MULTI-RESERVOIR OPERATIONAL MANAGEMENT FOR OPTIMAL ELECTRICITY PRODUCTION OF NAMKHAN 2 AND 3 HYDROPOWER PLANTS

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Abstract— The objective of this research was to study the reservoir operation management for optimizing electricity production, reservoir control, and water supply to the downstream river. The two medium size hydropower plants located in northern Laos, which are Namkhan 2 and 3 hydropower plants, are the case study of this work. The multireservoir algorithms used are streamflow synthesis and reservoir regulation algorithm, and the improved particle swarm optimization algorithm for a long-term multi-reservoir system operation. The simulation software used is HECResSim3.1 and the input data used is the technical data of both power plants. The simulation results show that electricity generation is increased from 767.85 to 795 GWh/year, which is counted for 3.53% as compared to normal water year. The water released through the spillway in the rainy season decreases 404 million cubic meters for the averaged wet year. For the drought year, water of both hydropower plants can be managed to supply two more months for the power production purpose.

Keywords— Multi-reservoir Management, Electricity Production, Operation, Optimization.

I. INTRODUCTION

Lao People's Democratic Republic is located in south East Asia at the center of the Indochina peninsula between latitude 13-23 degree north and longitude 100-108 degree east. Lao PDR has a total area of 236,800 square kilometers and a population of 6.4 million people in year 2016. Laos has a border of 4825 kilometers, which consists of five nations Vietnam, Thailand, Cambodia, Myanmar, and China. The topography of Lao PDR has many rivers that appropriate for hydropower plant construction. The Namkhan River has many other smaller rivers which flow into it, which will allow for the construction of multiple dams. Laos has many hydropower resources, which will allow for up to 18,125 MW in 2025.[1]
Currently, Laos has the installed capacity of 5726.17 MW, which is divides into 66.79% of hydropower, 33.14% of thermal power, and 0.07% others power. These power plants are responsible under Electricité Du Laos (EDL) and Independent Power Producer (IPP domestic and IPP exported). Namkhan River is located in the northern region Laos, which is shown in Figure 1 and it has a drainage area of 7620 square kilometer (km2). Namkhan 2 and 3 hydropower plants have been constructed in the Namkhan River, which is owned by EDL. Both power plants are operated and managed by Electricité Du Lao-Generation public company (EDL-Gen), which is an adopted child of EDL. Both hydropower plants have the installed capacity of 190 MW and annual mean generating capacity of 794 GWh. Namkhan 2 and 3 hydropower plants are connected to the grid in the Laungprabang 2 substation in the Xiengnguen district [1].

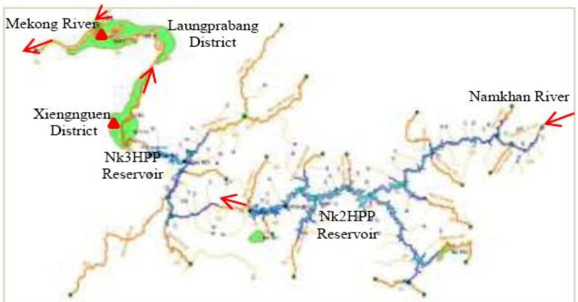

Figure1. Location of Namkhan 2 and 3 hydropower plants.

Namkhan 2 HPP has been constructed at upstream of the Namkhan 3 HPP, both HPP started the electricity production on September 2015 and April 2016 respectively. The various technical data was shown in table 1 as below [2]. The authors would like to thank Electricité Du Laos (EDL) and Electricity Generating Authority of Thailand (EGAT) for financial support for this research.

Table 1. The principal features of Namkhan 2 and 3 HPPs

Description	NK2HPP	NK3HPP
Hydrology data		
Catchment area of dam site (km^2)	5,167	7,049
Average annual inflow (cms)	67	92.1
Design peak flow (0.1%) (cms)	8,640	9,410
Index of engineering benefit		
Annual energy generation (GWh/y)	554	240
Installed capacity (2 Units) (MW)	130	60
Water discharge turbine (cms)	135	176
Spillway gate discharge (Radial Gate)		
Amount of spillway gate	4	3
Maximum discharge (cms)	9,974	5,710
Dimension of spillway (WxH) (m)	13.5 x 21	13.5 x 21

[1] The authors would like to thank Electricité Du Laos (EDL) and Electricity Generating Authority of Thailand (EGAT) for financial support for this research.

Data of reservoir storage			
Reservoir capacity	(MCM)	686.2	224
Full supply level	(m.a.s.l)	477.86	349.06
Dead storage level	(m.a.s.l)	465	343
Regulation storage capacity	(MCM)	229.1	48
Dam and rate head			
Type of the dam		CFRD	RCC
Height of the dam body	(m)	136	61
Crest Length	(m)	365	156
Dam crest elevation	(m.a.s.l)	481	353
Mean net head	(m)	111.00	39.00
Tailrace flood level	(m.a.s.l)	355.58	304.22
Tailrace check flood level	(m.a.s.l)	357.30	306.09

Many researchers have suggested the principles concern and adopted for this research. They are summarized as follow. The improved model of multi-reservoir management optimization was researched by J. Zhang researcher [3], which used improved particle swarm optimization (IPSO) algorithm, particle swarm optimization (PSO) algorithm, genetic algorithm (GA), and dynamic programming successive approximation (DPSA) algorithm. The objective of this research is scheduling configuration to optimizing electricity production of among reservoir. Conclusion, IPSO algorithm is outperform PSO, GA, and DPSA. The reservoir system operation of the Jayakwadi stage II in Maharashtra is studied by R.U Kamodkar [4], which considered the optimizing to release water for irrigation and hydroelectric generation. The fully fuzzy linear programing (FFLP) model is theory of this paper, which has the target to revise water release of both objective for efficiency and suitability. The reservoir operation design to supply the many purposes of Xiushui watershed in china was studied by B.Lu researcher [5], which used progressive optimization algorithm (POA), particle swarm optimization algorithm (PSO) and genetic algorithm (GA). The importance objective is evaluation of possible improvement for optimal yield benefit. This research demonstrates the usefulness for optimization procedure to improve the operation of a real-time reservoir system. The solution ranking for reservoir management optimization at Bathtiari reservoir in southwestern Iran was researched by B.Malekmohammadi [6], which used Electric-TRI method and NON-dominated sorting genetic algorithm II model (NSGA-II). The objective of this research is to manage between water resource and water demand for balancing, and to build the new model for controlling flood and deficits of the agricultural area. Conclusion, the solution method by Electric-TRI is the optimal model for short and long term operation of Bakhtiari reservoir.

II. PROBLEM FORMULATION OF RESERVOIR OPERATION

2.1 Reservoir operation management

Reservoir operation management of Namkhan 2 and 3 HPP has important role to the electricity production and to meet water demand, which results to all sections of economic-social development, especially the Northern provinces of Laos. Thus, multi-reservoir operation management is challenge for the production operators. Therefore, one importance of reservoir management is inflow estimate to plan for power generation and benefit for required water release to downstream and flood control. Reservoir management was defined the schematic representation as Figure 2 [7].

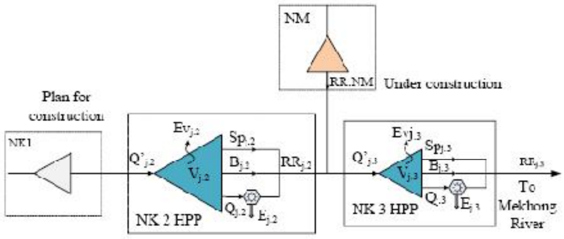

Figure 2. Schematic representations of Namkhan 2 and 3 HPP.

From the mentioned schematic, equations can be written as the following:

If $Q'_i = Q_{out}$

In that: $Q_{out} = Q_i + Sp_i + B_i + Ev_i$ (1)

$St_e = St_f$; $Hwl_e = Hwl_f$

If $Q'_i > Q_{out}$

$St_e > St_f$; $Hwl_e > Hwl_f$

And if: $Q'_i < Q_{out}$

$St_e < St_f$; $Hwl_e < Hwl_f$

Therefore, it can be written water balance equation as.

$$St_e = St_f + Q'_i - (Q_i + Sp_i + B_i) - Ev_i \qquad (2)$$

where: St_e_ Reservoir storage at the end time of the period i,
St_f_ Reservoir storage at the first time of the period i,
Q'_i Water inflow at the during period i,
Q'_i Total water outflow at the during period i,
Sp_i_Water released from spillway at during period i,
B_i _ Water released from bottom tunnel during period i,
Ev_i_ Evaporation loss at the during period i,
Hwl_e_Head water level at the end time of period i, and
Hwl_f_Head water level at the first time of the period i,

From considering the reservoir storage of both reservoirs, Namkhan 3 reservoir can be written equation as:

$$St_{3,i}\,(total) = St_{3,i}\,(op) + St_{2,i}\,(op) \qquad (3)$$

where: $St_{3,i}$ $(total)$ _ Total water storage usage of Namkhan 3 HPP at the during period i,
$St_{3,i}$ (op) _ Water storage usage in Namkhan 3 reservoir only at the during period i, and
$St_{2,i}$ (op) _ Water storage usage in Namkhan 2 reservoir at the during period i,

2.2 Reservoir management for electricity production

Hydraulic turbine is an important piece of the equipment, which transforms the energy from water energy into the mechanical energy to rotate the hydroelectric generator.

$$P_G = \rho g Q H \quad (1)$$

where: P_G _ Hydropower installation (W),
ρ Water density (kg/m^3),
g _ Gravitational acceleration (m/s^2),
Q _ Water volumetric flow rate (m^3/s), and
H Gross head (m),

Power plant efficiency is the ratio between the electrical power output of generator and input power from turbine of hydraulic power. Power output was measured at the generator terminals, which measure horse-power or kilowatts.

$$\eta = \frac{P_E}{P_M} \quad (5)$$

Where: η Power plant efficiency,
P_E _ Electrical power output of generator (W), and
P_M _ Hydraulic power, the input power to turbine (W),

Overall efficiency consists of two efficiency as: generator efficiency and hydraulic turbine efficiency which overall efficiency is equal to multiplied of the both efficiency.
$\eta TG = \eta T \times \eta G$ (6)
Where: ηTG_ Overall efficiency,
ηG_ Generator efficiency, and
ηT_ Hydraulic turbine efficiency,
Annual energy generation equation uses for energy output calculation of hydroelectricity [3].
That can be written the equation as below:

$$E - max \sum_{j=1}^{n} \sum_{i=1}^{N} P_{i,j} \Delta_t \quad ; \quad n - {}^{T}/_{\Delta_t} \quad (8)$$

Where: E _ Annual energy generation (kWh),
Δt _ Time step (Months),
n _ Number of time steps during operation period,
T _ Length of the operational period,
N _ Number of hydroelectric power plants, and
Pi,j _ Main output of the (i) hydropower plant during the
(j) time step,

2.3 Calibration and verification software of simulation result

a) Root mean square error (RMSE)
RMSE or the root mean square deviation (RMSD) is used to calibrate for difference between simulation results from the model and the actual data from real production [8].

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} (X_{obs,i} - X_{model,i})^2}{n}} \quad (9)$$

$RMSE = 0$ the simulation test is highly reliable

where: X_{obs} _ Actual data at consider i,
X_{model} _ Simulation results data at consider i, and
n _ Data number,

b) Pearson correlation coefficient (r)
The square of the Pearson correlation coefficient (r2) describes to find the variance between the two variables, which has equation as below [8].

$$r = \frac{\sum_{i=1}^{n} (x_i - \bar{x}) \cdot (y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n} (x_i - \bar{x})^2 \cdot \sum_{i=1}^{n} (y_i - \bar{y})^2}} \quad (10)$$

r2 = 1 the simulation test is highly reliable and it should be more than 0.6
where: xi, yi _ Variable at consider (i), and
$\bar{x}$, ȳ _ Variable average values at consider (i),
c) Efficiency index (EI)
Efficiency index is commonly used to assess the predictive of simulation models with actual data, which EI values indicated the accuracy of operation process [8].

$$EI = 1 - \frac{\sum_{i=1}^{n} (X_{obs,i} - X_{model,i})^2}{\sum_{i=1}^{n} (X_{obs,i} - \overline{X}_{obs})^2} \quad (11)$$

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

Where: X_{obs} _ Actual values at consider i, and
X_{model} _ Modelled values at consider i.
$\overline{X}_{obs}$ – Average values of observe data,

2.4 Multi-reservoir management optimization method

The Figure 3 shows the block diagram for the simulation step by multi-reservoir optimization technique, which is analyzed by HEC-ResSim program. The simulation model is to find the optimal electricity production, reservoir storage and water release of the both plants. The optimization methodology is configuration of several parameter to find out the parameter appropriation. Defining for power generation follow the reservoir elevation and generation time of each periods to optimum electricity production, which depend on the constraints of each hydropower plants. Furthermore, the modelling has the software verification between simulation model and actual data to find the accuracy of the simulation results [9].

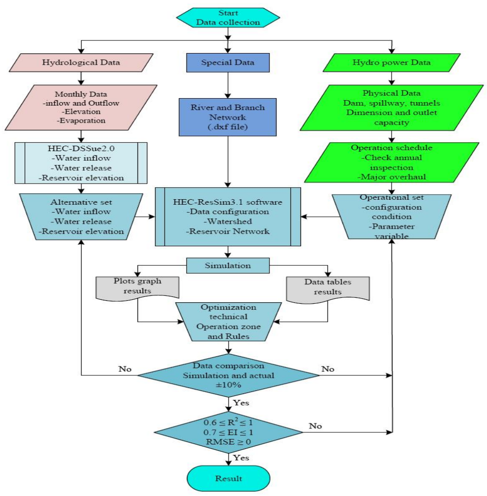

Figure 3. Flow charge of reservoir simulation concept.

III. HISTORY DATA FOR SIMULATION MODEL

Historical data of water inflow since 1960 to 2009 in the basic design of both dams were used to simulate the reservoir operation management and to forecast in future information. This paper considers into five cases, which shown in Figure 4 and Figure 5 for Namkhan2 and 3 HPP, respectively. The case study consists of maximum wet year (1963), average wet year, average normal year, minimum dry year (1992) and average dry year [10].

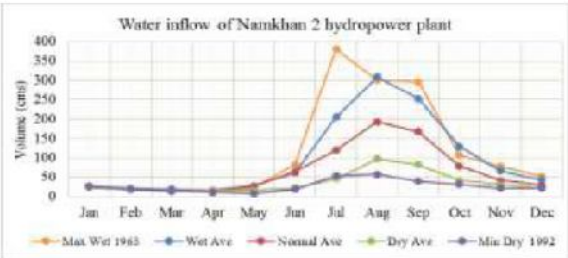

Figure 4. Inflow data of Namkhan 2 HPP.

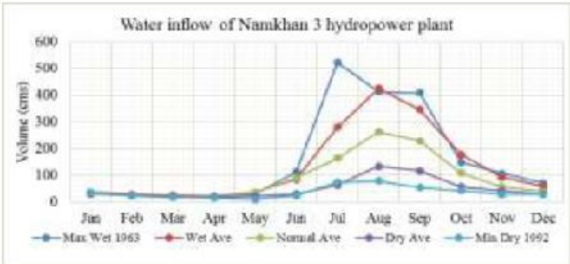

Figure 5. Inflow data of Namkhan 3 HPP.

Historical runoff data is measured by Ban Mout hydrological station to analyze and use in both power plants, which shown average water flow (cms) in Table 2 as below.

Table 2. Annual mean runoff for Namkhan 2 and 3 HPP

Months	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Namkhan 2 HPP Mean discharge	23.09	18.06	13.85	15.59	26.12	64.92	120.8	193.0	167.5	79.05	42.05	28.82	66.08
Namkhan 3 HPP Mean discharge	31.69	24.78	19.07	21.41	35.86	89.78	165.0	264.9	229.7	108.41	57.63	39.49	90.65
Percentage (%)	2.91	2.28	1.75	1.97	3.30	8.25	15.17	24.35	21.12	9.97	5.30	3.63	100.00

Historical of evaporation net is average monthly to use the software simulation for reservoir operation management, which evaporation information was shown in Table 3.

Table 3. The reservoir evaporation net

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
58.5	83.6	108.4	103.2	85.7	71.5	55.3	46.5	51.8	56	53	52.6	826.1

Water usage in station and hydraulic loss data are used to simulate software of the reservoirs management. These data were got from the both power plants, which shown in Table 4.

Table 4. The water usage and hydraulic loss data

No.	Station Use	Hydraulic loss	Efficiency
Namkhan 2 HPP	0.2 cms	1.15 m	97 %
Namkhan 3 HPP	0.2 cms	0.40 m	97 %

IV. SIMULATION RESULTS

The case studies of this paper have considered the five case of each watery criterion as: maximum wet yet (Max Wet), average maximum wet year (Wet Ave), normal water year (Normal Ave), minimum dry year (Min Dry) and average minimum dry year (Dry Ave). The simulation results consist of electricity production, water inflow, outflow, and reservoir elevation. The relation between water inflow, outflow, and elevation was shown in the Figure 6 and Figure 7, which presented the normal watery criterion case. The simulation results of others case will be shown the number of each items [11]-[12].

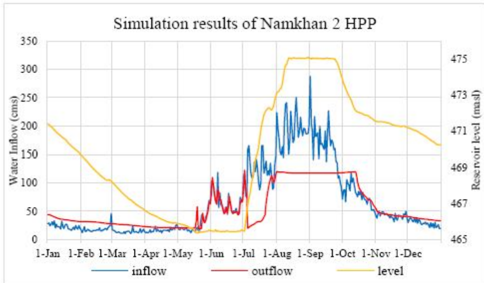

Figure 6. Graphic relation between water inflow, outflow, and elevation of Namkhan 2 HPP.

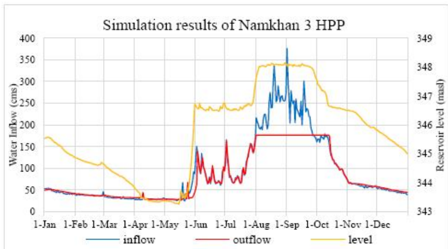

Figure 7. Graphic relation between water inflow, outflow, and elevation of Namkhan 3 HPP.

Among energy result of the simulation model will be revised for optimizing electricity production by technique optimization, which improved by power generation and scheduling configuration of production periods. The simulation results of before and after revise were shown in Table 5 for energy difference of before and after revise.

Table 5 Energy generation results of Namkhan 2 and 3 HPP Study

Study cases	Energy generation (GWh) of Namkhan 2 HPP			Energy generation (GWh) of Namkhan 3 HPP		
	Old	New	Difference	Old	New	Difference
Max Wet	596.98	636.24	39.26	286.20	302.49	16.29
Wet Ave	594.94	623.32	28.38	283.26	294.24	10.98
Normal	519.68	537.81	18.13	248.17	257.27	9.10
Dry Ave	334.77	337.51	2.73	165.33	166.58	1.24
Min Dry	253.15	255.54	2.38	125.36	126.36	1.16

Water release result from the simulation model will be revised to appropriate for each reservoir operation and watery criterion. Watery release can discharge by through spillway or bottom tunnel to control the reservoir elevation on rainy season, which shown in Figure 8 and Figure 9 of Namkhan 2 and 3 HPP, respectively.

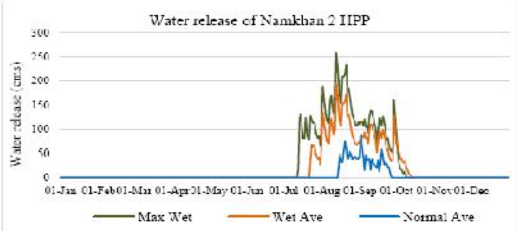

Figure 8. Water release simulation of Namkhan 2 HPP.

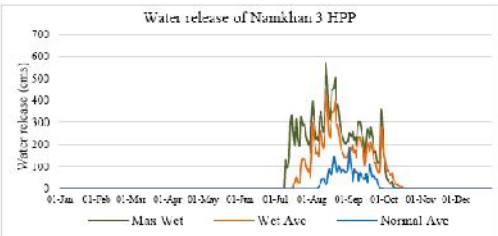

Figure 9. Water release simulation of Namkhan 3 HPP.

Simulation results shown that the management of water level by decreasing water release volume though spillway increases electricity production. Table 6 shows water release volume of both reservoirs for before and after revising the operation methodology.

Table 6. The annual energy generation and water release of the simulation result

Study case for simulation	Namkhan 2 HPP		Namkhan 3 HPP	
	Before revised release(MCM)	Annual water release(MCM)	Before revised release(MCM)	After revised release(MCM)
Maximum wet	924.00	659.96	2,039.54	1,899.30
Wet average	628.47	577.42	1,342.79	1,253.85
Normal average	175.69	139.91	349.41	291.56
Dry average	Non	Non	Non	Non
Minimum dry	Non	Non	Non	Non

For the dry year, if no planning for water releasing, there will not enough water to run turbine in the dry months including March to June. To maximize electricity production, the rule curve can be changed to save some water from the end of raining season for producing power on such dry months. The results from the simulations shown the Table 7. Water release is on Namkhan 3 HPP, which is downstream plant. That water released in the dry month is between 80 to 90 MCM.

Table 7 Water release to supply onto downstream area Watery criterion study cases

Watery criterion study cases	Water release on dry season of Namkhan 3 HPP (MCM)					
	Jan	Feb	Mar	Apr	May	Jun
Average dry year	93.75	90.92	90.28	84.19	83.78	83.17
Most dry year	89.71	84.61	82.78	80.86	79.66	80.81

Software calibration index used are EI, r^2 and RMSE. The calibration is calculated from the simulation results and actual data. The input data is energy generation and reservoir level of Namkhan 2 hydropower plant. The results show that EI = 0.74, r^2 = 0.82 and RMES = 0.14, which are in the acceptable ranges. Reservoir level comparison between the simulation and actual data is shown in Figure 10.

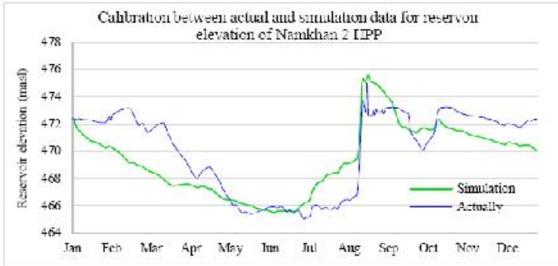

Figure 10. Calibration by reservoir level of Namkhan 2 HPP.

CONCLUSION

The study used HEC-ResSim3.1 to optimize electricity production and water management for the case of multi-reservoir hydropower plants. Fifty year of inflow data of Namkhan 2 & 3 hydropower plants are input of the software. The optimum results show energy increases from 767.85 to 795 GWh/year. The total water released through the spillway can be decreased of 404 MCM in the wet year, which equals 13.6% of water producing power. The optimum rule-curve shows water from both hydropower plants can extend the downstream requirement for about four dry months, March and June. The extra volume of water for the downstream used counts for 320-360 MCM.

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