Research article

Impact Assessment of New Dam Construction in Nam Ngum Watershed on Electric Generation at Num Ngum 1 Dam

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Abstract Lao PDR is a landlocked country and around 90% of the country is located in Mekong River Basin. Average annual rainfall is around 1,900 mm and 35% of the annual flow in the Mekong River is from Lao tributaries. Given the abundance of water resources in Laos, many hydropower dams have been constructed in the country. The generated electricity is exported to Thailand and other surrounding countries and has become an important means of earning foreign currency for Laos. In particular, the Nam Ngum 1 dam has been in operation since 1971 in the Nam Ngum watershed near Vientiane, the capital of Laos, and several additional dams have been completed in this watershed since 2010. Hydropower has great potential to boost the national income and raise living standards in Lao PDR. At the same time, hydropower reservoirs have a large number of potential cross-sector impacts, including changes in the downstream water environment. The purpose of the current study was to evaluate the impact of the construction of multiple dams in the Nam Ngum watershed on the river flow regime, as well as on the hydropower generation of the preceding Nam Ngum 1 dam. In this study, the fully distributed TOPMODEL was developed and applied to analyze the water flow in the Nam Ngum watershed with a spatial resolution of 1 km X 1 km. Simulated river discharge and dam storage were in good agreement with observed data. Subsequently, we investigated the impact of the construction of the Nam Lik 1/2, Nam Ngum 2, and Nam Ngum 5 dams, which were newly developed after 2010. Results indicated that new dam construction has positive effects in decreasing flood flow during the rainy season and increasing discharge in the dry season, while electricity generation at the Nam Ngum1 dam also increased by 6.8%.

Keywords water resource development, hydropower, multi reservoirs, Laos

INTRODUCTION

Lao PDR is a landlocked country and around 90% of the country is located in Mekong River Basin. Average annual rainfall is around 1,900 mm and 35% of annual flow in Mekong is from Lao tributaries, so many hydropower dams have been constructed against the backdrop of abundant water resources. The generated electricity was exported to Thailand or surrounding countries and has become an important means of earning foreign currency for Laos. Electricity demand in Laos has been growing at a high rate of more than 10% since 1999, both in terms of consumption and peak power and according to the national power supply development plan, demand exceeded supply until around 2014. To meet this growth in demand, the Lao government has decided to utilize its abundant hydropower resources, which are domestically produced energy, and to actively promote the development of power sources (Uematsu, 2019).

In particular, the Nam Ngum 1 Dam has been in operation since 1971 in the Nam Ngum watershed near Vientiane, the capital of Laos, and several dams have been completed in this watershed since 2010. Hydropower has great potential to boost the national income and raise living standards and create opportunities for the establishment of electricity-using industries in Lao PDR. While hydropower reservoirs also have a large number of potential cross-sector impacts, including changes in downstream flows and water quality, dam safety, and resettlement of living people (Lacombe et al., 2014). Likewise, Kudo et al. (2013) assessed how to change the flow discharge into Nam Ngum 1 reservoir due to new dam construction, however, impact on hydropower generation was not obtained.

OBJECTIVE

The purpose of this study was to evaluate the impact of the construction of multiple dams in the Nam Ngum watershed on the river flow regime, as well as on the hydropower generation of the preceding Nam Ngum 1 dam.

METHODOLOGY

Study Area

The Nam Ngum watershed in Laos is a tributary of the Mekong River. The river length is about 415 km, and the catchment area is about 17,000 km^2. The land use in the basin is paddy fields (16%), forests and bushes (72%), and residential land (only 0.2%), making the basin still rich in nature. In this watershed, several large-scale dams were constructed after 2010 to meet the increasing electric demand of domestic and surrounding countries (Fig. 1).

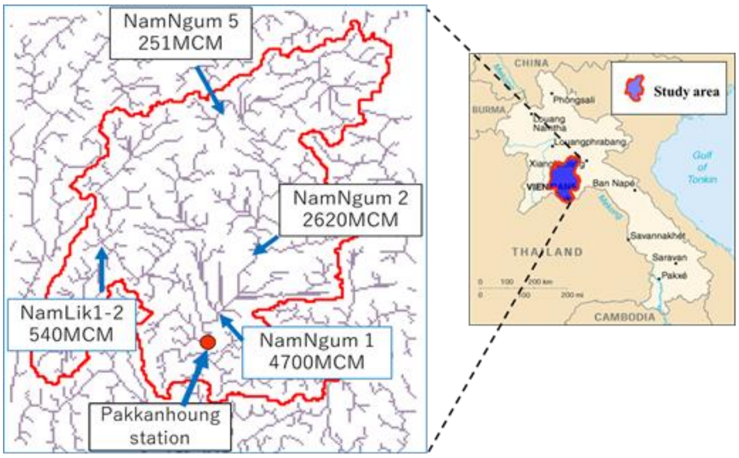


Fig. 1 Nam Ngum watershed and dams' location

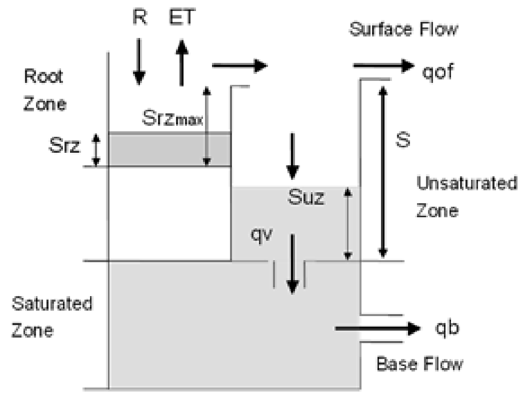
Nam Ngum 1 Hydroelectric Power Plant is located on the Nam Ngum River about 90 km north of Vientiane, the capital of Laos, and its reservoir has active storage of 4,700 MCM (million m^3), which started operation in 1971. As the main power source for the metropolitan area, its generation capacity was 155 MW until 2017. The utilization rate of the Nam Ngum 1 power plant was initially 66%, but the Nam Song and Nam Leuk power plants developed in 1995 and 2000, respectively, increased the flow rate by an average of 65 m^3/s and 15 m^3/s, respectively, and the utilization rate has increased to 74%. After 2018, the capacity was improved to 235 MW by the JICA project (Uematsu, 2019).

Nam Ngum 2 Hydroelectric Power Plant was completed in 2011, which is located about 100 km north of Vientiane, the capital of Laos, and is the second power plant on the Nam Ngum River. The Nam Ngum 2 Power Project is a concrete surface impermeable rockfill dam with a dam height of 181 m. The installed capacity is 615 MW, and 100% of the power be exported to Thailand. Its basin area accounts for 67% of the Nam Ngum 1 power plant basin area, having an effective storage capacity of 2,620 MCM. Nam Ngum 5 was completed in 2012, with a dam height of 99 m. With a catchment area of 413 km^2 and an effective storage capacity of 251 MCM, the project is smaller than the Nam Ngum 2 power project (Kudo et al., 2013).

The Nam Lik 1/2 Power Project started operation in 2011, having 100 MW power generation and 101 m height concrete surface impermeable dam in the middle reaches of the Nam Lik River, a tributary of the Nam Ngum River. With a medium-sized active storage capacity of 540 MCM, this dam is expected to smooth the flow conditions in the lower reaches of the dam throughout the year and increase the dry season flow.

Rainfall-Runoff Model

To evaluate the river water flow, a distributed water cycling model was developed and applied to analyze the water balance in the basin. TOPMODEL was employed for the rainfall-runoff analysis. Such a distributed model can include the spatial distribution of topography, land use, and soil characteristics. Therefore, TOPMODEL is widely used for hydrological characteristic analysis, water management, water quality analysis, and future forecasting. TOPMODEL was proposed by Beven and Kirkby (1979) based on the contributing area concept in hill slope hydrology. This model is based on the exponential transmissivity assumption, which leads to a topographic index ln (*a*/*To*/tan*b*), where *a* is the upstream catchment area draining across a unit length, *To* is the lateral transmissivity under saturated conditions, and *b* is the local gradient of the ground surface. Figure 2 illustrates the conceptual structure of the water cycle as estimated by TOPMODEL. For details, refer to Yoshida et al. (2017).



Notes: R:precipitation, ET: evapotranspiration, Srz: storage in root zone, Srzmax: maximum storage in root zone, Suz: storage in unsaturated zone qv: discharge from unsaturated to saturate zone, S: soil water deficit until saturated condition, qof:surface flow discharge, qb: base flow discharge

Fig. 2 TOPMODEL structure

Dam Operation Model

Large scale dams having quite huge water storage capacity makes a significant effect to control river water discharge (Hanasaki et al., 2003). Normally, the dam reservoir stores water in the rainy season and releases water in the dry season so that downstream river discharge becomes stable compared to the variation of natural river flow. In the Nam Ngum watershed, several dams have more than 250 MCM capacity which is mostly used for electric generation. In this study, a simple dam storage model was applied to describe the river discharge stabilization effect (Juthithep et al., 2014). The storage of a reservoir Vres (m^3) can be calculated by the following equation.

$$V_{res}^{t+\Delta t}=V_{res}^{t}+(Q_{in}^{t}-Q_{out}^{t})\times\Delta t \tag{1}$$

$$Q_{out}^{t}=Q_{pw}^{t}+Q_{spill}^{t} \tag{2}$$

$$Q_{pw}^{t}=Q_{pwmax}\times(V_{res}^{t}/V_{resmax}) \tag{3}$$

Where Q_{in} is the inflow of a reservoir (m^3/s) calculated by flow accumulation along the upstream river network, Q_{out} is the outflow of a reservoir (m^3/s), Q_{pw} is the turbine discharge (m^3/s), Q_{pw} is the spillway discharge (m^3/s), V_{resmax} is active storage(m^3) and Q_{pwmax} is maximum turbine flow (m^3/s).

1 Dam Case and 4 Dam Case Scenarios

In this study, we used the data from 2002-2010. During this period, only the Nam Ngum 1 plant was operating, so first we checked model performance under the 1dam case scenario. And then, 4 dams' case was also simulated by using the same input data and compared with the 1 dam case scenario to investigate the impact of newly developed dams on downstream river flow and hydropower generation at Nam Ngum 1 dam, considering Nam Lik 1/2, Nam Ngum 2, and Nam Ngum 5, which were newly developed after 2010. To evaluate the hydropower generation at Nam Ngum 1 dam, the relation between turbine discharge and hydropower generation was used in Fig. 3.

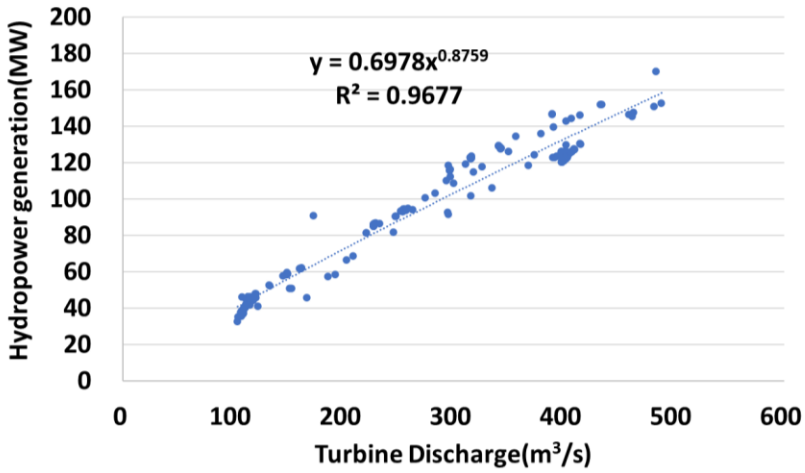


Fig. 3 Relation between turbine discharge and hydropower generation at Nam Ngum 1

RESULTS AND DISCUSSION

By using the proposed model, river flow at Pakkanhoung (catchment area of 14,300 km^2) station was simulated from 2002 to 2010. The first 5 years of data were used for parameter calibration, and the latter 4 years of data were used for validation. Parameters were calibrated by the try-and-error method to maximize the Nash-Sutcliffe efficiency (NSE). Solid line and plot in Fig. 4 show the calculated and observed river discharge at Pakkanhoung station under 1 dam case. Estimated NSE were 0.59 and 0.50 in the calibration and validation periods respectively. Model performance can be evaluated as "satisfactory" if NSE > 0.50 (Moriasi et al., 2007). The reason for the relatively low accuracy is that there is no station in a relatively high-elevation area. The dashed line in Fig.4 shows river discharge under 4 dam cases. Due to the flow regulation effect of multiple dam reservoirs in upstream, positive effects to decrease in flood flow in the rainy season and to increase discharge in the dry season were obtained. Especially, minimum discharge in the dry season increased from 221 m^3/s to 264 m^3/s and it contributed to generating more electricity. Figure 5 shows the comparison between calculated and observed monthly storage at Nam Ngum 1 reservoir for 2002-2004. The correlation coefficient between the calculated and observed values is R = 0.65. Calculated storage ranging more than 3,000 MCM shows relatively good agreement, however, the calculated values are slightly overestimated when storage became less than 3,000 MCM. Figure 6 shows the annual hydropower generation with 1 dam case and 4 dam cases. Under the 1 dam case, annual hydropower generation varied from 857.8 -1077.6 GWh. Under the 4-dam case, annual hydropower generation was increased by 6.8% due to the flow regulation effect of newly developed dams upstream, however, the increment in 2004 was only 3.2%. The year 2003 was a drought year so dam storage at the end of rainy season in 2003 was relatively small. That is why additional release discharge was insufficient to increase hydropower generation in the dry season of 2004. The electricity demand for air conditioners increases especially during the dry season when the weather becomes very hot, but the amount of electricity generated decreases due to a decrease in the flow of rivers. In 2002, 30% of domestic power consumption was imported, but the import price from Thailand was 10% higher than the price of electricity exported by the Lao PDR, resulting in a loss of foreign currency earned through exports. Under the Independent Power Producer (IPP) concession of new dam construction projects, most of the generated electricity is exported to Thailand. However, in Vientiane city capital of Laos also, electricity demand increases by around 10% per year, so even a small amount of increment in Nam Ngum 1 hydropower dam can contribute to reducing the electricity import from Thailand.

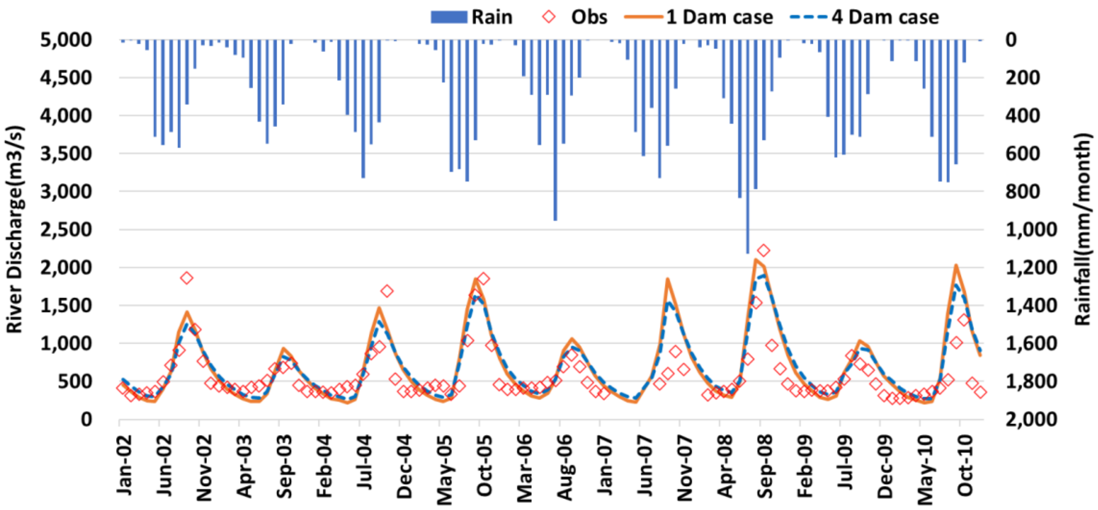


Fig. 4 Calculated and observed river discharge at Pakkanhoung station

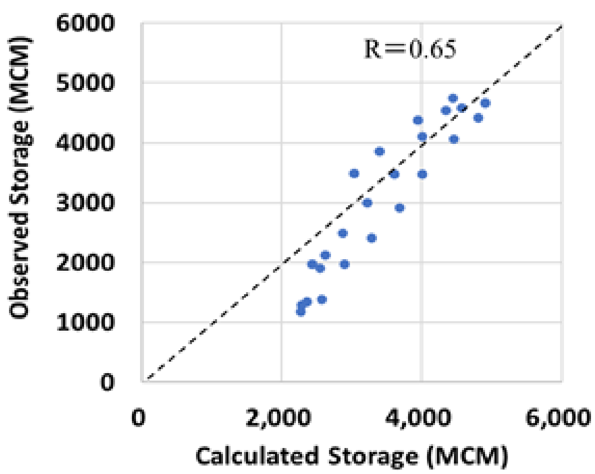


Fig. 5 Calculated and observed monthly storage at Nam Ngum 1 reservoir

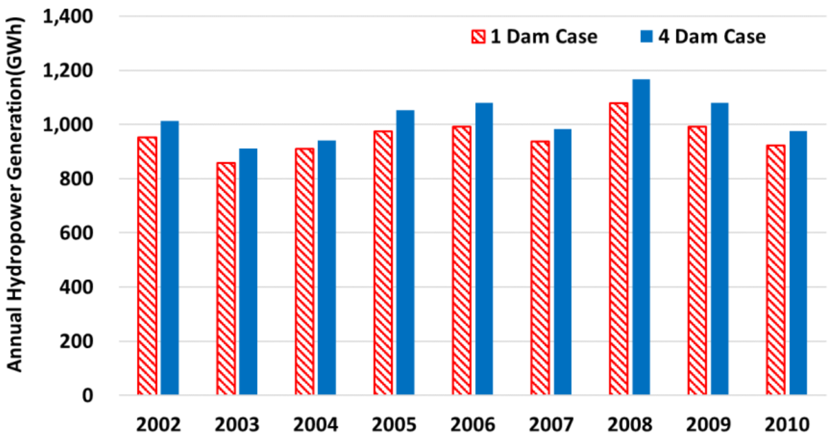


Fig. 6 Estimated annual hydropower generation under 1 Dam and 4 Dam cases

CONCLUSION

In this study, the fully distributed TOPMODEL was developed and applied to analyze the water flow in the Nam Ngum watershed to assess the impact of newly developed dams on downstream river flow and hydropower generation in the Nam Ngum 1 dam. Simulated river discharge and dam storage were in good agreement with observed data, and then, we investigated the impact of dam construction considering NamLik1/2, NamNgum2, and NamNgum5, which were newly developed after 2010. As a result, new dam constructions have positive effects to decrease flood flow in the rainy season and to increase discharge in the dry season, and electricity generation at the Nam Ngum1 dam also increased by 6.8%. In this simulation, the same simple reservoir model was used in 1 dam and 4 dam cases due to the lack of data, however, normally reservoir operation rule curve became more complex under multiple dam operations. Therefore, the dam operation model should be improved by using the actual rule curve and river flow data after 2010.

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