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Assessing Reservoir Reoperation Performances through Adapted Rule Curve and Hedging Policies under Climate Change Scenarios: In–depth Investigation of Case Study of Bhumibol Dam in Thailand

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ABSTRACT
The adaptation measures on water resources management through the forecast–based dam and reservoir reoperation have been intensively introduced to reduce the persistence of disaster risk and enhance water supply reliability. In this study, reoperating the Bhumibol (BB) dam with adapted rule curve and hedging policy as well as modelling exercise with MIKE11 to generate series of reservoir inflow was conducted. Five periods of the projected inflow of BB dam were then generated; 2000–2020 (baseline), 2021–2040, 2041–2060, 2061–2080 and 2081–2099 based on the simulation of EC–EARTH under RCP4.5. The water balance–based reservoir reoperation model for current and projected incidents were established using MATLAB Simulink Toolbox to explore the operational performances in terms of reliability, vulnerability and resiliency indices. The simulation results show considerable changes in the seasonal and annual patterns of reservoir inflow, which are key factors influencing the complexity and effectiveness of reservoir management in both the current and future operations. Additionally, the percentage increase in water storage after reoperating with all scenarios of adapted rule curve are not much deviated in comparison with the observed results. However, applying two–point, three–point, and zone–based hedging for reservoir reoperations exhibit high potential to significantly increase reservoir water storage in dry and wet seasons. The simulation results also show that even hedging policy provides good results in raising water storage in the reservoir. However, effectiveness of operational performance is apparently lower than those scenarios performed by adapted rule curve. All the performance indices for the future case signify level of incapability of dam operation system in meeting target water demand, which is worse than the current case due to the declined pattern of reservoir inflow. Therefore, optimal reoperation with optimization–based approach is highly suggested in maximizing the multiple benefit of dam and reservoir systems and coping with climate variability.

Keywords : reservoir performance; climate change; adapted rule curve; hedging policies; water balance model

INTRODUCTION

Dam and reservoir operation in the era of climate change have become a challenging task. As the climate change is expected to quantitatively affect the future supply and demand of water resources in the spatial and temporal manners, adaptation measures are therefore necessary. The issues on adaptive water resources management through dam and reservoir reoperation have been adopted intensively. Dam and reservoir reoperation attempt to change the existing operation and management procedures and to maintain or maximize the multiple benefit obtained from dam operation, while reducing damages and cost of dam and reservoir operation [1]. It can cope with basic elements of hydrological variability and changes in water demands. The reoperation of dam and reservoir system can help improve the efficiency of existing water uses [2]. It can also increase water related benefits for the ecological and social perspectives [3]. In general, enhancing the performance of current reservoir operation can be achieved through the construction of new water facilities, physical modifications as well as applications of innovative and integrative management approaches [1–2]. It is the fact that the performances of dam and reservoir operation system are significantly affected by the climate change [4]. Evaluating the prospective performance of reservoir reoperation system and analyzing its risk under the current and future climate changes have become a crucial task for sustainable reservoir management.

Accordingly, this study aims to assess the performance of reservoir reoperation through the adapted rule curve and hedging policies of the Bhumibol (BB) dam. The in–depth investigations of current reservoir operation and reoperation were conducted to explore the operational performance under existing conditions and future climate changes. Bhumibol dam is a major dam built across the Ping River in the northern elevated plain of Thailand as shown in Figure 1. Bhumibol dam is the principal source of water supply in the Greater Chao Phraya River Basin (GCPYRB) which has jointly operated with Sirikit (SK) and Khwae Noi Bumrung Dan (KBD) dams to supply water for national domestic, agricultural, industrial uses, power generation, as well as the ecological needs downstream. Since floods and droughts have frequently occurred in this region, the weakness of existing operations of these major reservoirs was reported and criticized publicly to state a lesson learned. Consequently, reoperating BB and SK dams with the adapted rule curve has been carried out since 2012 to reduce flood and drought risks in the region. Moreover, management framework between the Electricity Generating Authority of Thailand (EGAT) and the Royal Irrigation Department (RID), which are a key institutional actor for dam operation, has been outlined to bring down the long–term risks of water resources mismanagement in GCPYRB.

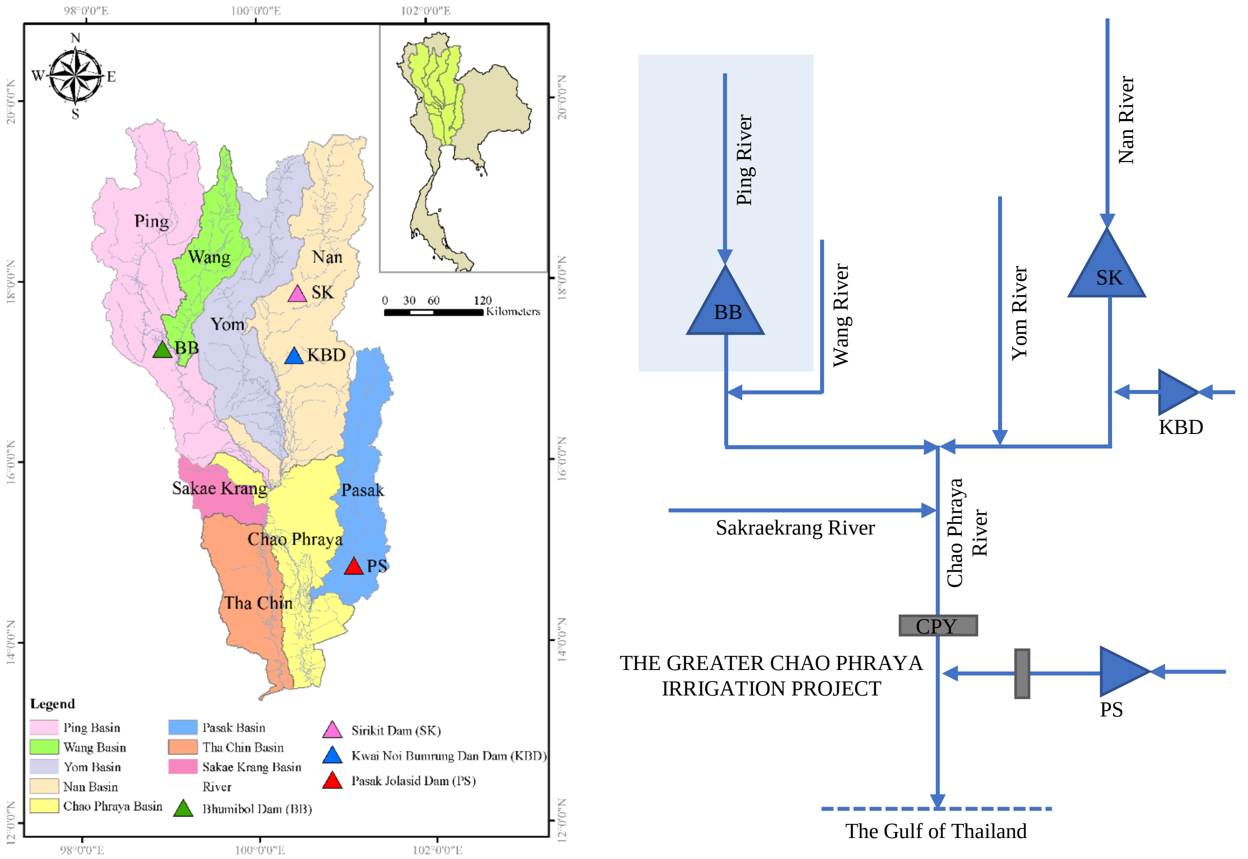

Figure 1 Bhumibol Dam in the Greater Chao Phraya River Basin (GCPYRB)

METHODOLOGY

Firstly, the projection of reservoir inflow of BB dam was implemented through the platform of MIKE11 Zero. MIKE11 RR NAM Model and MIKE11 HD, the lumped model, were applied for rainfall–runoff simulation into Ping River Basin. Prediction of rainfall and evaporation under climate change scenarios was based on the simulation of EC–EARTH under RCP4.5 scenario regionally downscaled by RegCM4 with 25 km x 25 km grid size over the study area [5]. The projected inflow of BB dam was then generated for five periods namely, 2000–2020 (baseline), 2021–2040, 2041–2060, 2061–2080 and 2081–2099. However, the baseline period was only used for this study. Secondly, the water balance–based reservoir reoperation model was developed using MATLAB Simulink Toolbox, as typically shown in Figure 2 and Figure 3. Two operating policies: (1) adapted rule curve which was modified from the rule curve developed in 2012 and (2) hedging policy, were used to reoperate dam and reservoir system. The long–term simulation based upon the relevant reservoir data were then performed during 2002–2018 under current and future inflows. Determination of water demand for BB dam was referred to annual plan of water allocation to reach all the water use sectors in GCPYRB, which was established by RID and EGAT. Water supplied to the target demand nodes was shared by BB and SK dams in the proportion of 0.44:0.56. In the final step, the potential in increasing the reservoir water storage under current operation and operational performances in terms of reliability, vulnerability, and resiliency were investigated.

1. Adapted rule curve–based reservoir reoperation model

The reservoir rule curve is regarded as the common tool to provide useful guidance for the release decision. In this study, the adapted rule curve–based reservoir reoperation model for BB dam was established based upon the existing rule curve developed in 2012 by EGAT. To execute the reservoir reoperation practice, four main scenarios of adapted rule curve was generated by increasing and lowering the levels of upper rule curve (URC) and lower rule curve (LRC) of ±0.5 m from existing rule curve in 2012. The operating policies were set up in accordance with the standard operating policy (SOP) aiming to reach water demand if possible. The water release from the reservoir is considered as the same amount of target demand when the reservoir storage is between LRC and URC. However, the water can only be released with the minimum water requirement when the reservoir storage is lower than LRC. In case of reservoir storage is higher than URC, the reservoir water release is accordingly based on conditions of surplus water and maximum turbine discharge of the hydropower system. All amount of the water storage is specified as a spilled water when the water level is above normal high water level (NHWL). Moreover, the reservoir water could not be released in case of the reservoir storage is lower than minimum pool level (MPL).

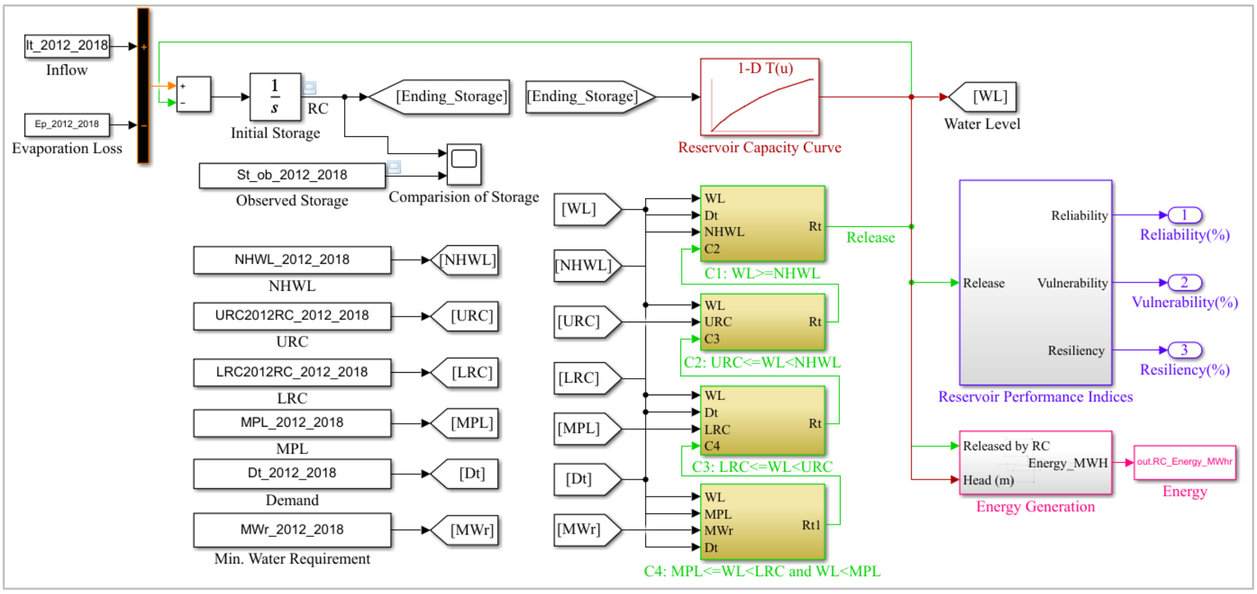

Figure 2 The Water Balance–Based Reservoir Reoperation Model Using Adapted Rule Curve

2. Hedging policy–based reservoir reoperation model

The hedging policy–based reservoir reoperation model was also applied by aiming to reduce the risk of water shortage particularly for the extreme drought conditions. Hedging policy is commonly used for rationing operation to flatten the fluctuation of water deficit by providing portion of reservoir yield in advance [6–7]. In this study, various hedging policies: one–point, two–point, three–point and zone–based were investigated to examine the various operational conditions and to preserve reservoir water for later use in the current and future periods. Determination of water release by hedging during refilled and drawdown operation periods was considerably referred to the operating policies adopted for adapted rule curve. During normal operation periods, the release rules of BB dam were specified according to the specific parameters of each hedging as follows:

i. One–point hedging: four target levels of reservoir release were set up; MPL, 1P–1, 0.95RC, and NHWL, representing the minimum pool level, 40% and 95% of the reservoir capacity and normal high water level, respectively. When the resevoir water level is between MPL and 1P–1, the water is released as a linear portion of target demand. The water release is specified as the same amount of the target demand if the water level is between 1P–1 and 0.95RC.
ii. Two–point hedging: five target levels of reservoir release were identified; MPL, 2P–2, 2P–1, 0.95RC, and NHWL, representing the minimum pool level, 30%, 40% and 95% of the reservoir capacity and normal high water level, respectively. When the resevoir water level lies between MPL and 2P–1 or between 2P–1 and 2P–2, the water release is specified as a linear portion of target demand relating with their corresponding water level.
iii. Three–point hedging: six target levels of reservoir release were identified; MPL, 3P–3, 3P–2, 3P–1, 0.95RC, and NHWL, representing the minimum pool level, 20%, 30%, 40% and 95% of the reservoir capacity and normal high water level, respectively. When the resevoir water level lies between MPL and 3P–3, or between 3P–2 and 3P–1, the water release is specified as a linear portion of target demand relating with its corresponding water level. The water release is specified as the same amount of the target demand if the storage water level is between 3P–1 and 0.95RC.
iv. Zone–based hedging: the discrete proportions of target release for differennt zonal levels were identified; MPL, Z–3, Z–2, Z–1, 0.95RC, and NHWL, representing the minimum pool level, 25%, 50%, 75% and 95% of the reservoir capacity and normal high water level, respectively. The water release is specified as 70% of target demand when the resevoir water level is between MPL and Z–3. In addition, 80% and 90% of target demand are achieved when the reservoir water levels lie between Z–3 and Z–2, and between Z–2 and Z–1, respectively. The water release is specified as the same amount of the target demand if the storage water level is between 3P–1 and 0.95RC.

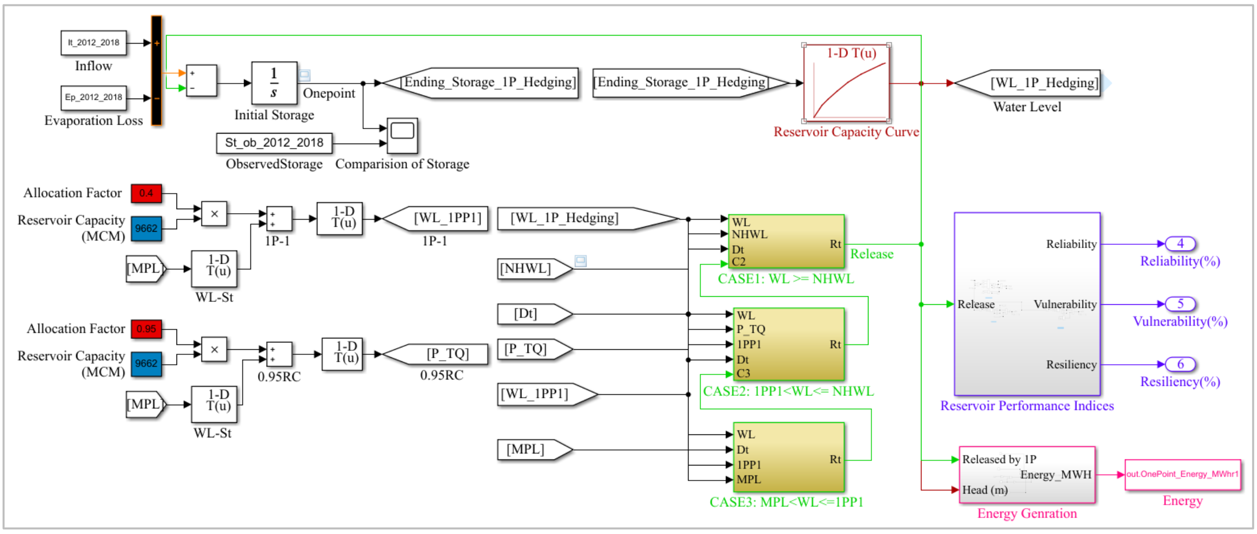

Figure 3 The Water Balance–Based Reservoir Reoperation Model Using Hedging Policies

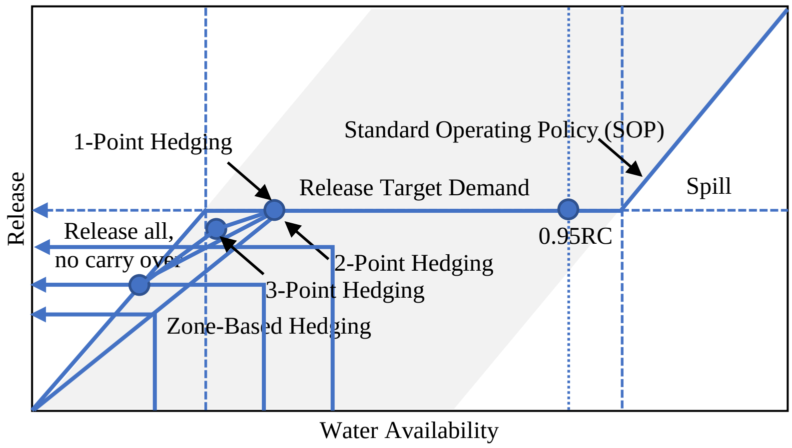

Figure 4 Standard Operating Policy and Hedging [6]

3. Reservoir Performance Indices (RPI)

A large number of Reservoir Performance Indices (RPI) have been introduced and applied to assess the performances of the reservoir operation system for more than a decade [8–9]. In this study, three famous reservoir performance indices were used namely; reliability, resiliency and vulnerability.

i. Reliability Index

The reliability index measures how much the system is accessible or the system performs unsatisfactorily within the simulation time periods [8–9]. It can be mathematically computed using the equation (1).

$$\text{Reliability (\%)} = \frac{\text{events that water demand are satisfied}}{\text{total events}} \text{x}100 \tag{1}$$

ii. Vulnerability Index

The vulnerability index describes the severity of deficit occurrence throughout the simulation time periods [8–9]. The expression of vulnerability is given in the equation (2).

$$\text{Vulnerability (\%)} = \frac{\text{total amount of water deficit}}{\text{total amount of target demand}} \text{x}100 \tag{2}$$

iii. Resiliency Index

The resiliency explains how long the system is likely to recover from the failure events to satisfied events [8–9]. Therefore, continuous consequences of unsatisfied events are counted over the entire simulation time periods and divided by the total unsatisfied events as expressed in the equation (3).

$$\text{Resiliency (\%)} = \frac{\text{continuous consequences of unsatisfied events}}{\text{total unsatisfied events}} \text{x}100 \tag{3}$$

RESULTS AND DISCUSSIONS

1. Influence of climate change on the reservoir inflow

For emphasis on the influence of climate change on the reservoir inflow of Bhumibol dam, the recorded inflow during 2000–2020 and projected inflow performed by MIKE11 were investigated and compared. It is found from record that the average annual inflow of the BB reservoir during 1969–2018 is approximately 5,694 MCM/yr. Due to the 2011 Thailand major flood [10], the annual inflow of BB dam was declined by 750 MCM/yr compared to the average inflow. More than 80% of the total inflow is contributed to BB dam in wet season (May–Oct) and the remaining is occurred in dry season (Nov–Apr). Table 1 and Figure 5 also indicate that the projected annual inflow into BB dam under RCP4.5 tends to be decreased predominantly. In comparison with the baseline period (2000–2020), RCP4.5 scenario indicates the increase in inflow in dry season (Nov–Apr) by +0.07%, +10.00%, +15.42% and +6.25% in 2021–2040, 2041–2060, 2061–2080 and 2081–2099, respectively. However, the results are generally converse in wet season (May–Oct) as the change are expected to be –10.44%, +9.60%, –13.01% and –2.63%. The results show considerable changes in the seasonal and annual patterns of reservoir inflow which are key factor influencing the complexity and effectiveness of reservoir management in both the current and future operations.

Table 1 The recorded and projected reservoir inflows of Bhumibol dam

Month	Recorded Inflow (MCM)	Projected Inflow under RCP4.5 (MCM)				
	1969–2018	2000–2020[1/]	2021–2040	2041–2060	2061–2080	2081–2099
Jan	132.20	117.25	116.49	125.56	127.85	130.11
Feb	59.08	71.31	69.96	75.19	72.42	73.30
Mar	38.02	60.30	55.07	65.30	140.95	55.70
Apr	48.12	56.24	81.80	72.12	76.07	65.92
May	247.46	227.58	328.21	403.26	281.83	264.96
Jun	317.08	425.75	288.30	657.90	356.29	465.86
Jul	379.35	428.09	378.96	414.31	342.98	428.75
Aug	923.49	726.06	584.56	707.69	672.31	651.17
Sep	1,504.04	1,351.93	1,185.17	1,420.61	1,061.18	1,342.31
Oct	1,209.42	1,264.98	1,197.26	1,245.40	1,134.31	1,154.85

Table 1 Cont'd

Month	Recorded Inflow (MCM)	Projected Inflow under RCP4.5 (MCM)				
	1969–2018	2000–2020[1/]	2021–2040	2041–2060	2061–2080	2081–2099
Nov	590.14	352.97	348.38	398.26	359.56	385.30
Dec	245.24	197.31	184.27	204.51	210.40	198.50
Annual Δ%	5,693.64	5,279.77	4,818.43 (–8.74)	5,790.10 (+9.67)	4,836.15 (–8.40)	5,216.72 (–1.19)
Dry Season Δ%	1,112.80	855.37	855.99 (+0.07)	940.93 (+10.00)	987.26 (+15.42)	908.83 (+6.25)
Wet Season Δ%	4,580.84	4,424.40	3,962.44 (–10.44)	4,849.17 (+9.60)	3,848.89 (–13.01)	4,307.89 (–2.63)

Remark: [1/] the baseline period

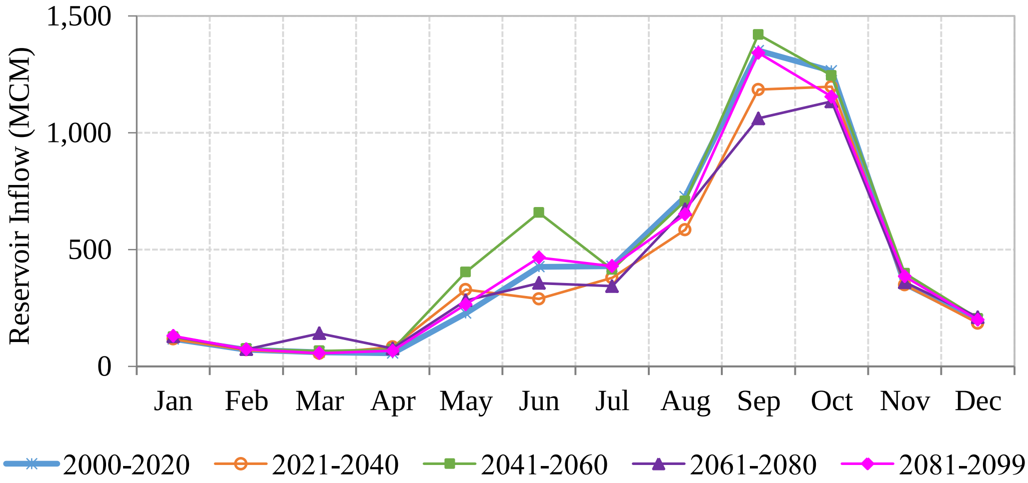

Figure 5 Changes in Monthly and Seasonal Projected Inflows of BB Dam

2. Reservoir reoperation performances performed by adapted rule curve and hedging policies

The reservoir reoperation performances of Bhumibol dam in term of the potential in increasing reservoir water storage during 2012–2018 are summarized in Table 2. In comparison with the simulation results obtained by RC2012, it is found that raising URC of +0.5 m cannot help to increase the reservoir water storage in both wet and dry seasons. Conversely, lowering URC of –0.5 m can cause the reduction in reservoir water storage as a result of the standard operating rules employed during the refilled period. Adjusting LRC of ±0.5 m can deliver the positive results in a way of retaining water at the specific time periods for later use. However, percentage increase in water storage after reoperating with all scenarios of adapted rule curve are not much deviated in comparison with the observed results. Applying two–point, three–point, and zone–based hedging for reservoir reoperations exhibit high potential to significantly increase reservoir water storage in dry and wet seasons. This might be because these types of hedging provide significant parameters to help reduce amount of excessive water during refilled periods except one–point hedging. Therefore, water storage in reservoir is high over a year.

The operational performances in terms of average annual release and annual power production were also investigated among all scenarios of adapted rule curve and hedging. Under the current operation, the average annual releases and power production of BB dam performed by various scenarios of adapted rule curves are approximately 4,333 MCM/yr and 908 GW–hr, respectively which are really close to that obtained by RC2012 and observed values. Average annual releases performed by hedging are likely decreased with the average of 3,965 MCM/yr meanwhile the power generation is approximately 909 GW–hr. Under the impact of climate change on reservoir inflow, amount of dam release and power production tends to be increased to supply water especially in dry season.

Table 2 Potential in increasing reservoir water storage during 2012–2018

Simulation Results	Increase in Water Storage (%Active Storage)			
	November	Dry Season	Wet Season	Annual
RC2012	–0.20	+1.78	+1.05	+1.37
+0.5 m. URC2012	–0.20 (0.00)[1/]	+1.78 (0.00)[1/]	+1.05 (0.00)[1/]	+1.37 (0.00)[1/]
–0.5 m. URC2012	–0.35 (–0.14)[1/]	+1.58 (–0.20)[1/]	+0.18 (–0.18)[1/]	+1.19 (–0.19)[1/]
+0.5 m. LRC2012	–0.14 (+0.06)[1/]	+1.86 (+0.08)[1/]	+1.10 (+0.05)[1/]	+1.44 (+0.07)[1/]
–0.5 m. LRC2012	–0.17 (+0.03)[1/]	+1.82 (+0.04)[1/]	+1.09 (+0.04)[1/]	+1.41 (+0.04)[1/]
One–Point Hedging	–6.93 (–6.73)[1/]	–6.95 (–8.73)[1/]	–5.47 (–6.51)[1/]	–6.14 (–7.51)[1/]
Two–Point Hedging	+29.20 (+29.41)[1/]	+39.69 (+37.92)[1/]	+29.63 (+28.59)[1/]	+34.18 (+32.80)[1/]
Three–Point Hedging	+19.80 (+20.00)[1/]	+27.70 (+25.92)[1/]	+20.27 (+19.23)[1/]	+23.63 (+22.26)[1/]
Zone–Based Hedging	+31.55 (+31.75)[1/]	+44.36 (+42.58)[1/]	+32.82 (+31.77)[1/]	+38.03 (+36.65)[1/]

Remark: [1/] the different values compared with using rule curve developed in 2012

The reservoir performance indices in terms of reliability, vulnerability, and resiliency indices were also assessed, as shown in Figure 6. For the current case simulating with observed inflow, even hedging policy provides good results in raising water storage in reservoir. However, the reliability index describing the capability of a system to satisfy target water demand is much lower than those scenarios performed by adapted rule curve. Likely, the vulnerability index measuring the severity level of unsatisfactory operation is relatively higher when all scenarios of hedging policies were performed (except one–point hedging). Likewise, the lower possibility to recover the operational system into satisfactory operation can be found in a form of resiliency index when all scenarios of hedging policies were performed (except one–point hedging). For the future case simulating with the projected inflow, all the performance indices signify level of incapability of dam operation system in meeting target water demand worse than current case. This might be because volume of annual projected inflow of BB dam is likely decreased.

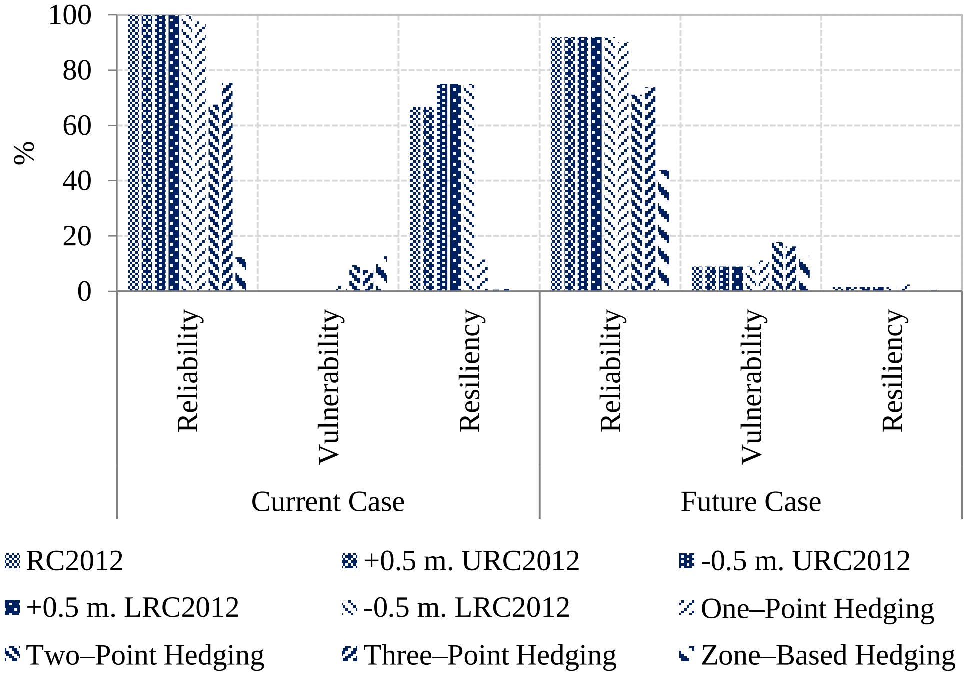

Figure 6 Reservoir Performance in Current and Future Cases

CONCLUSION

The climate change has obviously influenced on the seasonal and annual variability of reservoir inflow to the Bhumibol dam since the central Thailand faced the severe flood in 2011. The adaptation measure through the forecast–based reservoir reoperation has been accordingly suggested to reduce the persistence of disaster risk and enhance water supply reliability. Reoperating the Bhumibol dam with adapted rule curve and hedging as well as modelling exercise to generate series of reservoir inflow representing an anticipation of future climate change was conducted in this study. The simulation results imply that altering the operating policy for reservoir reoperation with various scenarios of adapted rule curve and hedging might not reach all views of operation performance. However, optimal reoperation with optimization approach can be one of a good alternative in maximizing the multiple benefit of dam and reservoir system.

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