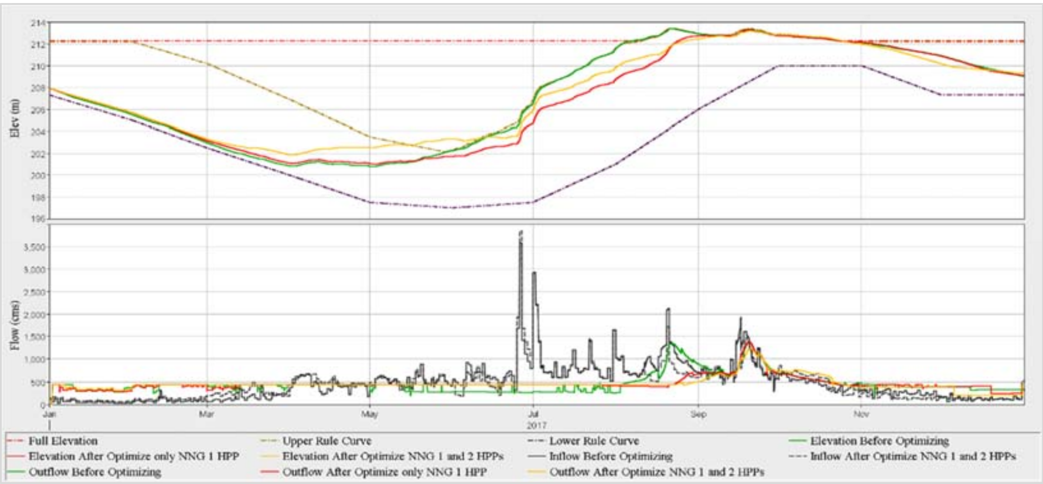


Figure 7 Switching operation curve of NNG 1 HPP

For NNG2 HPP simulation results, water volume of spillway decreased from 1,109 to 232 MCM per year, which equals 20.91% as compared to the case B. Direct benefit of water control is the increase of electricity production from 3,025 to 3,290 GWh per year, which is 8.76% as compared to the case B. The summary shown in table 3.

The calibration equation used is EI, r^2 and RMSE. The reservoir level and electricity production of NNG 1 HPP were input for calibration. The results show that, the calibration index are acceptable ranges, which RMES is 0.01, r^2 is 1 and EI is 1. Figure 8 shown the comparison of model and actual.

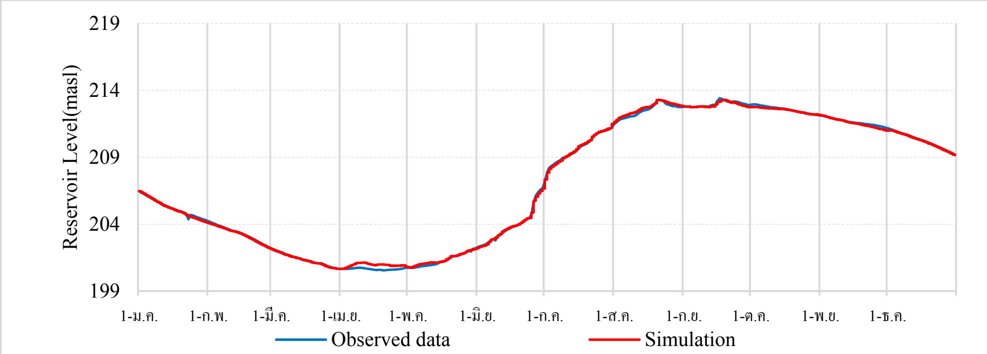


Figure 8 Reservoir level Comparison of NNG1 HPP

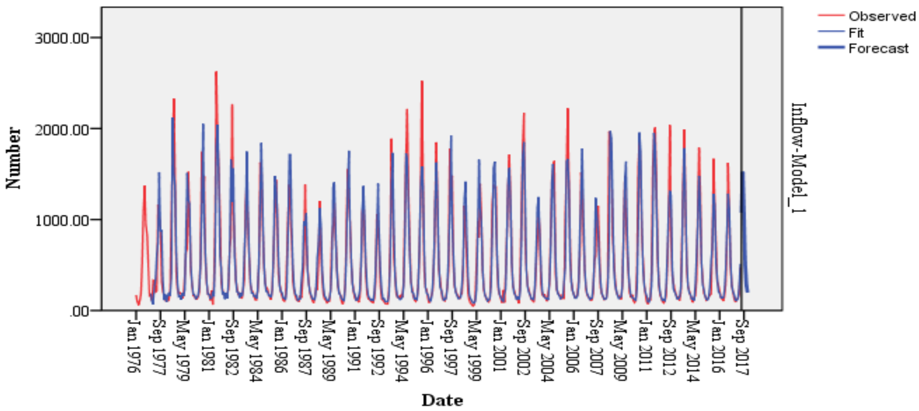


Figure 9 Comparison between observed and fit

Table 4 Total water inflow of year 2017 of NNG 2 HPP (Unit: MCM).

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
131	93	123	132	176	298	1,076	1,524	1,037	507	274	197	5,567

2) The medium-term inflow forecasting used is IBM SPSS Statistics software to forecasts the water inflow during July to December 2017. The data used is 40 years between Jan 1976 to June 2017. The ARIMA Method (Auto Regressive Integrated Moving Average) was used in IBM SPSS Statistics. The coefficient in ARIMA Method was adjusted for optimizing the forecast. The forecasting result is acceptable value such as the Mean Absolute Percentage Error (MAPE) is close to actual, which is 24.892. MAPE limited must be lower than 30% of observation data. Root squared (R-squared) is 0.827, which limited is value between 0.6 to 1.

The sum inflow of NNG2 HPP is 5,567 MCM. Therefore, this year 2017 is normal case year. The water inflow is lower than 7,401 MCM, which define the normal case year. Table 4 shows the total inflow of 2017.

2017 was a normal case year, the spillway of both hydropower plants was not used for water released. Therefore, flooding downstream did not occur. The multi-objective optimization technique was used only electricity production. After optimization, the electricity production of NNG 1 and NNG 2 HPPs were increased 4.38% and 0.10%, respectively. The NNG 1 HPP reservoir elevation is increased from 207.85 to 208.39 m.MSL. Table 5 shows simulation results and figure 10 to 11 shows reservoir operation of both hydropower plants for the forecast cases. Curves detail, Elevation before optimization of both Hydropower Plants from Jan to Jun are actual data.

6. Conclusion

This paper demonstrates the multi-objective optimization technique and HEC-ResSim3.1 to optimize the reservoir operation for flood control and electricity

Table 5 The generation results of NNG 1 and 2 HPPs for the medium-term inflow forecasting.

Item	NNG 2 HPP				NNG 1 HPP			
	Energy (GWh)	**Turbine release (MCM)**	**Spillway release (MCM)**	**Level of end year (masl)**	**Energy (GWh)**	**Turbine release (MCM)**	**Spillway release (MCM)**	**Level of end year (masl)**
Before	2,068	5,566	-	369.72	852	9,234	-	207.85
After	2,070	5,566	-	369.72	890	9,055	-	208.39

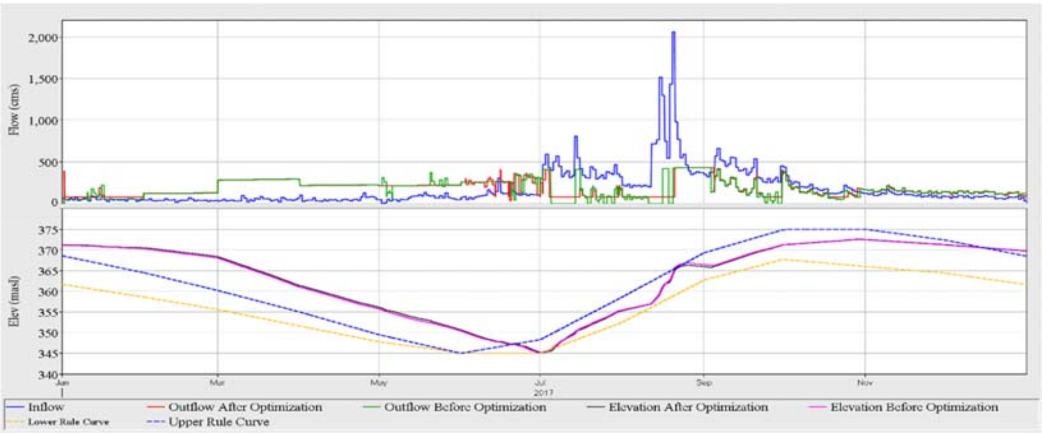


Figure 10 Switching operation curve of NNG 2 HPP

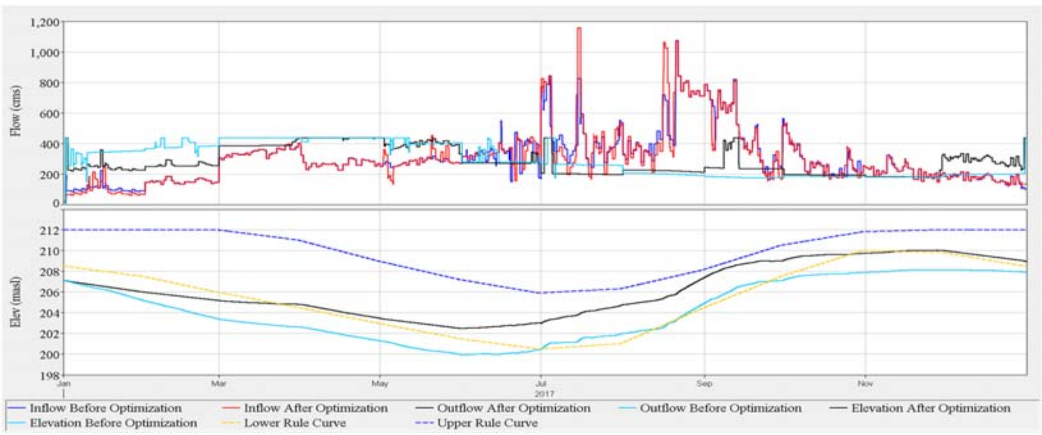


Figure 11 Switching operation curve of NNG 1 HPP

production. HPP are Nam Ngum 1 and 2, located in central Laos. The case studies used inflow data of year 2011 and medium-term inflow forecasting between July-December 2017, inflow recorded data of 41 year were input to the forecasting model. The multi-objective optimization technique has validity and can help solved the reservoir operation for flood control and electricity production problem. The medium-term inflow forecasting can help decision and prediction in the reservoir operational planning. The simulation results demonstrate spillway release of both hydropower plants decreased, which affects the decrease of flood day from seven to zero. Direct benefit of water control is the increase of electricity production of NNG1 HPP from 1,140 to 1,231 GWh/year, which increase 7.93% as compared to the conventional operation. The forecasting result is show percentage error is in acceptable range.

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