Impact assessment of reservoir operation in the context of climate change adaptation in the Chao Phraya River basin

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Abstract
Climate change adaptation has become the current focus of research due to the remarkable potential of climate change to alter the spatial and temporal distribution of global water availability. Although reservoir operation is a potential adaptation option, earlier studies explicitly demonstrated only its historical quantitative effects. Therefore, this article evaluated the possibility of reservoir operation from an adaptation viewpoint for regulating the future flow using the H08 global hydrological model with the Chao Phraya River basin as a case study. This basin is the largest river system in Thailand and has often been affected by extreme weather challenges in the past. Future climate scenarios were constructed from the bias-corrected outputs of three general circulation models from 2080 to 2099 under RCP4.5 and RCP8.5. The important conclusions that can be drawn from this study are as follows: (i) the operation of existing and hypothetical (i.e., construction under planning) reservoirs cannot reduce the future high flows below the channel carrying capacity, although it can increase low flows in the basin. This indicates that changes in the magnitude of future high flow due to climate change are likely to be larger than those achieved by reservoir operation and there is a need for other adaptation options. (ii) A combination of reservoir operation and afforestation was considered as an adaptation strategy, but the magnitude of the discharge reduction in the wet season was still smaller than the increase caused by warming. This further signifies the necessity of combining other structural, as well as non-structural, measures. Overall, this adaptation approach for assessing the effect of reservoir operation in reducing the climate change impacts using H08 model can be applied not only in the study area but also in other places where climate change signals are robust.

Keywords
adaptation measures, afforestation, H08 global hydrological model, hypothetical reservoir, Nakhon Sawan, regional scale, Southeast Asia, Thailand
Climate change has the potential to imperil global water resources by altering their availability in every part of the world, which would have a great impact on human society and its normal life (IPCC, 2014a, 2018; Lehner, Döll, Alcamo, Henrichs, & Kaspar, 2006). Climate change may also intensify or change the frequency of extreme hydrological events, such as floods and droughts, which will put additional pressure on future water resources (Chun, Wheater, & Onof, 2013; D’Oria, Ferraresi, & Tanda, 2019; Easterling et al., 2000; Hribayashi et al., 2013; Mora et al., 2018; Piniewski, Szczesniak, Kundzewicz, Mezghani, & Hov, 2017; Schewe et al., 2014). This highlights the significance of impact studies related to such extreme events for developing suitable adaptation strategies under a warming climate (Gädeke, Hözel, Koch, Pohle, & Grünewald, 2014). Strengthening the capacity to adapt to climate-related hazards is one of the proposed sustainable development goals of the United Nations (UN, 2019), and adaptation has emanated as the focus of climate change research in country-level planning (IPCC, 2014a).

Adaptation strategies are place- and context-specific and no single approach can reduce the climate change risk across all settings (IPCC, 2014a). Effective adaptation strategies are a combination of structural and non-structural measures (UNECE, 2009). Among the different adaptation strategies in water sector, the reservoir operation can be an influential driver to tackle the effect of climate change (Lauri et al., 2012). Reservoirs partly mitigate the seasonal differences in water resources by storing surplus water during the wet season and releasing the same during the dry season to address flood and drought problems (Biemans et al., 2011). They progressively control regional and even continental-scale hydrology, although they are cost-intensive infrastructure (Ehsani, Vörösmarty, Fekete, & Stakhiv, 2017). Hence, hydrological models (HM’s) representing reservoir operations are necessary to evaluate the adaptation potential of dams (Masaki et al., 2017). However, such representation in HM’s is limited due to the complexity of reservoir operations and lack of data, and the adaptation potential of dams remains largely unexplored.

Despite this fact, the effect of reservoir operation has been recognized and demonstrated by several regional and global HM’s (RHM’s and GHM’s) in the past. Subsequently, these models were utilized to carry out the impact assessment of reservoir operations on future river flow. For instance, Lauri et al. (2012) analysed the cumulative impact of climate change and reservoir operation in the Mekong River using the VMod RHM and concluded that the impact of the reservoir operations, both existing and planned, would be larger than the effect of climate change during the dry and wet seasons. The focus of interest of some studies was the assessment of the future water supply from the existing storage capacity to meet the growing water demand under a reduced precipitation climate scenario using the RHM’s of (i) Hydrologiska Byrån’s Vattenbalansavdelning (HBV) in the Lower Zab River (one of the main streams of the Tigris River), north-east Iraq (Mohammed & Scholz, 2017), (ii) Poly-Hydro in the Dez and Sufichai River basins, Iran (Akbari-Alashki et al., 2018), and (iii) GR4J in different Australian catchments (Nguyen, Mehrrotra, & Sharma, 2020). Their results provided evidence of potentially decreasing water availability and an overall reduction in water supply capability to meet a given demand in the future.

Recently, the possibility of reservoir operation as an adaptation option towards future climate, by increasing the storage capacity and number of reservoirs, has been the focus of several studies. Biemans et al. (2013) investigated the future irrigation water availability using the LPJmL GHM with two proposed adaptation strategies of (i) an overall improvement in irrigation efficiency, and (ii) doubling the reservoir storage capacity in different Indian river basins under increased temperature scenario. They concluded that the reservoirs alone could not mitigate water scarcity issues, and a combination of both options seems to be the best strategy in all basins. Similar studies using RHM’s were also reported from South Italy (Guyennon, Salerno, Portoghese, & Romano, 2017) and northeast Portugal (Carvalho-Santos, Monteiro, Azevedo, Honrado, & Nunes, 2017), in which the increased storage capacity of reservoirs was inefficient for water supply management under increased future temperature conditions.

Instead of increasing the size and number of reservoirs, few studies optimized the operation rule curves of existing reservoirs to adapt to future drought (SSARR RHM; Eum & Simonovic, 2010), water allocation (VIC GHM; Liu et al., 2018), water supply (Hybrid wavelet-M5 model; Nourani, Rouzegari, Molajou, & Baghanam, 2020), etc. However, the use of optimized rule curves partly mitigated the climate change effects in terms of the water supply failure, irrigation water deficit, and drought damage. Concurrently, some studies evaluated the effect of changes in reservoir management criteria on climate change and found that the implemented adaptation strategies can significantly reduce the adverse effects of climate changes on the future water supply (Ashofteh, Rajaee, Golfam, & Chu, 2019; Tukimat & Harun, 2019). Among all, very few studies come up with adaptation strategies by the reservoirs that could solve the future drought and water supply problems completely, which further calls for the combined adaptation options. In fact, researchers have paid more attention to the water supply problems by changing the size/number as well as the operational rules of the reservoirs. The adaptation studies towards the future floods have been rarely reported (Ehsani et al., 2017), and there is a need for the same to reduce the associated risk.

The IPCC (2014b) noted a general lack of case studies on adaptation to climate change that consider local characteristics, particularly for middle-income and developing countries recognized as vulnerable. A study conducted by Asian Development Bank (ADB, 2009) on the economic impacts of climate change in Southeast Asia revealed that this region is projected to suffer more from climate change than the global average. Thailand is the second-largest economy in Southeast Asia and the country incurred an economic loss of more than USD 1.75 billion during the period 1989–2002 as a result of floods, storms, and droughts (ADB, 2009). In 2011, there was an enormous estimated loss of USD 46.5 billion due to a massive flood in the Chao Phraya River basin (CPRB), the largest basin in Thailand (Komori et al., 2012; World Bank, 2012). Flooding occurs every year in the CPRB, but that of 2011 caused unusually severe damage. It has also been found that...
the basin is one of the most affected, flood-prone basins in Thailand due to a changing climate scenario (Kotsuki, Tanaka, & Watanabe, 2014; Kure & Tebakari, 2012; Watanabe et al., 2014). On the contrary, a decrease in river discharge has also been projected in the basin during the dry season (Champathong et al., 2013; Hunukumbura & Tachikawa, 2012; IPCC, 2014b).

Several studies have been carried out in the CPRB to evaluate the impact of either climate change or reservoir operation on river discharge (Apichitchat & Jung, 2015; Komori et al., 2012; Mateo et al., 2014; Tebakari, Yoshitani, & Suvanpimol, 2012; Wichakul, Tachikawa, Shiiba, & Yorozu, 2013; Zenkoji, Tebakari, & Dotani, 2019). Nevertheless, the river flow in the CPRB is highly regulated by large reservoirs, and thus river flow projection studies need to incorporate these reservoir operations into hydrologic simulation modelling. Although Wichakul, Tachikawa, Shiiba, and Yorozu (2015) considered the effect of two existing reservoirs on future flows of the CPRB to analyse changes in drought and flood risk, they did not consider reservoir operation as an adaptation measure that is essential in supporting policy decision making (Wilby et al., 2009). Hence, currently, it is not known whether the existing reservoir system is prepared for climate change impacts in the CPRB. Therefore, impact assessment studies of future water resources together with potential adaptation strategies are needed not only for the CPRB but also for other regions with similar hydroclimate characteristics. Such assessment can decide whether the storage capacity of existing reservoirs is enough or further enhancement is required to buffer the future water resources variability by incorporating human activities such as reservoir operation, which has been barely reported.

Moreover, the choice of the hydrologic model has a large effect on the future projections of streamflow and the associated portrayal of climate change impacts (Hagemann et al., 2013). Although the RHM’s have widely used for the impact assessment of reservoir operations with a high spatial and temporal resolution, they have many parameters that need to be calibrated or estimated regionally (Sood & Smakhtin, 2015), which makes their global application computationally intensive. Conversely, the GHM’s are progressing towards hyper-resolution in providing a better process understanding, and they become non-separable from the RHM’s in the coming decades. Among the different GHM’s, the H08 water resources model is one of the pioneering models made up of six modules that explicitly considered reservoir operations (Hanasaki et al., 2008a; Hanasaki, Yoshikawa, Pokhrel, & Kanae, 2018a). It can be easily integrated with other distributed river routing models (Mateo et al., 2014). The model has been validated and tested for global and regional applications: for example, river discharge (Hanasaki et al., 2008b; Masood, Yeh, Hanasaki, & Takeuchi, 2015), reservoir operation (Mateo et al., 2014), climate change-based adaptation studies (Okada et al., 2015; Zhou, Hanasaki, Fujimori, Yoshimitsu, & Hijikoka, 2018), etc. The model has recently been applied to study the global water withdrawal and availability (Hanasaki et al., 2018a; Hanasaki, Yoshikawa, Pokhrel, & Kanae, 2018b).

To the best of author’s knowledge, only a few studies have investigated the ability of reservoir operations as adaptation strategies to regulate the flow under a changing climate. Therefore, this study performed a spatially explicit impact assessment of reservoir operation on future river discharge with adaptation strategies using the CPRB as a case study by employing the H08 global hydrological model. This study will answer the following key questions:

1. Are the existing reservoirs sufficient to tackle the effect of climate change?
2. Would a hypothetical (construction under planning) reservoir be able to cope with the effect of climate change together with existing reservoirs?
3. Would the reservoir operation act as an effective potential adaptation strategy to mitigate the impacts of climate change?
4. What would be the combined effect of reservoir operation and afforestation in mitigating the impact of climate change?

2 | MATERIAL AND METHODS

2.1 | Study area

As mentioned, the CPRB (Figure 1) is the largest river basin in Thailand, covering an area of around 158,000 km², accounting for approximately 35% of the country’s area. The CPRB hosts 40% of the country’s population, generates 66% of the gross domestic product, and it encompasses the Bangkok City at the Chao Phraya River delta which is Thailand’s political, commercial, industrial, and cultural hub (Bond, Cross, Glotzbach, & Richaud, 2018). It is divided into an upper and a lower basin at Nakhon Sawan, C.2 station in Figure 1 (Komori et al., 2012). The upper basin consists of four principal tributaries, the Ping (catchment area: 36,018 km²), Wang (catchment area: 11,708 km²), Yom (catchment area: 24,720 km²), and Nan (catchment area: 34,557 km²) Rivers, all originating from the northern mountainous area. The Wang and Yom Rivers join the Ping and Nan Rivers, respectively, and the confluence of the Ping and Nan Rivers at Nakhon Sawan is the beginning of the Chao Phraya River. From Nakhon Sawan, the river flows to the lower basin through Ayutthaya and Bangkok, and finally empties into the Gulf of Thailand (Tebakari et al., 2012). Other tributaries, the Pasak and Sakae Krang Rivers, join the Chao Phraya River in the lower basin. The lower basin, as well as the downstream parts of the Yom and Nan River basins, is gently sloping, which makes the region highly prone to flooding (Komori et al., 2012). At the same time, the region has experienced frequent droughts in the past decade due to rapid economic development and a subsequent increase in water demand (ONWRC of Thailand Working Group, 2003).

The CPRB region has a tropical monsoon climate. The annual average rainfall in the basin is between 1000 and 1400 mm, of which 85% is received between April and October (JICA, 2013). The upper and lower basins of the CPRB have six and two major multi-purpose reservoirs, respectively, to manage irrigation, water supply, flood and drought risk, etc. Figure 2 shows the locations of the main hydrological observation stations and reservoirs in the CPRB. The operation of
some of these reservoirs (Bhumibol and Sirikit) reduced the flood risk in the past by storing precipitation in the wet season and making it available in the subsequent dry season (Tebakari et al., 2012).

2.2 | H08 model

To quantify natural as well as anthropogenic water availability and use in the past, present, and future, several GHMs have been developed. Among the different GHMs, the model used in this study is the H08, an integrated global water resources model that consists of six modules: land surface hydrology, river routing, reservoir operation, crop growth, environmental flow requirement estimation, and anthropogenic water withdrawal (Hanasaki et al., 2008a). The model simulates both natural and anthropogenic water flow globally at a spatial resolution of 0.5° × 0.5° on a daily basis (Hanasaki et al., 2018a). Each module can run separately, while there is a coupled module to run all the processes in an integrated manner. For a detailed description of the H08 model, see Supporting Information S1 and visit at https://h08.nies.go.jp/h08/index.html.

Among the six modules of the H08 model, the first three listed above were considered in this study to evaluate the effect of reservoir operation alone on river flow. The remaining modules, including the one for anthropogenic water withdrawal, were disabled. Additionally, some adjustments were made to the global setup of the H08 model, to include region-specific information. Firstly, instead of the global parameters, the key parameters of the land surface hydrology module were derived for the CPRB region from a previous study conducted by Mateo et al. (2014), in which the parameters were calibrated at Nakhon Sawan. These land-surface parameters and their values are listed in Table S1. Secondly, simulations were conducted at a finer spatial resolution of 5’ × 5’ on a longitudinal and latitudinal grid in a domain of 97°E–102°E and 13°N–20°N. Lastly, the generic operation rules of reservoirs in the global setup were improved by including the processes in an integrated manner. For a detailed description of the H08 model, see Supporting Information S1 and visit at https://h08.nies.go.jp/h08/index.html.

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release rates for the wet and dry seasons and upper rule curve based on the observed historical operation of reservoirs in the CPRB. This upgraded reservoir operation model can be implemented easily for elsewhere in the world and its detailed information is available in Mateo et al. (2014).

2.3 | Reservoir operation

The modelling approach used in this study to simulate reservoir operation was the improved version of the generic operation rules of reservoirs in the global setup algorithm (Hanasaki, Kanae, & Oki, 2006;
Mateo et al., 2014). This improved algorithm incorporates the wet and dry season releases and upper rule curves representing the historical reservoir operation rules specific to each reservoir in the H08 model. Mateo et al. (2014) considered the seasonal and interannual variability of the river inflow into the two reservoirs of Bhumibol and Sirikit by utilizing the observed reservoir operation data obtained from the Royal Irrigation Department (RID) and the Electricity Generating Authority of Thailand (EGAT). The algorithm also sets storage targets based on the reservoir storage guide curve so that the empty space in a reservoir is proportional to the expected inflows during the wet season.

Apart from Bhumibol and Sirikit reservoirs, in the present study, the algorithm of the reservoir operation module in the H08 model was modified to incorporate another six existing large-scale reservoirs (a total of eight existing reservoirs) of the CPRB because of increasing concern about their considerable cumulative effects. The detailed information of these reservoirs is given in Table S3 and their locations in the basin are shown in Figure 2. To maintain the seasonal variability of reservoir release in the H08 model, we set dry and wet season releases from each reservoir based on their historical means, which was necessary to simulate the high flows during the wet season (May–December) and the water demand during the dry season (January–April). However, these seasonal releases need to be corrected based on the simulated inflow because the simulated inflow to the reservoir may be biased compared to the observed inflow. Taking these factors into account, finally, we calculated the dry and wet season releases from each reservoir (Table S4) using a bias-corrected release equation (Supporting Information S1.3). Furthermore, storage targets were set to control the water storage in each reservoir based on their upper and lower storage guide curves, derived from historical data. The reservoirs could release constantly until the storage exceeds the storage capacity or the available volume of stored water is insufficient. However, in reality, the reservoirs can become depleted or full based on rainfall availability. In such cases, the release was forced to decrease or increase in such a way that it would be equal to the inflow when the storage was depleted, and that overflowing water was added to the release when the storage was higher than the reservoir capacity. Consequently, this study evaluated the effect of four adaptation options, three reservoir operation simulation scenarios, and a combined reservoir operation and afforestation scenario to devise an adaptation portfolio for the selected study area. The selected adaptation options are as follows:

i. The effect of all the existing reservoirs in the CPRB on mitigating the impacts of climate change, under the assumption that they will be operating at the end of the century.

ii. The additional effect of a hypothetical reservoir located in the upper reaches of the Yom River. The Kaeng Sue Ten (KST) reservoir, which has been under debate for a long time, and has not been built yet due to CPRB inhabitants’ protests. Therefore, this reservoir was considered as a hypothetical one and we evaluated whether its implementation could reduce future flood damage along the lower reaches of the Yom River and at Nakhon Sawan station, where flooding is a regular issue due to the gentle slope.

iii. Doubling the storage capacity of the existing and hypothetical reservoirs. The river discharge in the CPRB is highly variable due to heavy precipitation and creating extra space to accommodate the increased flood volume may offset water scarcity in the dry season and flood risk in the wet season. An enhancement of storage capacity can be achieved by several ways such as desiltation, remobilising a significant portion of the unused storage volume, raising the dam body, etc.; however, to what extent in the future is unknown. Therefore, an extreme condition of doubling the storage capacity was used to estimate the maximum level of adaptation achievable from the reservoir operation. However, in reality, this reservoir operation scenario would be extremely difficult to attain.

iv. Evaluating the combined effect of reservoir operation and afforestation under changing climate scenarios. For this purpose, the relative effect of three afforestation cases was extracted from Takata and Hanasaki (2020) for the future annual, wet, and dry season discharge at C.2 station, rather than simulating its effect using the H08 model, because their study used the same general circulation models (GCMs) under the same representative concentration pathway (RCP) scenarios as our study. The considered afforestation cases were, (i) case 1–20% afforestation (corresponds to the land use map of 1970), (ii) case 2–100% afforestation (corresponds to the land use map of 1950), and (iii) case 3–100% afforestation with modified soil properties (modified soil parameters to better represent the formation of litter layer in forest land use). Further, the extracted values of afforestation effects (the ratio of changes in discharge due to afforestation cases to the changes due to climate change) were combined with the respective simulated rates achieved from reservoir operation as follows: (i) case 1—existing reservoirs + 20% afforestation, (ii) case 2—existing and hypothetical reservoirs + 100% afforestation, and (iii) case 3—doubling the capacity of existing and hypothetical reservoirs + 100% afforestation along with modified soil properties.

3 | SIMULATION SCENARIOS AND DATA USED

3.1 | Adaptation scenarios

The river flow in the CPRB is highly regulated by large reservoirs. However, the projected increase in river runoff towards the end of the 21st century is high compared to the capacities of the Bhumibol and Sirikit reservoirs (Kotsuki et al., 2014). Therefore, it is necessary to evaluate different reservoir operation options as adaptation scenarios, which will confirm whether the reservoir operation alone could mitigate the climate change impacts or there is a need for other adaptation options in the late future.
### Table 1

The different simulations carried out with and without reservoir operation

| Period       | Simulation | Reservoir operation | Warming scenario |
|--------------|------------|---------------------|------------------|
| 1980–2004    | Historical-NR | No reservoir (NR)   | –                |
|              | Historical-WR | 8 reservoirs (ER)   | –                |
|              |              | 9 reservoirs (EHR)  | –                |
|              |              | Doubled capacity (2EHR) | –               |
| 2080–2099    | Future-NR   | No reservoir (NR)   | RCP4.5 (3GCM)    |
|              | Future-WR   | 8 reservoirs (ER)   | RCP8.5 (3GCM)    |
|              |              | 9 reservoirs (EHR)  |                  |
|              |              | Doubled capacity (2EHR) |              |

Abbreviations: EHR, existing & hypothetical reservoirs; ER, existing reservoir; HR, hypothetical reservoir; NR, no reservoir operation; WR, with reservoir operation.

### 3.2 Simulations

In this paper, all the simulation experiments were conducted for two periods: (i) from 1980 to 2004, the historical simulation; and (ii) from 2080 to 2099, the future simulation. Previous studies conducted in the CPRB concluded that a higher global mean temperature would cause higher precipitation in the basin and the projected runoff will be higher in the late future compared with the near-future climate (Kotsuki et al., 2014; Kure & Tebakari, 2012). Therefore, to analyse the effect of reservoir operation under the extreme climate change conditions, the future scenario was selected between 2080 and 2099 with an assumption that the existing reservoirs will be operating at the end of the century. Under each period simulations, two types of discharge simulations were also conducted: (i) naturalized discharge, where the reservoir operation module was disabled; and (ii) regulated discharge, where the reservoir operation module was enabled.

The historical simulation with no reservoir (Historical-NR) was considered as the base simulation without any human interventions (Table 1). Further, the effect of different reservoirs’ operations on historical discharge data was evaluated, termed “Historical-WR” in Table 1. The different reservoir simulation scenarios considered were the effects of (1) existing reservoirs (ER), (2) existing reservoirs combined with a hypothetical reservoir (EHR), and (3) doubling the storage capacity of the reservoirs (2EHR) in scenario (2). Like the historical simulation, future simulations (Future-NR and Future-WR) were conducted to evaluate the efficacy of reservoir operation in future flow mitigation as an adaptation strategy under two warming scenarios, RCP4.5 and 8.5. The equilibrium for each meteorological variable was achieved using spin-up calculations.

The effect of the existing reservoirs (ER) was analysed on the hydrological extremes of high and low flows (represented by the $Q_{10}$ and $Q_{25}$ indices, respectively) that were generated by the flow-duration analysis of the daily discharge data at C.2 and Bangkok stations. Bangkok is located near the river mouth as shown in Figure 2 and hence the effect of all dams, especially Thap Salao and Pasak, can be analysed at this location. The tidal effect was not included in the model simulation although it is not negligible in reality due to the proximity of Bangkok to the Gulf of Thailand. Further, the combined effect of existing and hypothetical reservoirs (EHR) was assessed on the annual maximum daily discharge values at C.2 and Y.6 stations due to the high flood risk of these locations. Lastly, adaptation potential of all the considered reservoir operation scenarios (ER, EHR, and 2EHR) was evaluated by computing the number of days in which the daily discharge values exceeded the flood-carrying capacity (threshold value) at C.2 and Y.6 stations during the simulation periods.

Model calibration and validation were conducted using the naturalized discharge between 1980 and 2004 (i.e., historical simulation) to evaluate the ability of the model to simulate the natural flow. The fit between the modelled and computed naturalized discharge was evaluated using the Nash-Sutcliffe Efficiency (NSE; Nash & Sutcliffe, 1970), coefficient of determination ($R^2$), and other error functions: the percentage error in volume (PEV), percentage error in peak discharge (PEP), and percentage error in time to peak discharge (PETP) (Padiyedath, Kawamura, Takasaki, Amaguchi, & Azhikodan, 2018). In addition, the efficacy of the H08 model in reproducing the regulated discharge was evaluated by incorporating the reservoir operation module.

### 3.3 Meteorological data

The historical climate dataset named IMPAC-T Forcing Data (Kotsuki et al., 2014) comprises seven meteorological forcing’s of temperature, specific humidity, short-wave radiation, long-wave radiation, atmospheric pressure, wind speed, and precipitation at a horizontal resolution of 5 arc minutes was used to perform the historical simulation. The precipitation data, which was measured at field gauging stations, was provided by the RID and the Thai Meteorological Department, from which the daily amount of precipitation was generated in the IMPAC-T Forcing Data. The climate dataset for the future simulation was derived from IMPAC-T Driving Data (Watanabe et al., 2014), which was bias-corrected in the GCM outputs from the Coupled Model Intercomparison Project—Phase 5 (CMIP5). Three GCMs of CSIRO-Mk3.6 (cs36), GFDL-ESM2M (ge2m), and MIROC5 (mir5) were selected under RCP4.5 and 8.5. To validate the H08 model, observed river discharge data was collected from the RID for different stations in the CPRB, as shown in Figure 1, for various periods based on availability (Supporting Information S2).
3.4 | Reservoir data

3.4.1 | Existing reservoirs

Existing reservoirs considerably influence the hydrology of Thailand. GRanD (Lehner et al., 2011) is one of the most extensive global dam databases and lists a total of 39 dams in Thailand. Among them, eight large-scale reservoirs in the Chao Phraya River system, with a storage capacity greater than 0.1 billion m³, has been used for the analysis. The Bhumibol and Sirikit are the two major reservoirs in the CPRB, with storage capacities greater than 1 billion m³ (Komori et al., 2012). One of the main functions of these two reservoirs is to generate power; however, the weekly water release from the two reservoirs is determined by the RID because they are also designed to supply irrigation water and carry-over the flow from the wet to the dry season to control flooding (Tebakari et al., 2012). The released water from the reservoir is further diverted to the irrigation canals from the river channel for water supply. However, in the H08 model, the seasonal releases were set in accordance with the actual historical reservoir operations. Therefore, the release from reservoirs implicitly included the seasonal variation of downstream water requirement, although the water withdrawal was not explicitly taken into account. Neglecting this water withdrawal in the H08 model may result in a slight overestimation of the discharge predicted at Nakhon Sawan station, downstream of the reservoirs. Another large-scale reservoir that is not included in the GRanD database is the Khwae Noi (storage capacity of 0.94 billion m³) in the Khwae Noi River, which joins with the Nan River. The construction of the dam was completed in 2008 and therefore it was not included in GRanD database for Thailand. The effect of the Khwae Noi dam was excluded from this study because our historical simulations covered 1980 to 2004 when construction of this dam had not been completed. Instead, in the historical and future simulations, we assessed the effect of a hypothetical reservoir with a similar storage capacity. The reservoir operation data of the eight existing reservoirs were obtained from the EGAT and RID.

3.4.2 | Hypothetical reservoir

The construction of new dams remains a matter of intense debate in Thailand, although they provide potential benefits in terms of water management in the basin. The government of Thailand has been considering a large dam project called the KST in the upper reaches of the Yom River since the 1980s to alleviate the seasonal water resource problems along the lower reaches of the Yom River, where flooding is regular due to its gentle slope (Apichitchat & Jung, 2015). In this study, the KST dam was considered as a hypothetical one and used interchangeably in the text. The planned location of the KST dam is 18°36’N and 100°09’E in the Song District of Phrae Province with a catchment area of 3538 km². The storage capacity of the proposed dam is 1175 million m³ (active storage capacity of 1125 million m³) and the spillway capacity is 5355 m³/s (Wichakul et al., 2013). However, the project has not been implemented to date, due to objections from inhabitants and non-governmental organizations. Consequently, the Yom River remains as the only tributary in the CPRB that has no major structures for flow regulation. In this study, the historical release scenario from the KST dam was decided by a trade-off between the historical observed and simulated discharge values at Y.20 station from 1980 to 2004 (25 years of data). The dam releases were set at 58 m³/s during the dry season (January–April) and at 29 m³/s during the wet season (May–December). The release scenarios were modified for the future simulations based on the simulated inflows at Y.20 station under RCP 4.5 and 8.5.

3.5 | River channel capacity at Y.6 and C.2 stations

In the Yom River basin, the Y.6 station is above the Sukhothai region and below the KST dam, as shown in Figure 2. The flood-carrying capacity of the Yom River at Sukhothai region is 550 m³/s. A flood diversion canal (the Klong Hok Baht canal) has already been implemented in this basin immediately after Y.6 station to divert flood flow to the Nan River, with a carrying capacity of 300 m³/s. The discharge from upstream to the Sukhothai region, as well as to the diversion canal, is largely regulated by the Ban Hatsapan Chan sluice gate. Therefore, the flow at Y.6 station must be limited to a threshold value of 850 m³/s, which eventually restricts the flow to the Sukhothai region to 550 m³/s.

Simultaneously, analysis of historical hydrological data has shown that the downstream flood risk increases drastically when the discharge at C.2 station is more than 3590 m³/s, resulting in huge economic losses in the lower CPRB (Jamrusri & Toda, 2017). Therefore, it is necessary to evaluate the effect of the KST dam in reducing the peak discharge below this threshold values at Y.6 and C.2 stations.

4 | RESULTS

The H08 model calibration and validation were carried out on the naturalized as well as the regulated discharge in the CPRB and the results are shown in Supporting Information S4.

4.1 | Effect of existing reservoirs to tackle the effect of climate change

4.1.1 | Effect on monthly mean flow

In the CPRB, climate change will significantly increase the monthly mean discharge during the wet season, whereas the dry season discharge showed little change. Figure 3a,b show the impact of climate change at C.2 station without reservoir operation. During the wet season, the computed monthly discharges from all the considered GCMs under RCP 4.5 showed a consistent increase, with an average peak discharge value of 2860 m³/s in September (an increase of 36%
compared with the historical peak discharge). A similar pattern was observed under RCP8.5, with a peak discharge value of 3420 m$^3$/s (an increase of 63%). The monthly mean discharge among the different GCMs showed large variations during the wet season, whereas a stable trend was noted during the dry season.

Further, the effect of existing reservoirs in reducing the impact of climate change was analysed as shown in Figure 3c.d. The dry season discharge was close to the historical simulation with reservoir operation in both RCP scenarios, while there was a clear increase in wet season discharge values. Reservoir operation reduced the average peak discharge values to 2130 and 2558 m$^3$/s under RCP4.5 and 8.5, respectively, a reduction of ~25% in both scenarios. However, the existing reservoir operations cannot completely mitigate future flooding resulting from climate change because the climate change effects are larger than the reservoir operation effects.

### 4.1.2 Effect on high and low flows

The potential of existing reservoir operations for mitigating the future high and low flows (represented by the $Q_{10}$ and $Q_{95}$ indices, respectively) was evaluated at C.2 and Bangkok stations (Figure 4). It can be seen that climate change increases the high flow at both stations, whereas the low flow is similar in the historical and future simulations with values below 20 m$^3$/s. Once operations of the existing reservoirs are considered, there is a considerable increase in low flow at both locations in both the historical and future scenarios. Reservoir operations reduced the magnitude of high flow at Nakhon Sawan (i.e., C.2 station) by 28% in the historical simulation, 27% in RCP4.5, and 23% in RCP8.5. Similar reductions in high flow rates were observed for Bangkok (i.e., B station), with values of 27%, 25%, and 21%, in the historical, RCP4.5, and RCP8.5 simulations, respectively.

The estimated contribution of each reservoir in reducing the high flows and improving the low flows at the two locations are also shown in Figure 4. The Bhumibol and Sirikit reservoirs contributed the most to flow regulation; the share of the four remaining large-scale reservoirs was less than 4% at the Nakhon Sawan station. Conversely, after the Bhumibol and Sirikit reservoirs, the Pasak reservoir dominated the remaining reservoirs in controlling the flow at the Bangkok station. Therefore, the flow regulation at Nakhon Sawan and Bangkok can be explained by the operation of the Bhumibol and Sirikit reservoirs, with the Pasak reservoir giving an additional contribution to Bangkok.

Further, to investigate the relevance and need of flow-controlling structures in each sub-basin, each tributaries’ contribution to the $Q_{10}$ and $Q_{95}$ values was computed at Nakhon Sawan with and without the operation of existing reservoirs, as shown in Figure 5. Without the operation of existing reservoirs, the Nan River is the highest contributor of high flow to Nakhon Sawan (around 42%) in the historical.
FIGURE 4  The Q_{10} and Q_{95} values at Nakhon Sawan (C.2) and Bangkok (B) stations. The left, middle, and right panels show the historical, future under RCP 4.5, and future under RCP 8.5 simulations respectively. The whole circle in Q_{10} and Q_{95} indices represents the discharge without reservoir operation and discharge with reservoir operation respectively (whole circle values shown inside the circle). “After all dam/no dam” legend shows Q_{10} values after the existing reservoir operation (after all dam) and Q_{95} values before the reservoir operation (no dam). “All dam” legend represents the amount of reduction in Q_{10} values from the reservoir operation. The remaining legends represent the contribution of each reservoir either in reducing the Q_{10} values or in improving the Q_{95} values.
simulation. The Nan River was followed by the Ping (26%) and the Yom (23%) Rivers, whereas the contribution from the Wang basin was less than 10%. During the future simulations, the contribution from Ping and Nan basins become nearly equal (around 34%). The contribution of Yom (21%) and Wang (9%) basins remained close to the historical simulation. On the contrary, the low flow contribution to Nakhon Sawan was relatively similar for all the four tributaries.

With the operation of the existing reservoirs, there was a notable reduction in the high flows coming from the Ping and Nan tributaries under all scenarios. The high flows from the Wang basin exhibited only a very slight reduction, whereas the Yom River contribution remained unchanged because there are no major flow-control structures in that basin. This further elucidates the urgent necessity of a dam in the Yom basin because its flood flow contribution to Nakhon Sawan is quite high compared with the Wang basin. This also explains the inadequacy of existing dams in the Wang basin for regulating the river flow at downstream points. Concurrently, the low flow at C.2 station was mainly from the Ping and Nan rivers, which further confirms the relevance of the Bhumibol and Sirikit reservoirs.

The river flow in the CPRB and its tributaries are dependent on the monsoon rains from May to October and are highly seasonal (World Water Assessment Programme, 2003). The Nan River exhibited the highest flow contribution although the Ping River has a slightly higher catchment area. This can be explained by the higher average annual runoff recorded in the Nan basin (432 mm) above Sirikit reservoir compared with that of in the Ping basin (215 mm) above Bhumibol reservoir (Zenkoji et al., 2019). The inadequacy of existing dams in the Wang basin is due to their relatively small storage capacity that is not effective as large capacity reservoirs in regulating extreme hydrologic flow variability. This confirms the results of Ehsani et al. (2017) that a single large dam may be more beneficial and effective than many small ones. Ehsani et al. (2017) also identified that there could be a further increase in the number of water storage infrastructures hosted by river networks in the near future due to their ability to ameliorate the impact of climate change, which was the case in the Yom basin.

4.2 Effect of hypothetical and existing reservoirs to tackle the effect of climate change

In this section, we analysed whether the considered hypothetical reservoir (the KST dam) can maintain the annual maximum daily discharge below the channel carrying capacity because the CPRB is most susceptible to floods based on the results from Section 4.1. Figure 6a, b show the annual maximum daily discharge values at Y.6 and C.2 stations, respectively, with and without reservoir operation. The KST dam operation failed to lower the peak discharge values below the channel carrying capacity of 850 m$^3$/s at Y.6 station (dashed red line in Figure 6) in the future simulations, even though it did so in the historical simulation. The historical simulation at C.2 station exhibited peak discharge values less than the threshold value of 3590 m$^3$/s with the existing reservoir operation (except one value) and the contribution of the KST dam was negligible in reducing the peak further. In the future simulations, there were peak values higher than the threshold.
value at C.2 station even with reservoir operation. This further indicates that the changes in extreme flows due to climate change are larger than those achieved by the combined action of the operation of the hypothetical and existing reservoirs, even though the simulated discharge depends strongly on which GCM is used as input.

Figure 6c,d show the reduction rate of the annual maximum daily discharge values at Y.6 and C.2 stations, respectively. The reduction rate was moderate at Y.6 station, with values varying between 1 and 30% in the historical and future simulations, with a maximum of around 48% in the historical one. This further shows that, in the future, the hypothetical dam could moderately reduce the flood damage in the Sukhothai region (flood-prone area) and lower reaches of the Yom basin. The simulation results at C.2 station reveal that the existing reservoirs, mainly Bhumibol and Sirikit, resulted in an enormous reduction in the annual maximum discharge, by 10–40%, in all the simulation scenarios considered, whereas the impact of the hypothetical dam was negligible, with values ranging between 0 and 5%. The low impact of KST dam at C.2 station can be attributed to the relatively high catchment area of that station (109,973 km²) compared with that of Y.6 station (12,769 km²) as well as the smaller storage capacity of the hypothetical KST reservoir compared to the Bhumibol and Sirikit reservoirs.

On average, the annual maximum daily discharge reduction rate at C.2 station was approximately 25% from the existing reservoirs, whereas the effect of the KST dam was around 2%, as shown in Table 2. On the contrary, the KST dam exhibited a considerable impact in reducing the annual maximum daily discharge by 15% at Y.6 station in the Yom River basin. These results correspond to those of the study by Wichakul et al. (2013), in which they analysed the effect of the KST dam on reducing the peak of the 2011 flood at C.2 station.

| Simulations | C.2 (%) | Y.6 (%) |
|-------------|---------|---------|
|             | ER      | HR      | HR      |
| Historic     | 28.55   | 2.57    | 17.74   |
| RCP 4.5     | 24.27   | 2.09    | 14.68   |
| RCP 8.5     | 22.36   | 1.83    | 12.33   |
| Average     | 25.06   | 2.16    | 14.92   |
and downstream of the dam, in the Yom basin. They found that the impact of the KST dam on the flood peak reduction was insignificant at C.2 station, but it was notable in the immediate downstream of the dam, with a peak reduction of around 50%. Similar findings were also observed in Jamrusri, Toda, and Tsubaki (2018) and Apichitchat and Jung (2015), even though they evaluated the effect of the KST dam only in the upper part of the Yom basin.

### 4.3 Reservoir operation as an adaptation strategy to mitigate the climate change impacts

The effect of reservoir operation as an adaptation strategy (ER, EHR, and 2EHR) was examined by computing the number of days during which the daily discharge exceeded the channel carrying capacity (flooding days) at C.2 and Y.6 stations, as discussed in Section 3.2.

The results of the historical simulation without any reservoir operation showed that the number of flooding days was 4 and 100 at Y.6 and C.2 stations, respectively, as shown in Figure 7a,b. The operation of the existing and hypothetical reservoirs reduced the number of days to zero at both locations and, therefore, the first and second adaptation strategies together could mitigate the historic floods. Furthermore, the number of flooding days increased to 44 and 59 under RCP4.5 and 8.5, respectively, at Y.6 station and decreased to 18 and 36 when considering the hypothetical reservoir. Simultaneously, the number of flooding days at C.2 station decreased extensively to 159 from 227 under RCP4.5 and to 184 from 357 under RCP8.5, based on the operation of the existing reservoirs, with the major share owing to the Bhumibol and Sirikit reservoirs. The hypothetical dam further reduced around five flooding days under the considered warming scenarios. Considering the third adaptation strategy of doubling the reservoir capacity, the number of flooding days was still high with values greater than 100 days at C.2 station compared with the Y.6 station. Therefore, from these results, it can be predicted that the combined adaptation strategies of reservoir operation alone cannot manage future floods at C.2 station. This further indicates that the implementation of other adaptation options is necessary to mitigate the impacts of climate change in the basin.

### 4.4 Effect of combined afforestation and reservoir operation adaptation strategies

Lastly, the combined effect of afforestation and reservoir operation as an adaptation option was evaluated at C.2 station under changing climate scenarios. For this purpose, the ratio of changes in discharge due to reservoir operation to the changes due to climate change was computed on an annual and seasonal (wet and dry) basis, as shown in Table 3. The derived afforestation effects were also shown in Table 3 along with the three considered cases. The negative and positive signs in Table 3 indicate the reduction and increase in discharge, respectively. It should be noted that the reservoir operations did not significantly affect the annual flow (Table 3) because the reservoirs store flood volume during the wet season and release it during the dry season, thereby maintaining an equilibrium between the annual inflows and releases. On the contrary, the afforestation reduced the annual flow due to enhanced evapotranspiration (Takata & Hanasaki, 2020). The reduction rate of the wet season discharge due to reservoir operations was remarkable compared with that achieved by the afforestation options. In both adaptation options (reservoir operation and afforestation), case 3 generated the maximum discharge reduction during the wet season, which further shows the potential of this adaptation strategy in effectively mitigating the impacts of climate change. The dry season flow increased greatly in all the considered reservoir adaptation measures, whereas it decreased in the afforestation scenarios. This reveals that either reservoir operation or afforestation alone cannot mitigate the impacts of climate change, especially in the wet season.

Therefore, the three cases of afforestation were combined with the respective reservoir adaptation options (Section 3.1) to assess

![Figure 7](image-url)
their integrated adaptation potential, as shown in Figure 8. The afforestation scenarios significantly reduced the annual flow and the net impact of the two adaptation strategies together was the annual flow reduction at C.2 station, as shown in Figure 8a. The wet season flow decreased greatly at C.2 station under RCP4.5 and 8.5, as shown in Figure 8b. Reservoir operation exhibited a promising role in reducing the flood flows of the wet season, with its case 3 possibly mitigating the effect of climate change under RCP4.5, in combination with afforestation. Similarly, reservoir operation was able to improve dry season flows by releasing the flood water stored during the wet season, as shown in Figure 8c.

### Table 3

| Warming scenario | Adaptation       | Annual (%) | Wet (%) | Dry (%) |
|------------------|------------------|------------|---------|---------|
|                  |                  | Case 1     | Case 2  | Case 3  | Case 1     | Case 2  | Case 3  | Case 1     | Case 2  | Case 3  |
| RCP4.5           | Afforestation    | −2.8       | −8.9    | −33     | −2.9       | −9.2    | −19.7   | −2.3       | −6.8    | −2.4 |
|                  | Reservoir operation | 3.2       | 3.4     | −3.0    | −76.4      | −81.6   | −89.8   | 5772.9     | 6164.8  | 6297.1 |
| RCP8.5           | Afforestation    | −2.2       | −6.8    | −28.7   | −2.2       | −7      | −15.2   | −1.9       | −5.5    | −1.3 |
|                  | Reservoir operation | 3.5       | 3.7     | −0.8    | −49.2      | −52.1   | −59.8   | 6296.7     | 6676.1  | 7063.8 |

**Note:** Reservoir scenarios: Case 1—existing reservoirs; Case 2—Case 1 + hypothetical reservoir; Case 3—Doubled capacity of reservoirs in Case 2. Afforestation scenarios: Case 1—20% afforestation; Case 2—100% afforestation; Case 3—100% afforestation + modified soil properties.
shown in Figure 8c. The net effect of the two adaptation options was an increase in dry season flow at C.2 station, although the afforestation exacerbated the risk of water shortage in the dry season.

5 | DISCUSSION

5.1 | Climate change and reservoir operation

The CPRB exhibited an increase in discharge during the wet season and relatively no change during the dry season owing to climate change. This seasonal changes in discharge caused by warming were in agreement with earlier studies (Kotsuki et al., 2014; Watanabe et al., 2014). They reported that the precipitation in the CPRB is projected to increase in the wet season, which in turn will increase the runoff; whereas neither precipitation nor runoff was expected to increase significantly during the dry season towards the end of the 21st century. The incorporation of existing reservoir operations reduced the wet season discharge and increased the dry season discharge. However, the magnitude of reduction was still smaller than the increase caused by warming in the wet season. This indicates that the flood risk becomes higher in the basin although the results suggest a reduction in drought risk. Generally, the existing infrastructures will be tuned to historical hydrologic regimes and unable to cope effectively with the more variable future climate (Ferrazzi, Vivian, & Botter, 2019; Georgakakos et al., 2012).

The increased future water availability during the wet season is difficult to utilize as a water resource because of the limited storage capacity and the existing operation rule curves of the basin reservoirs. The potential of dams to change the downstream river flow is directly proportional to their storage capacity (Graf, 1999). Ehsani et al. (2017) strengthened this argument by reporting that increasing the storage capacity and the number of dams, in addition to modifying their operations, may become necessary to offset the water resources vulnerabilities in the context of climate change. Ferrazzi and Botter (2019) also revealed that the river impoundments affect both high and low flows with an intensity that is modulated by the storage capacity of reservoirs and the mean annual runoff. Therefore, the higher potential of Bhumibol and Sirikit reservoirs to attenuate the effect of climate change is strictly related to their storage capacity, which is the highest among all the reservoirs characterizing the CPRB.

5.2 | Combined adaption strategies

It was found that the reservoir operation adaptation strategies alone cannot manage future floods at C.2 station and there is a need for other adaptation options to mitigate the impacts of climate change in the CPRB. A previous study conducted in the CPRB by Kotsuki et al. (2014) also suggested that new flood management and mitigation plans will likely be necessary based on their projection of increased runoff compared to the capacities of the Bhumibol and Sirikit reservoirs at the end of 21st century. Therefore, the combined effect of reservoir operation and afforestation as an adaptation option was evaluated in the basin under changing climate scenarios. As can be expected, a combination of both the adaptation options reduced the flood risk in the wet season. Nevertheless, the magnitude of discharge reduction was smaller than the increase caused by warming where the climate change signal is robust. At the same time, the adaptation measures increased the low flows well. The water availability in the dry season can be further improved through a plethora of options such as smaller dams, aquifer recharge, rainwater harvesting, etc. rather than going for only the large-scale infrastructures (Gaupp, Hall, & Dadson, 2015).

The runoff trends in watersheds are generally linked to the regional trends in precipitation and reference evapotranspiration (Ficklin, Abatzoglou, Robeson, Null, & Knouft, 2018), and often, no single adaptation measure can thoroughly address this climate change impacts, as seen in the present study. This study indicates that the size and number of reservoirs need to be reconsidered to maintain flood control storage and drought resilience in light of climate change by combining with other structural as well as non-structural measures in parallel, as countermeasures.

5.3 | Simulation uncertainties

Although this study presented an adaptation framework for the CPRB, uncertainties remain for the climate change simulations. The source of those uncertainties associated with the simulations are summarized below:

1. Spatially and temporally uniform parameters (parameters of land surface hydrology module in Table S1) were assigned for simulations under the assumption that these parameter values do not fluctuate much. However, these parameters will be subject to change attributable to the climate change effects, which may contribute some uncertainties in the future discharge prediction by the H08 model.
2. The water withdrawal is disabled in the H08 model due to the lack of corresponding data. This may introduce some uncertainties by slightly overestimating the discharge predicted at stations, downstream of the reservoirs.
3. Non-consideration of several important water infrastructures such as canals, retentions ponds, etc., which might explicitly represent the water resources in the study area, may also attribute some non-negligible amount of uncertainty.
4. The effect of reservoir operation was analysed under the assumption that the dams will be operating at the end of the century. This assumption may propagate notable uncertainties in the adaptation levels attained.
5. The capacity of existing reservoirs is fixed and “doubling the storage capacity” scenario is therefore virtually impossible to achieve. Thus, the degree of adaptation level achieved in reducing the flood risk would be rather small under actual adaptation measures.
6. The temporal and spatial resolution of the model domain was set as 1 day and 5' × 5' grid cell, respectively. A further increase in spatiotemporal resolution would reduce the uncertainties involved.

7. Finally, the climate dataset used for the simulations may also attribute some uncertainties in the discharge prediction.

Overall, this study supports the first step in policymaking, but a more detailed analysis is needed to support the final design of adaptation strategies due to the existence of uncertainties, even though such uncertainties are unavoidable in climate change simulations. In addition, the economic feasibility of the considered adaptation scenarios is a challenging question. There are questions we need to answer, such as “Is it economically viable to construct new reservoirs or to double the capacity of the existing ones, and thus minimise the losses resulting from floods and droughts?”, and such economic aspects should be considered before implementing these adaptation measures.

6 CONCLUSIONS

There is a lack of studies and limited knowledge about how the combination of reservoir operation and projected climate change might alter the discharge in river basins around the world. Therefore, to fill this knowledge gap, we investigated the impact of reservoir operation on flow regulation, as an adaptation measure for climate change, using a case study in the CPRB by employing the H08 global hydrological model. The H08 model was calibrated and validated satisfactorily to reproduce the naturalized and regulated flows in the basin against observed discharge data, and future flows were generated under the two warming scenarios of RCP4.5 and 8.5 from 2080 to 2099. This study mainly addressed four key questions of concern in the CPRB as follows:

i. Whether the existing reservoirs are sufficient to tackle with the effect of climate change towards the end of 21st century, and the answer is “no” because the assessment of the cumulative impact of climate change and operation of the existing reservoirs revealed that reservoir operation can reduce the flood flows only partially, although the low flows improved substantially.

ii. Whether the construction of the KST dam could cope with the effects of climate change along with the existing reservoirs, and the answer is still “no.” Although the KST dam has discernible effect in the Yom basin, the changes in high flows due to climate change were larger than those achieved by the combined action of the hypothetical and existing reservoir operations at C.2 station.

iii. Whether reservoir operation would act as an effective potential adaptation strategy to mitigate the impacts of climate change, and again the answer is “no.” This scenario examined the maximum level of adaptation achievable from the reservoir operation by assuming an extreme condition of doubling the storage capacity. The results further affirmed that the adaptation strategy of reservoir operation alone cannot manage future floods even after doubling the storage capacity and thus there is a need for other adaptation options.

iv. Whether the combined effect of reservoir operation and afforestation as an adaptation strategy would address the impacts of climate change, and the answer remains the same as “no.” The combined effect was analysed on an annual and seasonal basis and there was a net reduction in the basin flow on an annual basis. During the dry season, there was a net increase in discharge, which further reduced the risk of water scarcity. In the wet season, there was a net decrease in discharge; however, the impact of climate change was clearly larger than the effects of the adaptation options, which exacerbated the flood risk.

This study shows the potential effects of the selected reservoir operation measures on future flood mitigation in the CPRB. Climate change can aggravate water-related risks, such as flooding in the wet season and water shortage in the dry season, and the considered adaptation options could assuage these issues to some extent in the CPRB. However, uncertainties remain for the projected climate change simulations, and decision-makers need to consider this uncertainty in both water management and climate change adaptation activities. Although such caveat exists, the merit of this study is that it can provide flexible adaptation strategies based on reservoir operation that can be revised easily in the future, whenever new scenarios become available, and can be readily adapted to any other region.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the authors upon reasonable request.

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