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Article

Optimal Multi-Reservoir Operation for Hydropower Production in the Nam Ngum River Basin

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Abstract. This research aims to investigate optimal hydropower production of multi-reservoirs in Lao PDR and develop optimal reservoir rule curves. The Nam Ngum 1 and 2 (NN1 and NN2, respectively) reservoirs in the Nam Ngum River basin (NNRB), which is located in the middle of Laos, are selected as study areas. Mixed integer nonlinear programming (MINLP) is developed as an optimization model to maximize the hydropower production of joint reservoir operation of NN1 and NN2. The optimal operation rule curves are established by using the storage level estimated by the optimization model. Given the limited sideflow data, an integrated flood analysis system (IFAS) and water balance equation are used to simulate the sideflow into NN1 reservoir. A good fit is observed between the monthly streamflow simulated by IFAS and that calculated by the water balance equation. Compared with the observed data, the MINLP model can increase the annual and monthly hydropower production by 20.2% (6.0% and 14.2% for NN1 and NN2, respectively). The water storage level estimated by the MINLP model is used to build the operation rule curves. Results show that the MINLP model of multi-reservoir is a useful and effective approach for multi-reservoir operations and is expected to hold high application value for similar reservoirs in NNRB.

Keywords: Optimization model, MINLP, IFAS, hydropower, reservoir rule curves.

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Table 1. Nomenclature used in this paper.

Abbreviation	Explanation
DP	Dynamic Programming
EGAT	Electricity Generating Authority of Thailand
GDP	Gross Domestic Product
GAMS	General Algebraic Modelling System
GA	Genetic Algorithms
GUI	Graphical User Interface
ICHARM	International Centre for Water Hazard and Risk Management
IFAS	Integrated Flood Analysis System
LP	Linear Programming
Lao PDR	Lao People's Democratic Republic
LRC	Lower Rule Curve
MINLP	Mixed Integer Non-Linear Programming
NLP	Non-Linear Programming
NNRB	Nam Ngum River Basin
NSan	Nam San River
NS	Nam Song River
NB	Nam Bak River
NN1	Nam Ngum 1 reservoir
NN2	Nam Ngum 2 reservoir
NN1 HPP	Nam Ngum 1 Hydropower Plant
NN2 HPP	Nam Ngum 2 Hydropower Plant
NASA	National Aeronautics and Space Administration
URC	Upper Rule Curve

1. Introduction

The optimal operation of a multi-reservoir system is complex owing to various variables and objectives [1]. A multi-reservoir system operation must be able to maximize or minimize the use of optimal policies for reservoir inflow, storage volume, and release management [2]. Generally, a reservoir is operated by using upper and lower rule curves to control the release of water to the demand sites downstream [3]. The reservoir operation is generally not optimal due to certain constrains and uncertainties. Various optimization techniques have been developed and widely applied to address non-linear problems in multi-reservoir system operation and in the search for optimal reservoir operation rule curves [4], including linear programming (LP) [5], nonlinear programming (NLP) [6], genetic algorithms (GA), dynamic programming (DP) [7], and fuzzy stochastic [8]. In recent years, novel techniques have been applied to optimize multi-reservoir operations [9]. Some of these techniques include 2D dynamic programming [10], stochastic dynamic programming [11], mixed-integer nonlinear programming (MINLP) [12, 13], artificial intelligence [14], artificial neural network [15], and deep learning algorithms [16].

Lao PDR has many rivers that can be used for hydropower projects [17]. According to its Millennium Development Goals (2011), Lao PDR aims to be the "battery of Southeast Asia" that exports hydropower to its neighboring counties. To this end, hydropower systems have been constructed in the country to supply its internal and external hydropower demands. The Lao PDR government has persistently searched for techniques that can help them maximize their hydropower production, which is expected to significantly increase in the future through effective reservoir operations. As of 2018, Lao PDR has 516 hydropower projects, among which 61 are under operation, 52 are under construction, 148 are expected to operate by 2030, and 255 have signed memorandums of understanding [18].

The Nam Ngum River, which is the fourth largest river in Lao PDR and is connected to the Mekong River in Vientiane, has the ideal geographical conditions for launching hydropower projects. Many reservoirs have been constructed within this river for hydropower production. There are six reservoirs in operation, two under construction, and three are planned. Among these reservoirs, the Nam Ngum 1 (NN1) and Nam Ngum 2 (NN2) hydropower plants (HPPs) have the largest size and highest power production capacity. The operation of these reservoirs is managed by different organizations, whereas their power grid connection varies across different periods along with their load demand. These problems have introduced difficulties and complexities in the operation of these reservoirs. Moreover, the operation of these reservoirs sometimes depends on the experience of their operators [19].

The Nam Ngum River basin (NNRB) has faced water-related disasters and insufficient power supply due to their natural variability and lack of coordination between organizations upstream and downstream of the river. In addition, hydropower production business providers aim to gain maximum profit from hydropower production by reaching agreements with neighboring countries. Moreover, NNRB lacks an integrated water management due to the conflicts among the various departments and ministries in Laos that are in charge of the water resources of the country [20].

In recent years, several simulation approaches have been used in NNRB, including GA, DP, water evaluation and planning system, and Hydrologic Engineering Center-Reservoir system simulation (HEC-ResSim) towards optimal reservoir operations, however, they are still subject to nonlinearity, complexity and other limitations [21, 22].

A multi-reservoir operation can be achieved by using not only traditional techniques but also advanced and complex approaches to maximize hydropower production, enhance reservoir operation efficiency, and mitigate natural disasters. A multi-reservoir operation requires a balancing of all objectives of a reservoir, including hydropower generation, water supply, flood control, and environment flow [23]. In 2017, Ashrafi and Dariane found that the complexity of multi-reservoir operations prevents the application of simple optimization techniques [24].

To maximize the hydropower production of the NN1 and NN2 HPPs, this study examines a technique for increasing the hydropower production capacity and improving water resources management of NNRB. The optimization model for multi-reservoir operation of NN1 and NN2 in NNRB is developed and solved using the General Algebraic Modelling System (GAMS) software. An integrated flood analysis system (IFAS) is also applied for sideflow simulation.

2. Study area

The Nam Ngum River is one of the most important rivers in Lao PDR that starts from the Xiengkhouang Province and connecting to the Mekong River in Vientiane Capital as shown in Fig. 1. The NNRB basin has a drainage area of 16,931 km² or approximately 7.3% of Lao PDR.

This study focuses on two reservoir systems in this basin, namely, NN1 and NN2, which are operated by different organizations. NN1 is the largest reservoir in NNRB and is located approximately 35 km downstream of NN2.

NN1, which is operated by the EDL-Generation Public Company, started generating hydropower in 1971 with a hydropower capacity of 30 MW, which increased to 80, 150, and 155 MW in 1978, 1984, and 2004, respectively, and is planned to increase to 275 MW in the future [25]. Meanwhile, NN2 is located approximately 90 km north of Vientiane and approximately 35 km upstream of NN1. NN2 started operating in 2011 and is managed by Nam Ngum 2 Power Company Limited. The operations of NN2 follows the hydropower load demand of the Electricity Generating Authority of Thailand (EGAT). NN2 started out with an installed capacity of 615 MW to supply hydropower to the power network of Thailand, and all of its generated hydropower amount is sold to EGAT as specified in the Power Purchase Agreement (PPA).

In 2015, the electricity consumption of six regions in NNRB accounted for 42% of the country's total consumption (Table 2) possibly due to the rapid economic development of Vientiane, the capital city. NNRB is a potential hydropower production base that is expected to account for approximately 3% of the GDP growth rate of Laos [26].

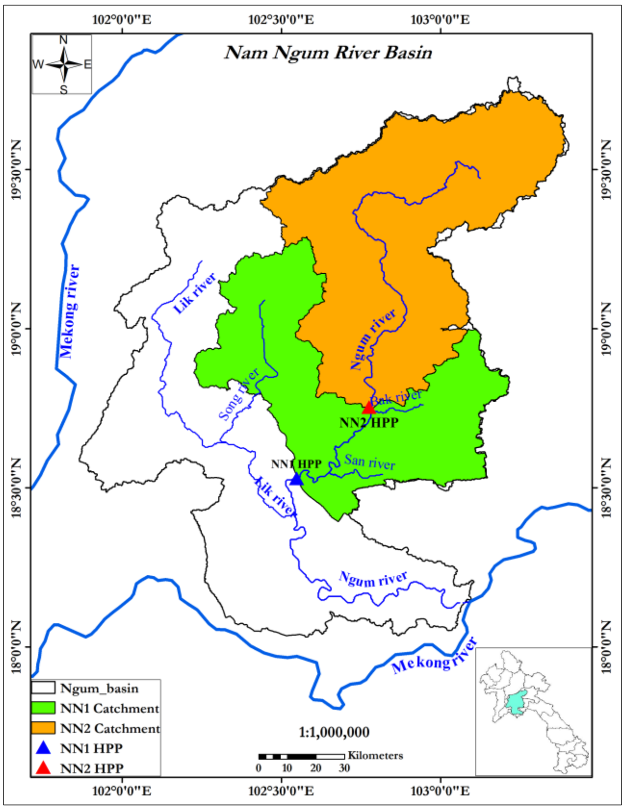

Fig. 1. Location map of Nan Ngum River Basin.

Table 2. Electricity consumption of the six regions within NNRB (Unit: GWh).

Province	2011	2012	2013	2014	2015
Luangprabang	92	100	121	136	147
Vientiane Capital	1,028	1,184	1,187	1,173	1,258
Vientiane	435	555	439	170	181
Xiengkhuang	30	39	45	43	47
Bolikhamxay	86	101	106	117	125
Xaysomboun	-	-	-	6	21
Total	1,670	1,978	1,898	1,644	1,780

3. Methodology

3.1. Data Description

An optimization model requires a large amount of data, including physical and operational reservoir data and time series data, to join the operations of NN1 and NN2.

The time series data used in this study include the observed historical reservoir inflow recorded at the tributaries and mainstreams within NNRB and the observed release and historical hydropower production data of NN1 and NN2. These data, which cover the years 2012 to 2015, are used to optimize the release of water from the reservoirs. These data were supported by Department of Meteorology and Hydrology, Ministry of Natural Resources and Environment, Lao PDR.

Eleven stations of the daily observed rainfall data during 2012 to 2015 used for sideflow simulation (Fig. 2)

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were supported by Department of Meteorology and Hydrology, Ministry of Natural Resources and Environment, Lao PDR. The technical data of both NN1 and NN2 are summarized in Tables 3. NN1 consists of 5 turbines. Three turbines have combined rated inflow per turbine of 117 m^3/s and the other two turbines have combined rated inflow per turbine of 57 m^3/s.

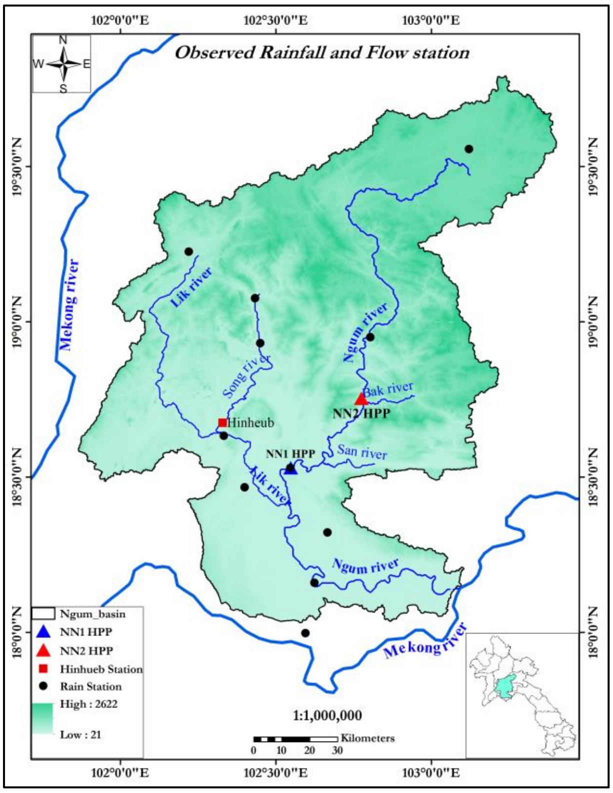

Fig. 2. Location of observed stations in NNRB.

Table 3. Principal feature of NN1 and NN2 HPPs.

Data category	NN1 HPP	NN2 HPP	Unit
Catchment Area	8,460	5,640	km^2
Annual average inflow	328	198	m^3/s
Weir crest elevation	202.3	359	masl
Max flood level	215	378.5	masl
Full supply level	212	375	masl
Minimum supply level	196	345	masl
Maximum tailwater level	178	225	masl
Full operation tailwater	166	212	masl
Rated flow per turbine	117/57	149.4	m^3/s
Installed capacity	155	615	MWh

One of the inputs into the MINLP model is the sideflows from the tributaries of the Nam Ngum River as shown in Fig. 3. These include the Nam San (NSan), Nam Song (NS), and Nam Bak (NB) rivers. These sideflows connect to NN1, but the streamflow data for NSan and NB are unavailable. Therefore, IFAS is used to simulate the streamflow of these rivers. The Nam Lik (NL) River is not considered for this study because it joins the Nam Ngum River at the downstream of NN1 HPP and it does not affect the reservoir operation. The release from NN1 and NL River are also used for domestic and irrigation at downstream of NN1 reservoir. The domestic water use is about 4.261 MCM/month on average and the irrigation water use is about 65.007 MCM/month on average. The domestic water use is estimated based on the amount of raw water use from Nam Ngum river per day for water supply system [27]. The irrigation water use is estimated based on the crop water consumption in the Mekong River Basin [28].

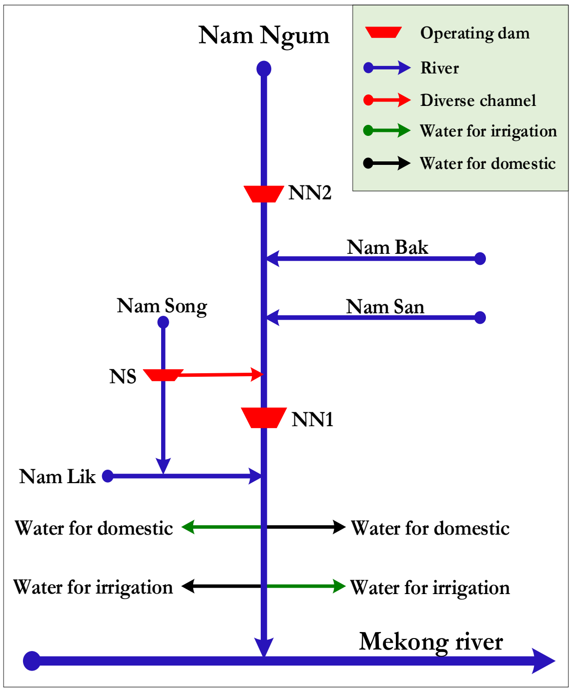

Fig. 3. Schematic diagram of river network of NNRB.

3.2. Model Formulation

3.2.1. Simulation of sideflows using IFAS

The NNRB is mostly mountainous area with very limited number of meteorological and hydrological stations. This area can be considered as ungauged or poorly gauged basin. In developing IFAS, ICHARM considered the issues for the underdeveloped and developing countries where there are not sufficient available data for developing model [29]. The application of IFAS includes interface for the global data that can be downloaded from website and local data as the input, which is suitable for study area with limited rain gauges. In addition, IFAS model performs well in streamflow simulation for the Nam Song River basin which a tributary of Nam Ngum River. It is therefore expected to perform well in NNRB area with similar hydrological characteristics [30].

The IFAS model was developed in Japan in the 1990s by a collaborative research team from the International Centre for Water Hazard and Risk Management (ICHARM) and the Public Work Research Institute. IFAS is a GUI tool for distributed rainfall-runoff model analysis with consideration of limited available observation for developing model [29]. IFAS model consists of a routing-model-based hydrological model and a tank-model-based kinematic wave hydraulic model. Several tank models are available in IFAS, including the river channel, surface, and groundwater tank models. IFAS uses Darcy's law, Manning's law, and the kinematic wave formula to simulate streamflow. If local data are not available, the input can be obtained from grid-based global satellite dataset that contains information on topography, soil classes, and land use. The steps in IFAS are not elaborated in this paper; instead, the reader can refer to ICHARM (2011) [23].

The IFAS parameter values are calibrated automatically using the IFAS calibrator. The parameters are calibrated by adjusting their values until a good agreement between the observed and simulated hydrographs is obtained. Seven model parameters are selected for the calibration due to their initial sensitivity. An indirect modeling of the target site is performed to model and simulate the streamflow in a neighboring catchment.

In this study, the input data are from both local data and global data. The rainfall data from eleven rain gauge are used. The observed flow at the Hinhueb Station (Fig. 2.) is used for calibration–due to their availability and quality. The time period of 2012 to 2015 is used for the calibration and validation. The rainfall and flows data were supported by Department of Meteorology and Hydrology, Ministry of Natural Resources and Environment, Lao PDR. The land use data were obtained from the National Agriculture and Forestry Research Institute of Laos (2010) with a resolution grid of 30 meters. The major land use in the study area is forest covering approximately 81% of the entire river basin. The soil data are available from the United Nations Environment Programme. The soil types are mostly clay loam accounting for 71.6% of the entire river basin. While realizing the crucial role of the land use and soil data on estimating the runoff, the global data with available resolution used in this study is considered acceptable.

3.2.2. Reservoir water-balance model

Due to the unavailable observed flows of NSan and NB, the sideflow simulation of NSan and NB from IFAS are verified by comparing the simulations with the sideflow calculated from the water balance equation. The monthly water balance of NN1 is formulated based on the inflow, outflow, and evaporation as shown in Fig. 4.

The monthly inflows to NN1 are assumed to be equal to the sum of the monthly outflows from NN2 and the total sideflow after deducting the precipitation, outflow, and evaporation from NN1. The infiltration loss is assumed to be negligible in this case. The sideflow from the water balance system (NB and NSan) can be calculated as shown in Eq. (1).

$$Q_{NB+NSan} = In_{NN1} + E_{NN1} - NS - Out_{NN2} - P_{NN1} \tag{1}$$

where $Q_{NB+NSan}$ is sum of NB and NSan streamflow, In_{NN1} is total monthly inflow to NN1, E_{NN1} is monthly evaporation from NN1, NS is diverted flow from NS reservoir, Out_{NN2} is total monthly outflow from NN2 reservoir estimated from the release of water through the turbines and spillway of NN2, and P_{NN1} is monthly precipitation of NN1 as expressed in MCM.

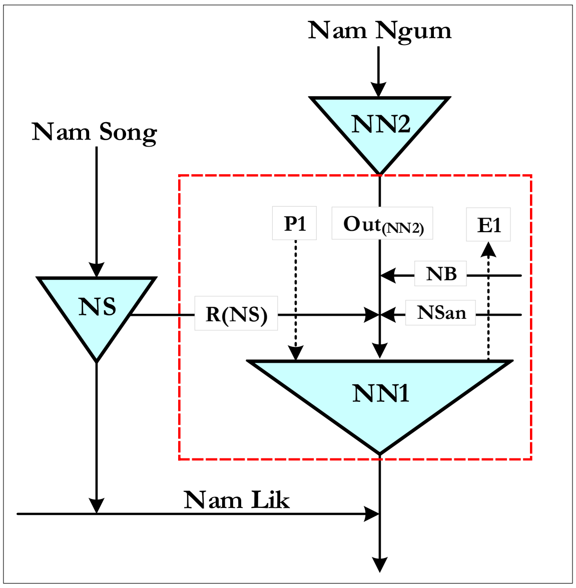

Fig. 4. Schematic diagram of NN1 reservoir water balance.

To evaluated model's performance, three statistical indices including Nash-Sutcliffe coefficient (NSE), Coefficient of Determination (R^2) and Relative Error (RE) are selected [31, 32]. These indices are calculated as shown in Eq. (2)-(4).

1) Coefficient of Determination (R^2)

$$R^2 = \left[\frac{n\left[\sum_{i=1}^{n}(Q_{obs,i} \times Q_{sim,i})\right] - \left[\left(\sum_{i=1}^{n} Q_{obs,i}\right) \times \left(\sum_{i=1}^{n} Q_{sim,i}\right)\right]}{\sqrt{n\left(\sum_{i=1}^{n} Q_{obs,i}^2\right) - \left(\sum_{i=1}^{n} Q_{obs,i}\right)^2} \times \sqrt{n\left(\sum_{i=1}^{n} Q_{sim,i}^2\right) - \left(\sum_{i=1}^{n} Q_{sim,i}\right)^2}} \right]^2 \tag{2}$$

where Q_{obs} is observed streamflow, Q_{sim} is simulated streamflow during time period i, n is number of data.

2) Nash-Sutcliffe coefficient (NSE)

$$NSE = 1 - \left[\frac{\sum_{i=1}^{n}\left(Q_{obs,i} - Q_{sim,i}\right)^2}{\sum_{i=1}^{n}\left(Q_{obs,i} - \overline{Q}_{obs,i}\right)^2} \right] \tag{3}$$

where Q_{obs} is observed streamflow, Q_{sim} is simulated streamflow during time period i, n is number of data.

3) Relative Error (RE)

$$RE = \frac{\left|Q_{sim,i} - Q_{obs,i}\right|}{Q_{obs,i}} \times 100 \quad (4)$$

where Q_{obs} is observed streamflow, Q_{sim} is simulated streamflow during time period *i*.

3.2.3. Optimization model (MINLP) formulation

The hypothesis that joint operation between NN1 and NN2 would increase hydropower production is investigated in this study by formulating the optimization model. The main decision variables are release from NN1 and NN2 and hydropower production from NN1 and NN2. NN1 and NN2 are multi-purpose reservoirs for hydropower, domestic water use, irrigation, and environmental flow. In this study, the objective function is set to be a single objective to maximize hydropower production of NN1 and NN2 and the water demand for domestic use, environmental flow, and irrigation is treated as a constrain. For flood consideration, the channel capacity is set as a constraint. The decision variable considering whether there is flow through the spillway is set as integer of 0 (no spillway) and 1. Therefore, the optimization model developed in this study is mixed integer nonlinear programing (MINLP) and it is solved using GAMS.

The main objective of this study is to maximize the hydropower production of NN1 and NN2 over period of 2012 – 2015 on monthly time scale as shown in Eq. (5).

$$Maximize: \quad HP_{Total} = \sum_{t=1}^{n}(HP_{t,NN1} + HP_{t,NN2}) \quad (5)$$

where, HP_{Total} is total hydropower production of NN1 and NN2, $HP_{t,NN1}$ and $HP_{t,NN2}$ are total hydropower production from NN1 and NN2 Has expressed in kWh, at time *t*.

Hydropower is very important for Laos to boost economic growth. Hydropower production is a function of the release of water through turbines, the time of hydropower generation, the effectiveness of the storage head, and the installed capacity of an HPP as shown in Eq. (6).

$$HP_t = \eta \times \gamma \times R_t \times H_t \times T \quad (6)$$

where, HP_t is the hydropower generated from HPPs at time *t*, η is the efficiency of turbine, γ is specific weight of water $(\approx 9.81\ KN/m^3)$, R_t is the release water through the turbine at time *t*, H_t is the differences in water between the head and tailwater levels as expressed in meters (m) at time *t*, and *T* is the time for generating hydropower as expressed in hours (hr).

The constrains considered in the MINLP model include water balance of reservoir, water use downstream, channel capacity, turbine capacity, hydropower generation capacity, reservoir storage capacity, and water released through spillway. The water balance equation is applied to define the outflow of reservoirs. The seepage is assumed to be negligible. Following the cascade reservoir system, the water balance is expressed as.

$$S_{t+1} = S_t + In_t - E_t - R_t - Spill_t \quad (7)$$

where, S_{t+1} is the final storage capacity at time $t+1$, S_t is the initial storage capacity at time *t*, R_t is the total release through turbines at time *t*, In_t is the reservoir inflow at time *t*, E_t is monthly evaporation from the reservoir at time *t*, and $Spill_t$ is the release through the spillway at time *t* as expressed in MCM.

The release from the reservoirs must be greater than or equal the summation of domestic water use, environmental flow requirement, and irrigation downstream as shown in Eq. (8).

$$R_{Total,t} \geq \sum ID_t + DD_t + ENVI_t \quad (8)$$

where, $R_{Total,t}$ is total release from the reservoirs at time *t*, ID_t is irrigation water demand at time *t*, DD_t is domestic water demand at time *t*, and $ENVI_t$ is environmental flow requirement at time *t*.

For flood consideration, the channel capacity is included as a constraint as shown in Eq. (9).

$$R_{Total,t} + Spill_t \leq Channel\ capacity_{\max,t} \quad (9)$$

where, $R_{Total,t}$ is total release from the reservoirs at time *t*, $Spill_t$ is water over spillway at time *t*, and $Channel\ capacity_{max,t}$ is maximum channel capacity at time *t*.

The water released through turbines should be less than the turbine capacity as shown in Eq. (10).

$$R_t \leq R_{\max} \quad (10)$$

where, R_t is the total water release through turbines at time *t*, R_{max} is turbine capacity at any time as expressed in MCM.

The hydropower production at time *t* should not exceed or be equal to the maximum generating capacity of HPPs.

$$HP_{n,t} \leq HP_{\max,n,t} \quad (11)$$

where, $HP_{n,t}$ is the hydropower produced by HPP *n* at time *t*, whereas $HP_{max,n,t}$ is the maximum hydropower production capacity of HPPs *n* at time *t* as expressed in kWh.

The storage in a reservoir at time *t* should not exceed the maximum storage capacity or normal pool level and should not be less than the dead storage or minimum pool level at time *t*.

$$S_{\min} \leq S_t \leq S_{\max} \quad (12)$$

where, S_t is the storage capacity at time t, whereas S_{min} and S_{max} are the minimum and maximum storage capacities at time t as expressed in MCM.

During flooding periods, when the water release is higher than the normal pool level, the excess water will be released through spillway. The overflow can be defined as the difference between the final and maximum storages at any time t.

$$Spill_t = S_{t+1} - S_{\max} \quad (13)$$

where, $Spill_t$ is the water released through the spillway at time t, whereas, S_{t+1} is the final storage at time t. In the absence of overflow, the final storage can serve as the initial storage for the next time step $t+1$, but in the presence of overflow, the maximum storage (S_{max}) can serve as the initial storage.

4. Results and Discussions

This study considers both NN1 and NN2 as multi-reservoir systems and uses GAMS to solve for optimal release and hydropower production. The major inflow into NN1 is the water released by NN2 through its turbines and the sideflows. Therefore, the operation of NN1 depends on the water release from NN2 and the sideflows. The simulated streamflow from the tributaries of the Nam Ngum river is from IFAS. In this section, the results of the streamflow simulation, the optimal release and hydropower production are discussed.

4.1. Streamflow Simulation

4.1.1. Parameter sensitivity analysis

IFAS is calibrated using the observed flow at Hinhueb station before being applied to simulate the sideflows of NSan and NB. The sensitivity analysis of IFAS model parameter is carried out. The result of parameter sensitivity analysis demonstrated that flows in NNRB are sensitive to seven parameters. The optimal values of these seven parameters are shown in Table 4. The highest sensitive parameters for discharge are Final infiltration capacity (SKF), Manning's roughness coefficient (RNS), and Surface roughness coefficient (SNF). These parameters are related to the land use and soil type within the study area. Coefficient of baseflow (AGD) and Maximum water height (HFMXD) are less sensitive compared to SKF, RNS and SNF but more sensitive than HCGD and FALFX.

4.1.2. Calibration results

The IFAS calibration results at Hinhueb station show a good fit between the simulated and observed streamflow. The correlation coefficient highlights some consistency between the simulated and observed streamflow as shown in Fig. 5 However, Fig. 6 shows that the simulated streamflow between May and July 2014 are slightly overestimated probably due to the fact that rainfall came earlier than usual, and that the river has a small baseflow.

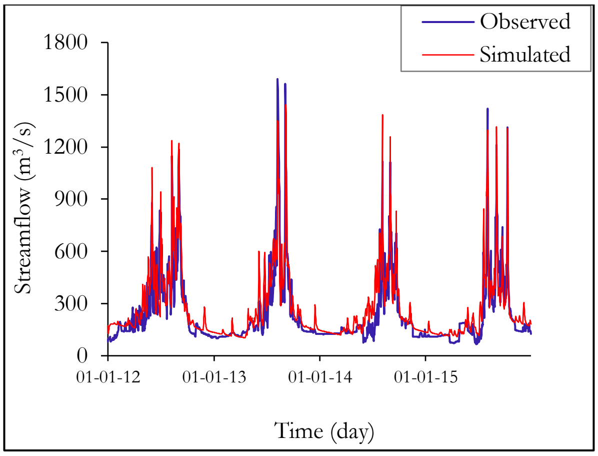

Fig. 5. Daily streamflow from IFAS model compare with observed at Hinhueb station.

Figures 5 and 6 also show that IFAS model successfully simulates daily streamflow at Hinhueb station with a reasonable accuracy. The Nash–Sutcliffe coefficient (NSE) = 0.75, the coefficient of determination (R^2) = 0.79 and the relative error (RE) = 23.39%. The calibrated parameters are used for the model validation of NB and NSan streamflow.

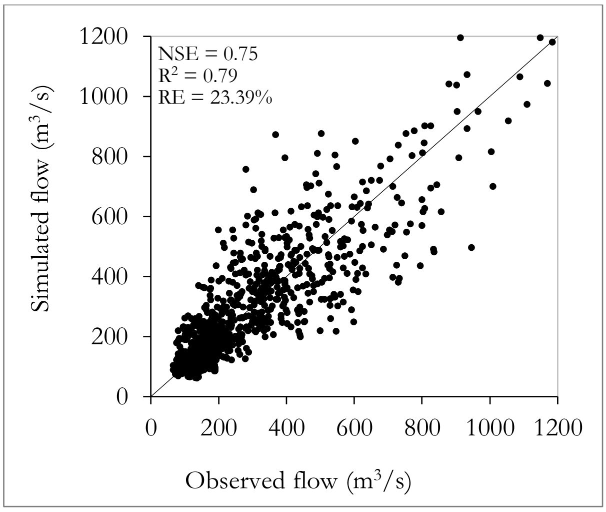

Fig. 6. Correlation between simulated and observed daily streamflow at Hinhueb station.

Table 4. Optimal parameter values from IFAS model calibration

Parameter	Notation	Optimal value

Final infiltration capacity	SKF	0.045
Manning's roughness coefficient	RNS	0.035
Roughness coefficient of ground surface	SNF	0.01
Maximum water height	HFMXD	0.75
Coefficient of baseflow	AGD	0.0035
Height where intermediate outflow occurs	HCGD	0.285
Coefficient of rapid intermediate outflow	FALFX	0.001

4.1.3. Validation results

The calibrated IFAS model is used to simulated streamflow of NB and NSan rivers. The simulated streamflow of NB and NSan between 2012 and 2015 are shown in Figs. 7 and 8. The IFAS and water balance equation results reveal that the former can effectively capture the NB and NSan river streamflows.

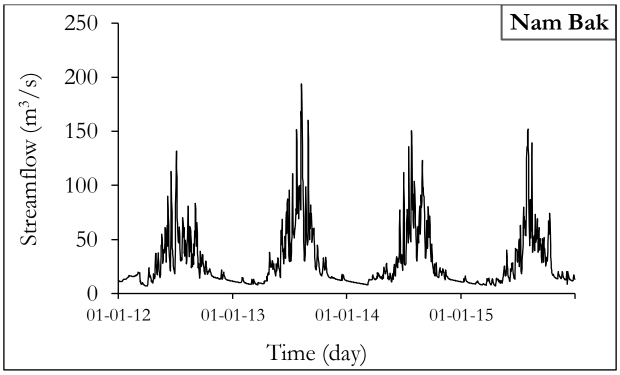

Fig. 7. Daily simulated streamflow of NB river

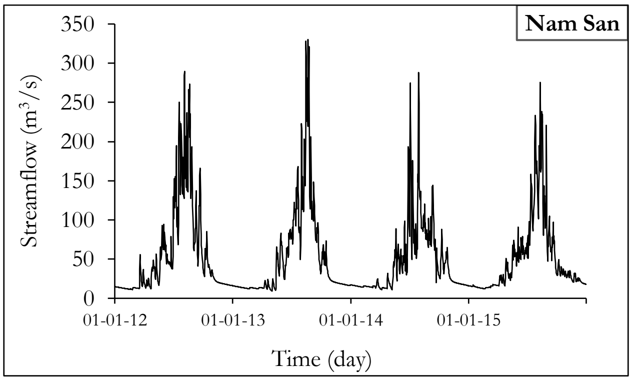

Fig. 8. Daily simulated streamflow of NSan river.

The total NB and NSan monthly streamflow simulated by IFAS is compared with the streamflow calculated from the water balance equation (Fig. 9). The model validation shows good performance with NSE = 0.78, R^2 = 0.86 and RE = 19.33%. The high level of NSE and R^2 values have been linked to the ability of IFAS model to capture the streamflow in NB and NSan catchments during the validation period. This indicated an acceptable performance of IFAS model at monthly time scale in limited data catchment. Therefore, the IFFAS model could be used to simulate monthly streamflow in ungauged catchment like NB and NSan.

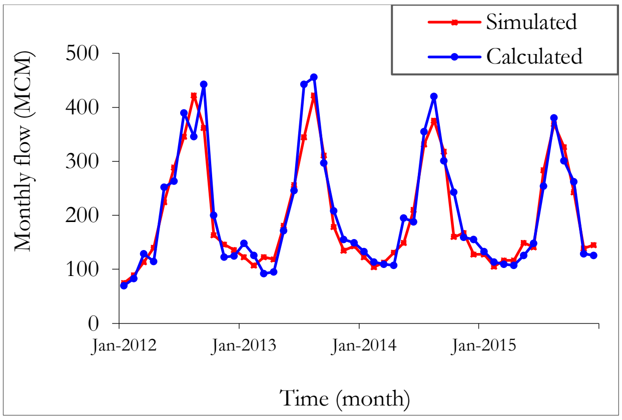

Fig. 9. Comparison between sum of NB and NSan monthly simulated and calculated streamflow.

However, the calculated streamflow for 2014 is slightly higher than that simulated by IFAS. Such discrepancy may be ascribed to the fact that the infiltration loss term is not considered in the water balance equation, thereby increasing the streamflow in some months.

4.2. Optimization of Hydropower Production

The optimization model is formulated to assess the potential of joint operation of NN1 and NN2. From the MINLP model, the average hydropower production of NN1 and NN2 during 2012 to 2015 increase by 6.01% (Fig. 10) and 14.21% (Fig. 11), respectively. The average hydropower yield of NN1 is high when considered over a period of 12 months, while NN2 can produce prominently during the rainy season. The MINLP model can adapt the release based on various reservoir inflow in each month for energy production maximization. It also shows that the water discharges through the spillway gates of all two reservoirs could be reduced. These may cause the increasing of all hydropower production. In addition, the increasing of hydropower of NN1 may result in the increasing of released from NN2 which is inflow of NN1.

The results also demonstrate that the amount of monthly average releases from NN1 and NN2 are higher than the observed release. The monthly average observed releases of NN1 and NN2 vary from 825.19 to 1,092.2 and 325.06 to 885.39 MCM, respectively, whereas, the monthly average optimized releases of NN1 and NN2 from the MINLP model vary from 1,006.41 to 1,186.9 and 497.51 to 1,061.73 MCM, respectively. The average stored water volume of the NN1 reservoir at the last month of the wet season (November) and dry season (April) of 7,024.49 ± 216.99 and 6,198.84 ± 237.20 MCM, respectively. Similarly, The monthly average stored water volume of the NN2 reservoir at the last month of the wet season (November) and dry season (April) of 4,361.27 ± 108.19

and 4,159.55 ± 190.67 MCM, respectively. However, while the monthly time series data for reservoir inflow are inputted into the MINLP model, in actual operations, a long time series of inflow data is not readily available and reservoir operators only have the inflow data for the previous month. Therefore, the hydropower production from the MINLP model is higher than the observed levels.

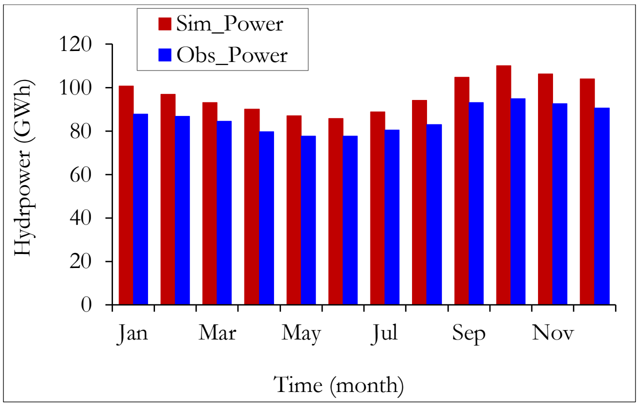

Fig.10. Comparison of average monthly hydropower production of NN1 between the MINLP model and the observation.

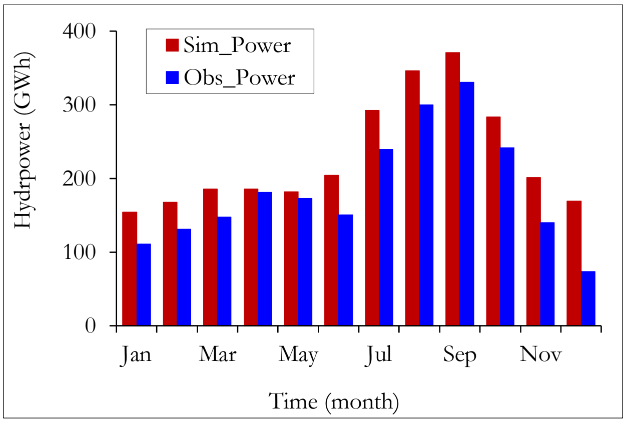

Fig. 11. Comparison of average monthly hydropower production of NN2 between the MINLP model and the observation.

The average monthly hydropower production of NN1 and NN2 from the MINLP model during 2012 to 2015 is shown in Fig. 12.

The maximum hydropower of 481.26 GWh is recorded in September, whereas the minimum hydropower of 252.52 GWh is recorded in December. Across all periods, the optimum monthly hydropower from the MINLP model is greater than the observed hydropower especially during the wet season.

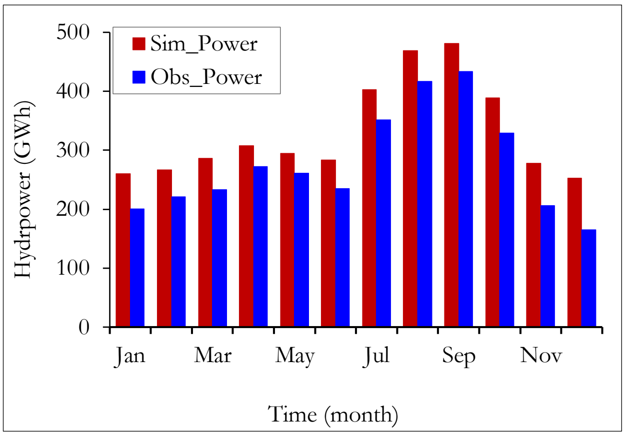

Fig. 12. Comparison of average monthly hydropower production of NN1 and NN2 between the MINLP model and the observation.

The optimal annual hydropower production is higher than the observed hydropower as shown in Fig. 13. All HPPs have generated the maximum possible amount of hydropower. The MINLP model can increase hydropower production by 20.2% on average compared with the observed hydropower production. The optimization model of joint operation increases the release of water to maximize the hydropower production of HPPs.

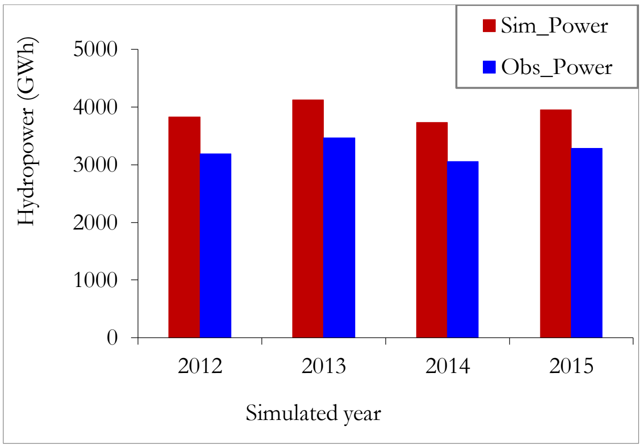

Fig. 13. Annual hydropower from the MINLP model compared to the observation of NN1 and NN2.

4.3. Optimal Reservoir Operation Rule Curves

The reservoir operation rule curves are also used to formulate monthly operational policies that can maximize the hydropower generation of NN1 and NN2.

The upper and lower rule curves (URC and LRC, respectively) of NN1 and NN2 are obtained from the results of MINLP model and shown in Figs. 14 and 15, respectively. These curves can be developed on the basis of the storage water level recorded at each period (i.e., each month in this study). URC and LRC are estimated from the maximum and minimum reservoir water levels, respectively, for each month from 2012 to 2015. These water levels are simulated by using GAMS, which achieves the maximum and minimum hydropower for every month. The reservoir water level is simulated by GAMS on the basis of the area–storage–water level curve. The optimal operation rule curves for NN1 and NN2 are shown in Figs. 14 and 15, respectively. The comparison between the existing and recommended rule curves is not possible due to the lack of data of existing rule curves both for NN1 and NN2. Increased operating efficiency obtained from applying the recommended rule curves is reflected in the increased amount of hydropower generated as shown in Figs. 10–11 for single reservoir operation and in Figs. 12–13 for joint reservoir operation.

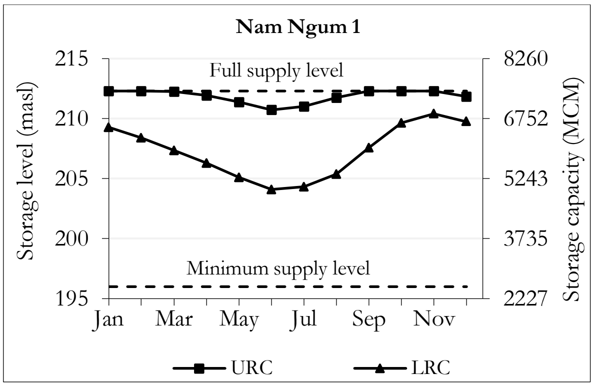

Fig. 14. Recommended optimal rule curve for NN1 reservoir.

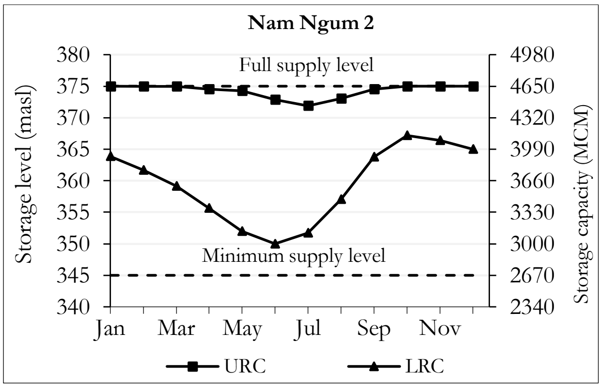

Fig. 15. Recommended optimal rule curve for NN2 reservoir.

It can be seen from Fig. 14 that the range between URC and LRC is generally small. The URC is almost constant with full supply level, whereas the LRC dropped in the dry season during the mid-year. These may be due to the storage capacity of NN1 reservoir is large and can store the amount of water from wet season to enough operating in dry season. For the characteristic rule curves of NN2 (Fig. 15) illustrated that the URC is similar to the NN1, but the range between URC and LRC is higher than the NN1, especially in wet season. This may cause from the storage capacity of NN2 reservoir is small and cannot keep the water in wet season for full operating in dry season. So, the amount of water has to release through the turbine in wet season, this leaded to the increasing of the hydropower production in wet season as shown in Fig. 11. Increased amount of hydropower generated based on the proposed rule curves for NN1 and NN2 suggests that the proposed rule curves could offer more efficient operation than the existing rule curves.

The impact on water use for other downstream activities was also assessed. The monthly average domestic and irrigation water use at downstream area of NN1 is about 4.26 and 65.01 MCM, respectively (see section 3.1) which is negligible in comparison with the monthly minimum release from NN1 of 825.19 MCM (see section 4.2). The monthly maximum release of 1,092.2 MCM from NN1 is less than 7,889.40 MCM which is the river capacity at downstream area of NN1. As the result, This suggests that the recommended rule curves proposed do not pose increasing risk of water shortage or flooding in the downstream area. However, these curves are established based on the optimal release of water for maximizing the hydropower production of NN1 and NN2 within the study period and may change along with the variations in reservoir inflow. The new rule curves of NN1 and NN2 may change the water release in each month in order to make the balance of water use and maximize hydropower.

5. Conclusions

This study aims to optimize the release for hydropower production from NN1 and NN2 reservoirs in NNRB in Lao PDR and establish multi-reservoir operation rule curves. Two tributaries, NB and NSan, of Nam Ngum river are ungauged so their streamflow is simulated using IFAS. IFAS is calibrated using the observed flow at Hinhueb station and the simulations of NB and NSan streamflow are validated by the water balance of NN1. The study period is 2012– 2015. The optimization model for joint operation is developed as MINLP to maximize the total hydropower production from NN1 and NN2 HPPs and GAMS is used to solve the MINLP model.

The daily streamflow at Hinhueb station simulated by IFAS fitted with the observed streamflow during the calibration period with NSE = 0.75, R^2 = 0.79 and RE = 23.39%. IFAS is then used to simulate streamflow in ungauged Nam Bak and Nam San rivers. The simulated flow is validated with the results from the water balance model of NN1. The validation results show that the total monthly streamflow of NB and NSan simulated by IFAS demonstrate a good fit with the monthly streamflow calculated from the water balance equation (NSE = 0.78, R^2 = 0.86 and RE = 19.33%). However, the calculated streamflow for 2014 is slightly higher than that simulated by IFAS. This might be from the assumption of this study that the infiltration is not considered in the water balance model.

The optimal hydropower production from the MINLP model developed in this study is higher than the observed hydropower production by 20.2%. Specifically, the hydropower production of NN1 and NN2 can be increased by 6.0% and 14.2%, respectively. Across all periods, the optimal monthly hydropower generation achieved by the MINLP model is higher than the observed levels especially during the wet season because of the higher gross head and reservoir capacity. In other words, the MINLP model increases the release of water to maximize hydropower production in all HPPs while meeting the water demand and not causing flood downstream. In this study, the reservoir inflow for the entire study period can be inputted into the optimization model, but in actual operations, a forecast series of inflow data is uncertain. This phenomenon may explain why the maximum hydropower generation is not reached. In addition, the optimal URC and LRC of NN1 and NN2 are developed based on the storage level estimated by the MINLP model for each month. These rule curves can be used along with the optimization model to maximize the hydropower production of NN1 and NN2. The optimization model can also serve as a guideline to maximize the hydropower production of NN1 and NN2 HPPs and other HPPs in NNRB.

6. Limitations and Future research

In this study, there are some limitations on data availability. In the upper part of Nam Ngum River Basin, there are very limited hydrological and meteorological stations. The period of available data is relatively short for streamflow simulation. The hydropower demand data in each month are not available. This may cause the hydropower generation from the MINLP model to be higher than the actual operation. The uncertainty from changing climate is not yet considered in this study. In the situation that future streamflows may be lower than the normal average or differ from the results shown in this study, the optimal rule curves and hydropower yield will be affected.

For future studies, the uncertainty from changing climate and extreme hydrological regimes should be taken into account in the optimization model to mitigate the impact of flooding and climate uncertainty on hydropower generation.

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