INVESTIGATING THE IMPACTS OF CLIMATE CHANGE AND DAM OPERATION ON RIVER REGIME AND FLOOD DYNAMICS USING HIGH-RESOLUTION RIVER-FLOODPLAIN-RESERVOIR HYDRODYNAMIC MODEL

By

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ABSTRACT

Dams are some of the most important man-made structures that provide significant benefits to societies by mitigating floods and droughts while supporting irrigation, domestic or industrial water supply, and power generation. However, global attention on the detrimental ramifications of dam operations has increased owing to the observed irreversible environmental impacts of existing dams in over-developed regions. Despite these concerns, the growing demands for energy and water in developing regions have led to a boom in the construction of large dams in recent years with hundreds more planned in the near future. Additionally, the construction and operation of dams in these regions are often based on localized, incomplete, or inconsistent observation-based hydrologic analyses, rendering them less effective in mitigating hazard risks. Simultaneously, climate change is intensifying flood and drought events, making them less predictable and more destructive, especially in developing regions. Thus, there is an urgent need for in-depth investigation of past changes as well as future uncertainties in hydrology of these regions under the compound impact of climate change and dam operations.

This dissertation addresses these critical issues by employing a high-resolution river-floodplain-reservoir model called the CaMa-Flood-Dam (CMFD), that realistically accounts for hydropower and irrigation dam operations. Model simulations are used to quantify the changes in river regime and flood dynamics in the Mekong River Basin (MRB). First, analyses of an important subbasin with unique hydrological features in the MRB, the Tonle Sap, are conducted to provide a comprehensive assessment on the alteration of the Tonle Sap Lake, Southeast Asia largest lake. Then, key insights are presented on the evolving river regime and flood pulse of the entire MRB over 83 years, focusing on the difference between climate and dam impacts on seasonal timing and water balance. Finally, potential changes in river regime and extremes across the MRB under multiple combinations of future climate and planned dam development are explored. The key findings from the aforementioned analyses are: (1) Mekong river flow’s trends and variabilities of are still mainly driven by climate variation, however, dam operations have exerted a growing influence on the Mekong flood pulse especially after 2010; (2) dams are causing a gradual shrinkage of the Tonle Sap lake by reducing its annual inflow from the Mekong mainstream; (3) dams are delaying the Mekong’s wet season onset and shortening its duration; (4) dams have largely altered the Lower Mekong flood occurrence by shifting substantial volume of water between the seasons; and (5) in the future, dams will notably increase dry season flow.

The results in this dissertation provide major advances and important insights on the integrated river-floodplain-reservoir dynamics in the MRB and paving pathways towards a more sustainable development based on the understanding of the continually changing hydrological systems in the region. Furthermore, this assessment could benefit future investigations in other developing regions worldwide where dam construction is similarly booming.

This thesis is dedicated to my first landlord, Mom.
Thank you for always being there for me, even though you are a wee bit late at times.

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Chapter 1. Introduction

1.1 Research Motivation

1.1.1 The changing global hydrology and high-resolution modelling

Freshwater availability has been a major concern in many global regions (Leal Filho et al., 2022). However, as human societies develop, the demand for freshwater has grown exponentially, threatening to destabilize many ecosystems, even in major river basins that are known to provide an abundance of freshwater in the past such as the Colorado, Yellow, and Amu Darya (Schlager, 2001). Evidence from previous studies suggests that global water usage has increased sharply since 1950 (Ritchie & Roser, 2017). Between 1950 and 2014, the global freshwater usage has tripled from approximately 1,230 km^3 to 3,990 km^3 (Ritchie & Roser, 2017); it increased by 600% in the last 100 years (Wada et al., 2016). Generally, an increase in global population will result in the increase of water, food, and energy consumption, which will drive even more anthropogenic activities, altering the natural environment. For example, the over exploitation of water resources through dam construction, water diversion and agricultural expansion has led to irreversible and catastrophic collapse of regional ecosystems such as in the Aral Sea (Micklin, 2007, 2016), Lake Urmia (Chaudhari et al., 2018) and Lake Chad (Coe & Foley, 2001; H. Gao et al., 2011). With a projected global population increase to between 9.4 and 10.2 billion people (World Water Development Report 2018 | UN-Water, 2018.) in the next two decades, global water demand is expected to increase by 20-30% (Boretti & Rosa, 2019), and especially, water demand for agriculture will likely increase by 60% (Alexandratos & Bruinsma, 2012). While the numbers are only estimates, and these projections could include substantial uncertainties (Wada et al., 2016), a further increase in water demands is inevitable.

Climate change has caused substantial adverse impacts to both human societies and the ecosystem; some studies suggest 74% of global regions are experience increasing magnitude and frequency of flash droughts (Christian et al., 2021; X. Yuan et al., 2023). Similarly, others suggest that anthropogenic climate change has also enhanced extreme river flooding events, especially in Asia and South America (Alifu et al., 2022). Under a warmer future climate (Calvin et al., 2023), the hydrological cycle will be further intensified, leading to an increase in the frequency of extreme hydrological events (Pokhrel et al., 2021a; Wasko et al., 2021). The severity of these events will also be further exacerbated, causing many major regions including Southwestern South America, Mediterranean Europe and Northern Africa to face unprecedented drought conditions in the next

30 years (Satoh et al., 2022). While intensification of extreme precipitation will increase water availability over all climate regions (Tabari, 2020), it also increases global exposure to flood risk especially when population is also expected to rise. Others also suggest that, due to climate change, there could be a limitation on freshwater in heavily irrigated areas, which can cause a loss of 8-43% of our main food ingredients such as maize, wheat and rice (Elliott et al., 2014). Consequently, many regions could result in more direct and extreme measures as in the past to mitigate the adverse effects of extreme events as well as ensuring the security of water, food, and energy but they could also destabilize the local environment.

With the inevitable changes to come, there is a consensus that detailed and accurate hydrological data is crucial in ensuring effective decision making and planning of water resource management strategies at both regional and local levels (Hirabayashi et al., 2021; Zhu et al., 2023) for future developments. Additionally, there is a lack of detailed and continuous hydrological monitoring system in many regions in the developing world, causing major gaps both spatially and temporally in the understanding of hydrodynamics changes in the past for areas such as the Amazon and Mekong River basins (Kabir et al., 2022; Timpe & Kaplan, 2017a). Models can address these gaps and demands as they are proven to be able to provide reliable simulation across space and time in many regions over the world (Chaudhari et al., 2021; Duc Dang et al., 2020; Felfelani et al., 2017; Pokhrel et al., 2017; Shin et al., 2019, 2021a; Try et al., 2018; J. Wang et al., 2021a). Furthermore, recent developments in modelling have resulted in enhanced hydrodynamic models and their variants (e.g., CaMa-Flood-Dam), capable of isolating and attributing the changes in hydrology condition to either nature or human related factors (i.e., dam operation). Lastly, with the rapid improvements in computational capacity and efficiency, high-resolution models require substantially less time to simulate than in the past. Thus, it is critical that we continue the effort to apply high-resolution modelling in advancing the understanding of historical changes in the hydrological cycle as well as predicting future changes and explore viable solutions to mitigate adverse impacts.

1.1.2 Dam cascade operation and their impacts: Mekong River Basin

Dams and reservoirs are crucial elements of water resource management under changing demands and availability (Poff et al., 2015a). While there are different usages of dams, most are built to harness water resources for multiple purposes including irrigation, drinking water supply, flood control and hydropower generation. However, despite the benefits they provide, dams are generally controversial as they are highly invasive, especially during the construction phase (Shahab et al., 2023; Wei et al., 2009), and more importantly, they fragment the river basin and practically alter the river regimes (Grill et al., 2014; Jumani et al., 2020; Spinti et al., 2023). This has resulted in an increase in dam removal in the US and other regions with aging dams (Doyle et al., 2005; Null et al., 2014; Pohl, 2002). On the other hand, the number of large dams in the Amazon, the Mekong and other river basin are increasing rapidly with hundreds planned in the near future (Grumbine & Xu, 2011; Pokhrel et al., 2018; Sabo et al., 2017; Stone, 2016; Timpe & Kaplan, 2017; Winemiller et al., 2016; Zarfl et al., 2015) as they are essential in providing a reliable source of energy and much needed support in water resources management for the developing regions. Therefore, there is an urgent need to better understand the historical impacts of these dams on regional hydrology and ecosystem as well as predict future impacts of planned dams in combine with climate changes.

Many studies have applied various statistical techniques on observed hydrological data and remote sensing products to examine the changes in regional hydrology due to dam impacts (e.g., Räsänen et al., 2017; Timpe & Kaplan, 2017). However, it is challenging to separate and attribute certain changes to either natural variation or dam operation using only observed data. Furthermore, analyses relying on observed data are fundamentally limited as they often have considerable gaps both temporarily and spatially (P. T. Adamson et al., 2009; Delgado et al., 2010a). Models can overcome these limitations as they can be used to provide regional wide information, isolating changes to each driving factor (H. Dang et al., 2022; Pokhrel, Shin, et al., 2018; Shin et al., 2020) and especially, used to analyze potential impacts in the future under different development scenarios (Alifu et al., 2022; Boulange et al., 2021a; Hirabayashi et al., 2010, 2021). Thus, it is imperative that we continue to advance high-resolution modelling in combination with better representation of dam operation to develop a better understanding of the complex interaction between natural climate variation and the growing human activities in developing regions such as the Mekong River Basin (MRB).

There is a consensus among many studies that the development and construction of dams in the MRB started relatively late compared to most other large global river systems (P. T. Adamson et al., 2009; Pokhrel, Burbano, et al., 2018). This was the case until end of the 2000s, but dozens of new large to mega-scale dams have been constructed across the MRB's mainstream and its tributaries since 2010(H. Dang et al., 2022; J. Gao et al., 2021; Hecht et al., 2019; Pokhrel &

Tiwari, 2022). In fact, between 2008 and 2022, the basin wide man-made storage capacity of the MRB have quadrupled from approximately 23 billion m^3 to more than 100 billion m^3 (see Figure 8, section III.2.1.). As a result, this has led to numerous studies across multiple disciplines focusing on this region. While the regional security of green energy generated from these new dams is crucial to the growing demand of this developing region, the compounded adverse effect of the dam cascade on downstream environment and residents is of great concern. More specifically, many studies suggest that the natural rhythm of the Mekong flood pulse has already been altered due to the combination of these dam operation and intensified hydrological under climate change (Binh et al., 2020b; Kummu and Sarkkula, 2008; Pokhrel et al., 2018b). Additionally, the unique reversal of flow in the Tonle Sap River (TSR) is also impacted, dampening the annual seasonal fluctuation of the inundated extent around the Tonle Sap Lake (TSL) (Arias et al., 2013; Pokhrel et al., 2018b). This is particularly concerning as the alteration of TSL inundation dynamics has negatively affected local agricultural and fishery yield (Halls and Hortle, 2021; Keskinen et al., 2007; Teh et al., 2019), potentially undermine food security and destabilize this region (Burbano et al., 2020; Kontgis et al., 2019; Orr et al., 2012; Pokhrel et al., 2018b; Yoshida et al., 2020; Ziv et al., 2012).

1.2 Research Goals, Objectives, and Questions

The aforementioned importance of applying high-resolution modelling into further understanding both historical and potential future changes of global hydrology (Chapter I.1.1) and the need for improving the representation of dam operation at large scale (Chapter I.1.2) led me to pursue the following **overarching goal**: to further enhance our understanding of the combined impacts of climate change and dams on river regime and inundation dynamics by applying high-resolution, large-scale models with optimized dam schemes. The analyzed results are expected to provide improved information to not just the broader hydrology community but also the general public and most importantly, the decision makers, toward establishing more sustainable plans for future development, ensuring the security of water, food and energy as well as protecting the environment in a changing climate.

Toward achieving these goals, this dissertation is driven by specific science questions which are categorized into three different parts.

Part 1. Analysis of dam impacts on the hydrodynamics of TSL.

Q1. How have dams in the mainstream Mekong altered the hydrologic balance and inundation dynamics of the TSL? More specifically:

- What are the changes in the MRB's mainstream flood pulse and TSR flow reversal?
- How have dams altered the water balance of the TSL?
- What are the changes in flood occurrences in and around the TSL region?

Part 2. Analysis of natural climate variation and dam impacts on the MRB's hydrodynamics

Q2. What is the long-term regional trend of river flow in the MRB?

Q3. What are the impacts of dams on the MRB annual flood pulse and extreme hydrological events?

Part 3. Analysis of potential future changes in the MRB hydrodynamics and the role of dams

Q4. How will the MRB flood pulse change under various scenarios of future climate scenarios?

Q5. How effective are dams in mitigating extreme events and supporting water availability during dry episodes?

1.3 Dissertation Outline

The research questions presented in section I.2. are tackled in separate chapters (from Chapter II through Chapter IV). The following provides a summary of the chapters:

Chapter II. Hydrologic balance and inundation dynamics of Southeast Asia's largest inland lake altered by hydropower dams in the Mekong River Basin.

Chapter III. Spatiotemporal evolution of the Mekong River Basin's surface water conditions and the role of dams in recent extreme hydrological events.

Chapter IV. Potential changes of the Mekong's flood pulse under future climate change and dam operations.

Chapter V. Summary and future work.

Chapter 2. Hydrologic balance and inundation dynamics of Southeast Asia's largest inland lake altered by hydropower dams in the Mekong River Basin

2.1 Introduction

Inland lakes around the world have been increasingly impacted by climate change and human activities, leading to unprecedented scales of adverse environmental impacts. Some examples of the disastrous consequences from water management activities in the past century include the desiccation of the Aral Sea (Micklin, 2016, 2007; Pokhrel et al., 2017), Lake Urmia (AghaKouchak et al., 2021; Chaudhari et al., 2018), Poyang Lake (Liu et al., 2016) and Lake Chad (Coe and Foley, 2001; Gao et al., 2011) among others. In Southeast Asia, the Tonlé Sap Lake (TSL)—the region's largest inland lake that supports one of the world's biggest inland fisheries is increasingly affected by the changes in the flood pulse of the Mekong River basin (MRB) due to upstream dam construction (Arias et al., 2014b; Chen et al., 2021; Kummu and Sarkkula, 2008; Shin et al., 2020). While these dams generate capital and expand productive capacity via power generation, agricultural water management, and flood mitigation, there are growing concerns that the continued dam-induced alteration of the MRB hydrology, potentially exacerbated by climate change and variability, is causing fundamental shifts in the water balance and inundation dynamics of TSL (Arias et al., 2014a; Frappart et al., 2018; Pokhrel et al., 2018b; Västilä et al., 2010; Yu et al., 2019; Yun et al., 2020).

Historically, water levels at Kompong Luong, located at the edge of the TSL permanent water body, has varied between ~1.2 m to 10.4 m (Arias et al., 2012; Kummu and Sarkkula, 2008; Pokhrel et al., 2018b). The average volume of water stored in the TSL and its floodplain during these fluctuations ranges from ~1.6 km^3 to 59.7 km^3 (Siev et al., 2016). The TSL has a vast surface area that extends from ~2,500 km^2 in the dry season to ~15,000 km^2 in the wet season (Arias et al., 2012), driven primarily by the strong seasonality in the Mekong River flow, known as the Mekong flood pulse (Arias et al., 2013; Junk, 1999; Pokhrel et al., 2018b). This dramatic seasonal fluctuation of the inundated extent around the lake is the foundation of the area's rich biodiversity and productive fishery and agricultural systems. The lake's seasonal inundation dynamics provide crucial areas for flood-recession farming (Cramb, 2020; Fox and Ledgerwood, 1999), diverse vegetation growth (Arias et al., 2013), and spawning and feeding locations for migratory fish (Barlow et al., 2008; Chua et al., 2021), among many other important societal and ecosystem services. The TSL fishery accounts for 8-12% of Cambodia's gross domestic product and 80% of animal protein consumed in the country (Baran and Gallego, 2015; Hortle et al., 2004; Teh et al., 2019). Thus, the TSL, with its unique hydrologic dynamics, has been a critical lifeline upon which local livelihoods and natural ecosystems have relied for generations.

The TSL has a watershed that drains into the lake, but a substantial portion of the lake's inflow is supplied by the Tonlé Sap River (TSR), the only channel that connects the lake to the Mekong mainstream. In terms of annual water balance, ~54% of the lake's inflow comes from the Mekong River through the TSR, with the remaining 34% and 12% contributed by the lake's watershed and precipitation over the lake and floodplains, respectively (Arias et al., 2014b; Kummu et al., 2013; Kummu and Sarkkula, 2008). Annually, more than 80% of rainfall in the MRB occurs during the summer monsoon season (Wen et al., 2021) resulting in a substantial increase in the Mekong mainstream flow. During this wet period, which typically begins between mid-May (Piman et al., 2013) and late-June (Arias et al., 2014b; Kummu and Sarkkula, 2008), water flows into the TSL from the Mekong through the TSR. As seasonal rains subside in the dry season that typically begins between October (Arias et al., 2014a) and December (Piman et al., 2013), the TSR flow reverses, draining the lake's water back into the mainstream Mekong, supplying additional flow to the downstream areas, specifically the Mekong Delta in Vietnam. This annual flow reversal—the primary driver of the TSL's unique hydrodynamics—has historically been modulated by the Mekong flood pulse (Pokhrel et al., 2018b). However, the intricate relationship between flow in the Mekong mainstream and the TSR flow reversal has begun to change in recent times. In particular, there have been shifts in the timing, duration, and magnitude of the flow reversal due to multiple factors including natural hydrological variability, climate change, and human alteration of the Mekong flood pulse (Arias et al., 2012; Kummu and Sarkkula, 2008; Li et al., 2017).

Because over half of the TSL water volume originates from the Mekong River, the alterations in the mainstream Mekong's hydrological characteristics caused by upstream dams can have direct impacts on the lake's water balance and inundation dynamics. Compared to other large global river basins, the MRB remained relatively undammed throughout the 20th century (Grumbine and Xu, 2011). However, since 2010, multiple mega-dams have been built in the Mekong mainstream including the Xiaowan (built in 2010) and Nuozhadu (built in 2014) dams in the Upper Mekong region (known as Lancang River in China). The construction of these mega-dams combined with other projects on the Mekong tributaries has doubled the basin-wide reservoir storage capacity compared to previous decades (Shin et al., 2020). In light of the growing energy demands driven by rapidly developing regional economies (Phoumin et al., 2021), combined with added flood and drought mitigation benefits (Fung et al., 2019; Wang et al., 2017), rich untapped hydropower potential and its perceived readiness (Schmitt et al., 2018), affordability (Intralawan et al., 2019), and the intent to promote renewable energy (Khan et al., 2018; Zhang et al., 2021), hydropower development in the MRB involving large dams is likely to continue in the foreseeable future.

As dam construction accelerated in the MRB in recent times, the region has also faced increased occurrence of hydrologic extremes such as severe floods (Delgado et al., 2010) and droughts (Lu and Chua, 2021; Thilakarathne and Sridhar, 2017), likely due to the intensified hydrological cycle under climate change (Wang et al., 2020; Wen et al., 2021; Yun et al., 2020). These extreme events, combined with the hydrological alterations inherent to dam operation, are altering the natural rhythm of the Mekong flood pulse (Binh et al., 2020b; Kummu and Sarkkula, 2008; Pokhrel et al., 2018b) and, consequently, the TSR flow reversal (Arias et al., 2013; Pokhrel et al., 2018b). The impacts have begun to manifest as alterations in the inundation dynamics of the Cambodian floodplains, adversely impacting agriculture and fishery yield (Halls and Hortle, 2021; Keskinen et al., 2007; Teh et al., 2019). In the long run, the impacts could potentially destabilize the regional economy and undermine food security (Burbano et al., 2020; Kontgis et al., 2019; Orr et al., 2012; Pokhrel et al., 2018b; Yoshida et al., 2020; Ziv et al., 2012).

With regard to the recent acceleration in dam construction across the MRB, the body of scientific literature has grown substantially in the past decade, with many studies focusing on the potential impacts of existing and planned dams as reviewed in Y. Pokhrel, Burbano, et al., (2018) and Soukhaphon et al., (2021). These studies have provided important insights regarding the changes in hydrological and ecological systems in the MRB and TSL. Similarly, many studies have linked the recent hydrological shifts in the TSL to not only dam operations (Arias et al., 2014b, 2013; Bussi et al., 2021; Piman et al., 2013; Wang et al., 2020), but also multiple other factors including irrigation expansion (Arias et al., 2012; Kummu and Sarkkula, 2008), climate variability (Chen et al., 2021; Frappart et al., 2018, 2006; Guan and Zheng, 2021), and excessive sand mining (NG and Park, 2021) by analyzing the *in-situ* observations and remote sensing products using various empirical and statistical techniques.

However, there are major gaps and limitations in these past studies. More specifically, since most previous studies have used observed data—either ground- or satellite-based—there is a lack of explicit attribution of the observed changes to climate variability and dams. The process-based numerical models used in the present study can overcome these limitations by enabling factorial simulations, for example, with and without dams. Further, many studies have focused on a short period within the last two decades (Ji et al., 2018; Lin and Qi, 2017) from 2000s to 2010s, leaving opportunities for a more temporally complete understanding of the effects of climate variability and dams. Some recent studies have attempted to address the limitation by using numerical models to examine the changes in the hydrology of the MRB (Binh et al., 2020b; Lee et al., 2020; Pokhrel et al., 2018b; Yun et al., 2021) between the 1980s and the 2010s as well as predicting future changes, but none have directly attributed the changes in flows and inundation dynamics of the TSL to climate variability and dam operation. Given the acceleration in dam construction in the past decade and findings of adverse impacts on the TSL hydrodynamics, it is imperative that we develop a more quantitative understanding of the lake's response to climatic and human drivers.

The goal of this study is to fill the aforementioned research gaps by using multi-decadal hydrological simulations that explicitly account for the impacts of dams on the Mekong flood pulse and hence on the hydrologic balance of the TSL. The central scientific question that we ask is: How have the dams in the mainstream Mekong altered the hydrologic balance and inundation dynamics of the TSL? The specific research objectives are to: (1) examine the changes in the mainstream Mekong flood pulse and the TSR flow reversal, (2) quantify the alterations in the water balance of the TSL, and (3) investigate the changes in flood occurrences in and around the TSL. In all of the analyses, the changes in hydrology and inundation dynamics are first examined under natural conditions. Then, the changes caused by dams are explicitly quantified.

2.2 Data and Methods

2.2.1 Data

Observed water level and river discharge data at the three selected gauging stations in the mainstream Mekong, one station in the TSR and one station near the TSL obtained from the Mekong River Commission (MRC) are used for model validation (see section 2.3.1). These are the stations within the study domain that include relatively complete observational data during the 1979-2016 period.

Attributes of dams and reservoirs including dam location, dam height, reservoir capacity, project purpose (e.g., irrigation and power generation), and commissioned year required for the reservoir operation scheme (see section 2.2.3) are obtained from the Research Program on Water, Land, and Ecosystem (WLE; https://wle-mekong.cgiar.org/). Specifically, we use 86 dams (Fig.

1) selected from this database by Shin et al., (2020) based on the following criteria: (1) dam height is at least 15 meters (≥ 15m), (2) storage capacity is over 1 million cubic meters (Mm^3), and (3) energy generation capacity is over 100 Mega Watts (MW). Additionally, only dams that are operational as of 2016 are considered; 2016 is the end of our simulation period determined by the availability of forcing data (see section 2.2.2).

Other relevant information required in constraining the reservoir operation scheme, particularly the reservoir operation rules, and downstream demands met by a given reservoir, is not publicly available for most reservoirs across the MRB; limited information was accessible only for a handful of reservoirs. Thus, water demand for irrigation is taken from simulated results of the Human Impact and Ground Water Modules in MATSIRO (HiGW-MAT) model, following Shin et al., (2019). These irrigation results are globally validated using available statistics (Pokhrel et al., 2015, 2012a). We generate turbine design flow and general reservoir operation rules using an optimization approach (Shin et al., 2020, 2019) considering the common practice of maximizing power production by storing water during low-demand (i.e., wet) periods and releasing it during high-demand (i.e., dry) periods (see section 2.2.3). This is a commonly used approach in the MRB given the lack of open data on hydropower operation (Dang et al., 2020).

2.2.2 Model Description and Simulation Settings

The modeling framework used in this study comprises of two models: CaMa-Flood-Dam (v3.94) (Shin et al., 2020) that simulates river-floodplain-reservoir hydrodynamics and the global hydrological model HiGW-MAT (Pokhrel et al., 2017, 2015) that simulates runoff required as input in CaMa-Flood-Dam. Such a combination where CaMa-Flood is driven by runoff from a global hydrological model has been used to simulate river-floodplain-reservoir systems over many global regions including the MRB (Pokhrel et al., 2018b; Shin et al., 2021, 2020; Wang et al., 2021; Yamazaki et al., 2014).

The CaMa-Flood-Dam is an enhanced version of the Catchment-based Macro-scale Flood-plain (CaMa-Flood) model version 3.94 (Yamazaki et al., 2014, 2011) that includes a reservoir operation scheme (Shin et al., 2019). CaMa-Flood is a global hydrodynamic model that solves shallow water equations of open channel flow, explicitly accounting for backwater effects using the local inertial approximation (Yamazaki et al., 2013) to compute river-floodplain hydrodynamic properties (i.e., river discharge, water level, and inundated areas). Considering computational requirements, the spatial resolution is set at 3-arcmin (~5 km), and the simulated inundated area is downscaled to a higher resolution of 3-arcsec (~90m) using a 90m digital elevation model (DEM). The high resolution DEM used here is the MERIT (Multi-Error-Removed Improved-Terrain; Yamazaki et al., 2017) DEM. Water levels and inundated areas are diagnosed from water storage in each unit catchment, river discharge from each unit catchment is calculated using shallow water equations, and water storage in each unit catchment is updated by a mass conservation equation considering inflow from the upstream unit catchment(s), outflow to the down-stream unit catchment and local runoff. Further details regarding model physics in CaMa-Flood, parameterization methods, and sensitivities to input parameters can be found in the previous literature on model description (Yamazaki et al., 2011, 2013) and application in the MRB (Pokhrel et al., 2018b; Yamazaki et al., 2014). Details on the reservoir operation scheme are provided in (Shin et al., 2020, 2019); for completeness, a brief description of the scheme is presented in section 2.3.

CaMa-Flood is driven by runoff simulated using HiGW-MAT (Pokhrel et al., 2015), a global hydrological model based on the MATSIRO (Takata et al., 2003) land surface model that simulates both the natural water cycle and human activities from canopy to bedrock including evapotranspiration, infiltration, irrigation, flow regulation, and groundwater pumping on a full physical basis. Because reservoirs are simulated within CaMa-Flood, the runoff based on natural simulation—with the reservoir scheme in HiGW-MAT turned off—is used. The spatial resolution of HiGW-MAT is set to ~50×~50 km and the meteorological forcing data are taken from the WATCH Forcing Data using the ERA-Interim (WFDEI) database (Weedon et al., 2018). A complete description of HiGW-MAT can be found in our previous studies (Pokhrel et al., 2015, 2012b; Takata et al., 2003).

To quantify the historical impact of reservoir operation on the hydrodynamics of the MRB and TSL, two simulations are conducted: (1) natural simulation without considering dams (NAT), and (2) regulated simulation by implementing dams based on their commissioned year (DAM). All simulations are conducted for the entire MRB to account for the impacts of dams across the basin, but results are analyzed only for a region around the TSL (Fig. 2-1).

2.2.3 Reservoir Operation Scheme

The reservoir operation scheme is based on Shin et al., (2020) and includes the same number of dams (i.e., 86; Fig. 2-1). Dam categorization is based on the reservoir's purpose as noted in the WLE database (i.e., 22 irrigation, 62 hydropower, and 2 multipurpose dams). While water release from irrigation dams is simulated to meet downstream water demands, the operation of hydropower and multipurpose dams is set to maximize power generation. Detailed information on the scheme and its implementation into CaMa-Flood model can be found in Shin et al., (2019, 2020); for completeness, a brief description of reservoir release calculations is provided in the following.

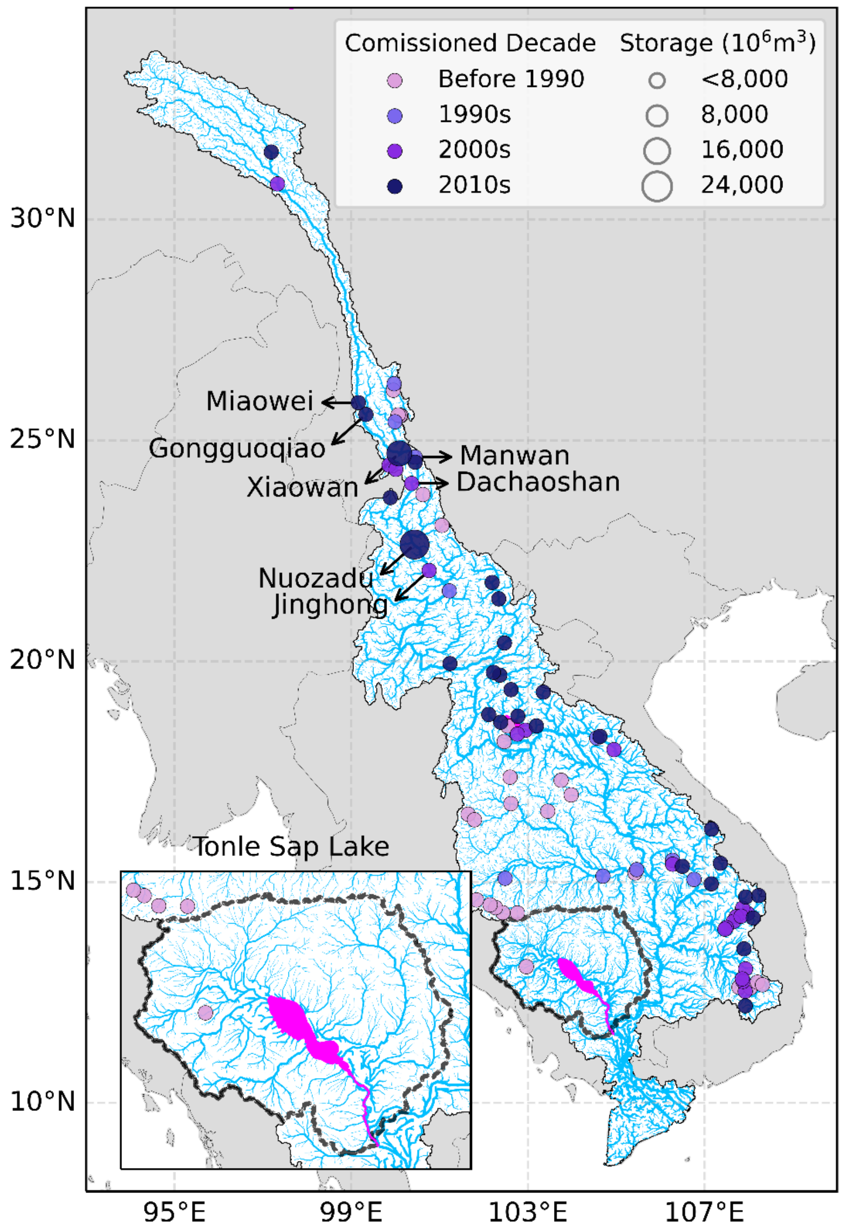

Figure 2-1. A spatial map of the MRB depicting the location of the 86 selected dams (color-coded circles) that are included in the model.The color-coding and size of the circles indicate the decade of commissioning and maximum storage capacity, respectively. The dams located in the Mekong mainstream (as of 2016) are named. The background shows the river network (blue lines) with

Figure 2-1 (cont'd)

scaled thickness based on simulated long-term mean river discharge from 1979 to 2016 at the 3-arcmin (~5 km) spatial resolution. The lower-left inset showcases the Cambodia floodplain, with the TSL and TSR indicated in magenta, and the boundary of the lake's watershed indicated by the dashed black line.

For irrigation dams, when reservoir storage meets the normal operating condition between the minimum and maximum capacity, a targeted monthly release rm [L3/T], is applied, which is calculated based on demand-controlled release ratio R [-], release coefficient krls [-], provisional monthly release rm' [L3/T], and long-term monthly inflow im [L3/T] as follows:

$$r_m = R \cdot k_{rls} \cdot r'_m + (1 - R) \cdot i_m,$$

where the interannual variability of storage is considered in calculating k_{rls} [-] while the water demand variability is reflected in the provisional monthly release r_m' [L^3/T]. When the reservoir storage increases to its maximum capacity, the scheme provisions spillway release in addition to targeted monthly release r_m [L^3/T], and when storage drops to the minimum (set at 10% of maximum storage capacity) reservoir release is set to zero.

For hydropower and multipurpose dams, the scheme optimizes power benefits F [$] in determining reservoir release as:

$$F = \sum_{t=0}^{T} P(t) \cdot W(t) \cdot \Delta t = P \cdot \eta \cdot \gamma \cdot \min(Q(t),\ Q_{turbine}) \cdot H(t) \cdot \Delta t,$$

where $P(t)$ [$/Watts-hour] is electricity price, $W(t)$ [Watts] is generated energy over the time of Δt [hr], η [-] is efficiency, γ [kg/m^3] is specific weight of water, $Q(t)$ [m^3/s] is reservoir release, $Q_{turbine}$ [m^3/s] is turbine design flow, and $H(t)$ [m] is turbine head. Since power pricing requires a tremendous amount of information on multiple technical and political aspects to calculate and predict, here, we consider it to be constant over time for simplicity. Hence the reservoir release is calculated to maximize total power generation. From our previous study, the streamflow with a 30% exceedance probability is found to be a reasonable proxy of $Q_{turbine}$ in the Mekong region (Shin et al., 2020), thus, we utilize this value as it is also widely adopted in previous hydropower literature (Gernaat et al., 2017; Hoes et al., 2017; Zhou et al., 2015).

Additional details regarding other factors influencing reservoir release, specifically those related to storing excess water during low-demand, wet season and releasing it during high-demand, dry season with cascade operation optimization can be found in our previous study (Shin et al., 2020).

We note that with any generic operational rules, it is challenging to fully capture the complex dynamics of real-world reservoir operation. Oftentimes, hydropower projects may not run at the designed capacity or optimized power generation due to reasons such as environmental concerns, power demand fluctuations, maintenance operation, among others. However, it is difficult to represent such operation uncertainties in the model, hence are not considered in the current operation scheme.

2.3 Results

2.3.1 Model Validation

The HiGW-MAT and CaMa-Flood modeling system has been thoroughly validated over the MRB in our previous studies (Pokhrel et al., 2018b; Shin et al., 2020) using observed river discharge and water level data from the MRC, and satellite-based surface water products from Landsat and Sentinel-1. For completeness, here, we revisit the evaluation of water levels and discharge at selected stations both in the mainstream Mekong and the TSL (Fig. 2-2). Model performance is indicated by statistical measures including the Nash-Sutcliffe coefficient (NSE), Kling-Gupta efficiency (KGE) and Coefficient of determination (R^2). Complete time series validation of simulated river discharge at the three stations on the Lower Mekong mainstream are also presented in Fig. 2-3. High values of the statistical measures suggest that the long-term variability in water levels and its seasonal cycle in the main stem as well as around TSL is well reproduced by the model (Fig. 2-2b-d). The simulated discharge at the most upstream station (i.e., Kratie; KT) agrees very well with observations. However, at Kompong Cham (KC, Fig. 2-2c) station, river discharge is underestimated, which is likely due to the challenges in representing channel bifurcation processes prevalent in that region. Further downstream, at Phnom Penh Port (PP, Fig. 2-2d) station, the performance is relatively good, but the model tends to slightly overestimate river discharge. In terms of water level, simulated results agree well with observations in the mainstream Mekong stations (Fig. 2-2e-g), Kompong Luong (KL, Fig. 2-2h) in the TSL and Prek Kdam (PK, Fig 2-2i) in the TSR. The water levels in the mainstream are slightly underestimated, especially during the dry season. Given the complexity of river-floodplain hydrodynamics and the use of a large and basin-wide model, we consider these results to be reasonable, especially to assess the effects of changes in mainstream hydrology on the TSL hydrodynamics. Some of the model-observation discrepancies could be attributed to various factors including uncertainties in forcing data (Kabir et al., 2022), model parameters (e.g., channel width) and the use of a generic reservoir operation.

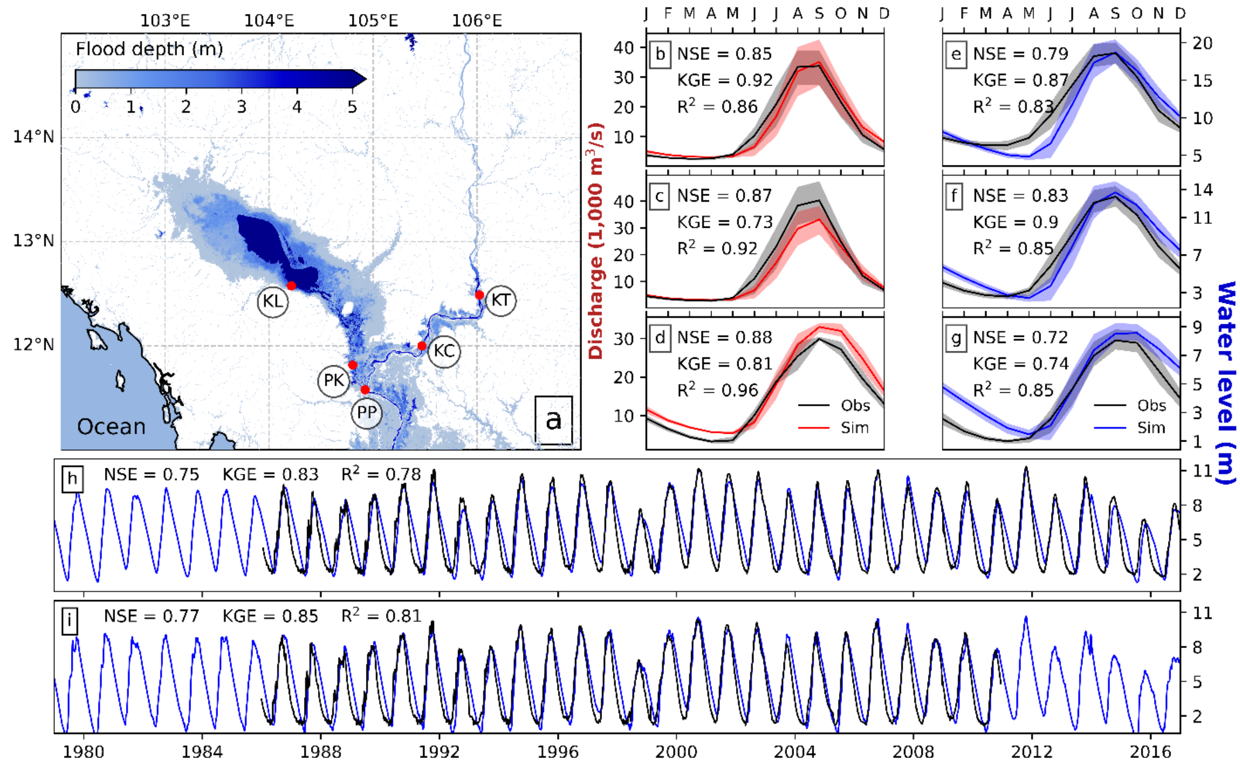

Figure 2-2. Long-term (1979-2016) average of simulated flood depth over the TSL area (a). Comparison of the seasonal cycle of simulated river discharge (b-d) and water levels (e-g) with observations at Kratie (KT; b and e), Kompong Cham (KC; c and f), and Phnom Penh Port (PP; d and g) stations. Shadings (red, blue, and grey for simulated river discharge, simulated water level, and observations, respectively) indicate interannual variability presented as the upper and lower 25% quantiles for each month. A complete time series validation of daily water level at Kompong Luong (KL; h) and Prek Kdam (PK; i) stations are also presented. Nash-Sutcliffe coefficient (NSE), Kling-Gupta efficiency (KGE) and Coefficient of determination (R2) are indicated for each station.

The long-term average of simulated flood depth for the TSL region is also shown in Fig. 2-2a but this could not be directly evaluated because observed flood depth data are nonexistent. While there have been recent studies and tools developed to derive flood depth using remote-sensing products (Bryant et al., 2021; Cohen et al., 2019; Nguyen et al., 2016), such derived data have been location-specific and there are no global datasets or datasets for the MRB that are readily available. Further, such data could not be used for direct model validation because of the need for manual correction (Cian et al., 2018; Teng et al., 2017) and inherent uncertainties arising from computational errors and biases, among other common issues in remote sensing products. Regardless, since the water level in the model is diagnosed from flood depth, the validation of water level serves as an indirect evaluation of flood depth. Overall, the accurate simulation of water levels at both the mainstream and lake locations provides confidence that the model reasonably simulates various flood attributes around the TSL.

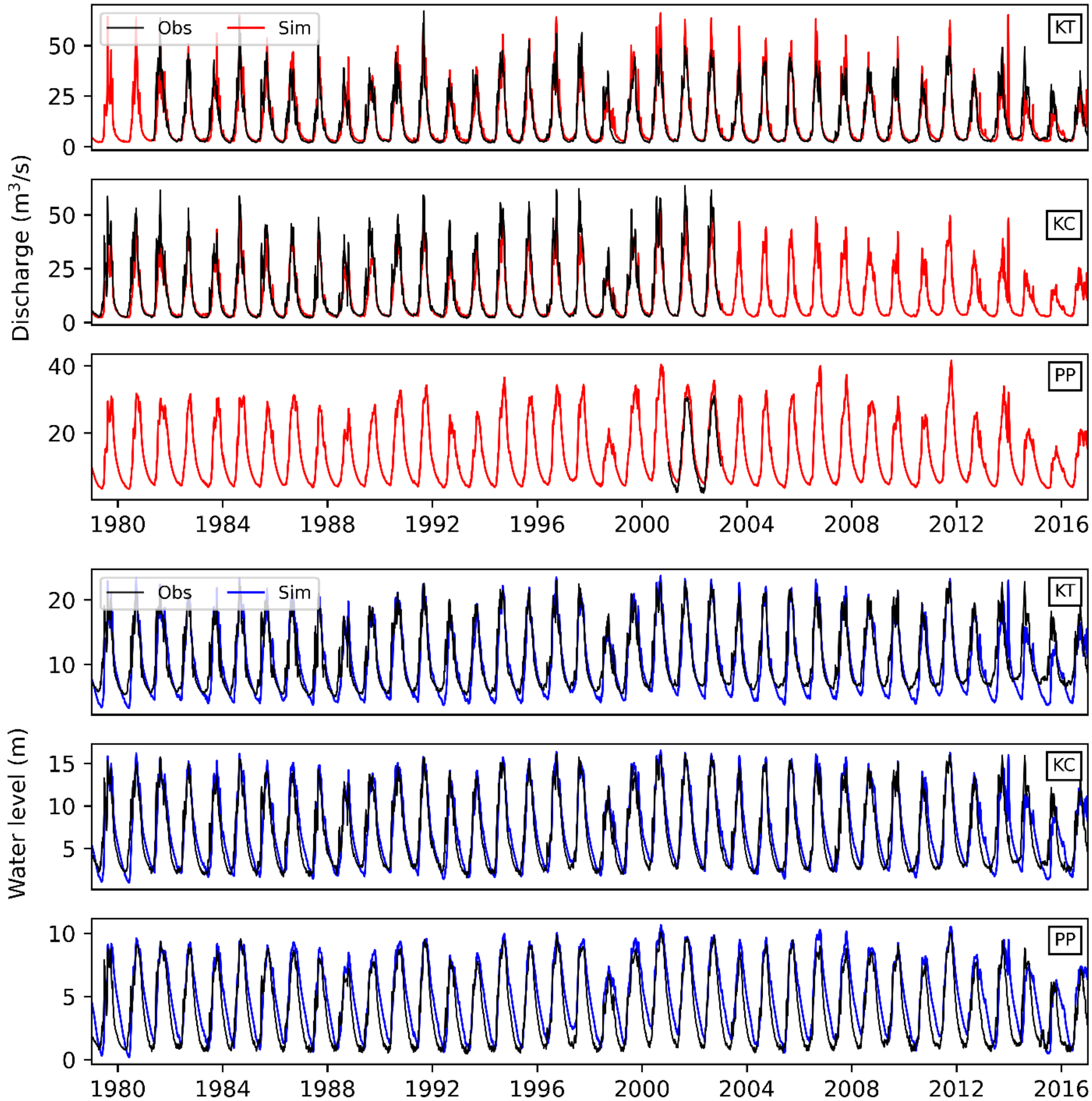

Figure 2-3. Complete time series validation of daily simulated water level (blue lines) and river discharge (red lines) at KT (Kratie), KC (Kompong Cham) and PP (Phnom Penh Port) stations with observed data (black lines) obtained from the Mekong River Commission.

2.3.2 Effects of Climate Variability and Dams on River Discharge and Water Level

Table 2-1 presents a summary of the dam-induced changes in the magnitude of river discharge at the selected mainstream Mekong stations and averages for each decade beginning in the 1980s.

The following observations can be made from these results. Evidently, dams have consistently reduced the peak flow and decreased the low flow at each of these stations, but the impacts vary across stations, between maximum and minimum flows, and over decades. Notably, the proportion of reduction in peak flow (~1.4% to 7.3%) is smaller than the increase in low flow (~8% to 30%) across stations. Further, our results are in line with previous findings (Binh et al., 2020b; Shin et al., 2020) that the impacts are highly pronounced during the 2010s compared to the preceding decades; for example, the dam-induced impact at both KT and KC stations surged from ~1.4-2.1% (during 1979-2009) to 7.1-7.3% (during the 2010s).

Table 2-1. Difference in maximum, average, and minimum flows at three Mekong mainstream stations between DAM and NAT simulations. The results shown are averages for each decade and the entire period of 1979 to 2016.

Station	Period	Difference in Discharge (%)		
		Max	Avg	Min
Kratie	1980 - 1989	-1.8%	-	+15.6%
	1990 - 1999	-1.4%	-	+14.1%
	2000 - 2009	-2.1%	-0.2%	+19.5%
	2010 - 2016	-7.3%	-1.5%	+31.6%
	Long term average	-2.8%	-0.3%	+15.7%
Kompong Cham	1980 - 1989	-1.5%	+0.2%	+15.2%
	1990 - 1999	-1.5%	-0.1%	+13.6%
	2000 - 2009	-1.9%	+0.3%	+19.2%
	2010 - 2016	-7.1%	-0.8%	+30.6%
	Long term average	-2.2%	+0.1%	+15.7%
Phnom Penh Port	1980 - 1989	-1.0%	+0.2%	+8.1%
	1990 - 1999	-1.2%	+0.2%	+13.2%
	2000 - 2009	-1.4%	+0.4%	+16.5%
	2010 - 2016	-4.5%	-0.6%	+14.0%
	Long term average	-1.8%	+0.1%	+12.9%

Fig. 2-4a depicts the decadal average of seasonal water level fluctuation at the KL station (location shown in Fig. 2-2). The figure reveals that, even in the NAT simulation, TSL water levels in the wet season during the 2000s were higher than the 38-year average, as well as those in the

1980s and 1990s, by ~0.74 m at the peak level (i.e., mid-October; Fig. 2-4a). On the contrary, TSL average water levels during the 2010s were substantially lower than the long-term average (i.e., by ~0.66 m), meaning that water levels during the 2010s dropped by ~1.4 m from those in the 2000s. Inflow to the TSR (Fig. 2-4b) during the wet season illustrates a similar pattern over the decades. Compared to the long-term average discharge, the peak outflow at Prek Kdam (PK) station was higher by ~1,270 m^3/s in the 2000s (late-October). And from the 2000s to 2010s, this outflow peak dropped by ~1,750 m^3/s. Evidently, an early increase in TSL water level closely follows the early start of TSR inflow in the 2000s, while the extended period of low water level in the 2010s corresponds to a late onset of inflow (Fig. 2-4). We note that the period between the onset of inflow from the mainstream Mekong into TSL (mid-June) and outflow from TSL (early-October) is referred to as the "wet season", which remains relatively unchanged among different decades (Fig. 2-4b).

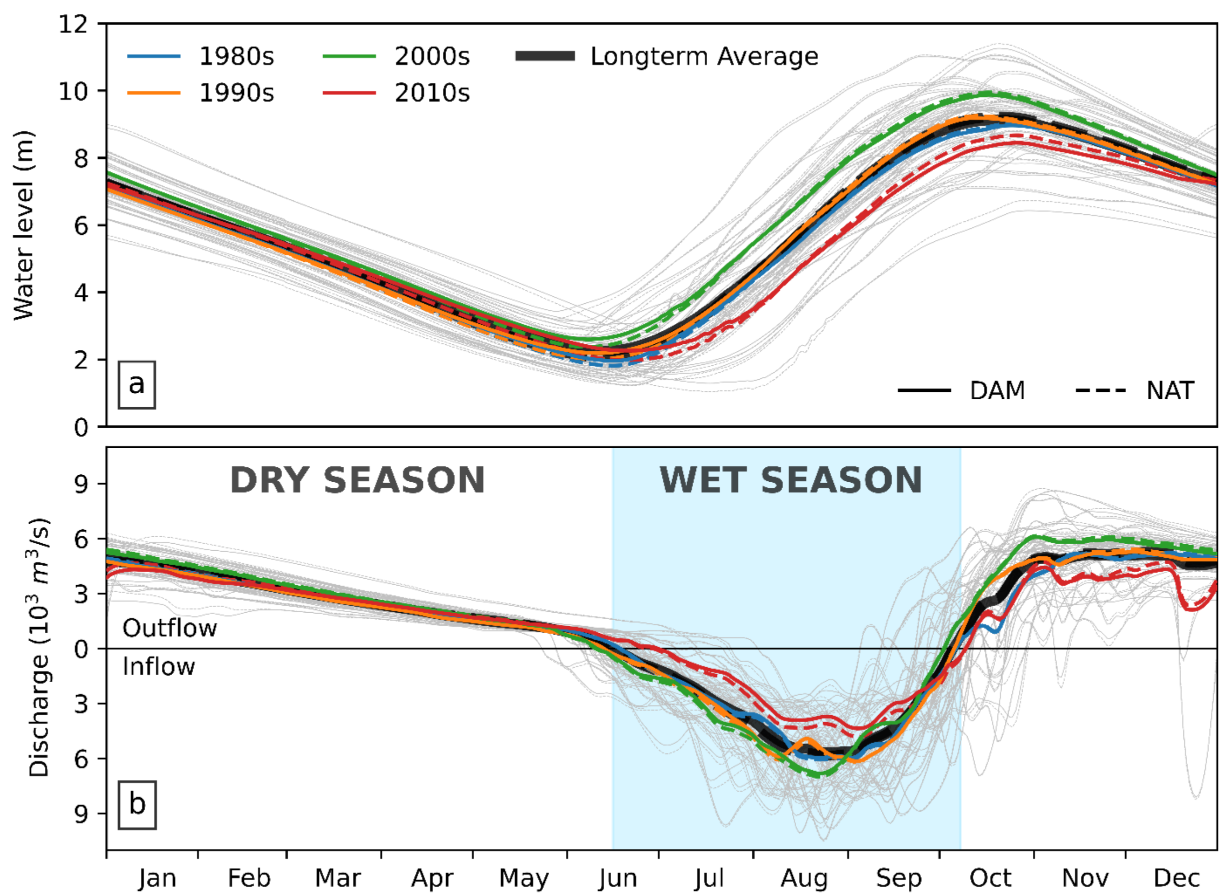

Figure 2-4. Decadal (color-coded lines) and long-term (thick black lines; 1979-2016) average of water levels at the KL station in the TSL (a) and river discharge at the PK station in the TSR (b). Solid and dashed lines represent the DAM and NAT simulation results, respectively.

Comparison of lake water levels from the NAT and DAM simulations (Table 2-2) for each decade during 1979 to 2016 indicates that the dam-induced reduction in water levels during the wet season prior to 2010 is relatively small (i.e., ~8cm or < 1%). During the 2010s, the numbers almost tripled to 23 cm (or 2.8%); given high water levels during the wet season (i.e., ~8m), the percentage reduction of ~3% is not dramatic but could constitute a large decline in water volume. Dam-induced changes are more prominent during the dry season, especially in the 2000s and 2010s, during which water levels increased by 23 cm (13.6%) and 28 cm (22.1%), respectively. Note that the percentage figures are high for these dry season changes because those are relative to lower water levels compared to that in the wet season.

Table 2-2. Differences in maximum and minimum water levels at KL station between the DAM and NAT simulations.

Decade	Differences in water level			
	Maximum		Minimum	
	cm	%	cm	%
1980s	-5	-0.6%	15	13.1%
1990s	-6	-0.7%	18	13.8%
2000s	-8	-0.8%	23	13.6%
2010s	-23	-2.8%	28	22.1%

The dam-induced changes in TSL water levels are direct consequences of the altered flow reversal in the TSR driven by the changes in mainstream Mekong water levels and river discharge. A comparison of the peak of the two-way flow in the TSR from the DAM and NAT simulations (Table 2-3) suggests that dams substantially dampened these peaks. In line with results presented earlier, these TSR peak flow alterations are highly pronounced during the 2010s with a reduction in the peak of inflow to and outflow from the TSL by ~9% and ~6%, respectively. These are an order of magnitude higher than both the long-term average and the decadal averages for the preceding decades (Table 2-3).

Table 2-3. Differences in peak flows at PK station between DAM and NAT simulations.

Decade	**Differences in Peak discharge (%)**	
	Inflow	**Outflow**
1980s	-1.5%	-1.6%
1990s	-0.6%	-2.5%
2000s	-2.6%	-1.1%
2010s	-9.5%	-6.2%
Long term average	-3.0%	-3.1%

2.3.3 Effects of Dams on the TSL Water Balance

Even though the effects of dams on the mainstream Mekong flow are rather small and have increased only in recent times (Section 2.3.2; Table 2-1), the impacts on TSL water balance are relatively substantial (Fig. 2-5). In general, and as also discernible in Fig. 2-4, the effects of the dam operations manifest as a substantial reduction in both inflow into and outflow from the lake (Fig. 2-5). While some inter-annual variability in this impact is evident, there is a clear tendency of increased impacts over time with a large reduction in both inflow and outflow volume during the 2010s; the reduction in the inflow of ~25% in 2015 is the highest. Note that both the changes in inflow and outflow volumes for a given year are not similar because the reduction in inflow into the lake can alter other hydrological processes within the lake, leading to an altered outflow dynamic. Further, the percentage changes are higher for inflows because the baseline values (i.e., inflow and outflow volumes under natural conditions) are different – outflow includes the TSL watershed contribution in addition to the TSR inflow.

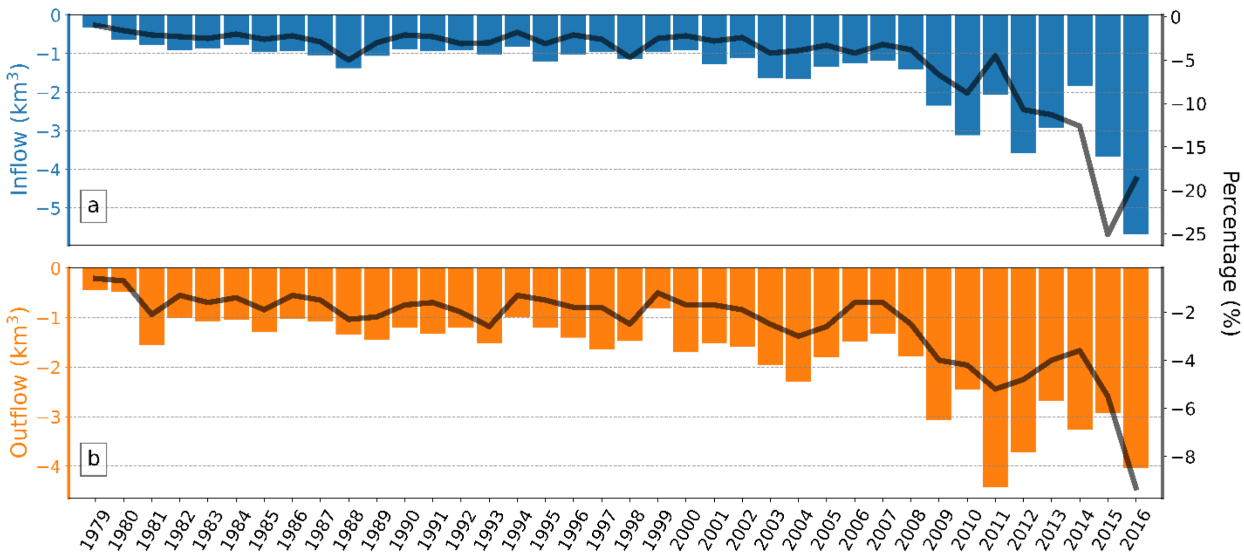

Figure 2-5. Difference in annual inflow (a) and outflow (b) volume (bars; left y-axis) between DAM and NAT simulations at the Prek Kdam station in the TSR. Grey lines (right y-axis) show the difference in percentage figures relative to the NAT simulation.

2.3.4 Effects of Climate Variability and Dams on Inundation Dynamics

The decadal shift in flood occurrence (Fig. 2-6) detected in the NAT simulation results indicates that there is no monotonous decline in flood occurrence over time because of strong inter-annual and inter-decadal variability. In comparison to the long-term average, the declines in flood occurrence across the lake were small (~2.5%) during both the 1980s and the 1990s (Fig. 2-6b and 2-6c). A notable increase in flood occurrence throughout the entire seasonally flooded portion of the lake can be observed in the 2000s (Fig. 2-6d), which ranges from 5 to 10%. This increase is equivalent to a longer inundated duration from 15 to 40 days. In contrast, the following decade (i.e., the 2010s) witnessed a notable drop in flood occurrence compared to the long-term average (Fig. 2-6e), especially in the outer periphery of the lake, ranging from 7.5 to more than 10% (i.e., 27 to more than 40 days).

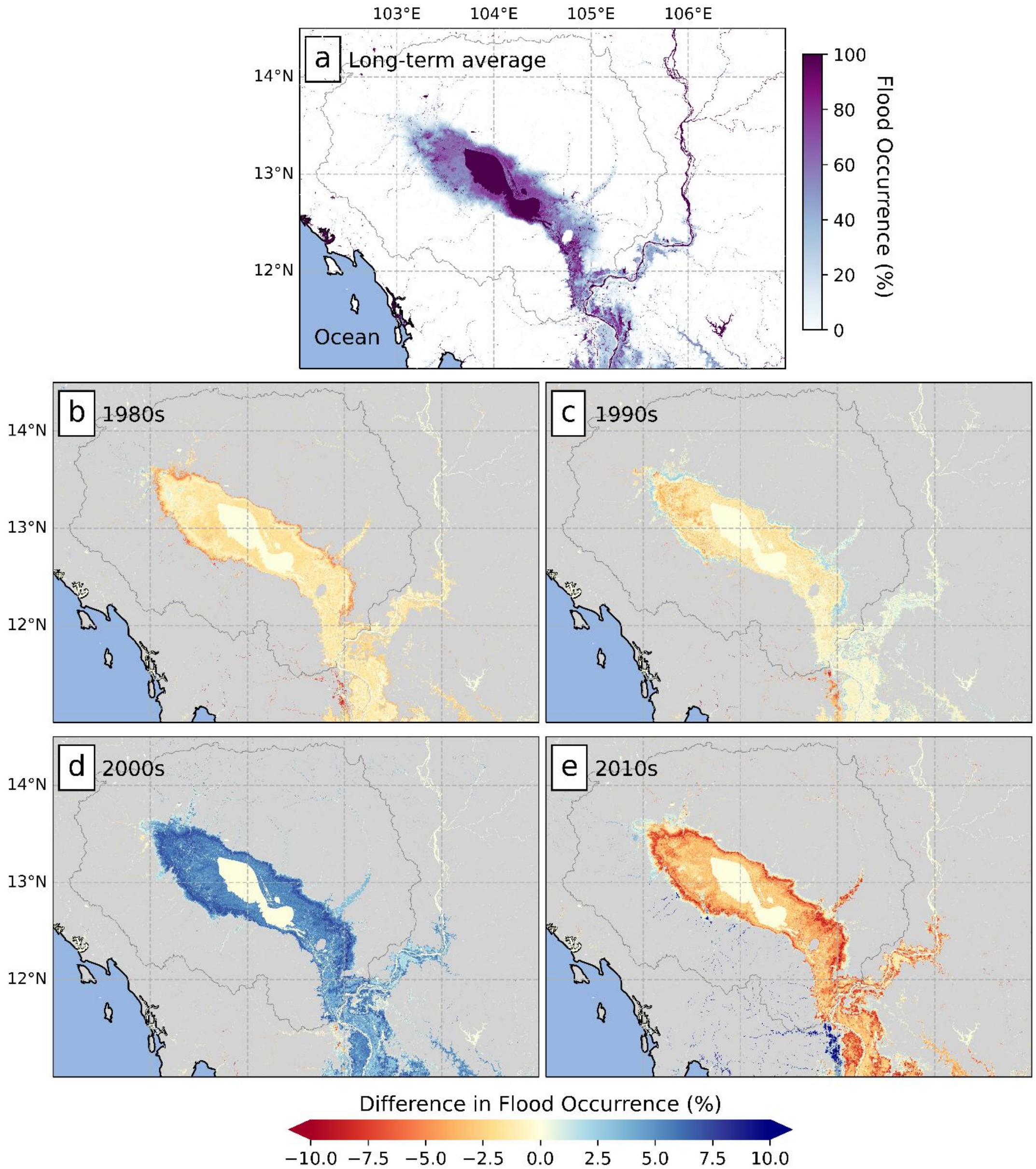

Figure 2-6. Long-term (1979-2016) average of flood occurrence (a). Difference between average flood occurrence for each decade and the long-term average in the NAT simulation: 1980s (b), 1990s (c), 2000s (d), and 2010s (e). The bottom color bar applies to panels b-e where results shown are percentage differences for a given decade compared to the long-term average. Areas with no flood occurrence in both long-term average and the decade being compared are indicated in grey (b-e).

Fig. 2-7 depicts the dam-induced changes in the decadal average of flood occurrence from the 1980s to the 2010s. In terms of the broad spatial patterns of change, flood occurrence increases around the main lake body as well as TSR and along mainstream channels and distributaries in the downstream region but decreases in the outer periphery of the lake. Relatively, the alterations in flood occurrence caused by dams are smaller than the temporal shifts under natural conditions (Fig. 2-6). However, as opposed to the large inter-decadal variability in the temporal shifts of the natural flood occurrence, there is a consistent increase in the magnitude of changes in flood occurrence caused by dams over time. Notably, the impacts are substantial during the 2010s (Fig. 2-7d) and constitute a large increase from the prior decades. The ~4% change in flood occurrence (~15 days reduction in inundation period) in the outer periphery of the lake during the 2010s on a decadal-average basis suggests a clear shift in inundation dynamics of the TSL as a result of mainstream Mekong flow regulation.

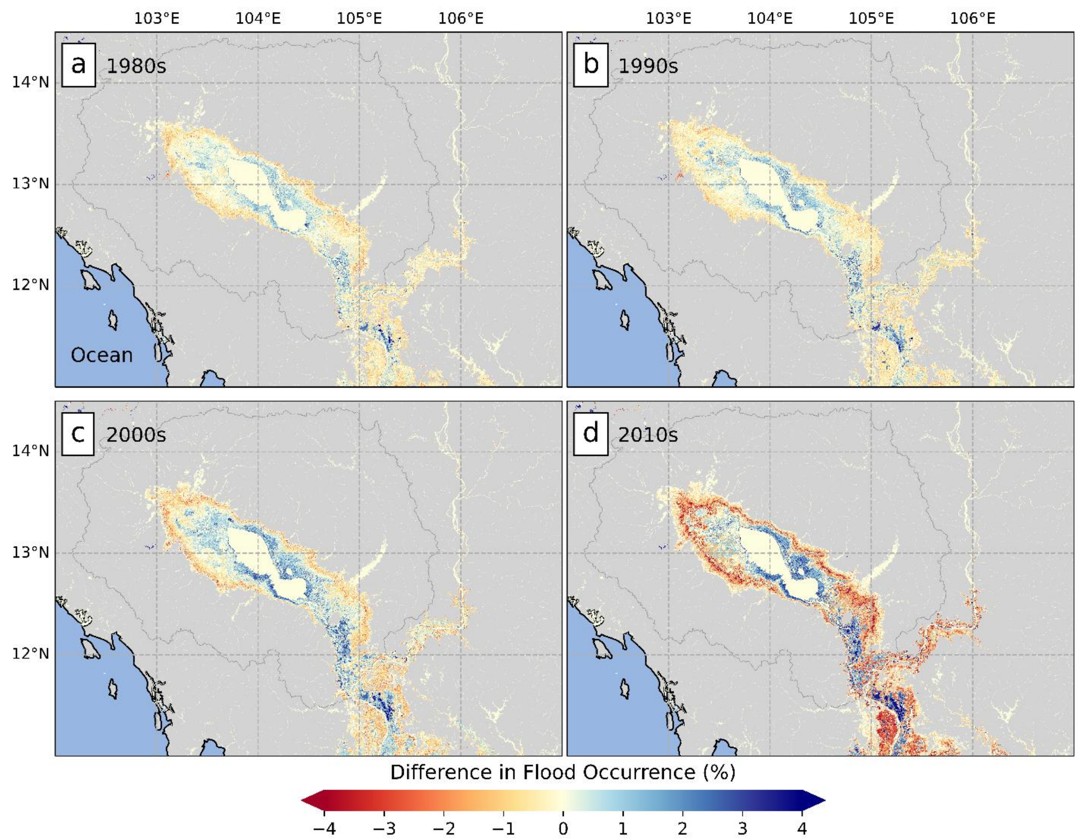

Figure 2-7. Differences in decadal-average flood occurrence (in %) between DAM and NAT simulations in the 1980s (a), 1990s (b), 2000s (c), and 2010s (d). Areas with no flood occurrence in both simulations are indicated in grey.

The dam-induced changes in flood occurrence relate to a substantial alteration in the Lake's surface area (Fig. 2-8). Consistent with our results on the shift in water levels and inundation dynamics (Figs. 2-4 and 2-7), the lake's surface area has increased (decreased) during the dry (wet) season as a result of the Mekong flow alteration by dams. A larger impact of dams is also evident through the months (except for January) in the 2010s compared to the preceding decades.

In the 2010s, the dam-induced increment (deduction) of inundated area of the TSL is ~2 times higher during February-July and ~3-5 times during August-December than in the prior decades (i.e., 1980s and 1990s). An increase in inundated areas of ~270 km^2 during April, equivalent to ~6% of the lake's surface area in the NAT simulation (Table 2-4), signifies a substantial alteration of the lake inundation cycle due to dam-induced alteration of the Mekong flood pulse. In the latter half of the 2010s, a similar magnitude of impact can be observed with a maximum decline in inundated areas by ~365 km^2 in October, while August has the highest percentage of reduction (~3%, equivalent to ~245 km^2). The timing of this reduction is supported by our findings on the dam-induced shifts in lake water levels (Fig. 2-4).

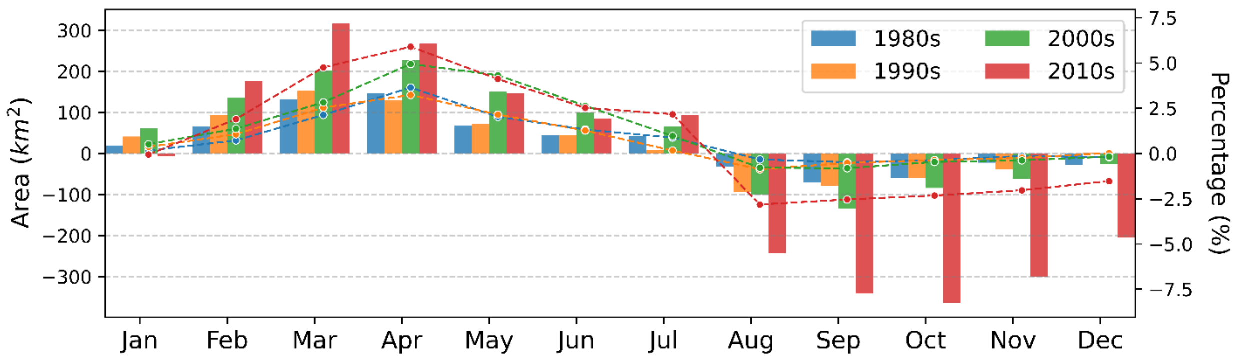

Figure 2-8. Differences in decadal-average inundated areas (color-coded bar; left y-axis) between DAM and NAT simulations. Results shown are spatial average for the TSL watershed shown above. Color-coded lines (right y-axis) show the difference in percentage figures relative to the total inundated areas in the NAT simulation.

Table 2-4. Differences in the TSL decadal average inundated area between DAM and NAT simulations. Percentages are relative to the total inundated area in the NAT simulation.

Month	**1980s**		**1990s**		**2000s**		**2010s**	
	km^2	**%**	**km^2**	**%**	**km^2**	**%**	**km^2**	**%**
January	29.54	0.26%	43.64	0.39%	55.89	0.46%	0.97	0.01%
February	68.98	0.76%	101.46	1.14%	133.08	1.34%	165.96	1.78%
March	137.91	2.21%	149.65	2.45%	206.22	2.87%	303.67	4.51%
April	135.96	3.34%	150.75	3.71%	222.22	4.75%	269.09	5.86%
May	78.46	2.33%	77.11	2.28%	142.79	4.04%	157.35	4.38%
June	46.33	1.36%	44.34	1.26%	109.27	2.85%	85.95	2.52%
July	50.12	1.03%	12.61	0.23%	71.68	1.03%	90.62	2.08%
August	-41.40	-0.41%	-89.67	-0.83%	-115.42	-0.90%	-244.77	-2.79%

Table 2-4 (cont'd)

Month	1980s		1990s		2000s		2010s	
	km²	**%**	**km²**	**%**	**km²**	**%**	**km²**	**%**
September	-73.77	-0.51%	-90.38	-0.59%	-131.27	-0.79%	-322.71	-2.38%
October	-53.97	-0.33%	-68.81	-0.41%	-88.14	-0.49%	-365.50	-2.31%
November	-43.44	-0.28%	-38.26	-0.25%	-79.42	-0.49%	-316.38	-2.13%
December	-14.48	-0.11%	-0.29	0.00%	-14.81	-0.10%	-201.83	-1.50%

2.4 Discussion

Numerous studies have examined the changing hydrology of the TSL, primarily by using ground- and satellite-based observation; however, a direct quantification of the impacts of climate change and Mekong dams on the observed hydrologic shifts in the lake is lacking. In this study, we used factorial model simulations to mechanistically quantify these impacts over the past four decades. While climate variability is found to be a key driver of the inter-decadal variations, the Mekong dams are found to have caused an accelerating impact on the lake's hydrologic regime, especially in the most recent decades.

No substantial differences are found in the annual river discharge in the mainstream Mekong between DAM and NAT simulations, suggesting that the annual water balance of mainstream Mekong has remained generally unaffected, which is in line with findings (Binh et al., 2020a). However, the difference in magnitude of peak (maximum) and low (minimum) flows at the mainstream Mekong stations indicates an increasing impact of newly added dams in recent years. Such alterations in flow signatures reflect the expected impacts of reservoir operation (i.e., dampened flood pulse and enhanced dry season flow); however, our results provide crucial insights on the magnitude of these effects and their time evolution under increased dam construction.

Regarding water levels in the TSL, our results indicate a direct influence of the Mekong dams on the lake's water level, corroborating previous findings (Arias et al., 2014a, 2012; Kummu et al., 2013; Kummu and Sarkkula, 2008) that TSL hydrological regime is strongly modulated by the Mekong mainstream through the TSR. However, our results provide crucial additional insights by directly attributing the changes in TSL water levels to climate variability and dams, including for more recent periods compared to the prior studies. Our results are also in line with recent findings (Lin and Qi, 2017; Lu and Chua, 2021; NG and Park, 2021) that there is an obvious decline in lake's water levels and extents between 2000 and 2016. The decline is detected in both NAT and

DAM simulations, suggesting that climate variability also partly contributed to the decline. However, a comparison of the results from the NAT and DAM simulations (Table 2-1 and Fig. 2-4) suggests that while the broad patterns of inter-decadal variabilities in the lakes water levels could be related to climate variability, the impacts of dams have consistently increased over time, and the impacts are more prominent during the dry season.

Over the study period (1979-2016), the lake's water balance underwent a fundamental shift as the impacts of dams became relatively more pronounced on the Mekong mainstream and, consequently, on the reversal flow in the TSR especially during the 2010s. Our results indicate that increased dam operations led to a two-fold reduction in annual volume of both inflow and outflow through the TSR in the 2010s compared to prior decades. Further, the results suggest that even though the dam-induced changes in the mainstream Mekong flow have yet to reach a critical point of hydrologic regime shift, the alterations in TSL hydrology are substantial. The recent acceleration in the reduction of inflow and outflow volumes also points to a potentially dramatic shift in TSL hydrologic regime if the current pace of dam development continues.

In terms of lake inundation dynamics, the seasonally inundated area in the outer periphery of the TSL is highly sensitive to both climate variations and dam operations. As noted above, our findings suggest that, according to the NAT simulations, there has been a substantial variation in climate in the most recent decades (2000-2016) compared to the prior period (1979-1999). The impact of these climate variations is especially noticeable in the outer periphery of the lake, evidenced by a large alteration of annual inundation period (up to one month increase or decrease). In addition, our study also highlights that the impacts of dams on the outer area of the TSL have steadily increased since the 1980s, with the 2010s seeing a 15 days reduction in inundation duration between in DAM simulation compared to the NAT.

In contrast, dams increased flood occurrence in the inner areas around the permanent water body of the lake over the last four decades, suggesting that dams have been fundamentally altering the flood pulse rhythm through counterbalancing effects during both flood and dry seasons. These results indicate that there have already been observable impacts of dam-induced altering of the lake's inundation dynamic and there are clear linkages to the dampening (enhancing) of peak (low) flow of the Mekong flood pulse. Regarding the magnitude of change in flood occurrence during the 2010s (Fig. 2-7d), our results are comparable to the dam-induced changes in flood occurrence under 20-30% dampening of mainstream Mekong flood peak (Pokhrel et al., 2018b), which imply that the transition toward a ceased reversal of the TRS flow and a more drastic transformation of TSL inundation dynamics is likely if the alteration of Mekong flow is further increased by new dams.

Moreover, our results also highlight that the countering effects of dam operations on the lake in the 2010s are not only substantially higher than previous decades in terms of decadal average but also monthly average especially on the total lake inundated areas. By comparing the monthly inundated area in each decade (Fig. 2-8), our study shows that there is a relatively monotonous trend of increase over the decades presented between February and July. However, from August to December, the magnitude of dam impact in 2010s on reducing the lake inundated area is evidently much higher than in the previous decades. Considering that the 2010s is the driest decade of the analysis period with evidently lower natural inflow and lake water levels (Fig. 2-4), the climate condition of this decade has amplified the dam impacts. While this may imply that the Mekong dams could potentially mitigate drought impacts in the TSL by increasing its inundated area during the dry season, there may be broader implications due to the alteration of the annual flood dynamics. Overall, dam-induced changes in the Mekong flood pulse have been increasingly weakening the seasonal fluctuations of total inundated areas in and around the TSL, which have important implications on socio-ecological systems and local communities.

As is true across the Lower Mekong River Basin (Intralawan et al., 2019), the social and ecological effects of dam development on the Tonlé Sap will be significant and highly uneven, creating opportunities for some and threatening the livelihoods and food security of others. The dam-induced dampening of the TSL's flood pulse imperils fish populations and the people who depend on them. Elevated dry season water levels threaten the forests surrounding the lake, which will have "a notable impact on sedimentation processes, ecosystems and aquatic productivity" (Keskinen et al., 2015). And the reduced extent and duration of wet season flooding limit spawning and feeding possibilities for fish, leading to reductions in "mean body size, fecundity, survival, and ultimately catches," especially of large species (Halls and Hortle, 2021). While further study of the relationship between hydrological changes and fish populations is needed, recent reports of dramatic fish catch declines—as high as 31% between December 2019 and December 2020 according to a recent government report (Chanvirak., 2020)—merit attention in a country where "up to 80% of all animal protein consumption…comes from fish and other aquatic animals, and [and where domestic] fisheries contribute considerably to regional food security thanks to fish migration and fish export" (Keskinen et al., 2012). While aquaculture production is offsetting the decline in capture fisheries to some degree, it is likely that those who benefit from aquaculture are in most cases not the same people whose livelihoods and food security are most negatively affected by declines in capture fisheries (Intralawan et al., 2019).

The dampened flood pulse is also changing the agricultural landscape and possibilities for farmers, and again, the effects will be uneven. While some in the upper floodplain may see the benefits of land no longer flooded in the wet season, thus opening possibilities for irrigated agriculture and tree crops, those in the lower floodplain may experience the loss of arable land due to higher dry season water levels (Keskinen et al., 2015). And the reduced extent and duration of wet season floods, along with the replenishing sediment they bring, "reduces the potential for flood-recession rice" (Cramb, 2020), a cornerstone of livelihoods and food security in Lower Mekong floodplain communities for centuries (Fox and Ledgerwood, 1999). Importantly, these changes are occurring within the context of rapid and inequitable agrarian transformation, characterized by dispossessory Economic Land Concessions (Beban et al., 2017; Schoenberger and Beban, 2018) and a recent uptick in relocations of communities on the lake, further complicating the future for farmers, fishers, and communities in the Tonlé Sap Basin.

We note that for a more comprehensive analysis of the lake's hydrological dynamics, all drivers that have potential impacts other than climate and dam operations should be considered, including detail of changes in riverbed morphology, land use, land cover, among others. Those drivers have been considered to remain unchanged throughout the study period due to lack of relevant, basin-wide information that can be used in our model. Further, our hydrodynamic model and generic dam operational rules might not have fully captured the complex dynamics of real-world reservoir operation due to limitation in available information and current computing capacity. However, the results presented in this study contribute to the understanding of the lake's hydrological shift in recent times and are fundamental for the quantification of climate variability and dam operations impacts.

2.5 Conclusion

In this study, the effects of altered mainstream Mekong flood pulse caused by upstream dams on the shifts in hydrologic balance and inundation dynamics of the TSL are quantified. To the best of the authors' knowledge, the study is the first to directly attribute the changes in river flow and flood dynamics of the lake to climate variability and dam operation by using a hydrological-hydrodynamic modeling system that explicitly simulates dam operation. We find that while climate variability has been a key driver of the inter-decadal variabilities in the lake's hydrology, the Mekong dams have exerted a growing influence over time—more pronouncedly after 2010—on the Mekong flood pulse, the TSR flow reversal, and TSL water balance and its inundation dynamics. Results indicate that even though the overall water balance of the mainstream Mekong has remained relatively unaltered by dams, its flood pulse has been dampened through ~7% reduction in the peak discharge in the 2010s compared to just 1-2% during 1979-2009 period, leading to a similar impact on the peak inflow from the Mekong to the TSL. It is found that during the 2010s, dams caused a reduction in the volume of annual inflow from the Mekong into the TSL by 10-25%, reducing the lake's peak water level by ~3% (~23cm). These shifts in the lake's water balance led to a reduction in the duration of annual inundation in the lake's periphery by ~15 days (~4% of flood occurrence), effectively shrinking the lake's seasonally inundated areas. Further, there is a comparable magnitude of reduction in annual inflow and outflow volume of the TSL through the TSR, which suggests that the dams have caused a more noticeable shift in the lake's water balance by minimizing its annual interaction with the mainstream Mekong in the 2010s than in the previous decades. Comparison of decadal-average inundated areas of the TSL suggests that during the 2010s, inundated areas decreased (increased) most substantially by ~245 km^2 or ~3% (~270 km^2 or ~6%) in August (April), essentially dampening the lake's seasonal inundation dynamics. Overall, the alterations of the TSL's hydrologic balance and inundation dynamics by the Mekong dam operation in the 2010s have far exceeded the impacts in prior decades, indicating a continued—and potentially an accelerated—impacts of Mekong dams on the TSL. The results should be interpreted with caution because they likely contain uncertainties arising from various sources including climate forcing data, model parameters, and the dam operation scheme, among others. Despite these limitations, the findings echo many growing concerns from a range of diverse stakeholders within and across the region regarding the adverse and multifaceted impacts of large dams in the MRB. To this end, our results offer novel and important insights for improved transboundary water management, water infrastructure development, fisheries conservation, riparian livelihood protection and overall decision making in light of rising concerns about the adverse and growing impacts of large dams in the MRB. The research framework presented could also be useful to climate and dam induced hydrologic shifts in other river basins.

Chapter 3. Evolution of river regime in the Mekong River basin over eight decades and role of dams in recent hydrologic extremes

3.1 Introduction

A consistent pattern of river regimes is crucial in sustaining healthy hydrological and ecological systems in river basins (Botter et al., 2013; Bunn & Arthington, 2002; Poff et al., 2015b). However, climatic and human drivers have been dramatically altering flow regimes in many global regions (Gudmundsson et al., 2021; Haddeland et al., 2014). For example, hydrologic extremes such as severe floods and droughts, which are being intensified by climate change (Calvin et al., 2023; Hirabayashi et al., 2010; Oki & Kanae, 2006a; Pokhrel et al., 2021b), are profoundly altering the hydrologic and hydrodynamic rhythms globally (Best, 2018; Grill et al., 2019; Nilsson et al., 2005a). Such intensified climate extremes are causing more catastrophic floods and droughts, especially in densely populated regions with high flood-drought risk such as Southeast Asia (Lauri et al., 2012; Smajgl et al., 2015; Try et al., 2020; Västilä et al., 2010a; S. Wang et al., 2021). Humans have been using water infrastructures (e.g., dams) to reduce risks from such hydrologic extremes and better manage water resources. The construction of tens of thousands of dams globally (Lehner et al., 2011; Mulligan et al., 2020; Zhang & Gu, 2023a) has greatly benefited our societies in reducing flood risk (Boulange et al., 2021b); however, dams have been highly controversial (Flaminio et al., 2021; Graf, 1999) because large dams and their reservoirs fundamentally alter natural river regimes by redistributing water seasonally, causing detrimental ecological impacts (Best, 2018; Dethier et al., 2022; Ziv et al., 2012). Yet, despite a slowdown in dam construction or even removal of existing dams in regions such as North America (Bednarek, 2001; Bellmore et al., 2017), dam building is booming in other regions such as the Mekong, Amazon, and Congo River basins (Winemiller et al., 2016; Zarfl et al., 2015).

In the Mekong River Basin (MRB), the alteration of river regime was historically small, at least in terms of mainstream Mekong flow (P. Adamson & Bird, 2010; P. T. Adamson et al., 2009; Grumbine & Xu, 2011a); however, the acceleration in dam construction in the recent past and associated management of land and water systems (Cho & Qi, 2021, 2023) have led to rapid increase in the alteration of river flow and flood dynamics (Arias, Piman, et al., 2014; Chua et al., 2021; H. Dang et al., 2022; T. D. Dang et al., 2016). Being driven primarily by the Asian Monsoon, the MRB's hydrological rhythm is characterized by high, and rather unpredictable, seasonal variability (P. T. Adamson et al., 2009; Delgado et al., 2010b; J. Wang et al., 2022). Yet, the pattern of MRB's river flow seasonal cycle is remarkably consistent with a single, concentrated annual wet season which, on average, features throughout its 795,000 km^2 basin between approximately late June to early November (P. T. Adamson et al., 2009; Kummu & Sarkkula, 2008; Chua et al., 2021; Västilä et al., 2010). This leads to a prolonged flooding period in many parts areas of the Lower MRB, which is also known as the "flood pulse" (Pokhrel & Tiwari, 2022). During the remainder of the year, river flow gradually reduces to less than 10% (sometimes 5%) of its flood peak (P. T. Adamson et al., 2009). Additionally, the MRB has a distinct flow-reversal mechanism in the Tonle Sap River, whereby water flows into the Tonle Sap Lake (TSL) in Cambodia from the Mekong mainstream during the wet season, dramatically increasing the lake's size (by ~80%) (H. Dang et al., 2022; Kummu et al., 2013; Teh et al., 2019); the lake drains in the dry season, leading to a reversed flow in the Tonle Sap River (TSR) and supplying water to the Mekong Delta (MD). Through this mechanism, the lake acts as a natural detention reservoir, creating a unique flood characteristic where areas between the TSL and MD are partially inundated for many months each year.

Owing to the unique and cyclic rhythm of the Mekong flood pulse, the river-floodplain ecosystems and local communities of the Lower MRB have been in harmony with the annual timing of this flood pulse. This flow rhythm supports fish migration and breeding including the seasonally flooded areas of the TSL (Arias et al., 2013; Baran & Myschowoda, 2009; Orr et al., 2012; Yoshida et al., 2020; Ziv et al., 2012). Simultaneously, the flood pulse also brings rich nutrients each year in the form of sediment and a large volume of water to the floodplains in the areas between TSL and MD, which is critical to rice production. As a result, Cambodia has been ranked among the top countries for inland fishery production (Chea et al., 2023) while Vietnam is among the top rice exporters globally (S. Yuan et al., 2022). Additionally, the enormous water volume in combination with the mountainous topography in upstream areas is highly favorable for hydropower production, leading to the planning and construction of hundreds of dams in China, Laos, and Vietnam, especially in recent years (H. Dang et al., 2022; Shin et al., 2020). While an increased number of dams could be beneficial for flood control, the majority of Mekong's large dams are intended for hydropower production, which prioritizes power generation over downstream flood mitigation. Furthermore, these dams are physical barriers that directly hinder local fish migration and production annually (Chowdhury et al., 2024). As such, changes in the Mekong's River regime—especially the flood pulse—caused by intensified climate extremes and accelerating human activities could lead to potentially catastrophic impacts on the region's water, food, and energy systems and critical ecosystems.

With the critical role of the Mekong, the study of its hydrological attributes has been the focal point of both regional and global research for decades. Many studies have focused on the overall long-term trends of river flow (Delgado et al., 2010b; D. Li et al., 2017) and the patterns of the Mekong flood pulse, especially its timing and water budget (P. T. Adamson et al., 2009). Others have assessed the ecological impacts of changes in this flood pulse (Arias, Cochrane, Kummu, et al., 2014). Furthermore, intensified extreme floods and droughts (Keovilignavong et al., 2021) and the role of rapid hydropower development across the MRB in recent years (J. Gao et al., 2021; Ngor et al., 2018; Pokhrel & Tiwari, 2022) have captivated the attention of many investigations, leading to an increase in studies on the impact of these events. Overall, the changes in the Mekong flood characteristics have been the subject of numerous studies (Västilä et al., 2010b; J. Wang et al., 2021b), especially on the impact of dams on river flow and inundation patterns (H. Dang et al., 2022; Pokhrel, Burbano, et al., 2018; Shin et al., 2020; W. Wang et al., 2017a) as well as other human activities (Arias et al., 2012; Kummu & Sarkkula, 2008; NG & Park, 2021).

While past studies have provided important insights into the MRB's hydrological regime, there are notable limitations and major scientific gaps. First, many previous studies have relied on observed hydrological data which is limited to only a handful of stations in the Mekong mainstream (P. Adamson & Bird, 2010; P. T. Adamson et al., 2009; Delgado et al., 2010a), with considerable temporal gaps. Remote sensing-based datasets have helped overcome this issue to a certain extent, providing enhanced spatial coverage; however, they are available only for recent decades, often at a monthly scale, and remote sensing products generally suffer from uncertainties from various sources including cloud contamination (Bryant et al., 2021; Lakshmi et al., 2023; Vu et al., 2021). As a result, there is a lack of analyses on the long-term trend of river flow across the entire MRB by using a spatially complete and temporally continuous dataset. Second, it is not possible to separate the impacts of dams from natural trends and variabilities in hydrologic extremes or the flood pulse by using only observed data for recent periods since there have been some large dams constructed in the MRB before the 1990s (H. Dang et al., 2022; Shin et al., 2020). Hydrological modeling can address this limitation; however, no studies to date have presented a full picture of the long-term hydrologic changes in the Mekong over the past century. Third, most studies on droughts in the MRB have focused primarily on the general drought indices and frequency (Y. Li et al., 2021; Lu & Chua, 2021; Tuong et al., 2021), while flood-related studies are more focused on changes only in the annual maximum flow (Chua et al., 2021; Delgado et al., 2010a; Västilä et al., 2010a), leaving critical research gaps regarding other aspects of these extreme events under the influence of both natural climate variability and dam operation.

In this study, we address the aforementioned gaps by applying a hydrodynamic model to simulate the hydrological attributes of the MRB over an 83-year period (1940-2022) and over the entire basin. We specifically address the following research questions. (1) How did the MRB's flow regime and flood pulse evolve over decadal time scales before and after the construction of major dams? (2) What are the relative impacts of dams compared to natural variability in the MRB's seasonal flows, hydrologic extremes, and inundation patterns in recent years? We address these questions by (a) examining the regional trend in river flow (i.e., annual total, maximum, and minimum) per decade across the MRB, and (b) attributing the observed trends and variabilities to natural variation and dam operation by comparing seasonal timings, flow volume and extreme conditions between simulations with and without dams.

3.2 Data and Methodology

3.2.1 Data

Observed river flow and water level data used for model validation (see Sect. 3.3.1) at thirteen gauging stations on the Mekong mainstream (Fig. 3-1) are obtained from the Mekong River Commission (MRC). These stations are selected considering (i) broad spatial coverage across the MRB and (ii) availability of at least 5 years of continuous observational data for both river flow and water level. Considering that there are temporal gaps in the observed dataset, model performance metrics were calculated only for periods for which observations are available for each station (Fig. 3-2). Additional information on the stations is provided in the supplementary information (Table 3-1).

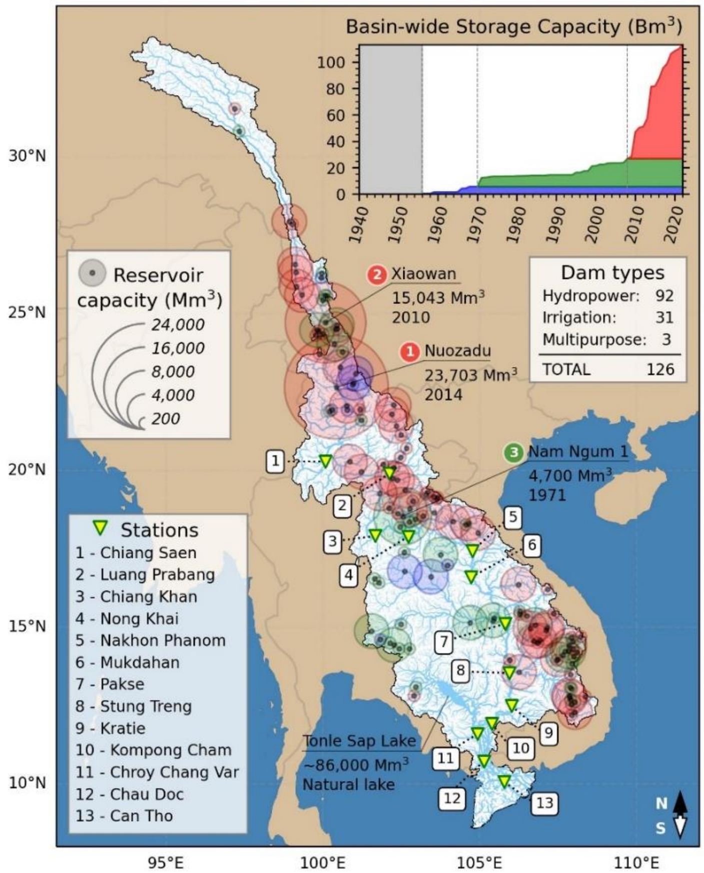

Figure 3-1. Spatial map of the MRB showing locations of the gauging stations (yellow triangles) used for validation and major dams (black dots) that are included in the simulation. Stations are numbered and their names are listed at the bottom left corner. Color coding and size of outer circles for each dam indicate the period of the dam commissioning and the reservoir's maximum storage capacity, respectively. The three largest reservoirs are numbered (color-coded circles) and named, along with their storage capacity and commissioned year; note that the color coding of the numbering for dams also indicates the period that the dam was commissioned. Tonle Sap Lake is also indicated. The background shows river network (blue lines) with thickness based on simulated long-term mean river flow from 1940 to 2022 at the 3-arcmin (~5km) spatial resolution. The basin-wide total reservoir storage capacity (billion cubic meters) for each year, color coded following dam's outer circles, is shown at the upper right inset with black dotted lines indicating the years that separate the periods.

Dam and reservoir specifications including coordinates, status (e.g., operational, planned, cancelled), year of commission, purpose (e.g., hydropower, multipurpose, irrigation, water supply), heights, storage capacity, or installed capacity are obtained from two primary sources: Research Program on Water, Land, and Ecosystem (WLE; https://wle-mekong.cgiar.org) which includes 445 dams and the Stimson Center (https://www.stimson.org/2020/mekong-infrastructure-tracker-tool/) which includes 777 dams in the MRB region. A comparison of the two datasets revealed that there is considerable inconsistency between them, including different dam specification values or duplicated dams under different variations of their names. Additionally, a substantial number of dam specifications that are critical in simulation setups such as commission year, dam height, and reservoir storage were missing. Such inaccurate dam specifications or the missing of a certain number of dams can yield inaccurate simulation results. Thus, we have synthesized the information on dam attributes for the entire MRB by building on the dam database prepared by Shin et al., 2020, and by combining additional information from WLE and the Stimson Center. Specifically, we have filled any missing values and corrected erroneous records in the merged dam database using publicly available information collected from various resources including published reports from local governments or the MRC, documents from design and construction companies, other peer-reviewed literature as well as news articles. This results in a database of 693 dams in the Mekong region. Of these, 126 dams (compared to 86 in Shin et al. 2020 and Dang et al. 2021) commissioned by 2022 are selected based on criteria similar to our previous studies (H. Dang et al., 2022; Shin et al., 2020): (1) dam height is at least 15 m (≥15 m), (2) storage capacity is over 1 million cubic meters (Mm^3), and (3) energy generation capacity is over 100 Mega Watts (MW). The location of these dams is shown in Fig. 3-1, and more information on dam specifications can be found in the supplementary information (Table 3-2).

Table 3-1. Selected hydrological monitoring stations.

No.	Name	Lat	Lon	Discharge		Water level	
				Start	End	Start	End
1	Chiang Saen	20.2741	100.0885	1/1/1960	9/19/2022	4/30/1960	9/19/2022
2	Luang Prabang	19.8928	102.1342	1/1/1939	12/31/2018	1/1/1960	9/19/2022
3	Chiang Khan	17.9003	101.6699	1/1/1967	9/19/2022	1/1/1965	9/19/2022
4	Nong Khai	17.8814	102.7322	1/1/1969	9/19/2022	1/1/1965	9/19/2022
5	Nakhon Phanom	17.4254	104.7739	1/1/1924	9/19/2022	4/1/1972	9/19/2022
6	Mukdahan	16.5828	104.7332	1/1/1923	9/19/2022	1/1/1960	9/19/2022
7	Pakse	15.0998	105.8132	1/1/1923	9/19/2022	1/1/1960	9/19/2022
8	Stung Treng	13.5325	105.9502	1/1/1910	9/19/2022	1/1/1910	9/19/2022
9	Kratie	12.4814	106.0176	1/1/1924	9/19/2022	1/8/1933	9/19/2022
10	Chroy Chang Var	11.5874	104.9384	1/1/1960	12/31/2002	1/1/1960	12/31/2012
11	Kompong Cham	11.9110	105.3841	1/1/1960	12/31/2002	1/1/1930	9/19/2022
12	Chau Doc	10.7053	105.1335	1/1/2001	12/31/2007		
13	Can Tho	10.0529	105.7871	1/1/2001	12/31/2007	4/1/1979	9/19/2022

Table 3-2. Selected dams for CaMa-Flood-Dam simulations and their attributes.

No.	**Project name**	**Lat**	**Lon**	**Purpose**	**COD**	**Height (m)**	**Total storage (FSL, Mm3)**
1	A Luoi	16.20	107.16	HPD	2012	49.5	
2	Battambang 1	12.80	102.91	MPD	2018	56.8	193.43
3	Bien Ho	14.06	108.00	ID	1983	21	42
4	Buôn Kuốp	12.53	107.93	HPD	2010		14
5	Buon Tua Srah	12.28	108.04	HPD	2009	80	522
6	Chulabhorn	16.54	101.65	HPD	1972	70	165
7	Cibihu	26.13	99.96	ID	1956		93.22
8	Dachaoshan	24.02	100.37	HPD	2003	111	940
9	Dahuaqiao	26.31	99.14	HPD	2019	106	293
10	Dak Doa	14.18	108.11	HPD	2010	20	29.13
11	Dak N'Teng	12.20	107.93	HPD	2011	31	25.49
12	Dak Psi 5	14.66	107.94	HPD	2012		3.53
13	Dak Wi	14.54	107.97	ID	1977		26.2
14	Dak Yen	14.29	107.98	ID	2008	22.5	6.45
15	Don Sahong	13.94	105.96	HPD	2020	22.5	25
16	Dong'erhe	23.08	101.06	ID	1959	26.43	1070
17	Dray H'Linh 1	12.67	107.91	HPD	1990		1
18	Ea Kao	12.61	108.04	ID	1983	17	17.74
19	Ea Sup	13.07	107.89	ID	1980	10	5.55
20	Ea Sup Thuong	13.03	107.93	ID	2004	26	146.94
21	ErChahe	24.44	99.86	HPD	2008	46	10.92
22	Gongguoqiao	25.59	99.34	HPD	2012	105	316
23	Guodazhai	24.30	99.78	ID	2017	83.5	50.93
24	GuoDuo	31.53	97.19	HPD	2015	93	82.72
25	Haixihai	26.28	99.97	ID	1995	21	62
26	Hoàng Ân	13.82	107.95	ID	1976	20	6.9
27	Houay Ho	15.06	106.76	HPD	1999	79	3530
28	Houay Lamphan	15.36	106.50	HPD	2015	75.6	141
29	Hua Na	15.13	104.70	HPD	1995	17	
30	Huai Kum	16.41	101.79	HPD	1980	35.5	22
31	Huai Luang	17.37	102.60	ID	1984	12.5	113
32	Huangdeng	26.56	99.12	HPD	2019	203	1613
33	Jinfeng	21.59	101.23	HPD	1998	45	19.48

Table 3-2 (cont'd)

No.	Project name	Lat	Lon	Purpose	COD	Height (m)	Total storage (FSL, Mm3)
34	Jinghong	22.05	100.77	HPD	2008	108	
35	Jinhe	30.81	97.33	HPD	2004	34	4.27
36	Kamping Puoy	13.08	102.97	ID	1977		110
37	Krông Buk Hạ	12.78	108.37	ID	2013	35.45	109.34
38	Lam Chamuak	15.08	102.49	ID	1992	18	26
39	Lam Nang Rong	14.3	102.76	ID	1982	23	150
40	Lam Pao	16.6	103.45	ID	1968	33	1340
41	Lam Phra Phloeng	14.59	101.84	ID	1967	50	110
42	Lam Plai Mat	14.3	102.44	ID	1988	44.6	98
43	Lam Sae	14.42	102.27	ID	1988	29.5	275
44	Lam Ta Khong P.S.	14.87	101.56	HPD	1974	40.3	310
45	Laoyinyan	24.47	99.82	HPD	1997	4.23	1092
46	Lidi	27.85	99.03	HPD	2019	75	75
47	Lower Sesan 2	13.55	106.26	HPD	2018	75	2715
48	Luozhahe 1	24.51	100.45	HPD	2016	59	14.33
49	Luozhahe 2	24.49	100.4	HPD	2017	71	3391
50	Manfeilong	21.91	100.78	ID	1958		10.64
51	Manman	21.88	100.21	ID	1970		14.5
52	Manwan	24.62	100.45	HPD	1995	132	1006
53	Mengbang Reservoir	21.92	100.28	ID	1958		17.86
54	Menglun	21.93	101.18	ID	2011		6.8
55	Miaowei	25.85	99.16	HPD	2017	139.8	660
56	Mun Bon	14.48	102.15	ID	1980	32.7	141
57	Nam Beng	19.95	101.24	HPD	2017	25.5	3611
58	Nam Chian 1	19.15	103.56	HPD	2018	93	23.12
59	Nam Houm	18.18	102.47	ID	1981	22	42
60	Nam Khan 2	19.69	102.37	HPD	2016	160	528
61	Nam Khan 3	19.75	102.22	HPD	2016	90	860.5
62	Nam Kong 1	14.54	106.74	HPD	2021	80	505
63	Nam Kong 2	14.49	106.86	HPD	2018	50	71.4
64	Nam Kong 3	14.57	106.91	HPD	2021	65	471
65	Nam Leuk	18.44	102.95	HPD	2000	51.5	185
66	Nam Lik 1	18.62	102.39	HPD	2019	36.5	6.8
67	Nam Lik 1-2	18.79	102.12	HPD	2010	103	11.13

Table 3-2 (cont'd)

No.	Project name	Lat	Lon	Purpose	COD	Height (m)	Total storage (FSL, Mm3)
68	Nam Mang 1	18.53	103.2	HPD	2017	70	16.52
69	Nam Mang 3	18.35	102.77	HPD	2005	28	49.43
70	Nam Nga 2	20.18	101.92	HPD	2017	47	157.7
71	Nam Ngiep 1	18.65	103.55	HPD	2019	167	1192
72	Nam Ngiep 2	19.3	103.35	HPD	2015	70.5	163
73	Nam Ngiep 3A	19.24	103.28	HPD	2014	30	
74	Nam Ngum 1	18.53	102.55	HPD	1971	75	4700
75	Nam Ngum 2	18.76	102.78	HPD	2013	181	3590
76	Nam Ngum 5	19.36	102.62	HPD	2012	99	314
77	Nam Ou 1	20.09	102.27	HPD	2020	65	89.1
78	Nam Ou 2	20.41	102.47	HPD	2016	49	121.7
79	Nam Ou 3	20.7	102.67	HPD	2020	72	181
80	Nam Ou 4	21.12	102.49	HPD	2020	47	141.6
81	Nam Ou 5	21.41	102.34	HPD	2016	74	335
82	Nam Ou 6	21.78	102.2	HPD	2016	88	409
83	Nam Ou 7	22.08	102.26	HPD	2020	143	1770
84	Nam Pha Gnai	19.01	102.87	HPD	2020	70	
85	Nam Pung	16.97	103.98	MPD	1965	41	165
86	Nam San 3A	19.13	103.66	HPD	2016	75	123
87	Nam San 3B	19.09	103.62	HPD	2015		11.7
88	Nam Tha 1	20.27	100.87	HPD	2019	93.65	1755
89	Nam Theun 1	18.36	104.15	HPD	2022	177	3009
90	Nam Theun 2	18	104.95	HPD	2010	48	3500
91	Nam Un	17.3	103.76	ID	1973	29.5	520
92	Nandeng	23.7	99.89	MPD	2010	89	51.49
93	Nanhe 1	24.34	100.01	HPD	2009	56.8	11.36
94	Nuozadu	22.64	100.44	HPD	2014	261.5	23703
95	Pak Mun	15.28	105.47	HPD	1994	17	0.13
96	Plei Krong	14.41	107.86	HPD	2008	65	1048.7
97	Pleipai	13.49	107.9	ID	2011	16.5	13.28
98	Sesan 3	14.22	107.72	HPD	2006	79	3.8
99	Sesan 3A	14.11	107.66	HPD	2007	35	239
100	Sesan 4	13.97	107.5	HPD	2009	74	893
101	Sesan 4a	13.93	107.47	HPD	2011	17.3	13.13

Table 3-2 (cont'd)

No.	Project name	Lat	Lon	Purpose	COD	Height (m)	Total storage (FSL, Mm3)
102	Siridhorn	15.21	105.43	HPD	1971	42	1967
103	Srepok 3	12.75	107.88	HPD	2009	52.5	219
104	Srepok 4	12.81	107.86	HPD	2011	155	
105	Theun-Hinboun	18.26	104.56	HPD	1998	27	
106	Theun-Hinboun exp.	18.3	104.64	HPD	2013	65	2450
107	Ubol Ratana	16.78	102.62	HPD	1966	35.1	2559
108	Upper Kontum	14.69	108.23	HPD	2021		145.52
109	Weiyuanjiang	23.28	100.56	HPD	2014		274
110	Wunonglong	27.93	98.93	HPD	2019	137	284
111	Xayaburi	19.25	101.81	HPD	2019	32.6	1300
112	Xe Lanong 1	16.36	106.24	HPD	2021		373
113	Xekaman 1	14.96	107.16	HPD	2016	120	3340
114	Xekaman 3	15.43	107.36	HPD	2013	101.5	141.5
115	Xekaman-Sanxay	14.89	107.12	HPD	2018	28	
116	Xepian-Xenamnoy	14.95	106.63	HPD	2019	75.5	1092
117	Xeset 1	15.49	106.28	HPD	1990	18	
118	Xeset 2	15.4	106.28	HPD	2009	26	9
119	Xiangshui	23.77	100.63	ID	1989	54	56.7
120	Xiaowan	24.7	100.09	HPD	2010	292	15043
121	Xi'er He 2	25.56	100.13	HPD	1987	37.25	0.2
122	Xi'er He 4	25.58	100.07	HPD	1971		14
123	Ximahe	22.78	100.98	ID	1956		420
124	Xinfang Reservoir	22.72	100.96	ID	1958		7.1
125	XunCun	25.42	99.99	HPD	1999	67	73.74
126	Yali	14.23	107.83	HPD	2001	65	1037.09

3.2.2 Model and simulation settings

We use CaMa-Flood-Dam (CMFD), a river-floodplain hydrodynamic model that includes an optimized reservoir operation scheme (H. Dang et al., 2022; Shin et al., 2020). This is an enhanced version of the Catchment-based Macro-scale Flood-plain model, CaMa-Flood (Yamazaki et al., 2011) version 4.0. The model discretizes the study domain into unit catchments, in which, each unit is assigned a set of river-floodplain topography parameters obtained from the MERIT Hydro dataset (Yamazaki et al., 2017) to present sub grid-scale hydrodynamic processes at ~5km (3-arcmin or 0.05°) resolution. Based on the unit's parameters and water storage, the model simulates river flow, water level, and inundated area following the local inertial and mass conservation equations (Yamazaki et al., 2013). At unit catchments where reservoir outlets (or dams) are located, the natural outflow was recalculated based on the reservoir's designed purpose as follows: (1) at irrigation or water supply dams, dam release is simulated to meet downstream irrigation demand, and (2) at hydropower, the release amount is set to optimize power generation. Due to the lack of operating priorities for multipurpose dams in this region, these dams are represented in the model in a way similar to hydropower dams. More detailed information on the implementation of the reservoir scheme can be found in our previous studies (H. Dang et al., 2022; Shin et al., 2020). Additionally, while water demand information is required for irrigation dam release calculation, there are no publicly available datasets for the MRB over the entire study period. Thus, we have applied the long-term seasonal average of the simulated irrigation demand from the HiGW-MAT model (Pokhrel et al., 2015), following our previous studies (H. Dang et al., 2022; Shin et al., 2020) as input in CMFD simulations.

CMFD simulations are driven by runoff data taken from the ECMWF Reanalysis version 5 (ERA5) global climate and weather dataset (Hersbach et al., 2020). We have selected the ERA5 dataset due to its (i) temporal completeness for our simulation period (i.e., 1940-2022) and (ii) higher spatial resolution (i.e., 0.25°) compared to other global forcing datasets used in our previous studies over the Mekong (e.g., Dang et al., 2022; Pokhrel, Shin, et al., 2018; Shin et al., 2020). This approach of using global runoff datasets for CaMa-Flood simulations has been proven to yield good model performance in major global river basins (Chaudhari & Pokhrel, 2022; Shin et al., 2021b; Tanoue et al., 2016; Yamazaki et al., 2012), especially the Mekong (H. Dang et al., 2022; Shin et al., 2020). However, initial results from ERA5 forcing indicated considerable overestimation of river flow at all stations upstream of Kompong Cham (Figs. S3-4). Thus, we applied bias correction to the ERA5 runoff dataset at basin scale as discussed in Sect. 3.2.3.

To quantify the effects of natural climate variation and reservoir operation on the MRB's hydrodynamic over the past decades, we conducted the following two simulations: (1) natural simulation without considering dams (NAT), and (2) regulated simulation by initiating dam operation from the start of their commissioned year (DAM). This results in 83 years of daily simulated river flow, water level, and flood depth for the entire MRB at the spatial resolution of ~5km (3-arcmin or 0.05°).

3.2.3 Data processing techniques and statistical measures

In climate impact studies, systematic deviations between simulated historical data and observations (precipitation, temperature, etc.) are commonly resolved by statistical and dynamical bias correction methods. However, to the authors' knowledge, studies with bias correction on runoff are scarce and uncommon because it is relatively difficult to collect runoff observations over large domains. Here, given substantial bias found in the simulated discharge when CMFD is forced with the ERA5 runoff data, we use runoff from the HiGW-MAT model—proven to yield accurate simulation results with CMFD for the MRB (H. Dang et al., 2022; Pokhrel, Shin, et al., 2018; Shin et al., 2020)—as a reference to bias correct the ERA5 runoff. We note that observed runoff data are not available for such bias correction at the basin scale and HiGW-MAT runoff could not be used because of its limited temporal coverage (1979-2016), especially for the purpose of examining extreme events in recent years. To preserve the general trend, variabilities, and extremes, while correcting the mean, standard deviation, quantiles, and frequencies of the ERA5 dataset, the Empirical Quantile Mapping (EQM) method (Mendez et al., 2020; Themeßl et al., 2012) was applied. First, the daily HiGW-MAT data were linearly interpolated from 0.5° to 0.25° to match the ERA5 resolution. Second, complete time series at each grid cell of HiGW-MAT data in the baseline period (1979-2016) was extracted to obtain its Cumulative Distribution Function (CDF). Similarly, two CDFs were obtained from ERA5 in each period (the baseline period and the remaining years). Third, values in ERA5 data during the baseline period were replaced by values with the same percentile in HiGW-MAT data. Fourth, we find the differences between HiGW-MAT and ERA5 values at each percentile in the baseline period. Then we applied these differences to the corresponding value in the ERA5 data based on their percentile from the CDF of the remaining years. The bias correction addresses the large overestimation found in the original ERA5-based results (Figs. S2-6), yielding notable improvements in the simulated river flow and water level across the MRB for periods both within (1979-2016; Figs. S3, 5) and outside (1940-1978; Figs. S4, 6) of HiGW-MAT data availability. Additionally, the results in Fig. 3-2 suggest that the combination of bias corrected ERA5 runoff and our dam scheme greatly improves the model's performance even at the daily scale. Thus, we use the results based on bias corrected ERA5 runoff for our analyses.

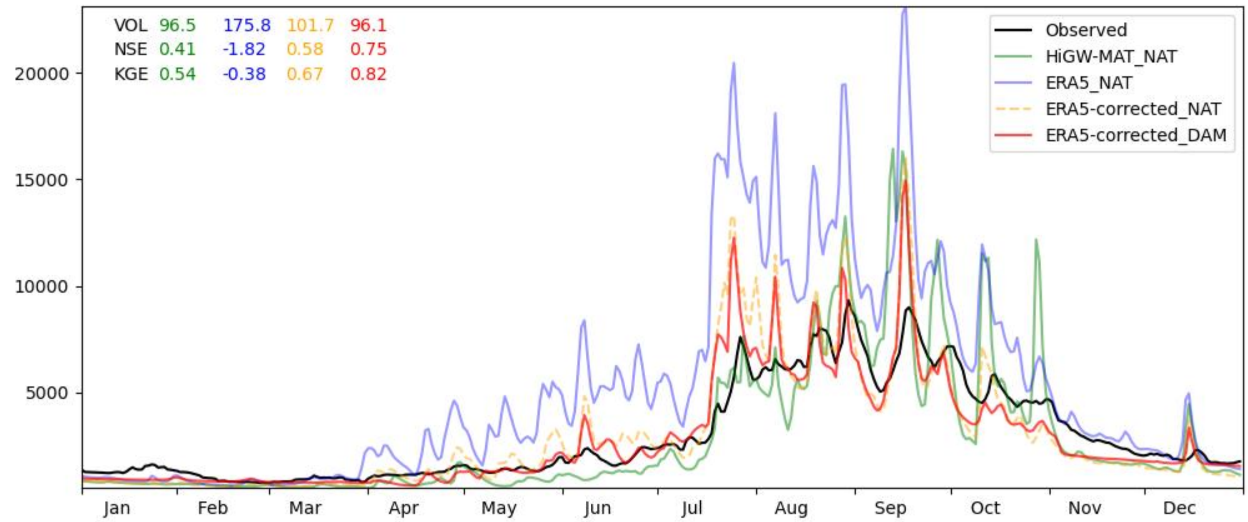

Figure 3-2. Comparison of daily observed river flow (black line) with simulated river flow with different runoff and simulation settings (color coded lines) at Luang Prabang station in 2010. Volume difference (VOL), Nash-Sutcliffe coefficient (NSE), Kling-Gupta efficiency (KGE) of each simulation are indicated in the top left.

At each grid cell, the time series of simulated river flow is analyzed to evaluate model performance, overall regional trends, and annual flood pulse characteristics. We first extracted time series data consisting of daily river flow and water level as well as total volume and maximum and minimum flow per calendar year. Daily and monthly simulated data is compared with observations using statistical measures such as volume changes (VOL), Nash-Sutcliffe coefficient (NSE) and Kling-Gupta efficiency (KGE). Then, the trend in flow at each cell was estimated using the Theil-Sen slope estimator (Gilbert, 1987), along with its statistical significance derived by applying the Mann-Kendall test (Mann, 1945). Additionally, various flood pulse characteristics, including the timing and magnitude of wet and dry season flow as well as annual extreme flows (maximum and minimum) using daily time series, were calculated. To detect the start and end of wet seasons, the long-term average river flow in the NAT simulation was applied as the season threshold following Adamson and Bird, 2010; Chua et al., 2021. Furthermore, we applied a seven-day moving average filter on the daily river flow in season timing analysis to avoid false detection of season onset due to early minor high-flow events (Fig. 3-3).

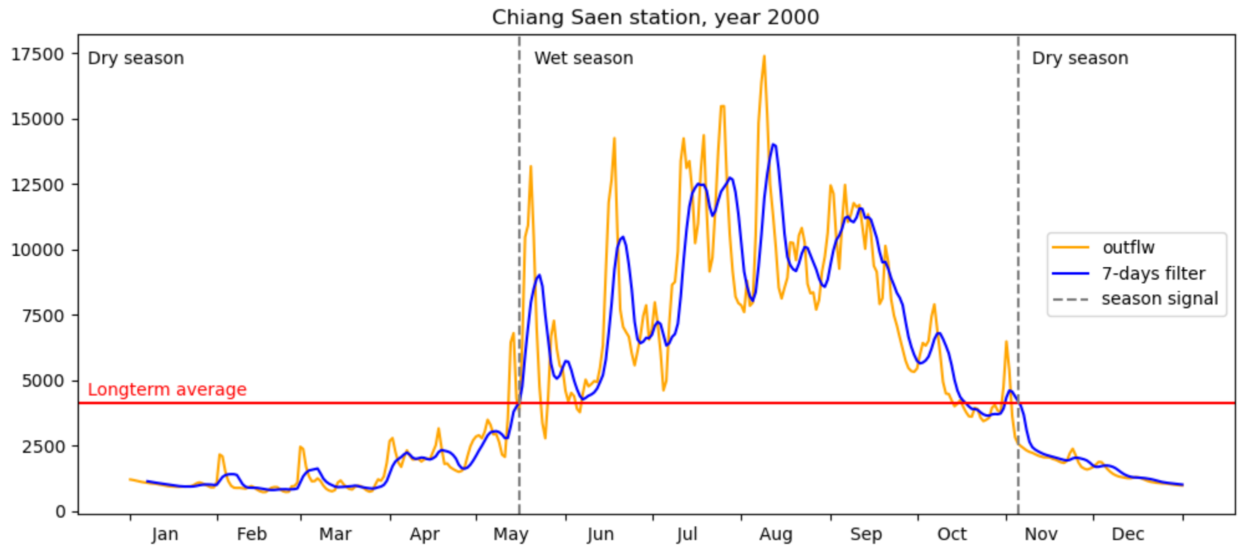

Figure 3-3. Sample of season separation after applying a 7-days moving window filter to the simulated outflow at Chiang Saen station in year 2000.

3.3 Results

3.3.1 Model performance

Results presented in Fig. 3-4—which also include statistical indicators—suggest that the model accurately reproduces the seasonal variations in river flow and water levels for most stations across the MRB. For river flow, the simulated results at all stations agree remarkably well with observations, especially given the size of the MRB and its hydrological and topographic complexities that are challenging to represent in basin-scale models. While there are small discrepancies between the simulated and observed river flow, the simulated annual volume (VOL) ranges between ~85-110% of the observed values, indicating slight overestimation (<10%) in stations upstream of Nakhon Phanom; in stations downstream of Pakse, the underestimations range from ~3% to 15%. Additionally, high NSE (0.74-0.92) and KGE (0.75-0.92) values at all stations with a wide range of observed data availability (AVL ranging from 7.4-99.7%) further confirm the accuracy of the model in capturing the natural variations in river flow. A similar observation can be made for the simulated water level at most stations where NSE and KGE values are relatively high (0.77-0.97 and 0.64-0.94, respectively) except for Pakse, Stung Treng, and Can Tho stations. The moderate performance at these stations could be attributed to uncertainties in the model's fixed parameters (e.g., channel width and depth) that are not specifically tuned as well as unaccounted human activities such as sand mining or other water infrastructure that could alter river morphology over time. The discrepancies in water levels could also be partly due to inconsistencies in the way water level is modeled and measured. For instance, the observed data are collected close to the riverbanks, which typically have a smaller difference between water surface to riverbed than the centre of the river, affecting water level readings. Considering that the river cross section is parameterized as rectangular (Yamazaki et al., 2011), simulated water level might include more discrepancies than river flow.

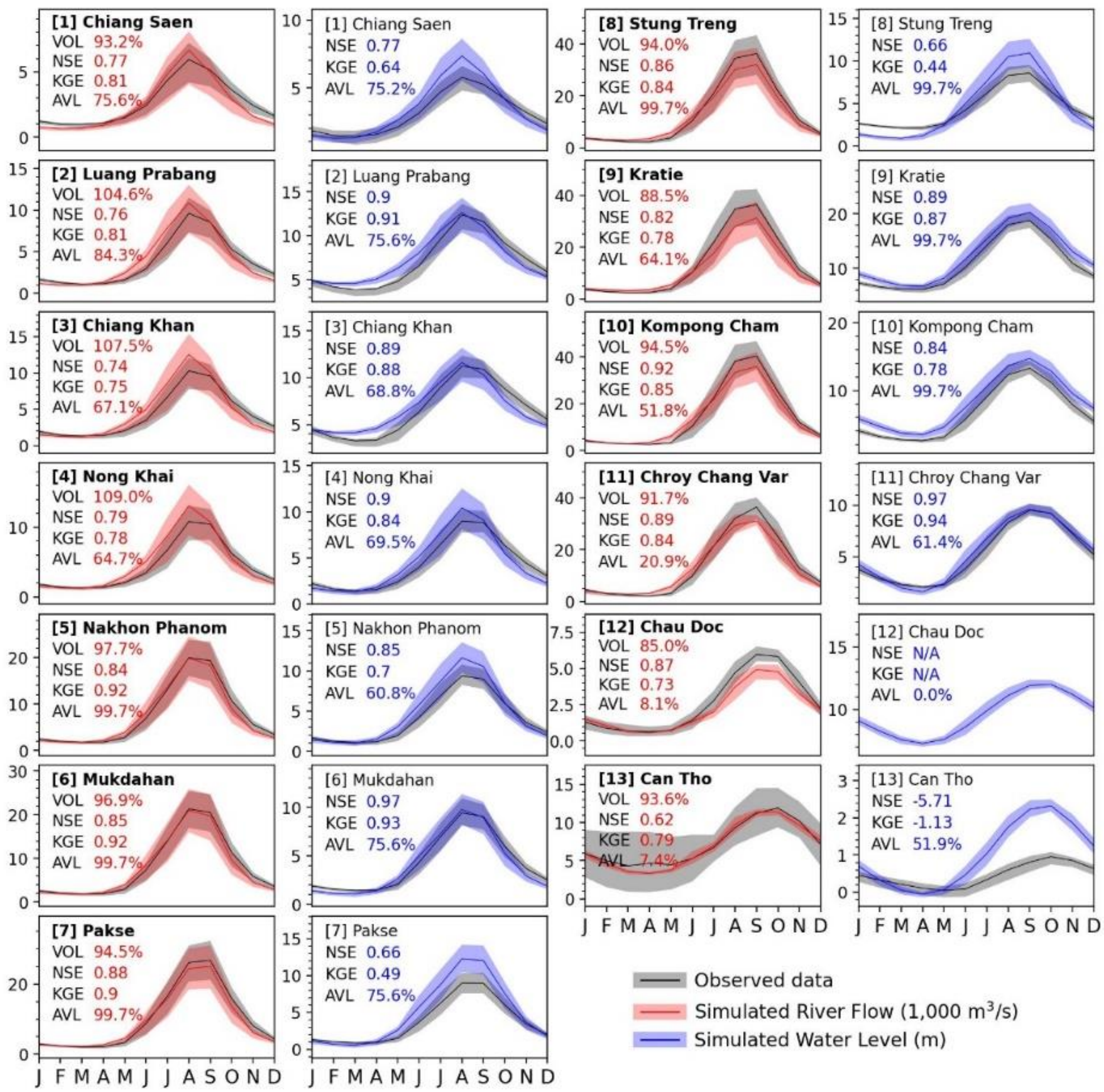

Figure 3-4. Comparison of seasonal cycle of simulated river flow (red lines) and water level (blue lines) with observations (black lines) from MRC at stations marked in Fig.1. Shadings of similar color coding indicate interannual variability presented as the upper and lower first quantiles for each month. Volume in percentage is indicated in panels with river flow validation while Nash-Sutcliffe coefficient (NSE), Kling-Gupta efficiency (KGE), and availability of observed data (AVL) in percentage are indicated in all panels.

Additional analysis on long-term trend of annual average, minimum and maximum river flow

(Figs. 3- 5-11) suggests that simulated results agree with observations at most stations with certain discrepancies especially when the detected trend is not statistically significant (p>0.05). Since the primary objective of this study is to assess the annual and decadal variations in the hydrologic regime, these minor discrepancies are not of particular concern. Overall, a good model performance over a considerably long period (i.e., eight decades) supports model application to examine long-term evolution of hydrological conditions in the MRB and quantify dam impacts in recent periods.

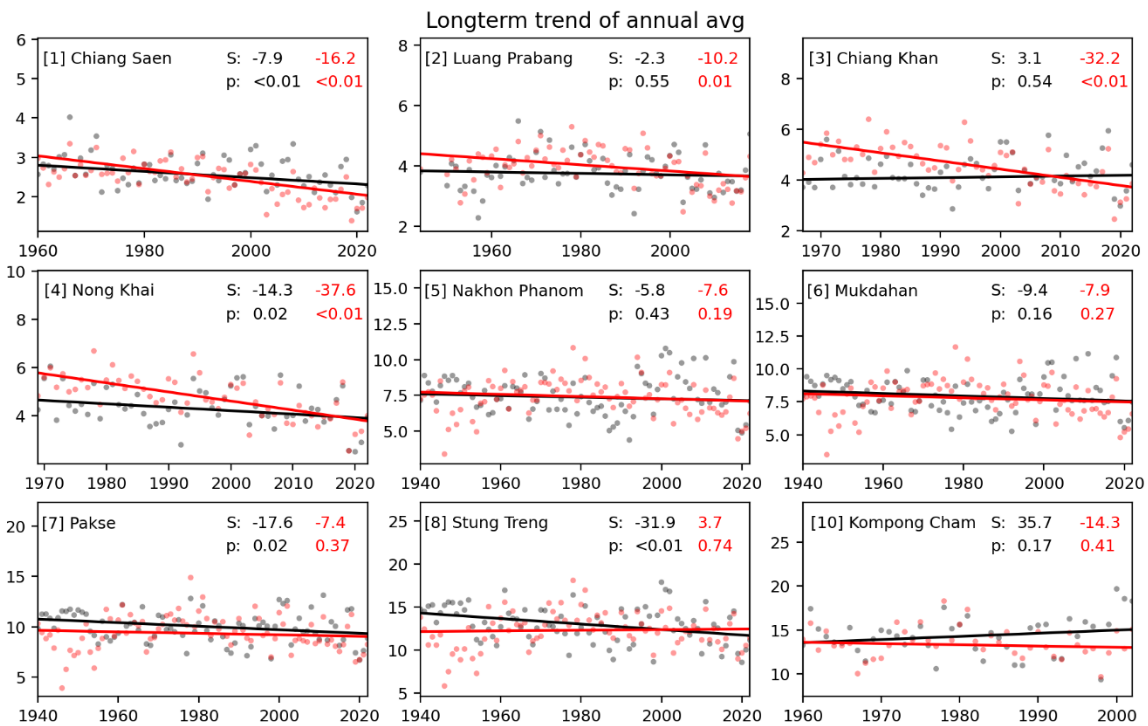

Figure 3-5. Complete time series validation of annual average river flow trend using the Theil-Sen slope estimator with its statistical significance derived by applying the Mann-Kendall test at selected stations between 1979-2022.

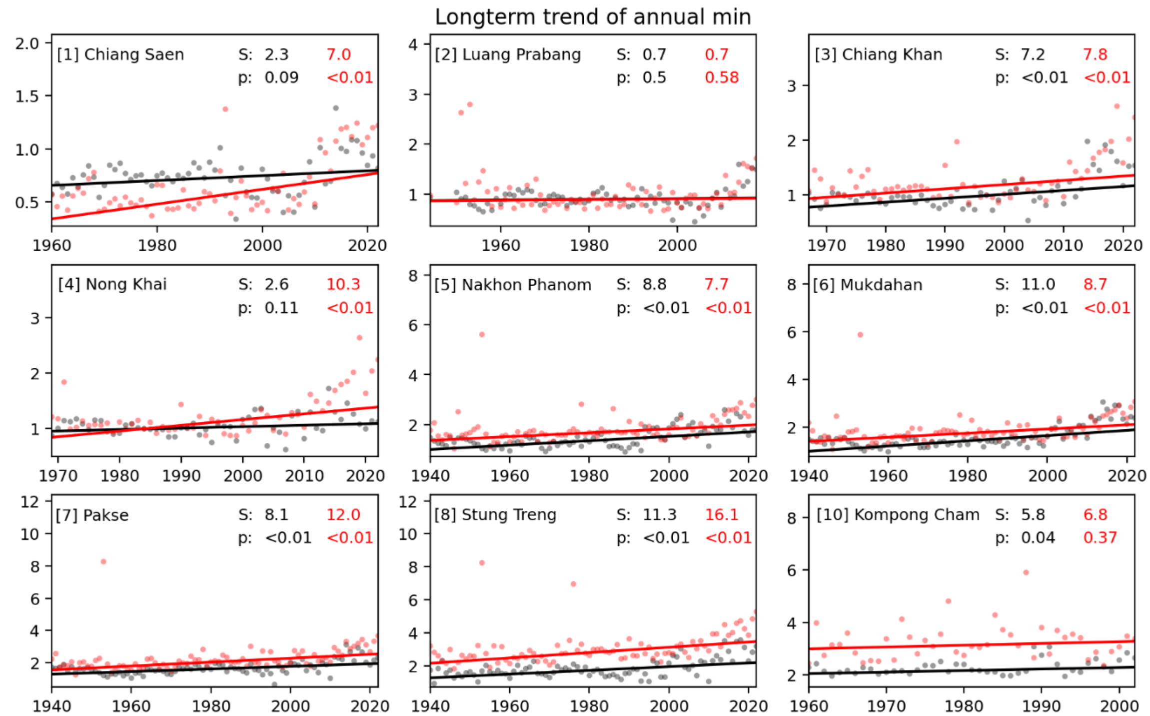

Figure 3-6. Same as Fig. 3-5 but for annual minimum river flow.

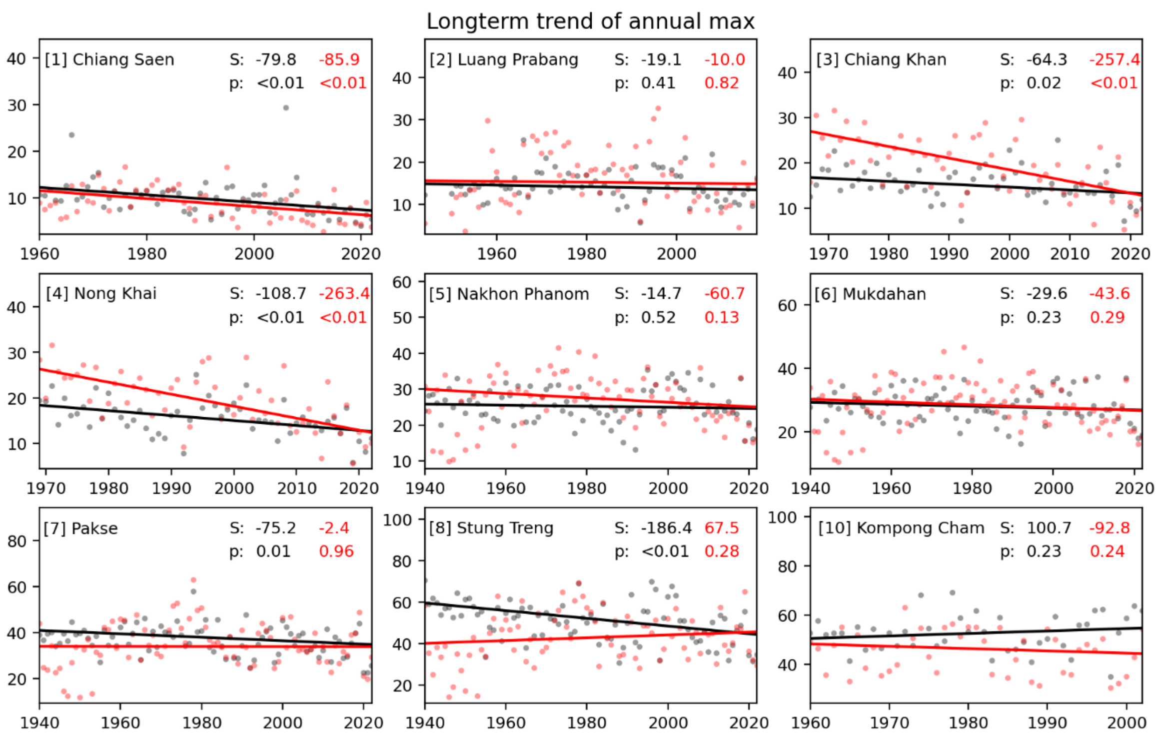

Figure 3-7. Same as Fig. 3-5 but for annual maximum river flow.

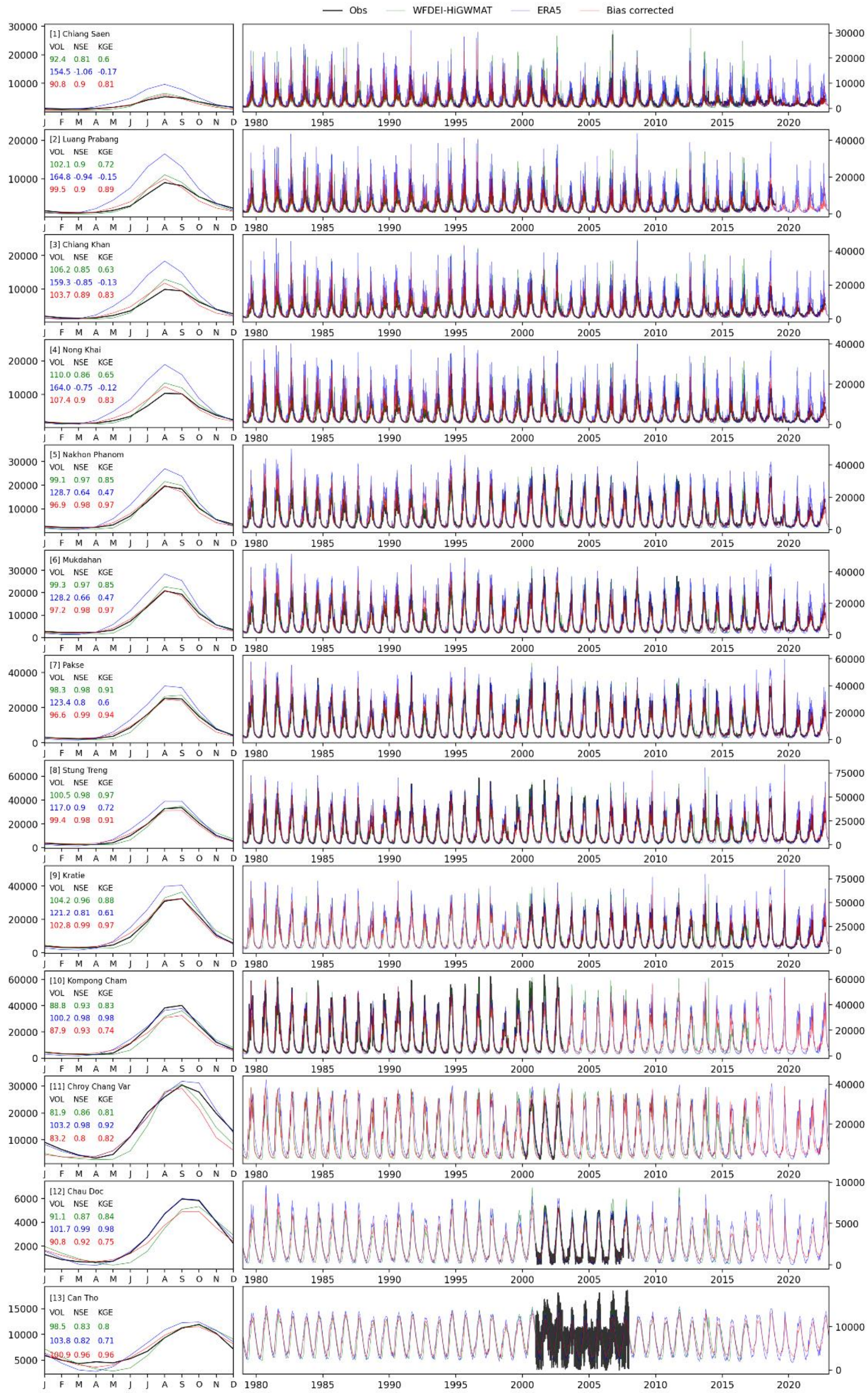

Figure 3-8. Complete time series validation of daily simulated discharge at selected stations between 1979-2022 from multiple runoff datasets. It should be noted that the simulated results of the year 1953 have been removed from further analysis due to problems caused by the ERA5 runoff dataset.

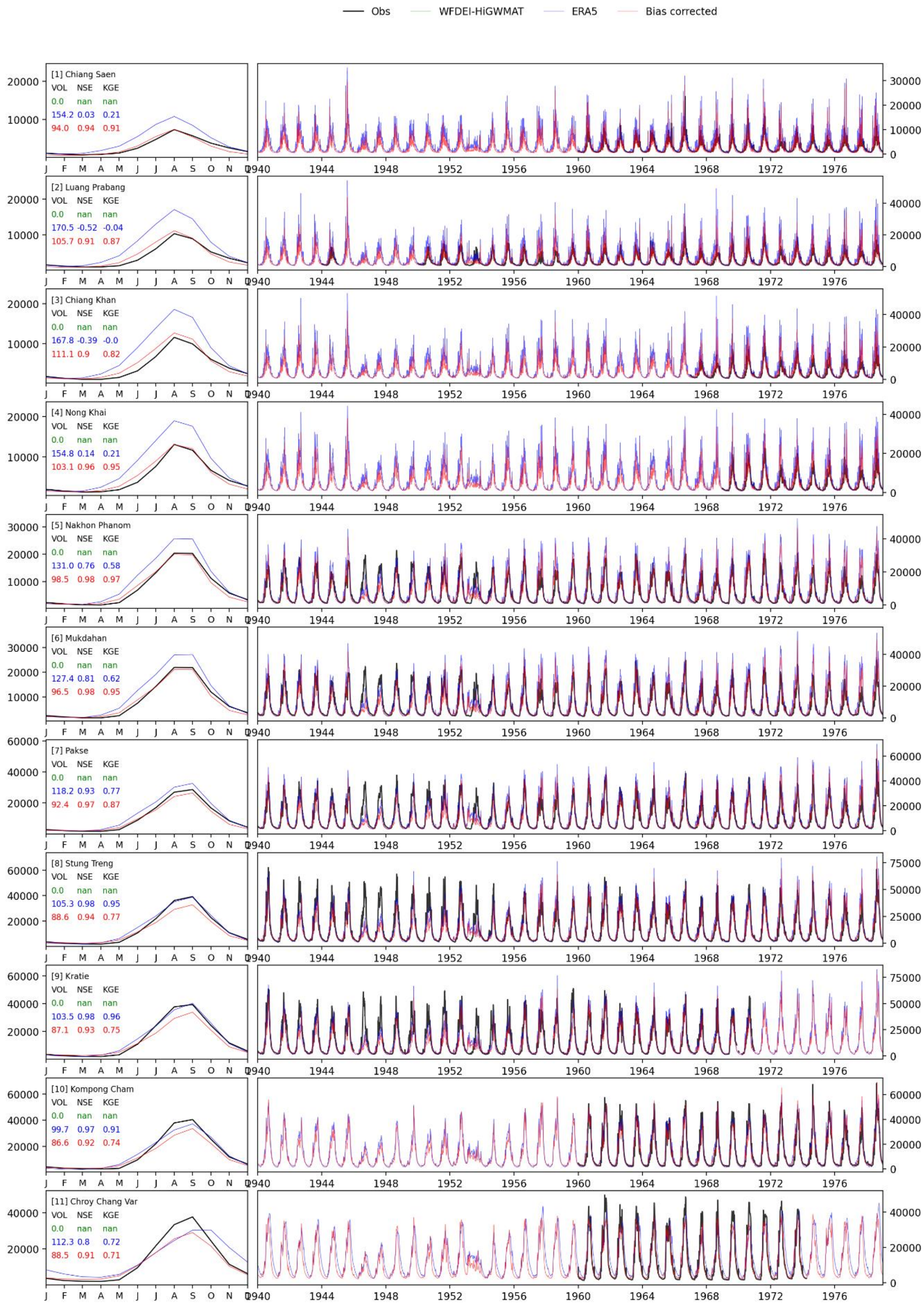

Figure 3-9. Same as Fig. 3-5 but for 1940-1978; note that HiGW-MAT simulations are not available for this period.

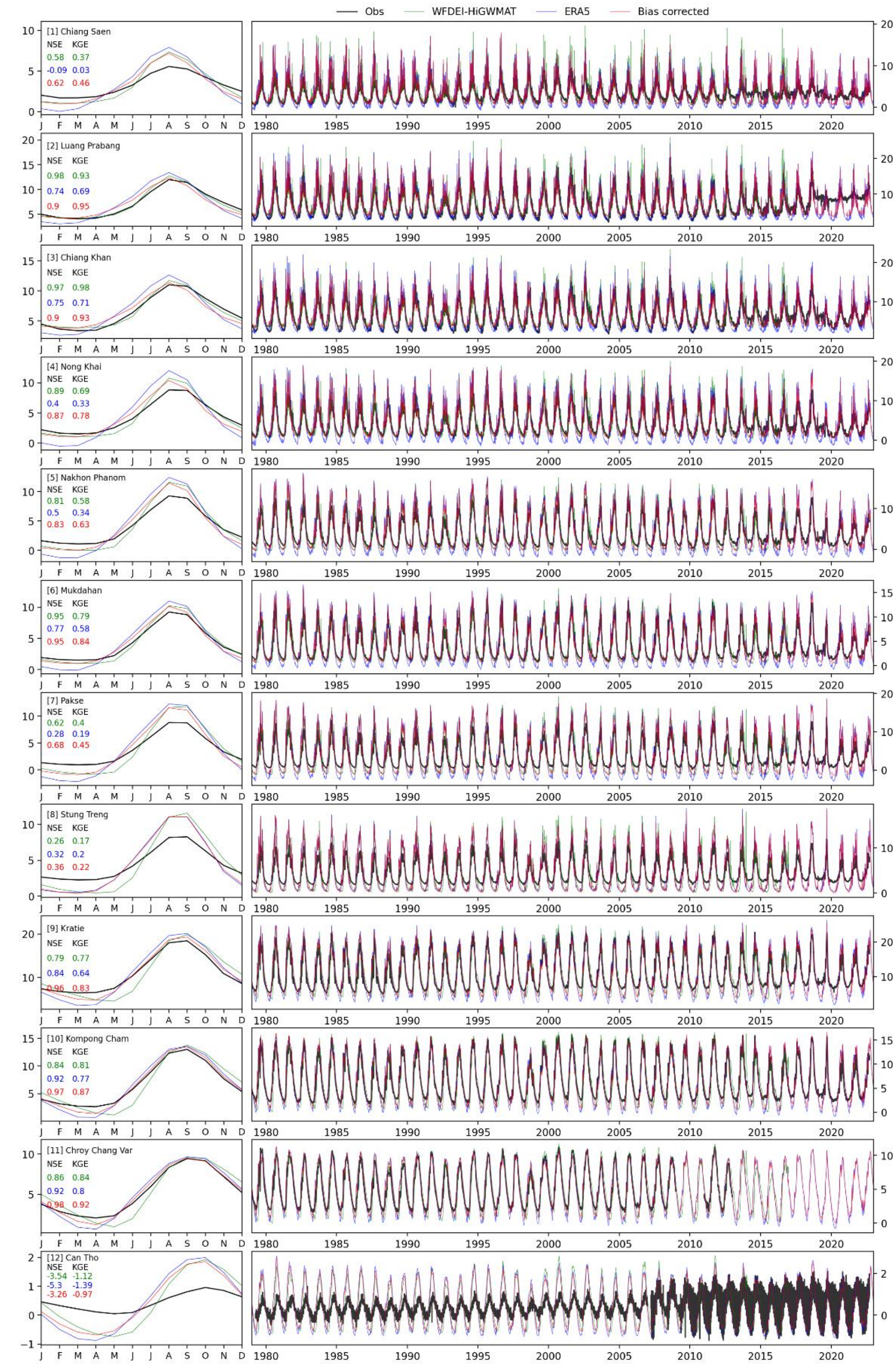

Figure 3-10. Complete time series validation of daily simulated water level at selected stations between 1979-2022 from multiple runoff datasets.

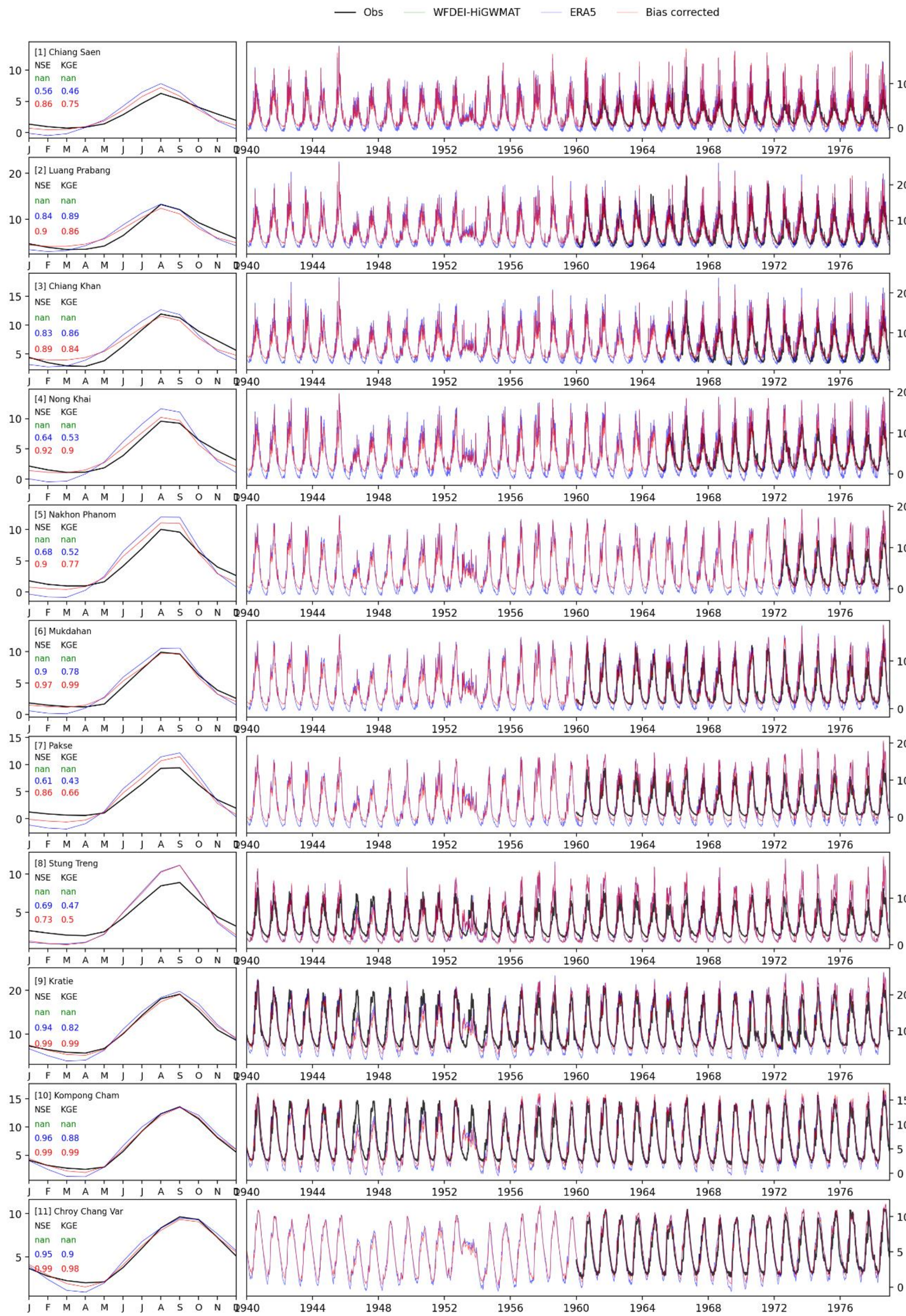

Figure 3-11. Same as Fig. 3-7 but for 1940-1978; note that HiGW-MAT simulations are not available for this period.

3.3.2 Regional trends in river flow

Our results show a readily discernible regional pattern in river flow trend across the MRB (Fig. 3-12). The annual volume, maximum flow, and minimum flow show a varied spatial pattern with a general decrease in the Lancang portion and increase in the lower portion of the MRB. In relation to mean annual volume, annual maxima, and annual minima of river flow over the 83-year period, regional trends typically vary within ±10% per decade (Fig. 3-12). Generally, the Mekong mainstream river flow is relatively stable with no distinct trend over the decades. In particular, only half of the total basin area shows a distinctly significant regional trend, mostly in the tributaries or subbasins. Local trends at the grid level range between -15% to +12% per decade for each of the flow characteristics. The spatial patterns of trends can be grouped into three main regions: a decreasing trend across all flow characteristics considered in the Upper Mekong (Lancang); an increasing but relatively mild trend in river flow in the mountainous areas of middle Mekong; and a mixed trend in the Sekong, Sesan, Srepok (3S) region in lower and Eastern parts of the basin.

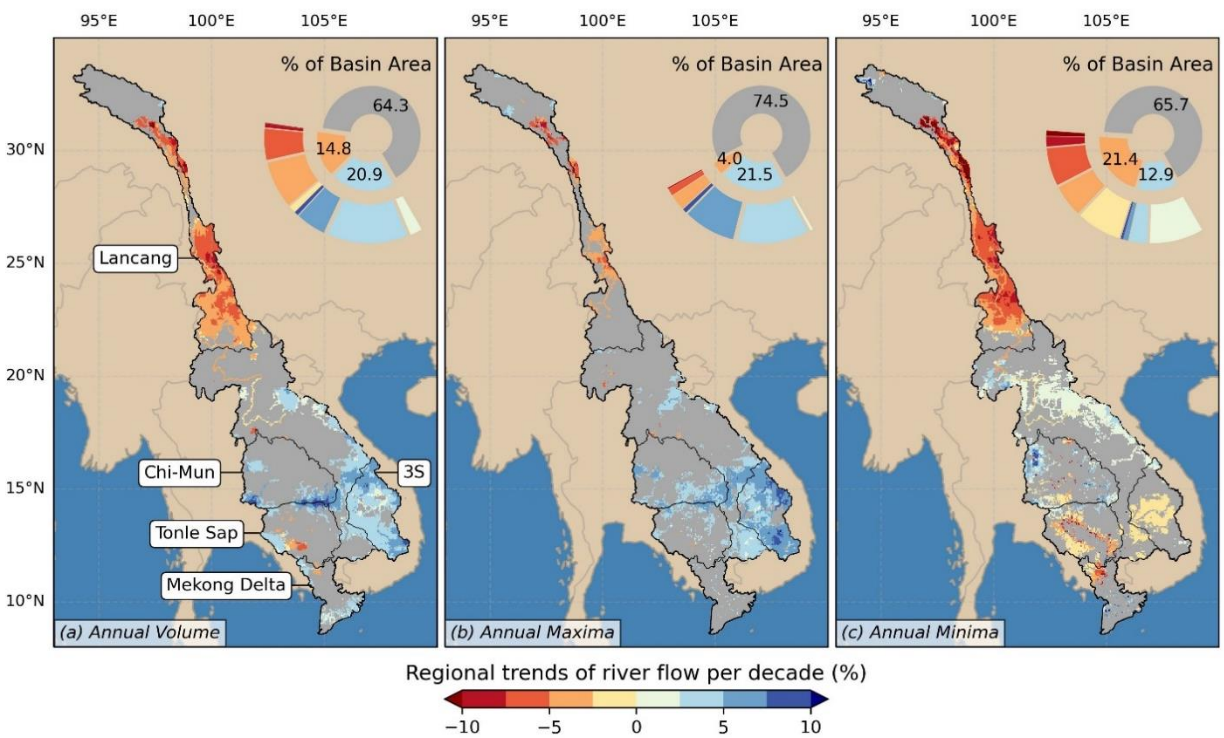

Figure 3-12. Decadal trends in simulated river flow (1940-2022), that are significant (p-value ≤ 0.05), shown for of (a) annual volume, (b) annual maxima (high flow), and (c) annual minima (low flow). Blue indicates increasing river flow, orange denotes decreasing river flow (in percent change of the long-term average values), and grey indicates areas with no significant trend. Similar color coding is applied to the inner pie chart in the top right corner, which indicates the percentage

Figure 3-12 (cont'd)

of basin areas which have respective trends. The outer semi-pie chart indicates a more detailed separation of areas with a significant trend following the color coding of the bottom color bar. Five major subbasins of the MRB including Lancang, Chi-Mun, 3S (Sesan, Srepok, and Sekong), Tonle Sap, and Mekong Mega-delta are named while their boundaries are indicated as thin black lines.

In terms of annual volume, ~36% of MRB area shows a significant trend, of which, 21% shows an increasing trend while 15% shows decreasing trend. Most areas with decreasing trend are located in the Lancang region in the upstream, especially its middle portions where the decreasing trend is more pronounced (2.5-10%). In contrast, an increasing trend in annual volume is mostly seen in the middle and lower MRB, specifically in the 3S subbasin and surrounding areas where a 2.5-7.5% increase per decade is prominent. Additionally, the region at the border between Chi-Mun and TSL regions or Southwest of Chi-Mun shows a higher increase, with values that range from 5-10% in some locations. Mild increase can be seen in the middle of MRB and some coastal areas of the MD. Additional analyses comparing the decadal difference of our simulated annual volume and the ERA5 snowfall data (Figs. 3- 13-14) suggest there is no clear linkage between a decline in annual volume to the changing snowfall pattern. However, there is a substantial resemblance in the pattern of decadal difference between ERA5 runoff, total precipitation (Figs. 3- 15-16), and annual volume (Fig. 3-13), which further confirms that the annual volume in the Lancang area is also largely influenced by rainfall instead of snowfall.

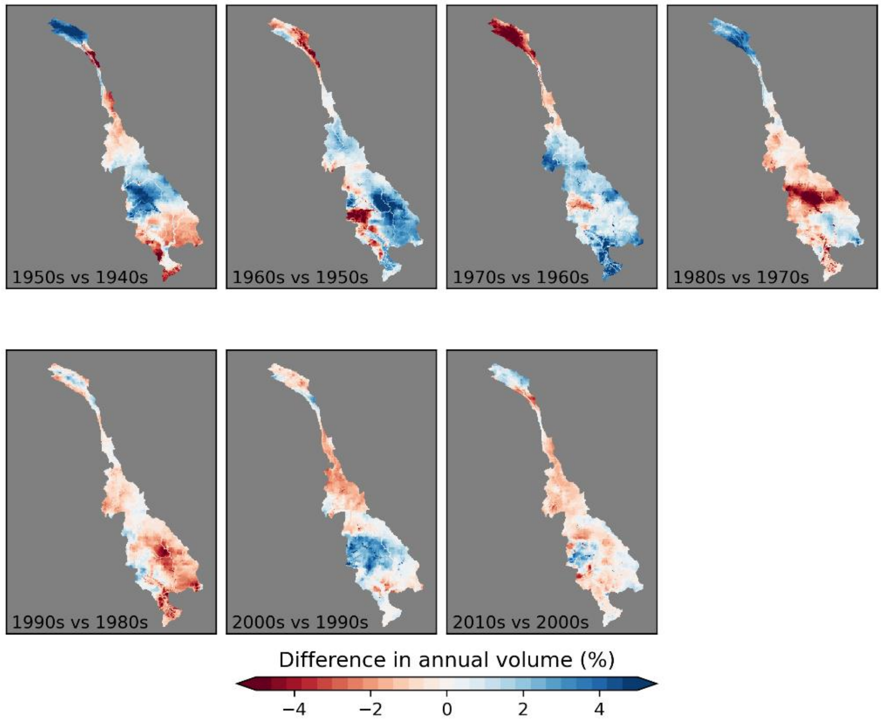

Figure 3-13. Decadal differences in CMFD simulated annual volume.

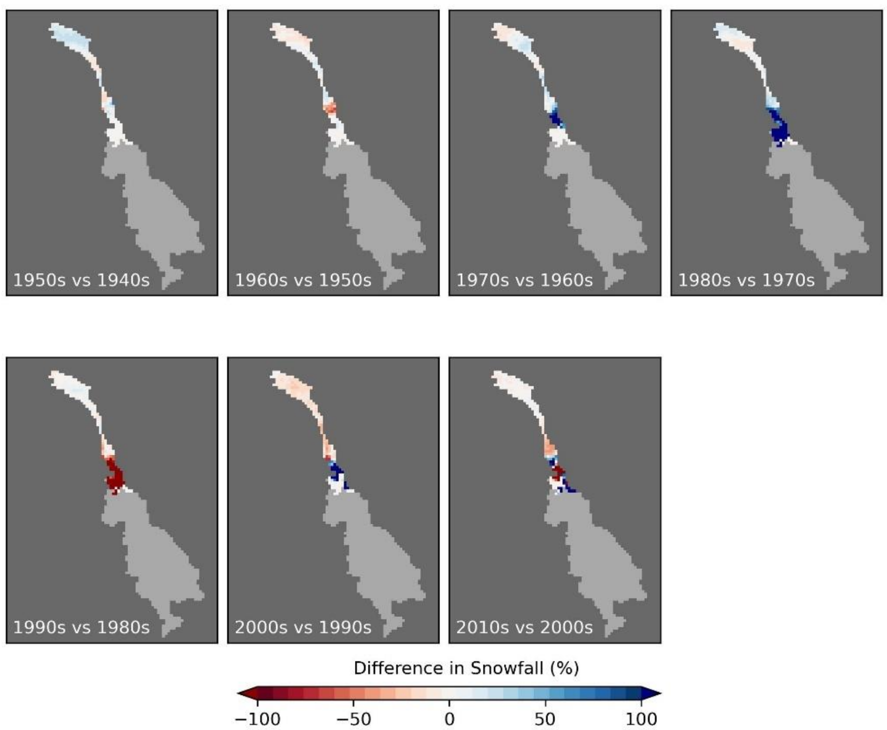

Figure 3-14. Decadal differences in snowfall from ERA5 dataset.

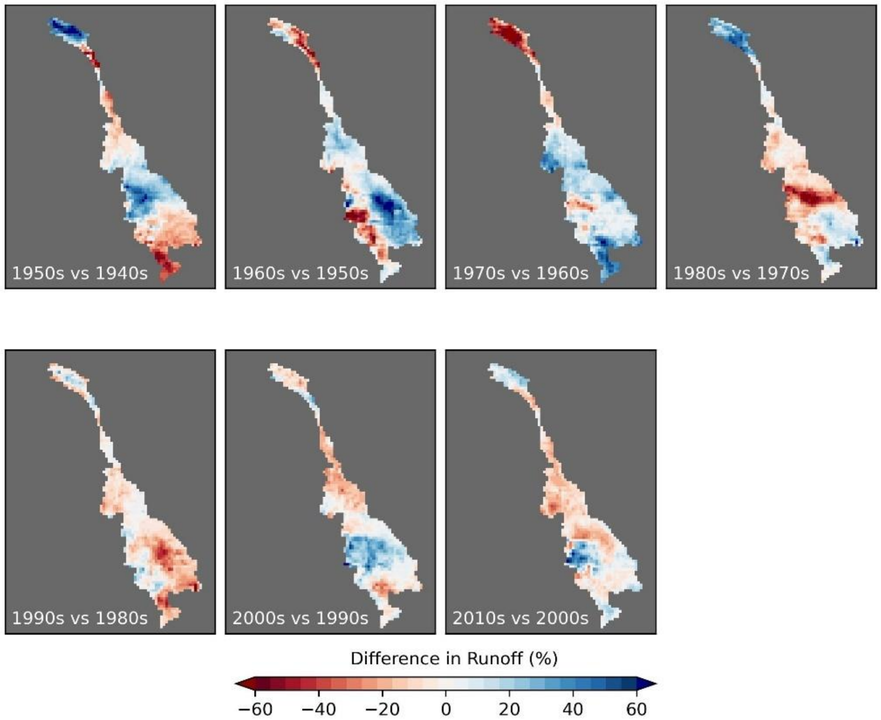

Figure 3-15. Decadal differences in runoff from ERA5 dataset.

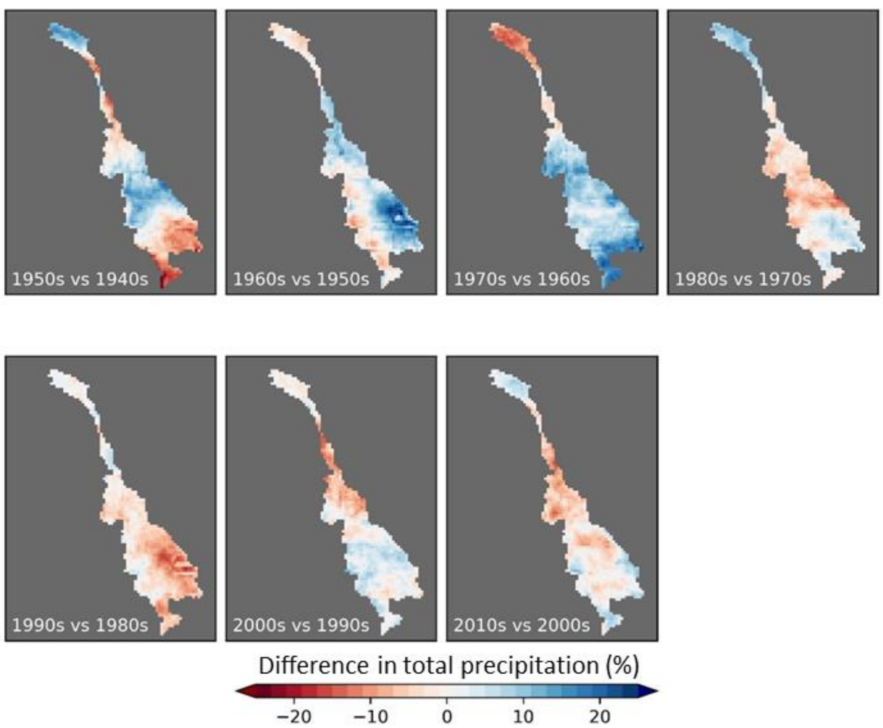

Figure 3-16. Decadal differences in total precipitation from ERA5 dataset.

In terms of annual extremes, only one-fourth of the MRB's total area shows significant spatial trend in annual maxima or flood peak, while this number in annual minima is approximately one-third. Out of the 25% area of Mekong with significant spatial trend in annual maxima, ~21% presents an increasing trend, located primarily in the lower Mekong and the 3S subbasin and its surroundings; these trend values range from 2.5-7.5% with some areas reaching to over 10%. While there are some signs of decreased flood peak in the Lancang region, these include small areas in the upper reaches where flooding is not prevalent. On the contrary, in the 34% of the Mekong area with significant trend in annual minima, there is ~21% of area that shows a decreasing pattern. Again, most of this decreasing trend is present in the Lancang region with a substantial drop from 2.5 to above 10% per decade. Surprisingly, the 3S region, which shows an increase in annual volume and annual maxima, also presents a minor drop of <2.5% per decade. Areas that are partially flooded in the outer areas of the TSL also witness a drop of annual minima flow between 2.5-5% per decade. Similar to annual volume, a slight increase in the middle of Mekong with 0-2.5% of annual minima per decade is also observed.

3.3.3 Natural variation and dam impacts on the flood pulse

3.3.3.1 Seasonal timing

Figure 3-17 presents a summary of the seasonal timing of various flow regimes (i.e., annual minimum, annual maximum, onset of wet season, and end of wet season) per calendar year, along with the variations in these attributes under natural drivers (i.e., climate variability) and dam operation over the past eight decades at selected stations. Figure 3-17a provides clear evidence that the overall hydrological timing of the Mekong is generally consistent across space (i.e., across stations in Fig. 3-17a) and time (i.e., temporal range for each attribute in Fig. 3-17a). All features of the seasonal timing across the stations from upstream to downstream only vary between two weeks to a month, which is in line with previous findings (P. T. Adamson et al., 2009). Typically, minimum flow occurs in March, while maximum flow occurs in between mid-August to mid-September. The wet season generally starts between mid-May to mid-June and ends in the first half of November. Additionally, there is a discernible delay in the timing of each attribute in the downstream stations, which ranges between a few days to a week compared to that for an immediately upstream station. However, the two most downstream stations in the Mekong Delta region (stations 12 and 13) show a distinct timing difference compared to other stations where all attributes are delayed by 2-4 weeks compared to only a few days for the upstream stations.

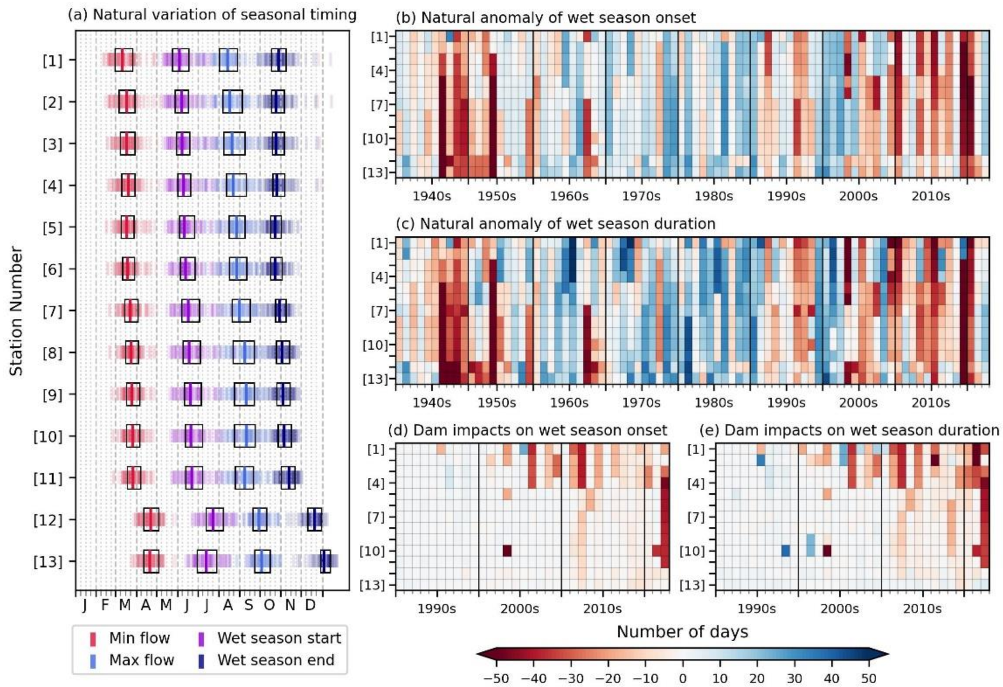

Figure 3-17. Variation in the seasonal timing of the flow regimes (a), anomaly of the onset (b) and duration (c) of the wet season driven by natural variations during 1940 to 2022, and impact of dams on wet season onset (d) and duration (e) during 1990-2022. Y-axes mark station numbers (as depicted in Fig. 1) for all panels. In panel (a) the timing of minimum flow, maximum flow, start of wet season, and end of wet season are indicated as thin color-coded lines, the black box indicates the 25th and 75th percentile, while the long-term median is shown as thick lines. Panels (b-e) share the same colorbar in the bottom right. Panels b and c show the difference in natural variation of wet season onset and duration, respectively, compared to the long-term average (in days). Panels (d, e) present the difference between DAM and NAT simulations for wet season onset and duration in recent years.

Comparison of the wet season onset and duration for each year to the long-term average (Figs. 3-17b-c) suggests that there is a high correlation between the two attributes. Similar anomalies for the two attributes (negative values indicating late onset or decrease in duration) suggest that the timing of the wet season onset can be a reasonable indicator of whether the wet season of that particular year will be reduced or extended compared to the long-term average. Furthermore, this alignment confirms that the ending of the wet season at upstream locations is relatively consistent, occurring at the beginning of November, regardless of the wet season onset being late or early. Additionally, the results further prove that there is a strong propagation effect from upstream to downstream Mekong despite the fluctuation in annual local precipitation patterns.

Results also show that the wet season onset has been significantly delayed with an alarmingly shorter length than the long-term average (by 20-50 days or higher) in recent years, especially in

2019 and 2020 (Figs. 3-17b-c). Lastly, close observation of the temporal evolution suggests that there is a notable interdecadal variation in the wet season timing, with noticeable period of late–short wet season in the 40s and 50s, followed by 3 decades of generally early–long wet season, and then followed by 3 decades of late–short wet season. We note that the results presented in Figs. 4b-c do not include any effects of dams, which are known to be prominent in the recent decade (discussed next). Overall, these results from the NAT simulation evidently illustrate that the natural hydrologic regime of the MRB had substantial inter-annual and inter-decadal variations in terms of the onset and duration of the wet season, two crucial elements of stable hydrologic and ecological systems, especially in the downstream of the basin. The results also imply that there could be potentially enhanced variabilities in the future in the face of climate change and the growing influence of dams.

We find that the construction of dams in recent decades (since 1990s) has impacted the seasonal timings in a substantial way (Figs. 3-17d-e). Compared to the effect of natural variation, dams are generally delaying the wet season onset with only a few rare instances where the impacts are the opposite at some of the most upstream locations (e.g., 1996 and 2005; Fig. 3-17d). Similarly, wet season duration is also being reduced by dams with only some exceptions at specific stations and years (e.g., 1995, 1998, 2001, 2005; Fig 4e). Further, dam impacts are generally localized and more pronounced in the upstream areas (immediately downstream of the dams), with the delay ranging between 10-30 days in these locations. Due to the propagation effect of the river's seasonal cycle, upstream dam operation is expected to have a basin-wide impact. However, the delaying effect of upstream dams on downstream season timing is typically contained within a few stations and is detectable on a basin scale only in some years, especially after 2010, a period during which many mega dams were constructed. With booming dams in recent years, wet season is being delayed basin wide, and as a result, the wet season duration is being reduced. While the impact is only a few days of delay, in critical environmental and agricultural areas such as the TSL or the MD, these adverse effects are detected in years that have already seen a substantial delay due to natural variations. In brief, dams are exacerbating the high natural variability in the onset and duration of the wet season even though the impacts of dams are smaller so far and constrained within the river reaches with major dams.

More detailed analyses of the long-term natural river flow at locations along the Mekong mainstream and TSR (Fig. 3-18) suggest that the abrupt shift in seasonal timing at stations 12 and

13 compared to upstream locations is likely due to the natural retention effect of the TSL. This shift in seasonal timing is first detected in location directly downstream to station 11, the confluence of Mekong mainstream and TSR, and is carried on to all selected locations further downstream, deep into the MD. Since there are no available gauging stations between 11 and 12 (or 16), for further analyses, we have selected one location (marked as 15 - Unknown) directly downstream where the Mekong mainstream and Tonle Sap River meet. Hydrographs at various locations in Fig. 3-18b suggest that long-term river flow at stations 9 and 10 are almost identical while similar flow timing can be observed at station 11, with visibly lower peak, however, the river flow timing change immediately downstream to station 11, at location 15. Additionally, the hydrograph indicates that, in the first five months, TSR contributes substantially to downstream river flow especially in January and February, similar to findings in Morovati et al., 2023, where TSR outflow (station 14) is equal or even higher than the flow from Mekong mainstream (station 10). As a result, while Mekong upstream river flow falls to its minimum in late March, minimum flow at all locations downstream of station 11 occurs much later in the middle of April. Similarly, the delayed wet season end date can also be directly attributed to the influence of TSL as there is a clear difference of river flow before and after station 11 from late September, when water flows out of TSR.

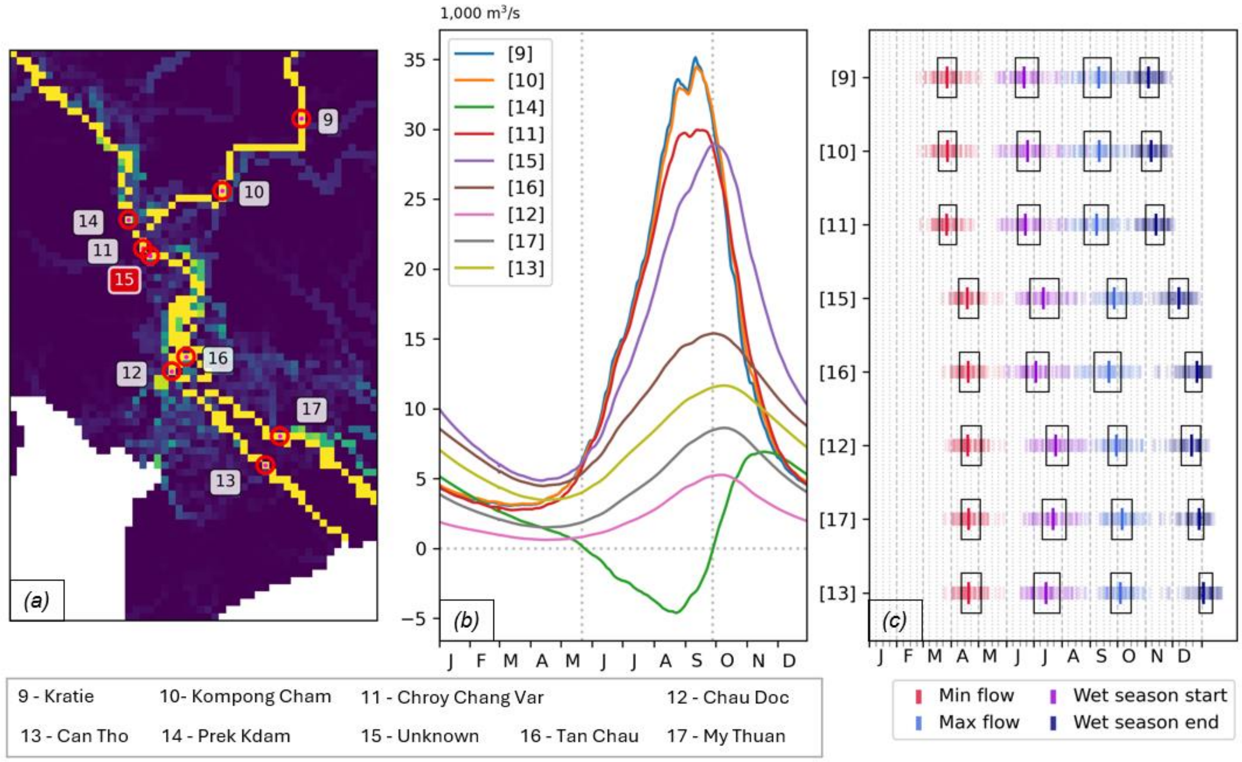

Figure 3-18. Variation in the seasonal timing of the flow regimes at most downstream Mekong mainstream locations driven by natural variations from 1940 to 2022. In panel (a), the locations of selected stations are indicated as numbered red circles on top of long-term average simulated river flow. Panel (b) shows the color-coded long-term average simulated river flow at each selected location with vertical dotted lines indicating when the TSR changes its flow direction (outflow from TSL is positive, while inflow to TSL is negative). In panel (c), the variation in seasonal timing at all selected locations on the Mekong mainstream and channels (station 14 not included) are shown in similar color-coding and format to Fig. 4.

Lastly, the wet season of station 13 is further extended by more than two weeks into January of next year compared to that for station 12. Additional analysis at similar locations of stations 12 and 13 on the other main channel of Mekong in MD (Fig. 3-18c) suggests that the end of wet season gradually shifts to later dates as we move from station 11 into MD on both Mekong main channels. A direct comparison in seasonal timing between location 15 with station 12 and 16 suggests that this prolonged effect is likely due to the river being divided into multiple channels instead of direct influence from TSL. When the river diverges into multiple channels, the progression of river flow in each channel becomes relatively stable, with less dramatic rises and drops from peak flow as can be seen in the hydrographs, resulting in a longer wet season. This is further confirmed by a clear difference between seasonal timing within a channel where there are more visible divisions (i.e., channel with stations 12 and 13) than the other (channel with stations

16 and 17) in the MD as shown in Fig. 3-18. Thus, while the abrupt shift in seasonal timing of the most downstream Mekong areas can be directly attributed to the TSL influence, the prolonged wet season effect in the MD can be attributed to the rather flat topography and the extensive irrigation channel network in this area. However, it should be noted that the representation of the river channel network and other water infrastructure (i.e., dikes) in the current model for this region is partially incomplete due to multiple limitations, thus, we expect the actual wet season-prolonging effect of the MD channel network to be even more substantial.

3.3.3.2 Water balance: natural interdecadal variability and dam impacts

To examine the impact of natural climate variability on the water balance at the Mekong mainstream stations, annual flow volumes for the last three decades at each station are compared to the long-term average (Fig. 3-19a). First, the model distinctly captures the anomalously dry (e.g., 1998, 2015, and 2019-2021) and wet (e.g., 2000 and 2011) years, discussed in previous studies (Pokhrel, Shin, et al., 2018; Shin et al., 2020). Second, while substantial interannual and interdecadal variability can be observed (Fig. 3-19a), it is clearly discernible that the MRB entered a prolonged water-deficit period starting in the mid-2000s, which intensified largely in recent years. Since 2004, results indicated multiple consecutive years with annual volumes well below average (e.g., ~10%) across the basin. This period reached its peak in 2019 (a major drought) with ~20 to over 40% decrease in annual volume at different stations. This is followed by two consecutive drought years with more than 20% lower volume than average across the entire basin; a sign of recovery started showing in 2022, especially in downstream areas. Overall, these results indicate that there is a generally consistent tendency of decline in annual volume due to climate variation in recent decades compared to long-term mean, which holds for all stations examined (Fig. 3-19a).

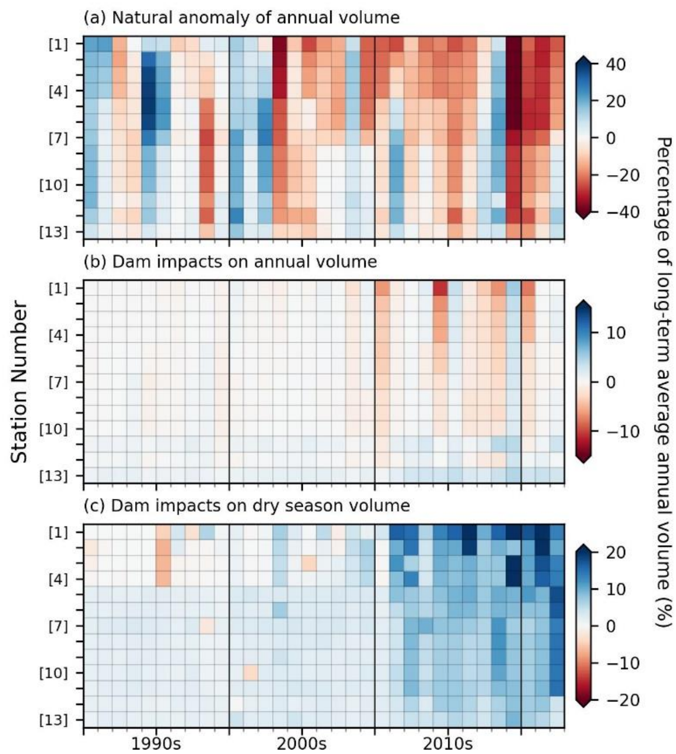

Figure 3-19. Anomaly of natural annual volume compared to the long-term (1940-2022) annual average (a), changes in each year's annual volume due to dam impacts (b), change in dry season volume due to dam operation (c). All results are normalized by the long-term annual volume at that station and then converted to percentage values. Y-axes mark station numbers (as depicted in Fig. 1) for all panels.

Figure 3-19b depicts how dams are affecting the annual volume over time and at different locations along the mainstream, indicating more pronounced impacts since 2010. Evidently, there are signs of dam impacts at an interannual scale, causing a ~5-10% decrease in the long-term average volume from one year to the next, especially in the upstream areas. However, a mild increase of <5% can be observed in recent years at the downstream areas (stations 9-13), which is due to dam operation in the Lower MRB tributaries (e.g., the 3S region). Evidence from comparing the effects on annual volume between Fig. 3-19a and 3-19b confirms that the magnitude of dam impacts on annual volume are not substantially higher than the natural variabilities, especially in dry years. In terms of seasonal volume difference due to dam operation (Fig. 3-19c), results suggest that there has been relatively small impact (<5%) in previous decades (e.g. 1990s, 2000s). However, the shift in seasonal volume from the wet season to the dry season (i.e., the difference in dry season volume between DAM and NAT simulations) has increased dramatically from <5% to ~10-20% across the Mekong mainstream since 2011 with areas in the upstream witnessing an increase by over 30% of the long-term average volume. These results illustrate that the impacts of dams have become more prominent in recent years in terms of both annual and dry-season flow volumes, which may have profound implications on downstream hydrologic, agricultural, and ecological systems.

3.3.4 Dam impacts on extreme events and flooding pattern.

Figure 3-20 presents the decadal average of the difference between DAM and NAT simulations for annual average flow, high flow, low flow and the flood occurrence in the TSL and MD areas. Additionally, a map of the mainstream grid cell can be found in the supplementary (Fig. S14). Result reveals that even in the 2000s, upstream dam operation had already caused visible impact to all flow regime attributes in the most downstream areas of the Mekong. In agreement with Fig. 6b, Fig. 7a suggests that the mainstream average flow in the 2000s is relatively unchanged compared to the long-term average. However, average flow over floodplain areas in the proximity of the Mekong mainstream and the TSL decreased marginally (<10%). Similarly, high flow in the mainstream shows a minor decrease (<2%) while this decrease is substantially higher in the surrounding floodplains (~5-10%; Fig. 3-20b). Additionally, further confirming dam-induced increase in dry season flow seen in Fig. 3-19c, Fig. 3-20c reveals that this effect was moderate in the mainstream during the 2000s. In contrast, low flow in the floodplain decreased similarly to the average and high flows. These results are closely related as flow in the floodplain areas is typically generated during high flow or flooding events, thus, a decrease in flood peak due to dam operation directly caused a decrease in river channel overflowing, effectively reducing flow in the floodplains and consequently, flood occurrence in these areas. Previous studies (H. Dang et al., 2022) suggested that upstream dam operation is shrinking the TSL by reducing flood occurrence in the lake's outer areas. However, our results in Fig. 3-20d suggest that this effect is not limited to the TSL but further propagates downstream to the MD where the outer areas of the mainstream also witness a decrease in flood occurrence (<5% or ~18 days per year). Additionally, due to the increased low flow, flood occurrence in the floodplain areas near the mainstream between TSL and MD increased (~5%) during the 2000s (Fig. 3-20d). In the 2010s, similar dam-induced impacts can be observed; however, the magnitude of these effects abruptly increased by two times or higher. The mainstream's average and high flow remained relatively unchanged with only a small difference (<3%); however, its low flow increased substantially (by ~50%) compared to the long-term average in some areas while all flow attributes in the majority of the floodplain decreased substantially (~20%). The effect of dam operation on the flood occurrence between TSL and MD also increased as flooding in the inner areas was further prolonged by 10-15% (~36-55 days), while the outer area flooding was diminished. That is, dam operation has largely altered the seasonality of river regime in this region, and subsequently changed the inundation patterns in the TSL and MD areas. This is concerning river-floodplain ecosystems and local communities considering that the 2010s was already a historically dry decade for the MRB.

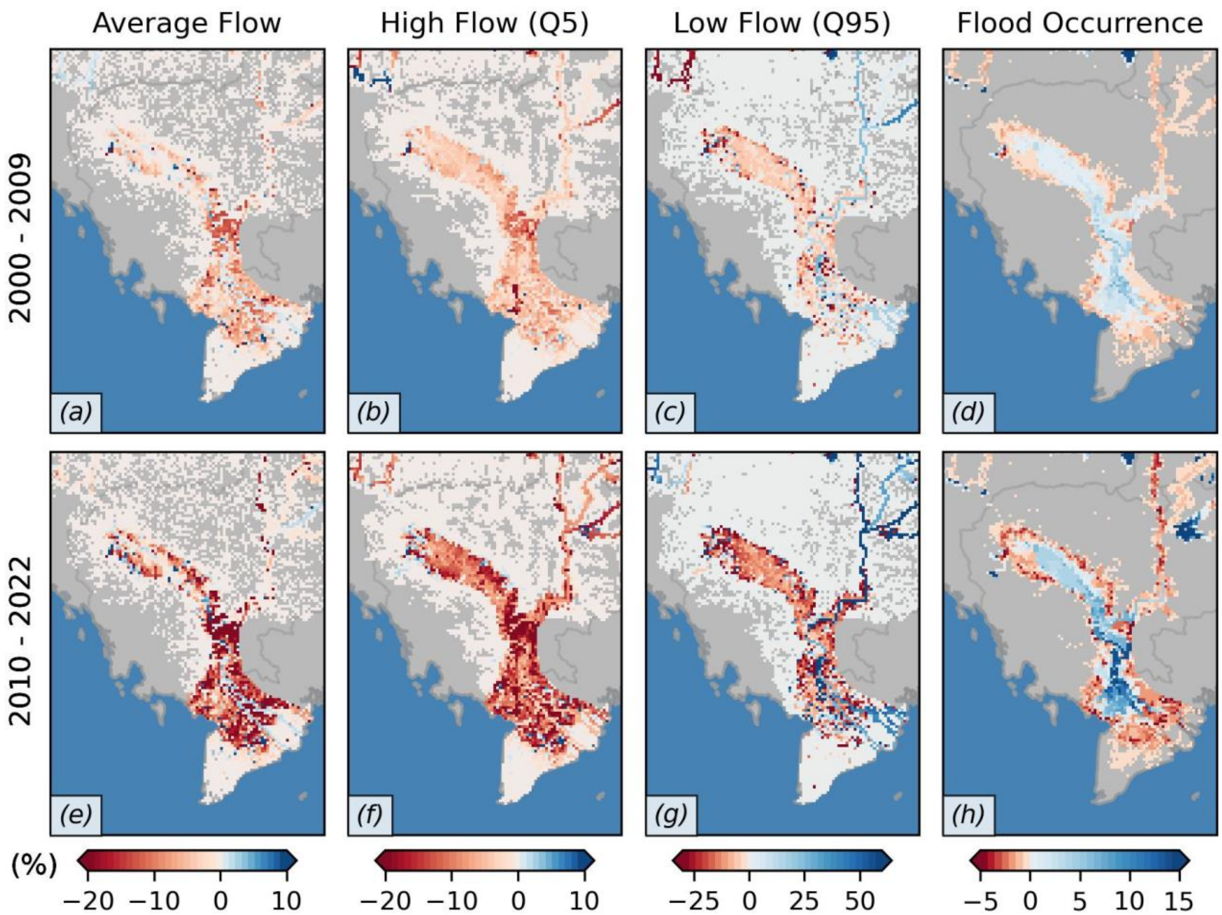

Figure 3-20. Differences in flow regime attributes between the DAM and NAT simulations (period indicated) relative to the long-term (1940-2022) average of the NAT simulation over the Tonle Sap and Mekong Dela areas including (a, e) average flow, (b, f) high flow (Q5), (c, g) low flow (Q95). Panels d and h show the difference in flood occurrence (percentage change) due to dam operation for the period indicated. Results for two periods are shown: 2000-2009 (a-d) and 2010-2022 (e-h). Areas outside of the MRB or having no changes are indicated in dark grey. Note that the color bar's range is different among the panels.

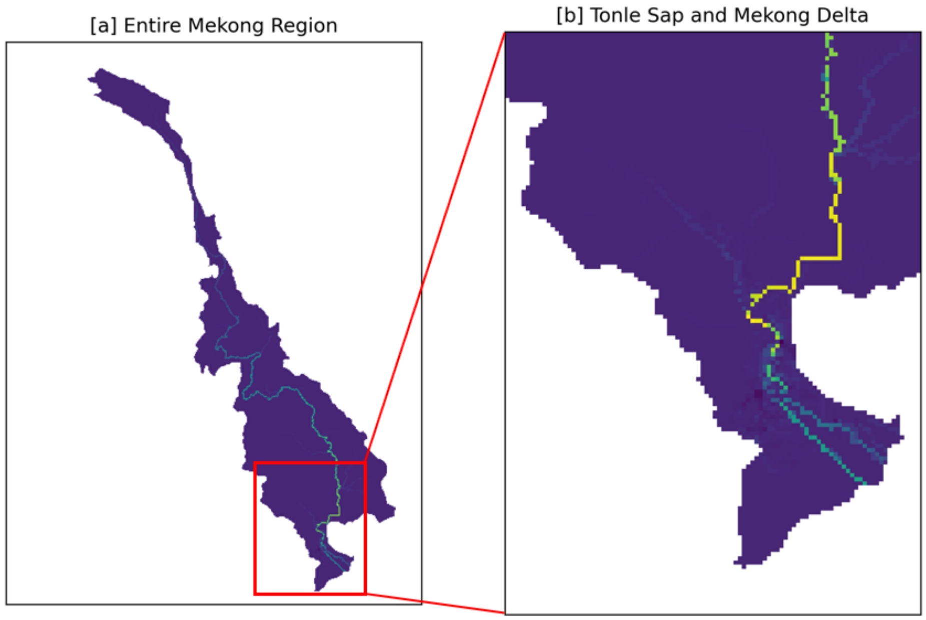

Figure 3-21. Long-term average simulated discharge across the entire Mekong Region and the Tonle Sap, Mekong Delta region.

3.4 Discussion

The changing hydrology of the Mekong River basin has been examined by numerous studies using various techniques and datasets; however, an in-depth analysis of the long-term (e.g., decadal and inter-decadal) trends in basin-wide river flow regime attributes has never been reported. Furthermore, the impacts of dams on the Mekong flood pulse and extreme events are generally studied separately and only assessed over short time periods. In this study, we use a combination of state-of-the-art modeling approaches and data analysis techniques to mechanistically quantify the changes in various river flow characteristics and flood occurrences, and attribute those to the primary drivers. While natural climate variation remains the key driver of Mekong's hydrologic changes and variabilities over the last eight decades, the emergence of new dams has caused considerable changes to the river's hydrologic regime and flood characteristics in the past decade, which may have potentially profound implications on the ecosystem and livelihood of downstream areas.

Regarding the regional trend under natural climate variation, our results indicate that two main regions in the Mekong have generally changed over the last eight decades: the Lancang and the 3S basins. Overall, the trends suggest a substantial decline in river flow in the Lancang region, with values ranging from ~2.5-10% per decade, which can be seen in both annual volume and flow minima. The detected trend is prevalent in multi-decadal historical periods and, hence is likely to continue into the future, indicating that we might need to rethink dam operation and water management in this region. For example, the high reduction in annual minimum in the Lancang region may lead to more water being held in the Lancang cascade dams, leading to dramatically reduced water levels in the downstream regions, especially during major droughts. Further, sustaining current hydropower production may become challenging in the future. In the 3S region, the tendency of increased (decreased) flow during the wet (dry) season indicates the potential for both increased flood risk and water scarcity. In this regard, existing dams may prove beneficial in mitigating floods and providing additional water in the dry season, if operated considering these changes as suggested in previous studies (Galelli et al., 2022; Pokhrel & Tiwari, 2022). However, such changes in flow patterns will have unintended consequences on downstream ecosystems and livelihoods (Arias, Cochrane, et al., 2014; H. Dang et al., 2022; T. D. Dang et al., 2016). Lastly, the decrease in annual minima in TSL's seasonally flooded areas suggests that the lake is becoming more stagnant, potentially contributing to less river flow to the downstream areas than in the past.

In terms of flood pulse, our results agree with previous studies (P. T. Adamson et al., 2009; Kummu & Sarkkula, 2008; Västilä et al., 2010a) that the average timing of the Mekong's flow regime has not drastically shifted during the past eight decades. The wet season typically occurs between June and November, while minimum and maximum flows occur in March and September, respectively. However, our results further reveal substantial fluctuations in the seasonal timing, sometimes exceeding 50 days per calendar year, and this is heavily dependent on the natural climate variation at each location. The results also show that while the onset of the wet season varies greatly over time, the end of the wet season has remained relatively stable. This means that the duration of the wet season each year can be predicted by how late the onset of the wet season was. Additionally, our results suggest that an abrupt shift of seasonal timing (~2-4 weeks) naturally occurs in areas downstream to station 11 compares to upstream locations, which can be directly attributed to the natural retention effect of the TSL. We also find that dam impacts on the seasonal timing of the Lower Mekong mainstream, specifically the MD, are relatively small, ranging between 2-5 days. However, the effect of accelerated dam operation has considerably delayed the wet season onset in the upper regions of the Mekong, sometimes by more than 30 days, especially in recent years. This can be particularly damaging to the environment as these impacts have been more pronounced in recent years when the Mekong was already witnessing a severe drought. This implies that dams are not mitigating extreme drought conditions in terms of seasonal timing but, in fact, are further worsening the delay of the wet season in upstream areas of the MRB.

On a similar note, our results suggest that the effect of mitigating extreme drought conditions through interannual water redistribution is relatively minor. While there are some effects of holding back water in one year and releasing it in another, the difference due to dam operation is found to be only one-fourth of what natural climate variation can cause. However, dams are particularly effective in shifting water seasonally. Results (e.g., Fig. 3-17) illustrate that, since 2010s, there has been a consistent shift by 10-20% of annual volume from the wet season to the dry season. While this impact is still more pronounced in the upstream, ~10% increase in most of the lower mainstream areas during the dry season is prevalent. Overall, this suggests that dams are causing the dry season to be wetter and wet season to be drier similar to previous findings (Piman et al., 2016; Räsänen et al., 2012), but less substantial than expected, especially in lower mainstream areas. While this effect can be positive in terms of agriculture as more water is available and is easily accessible for irrigation, it could cause a significant change and possibly irreversible adverse impact to the ecosystems. As also noted in previous studies (M. E. Arias, Cochrane, et al., 2014; M. E. Arias et al., 2013), water levels and inundated areas have increased in the dry season, causing many wetland areas to not have the dry period they need and could eventually destroy these important ecological systems. Our results further confirm that dams are negatively impacting the flow by reducing average flow and high flow in the floodplains of the TSL and MD. Further, due to the decreased high flow during the wet season, flood occurrence will be reduced in many downstream regions, especially outer areas of main water bodies, as also discussed in previous studies (H. Dang et al., 2022; Pokhrel, Shin, et al., 2018). However, due to the increase in low flow, flood occurrence in many areas of the TSL and Mekong near the main water bodies has been prolonged substantially by 10-15% (~36-54 days per year).

3.5 Conclusion

This study presents the first long-term (1940-2022) decadal trends and variabilities in river flow regimes over the entire MRB at a spatial resolution of ~5km. Historical changes in the seasonal timing and volume of the mainstream Mekong flow are examined and attributed to natural climate drivers and dam operation, with an emphasis on the temporal evolution of the Mekong’s flood pulse. Then, the dam-induced impacts on the spatial-temporal changes in flow regime attributes of the TSL and MD are investigated by examining the decadal difference between simulations with and without dams for average flow, high flow, low flow, and flood occurrence over the last two decades. We draw the following key conclusions. First, natural climate variation caused substantial decadal trends (±5-10%) in river flow during 1940-2022 in portions of the MRB, especially the Lancang and the 3S regions. Second, dams are found to have intensified the high natural variability in seasonal timing of mainstream Mekong flow even though dam-induced impacts are still smaller compared to natural climate variation and typically more pronounced in areas directly downstream of dams. This can be observed in 2019 and 2020, during which dams exacerbated drought conditions by substantially delaying the MRB's wet season onset. We note that the wet seasons under natural conditions (simulation without dams) in these years were already alarmingly shorter than in average years (by 20-50 days). Third, upstream dam operation had minimal impact on annual flow but is largely altering the seasonality of MRB's flow regime attributes and flood dynamic in the TSL and MD by redistributing a substantial flow volume (~10-20% annual volume) from wet season to the dry season; this is found to be substantial in the Mekong mainstream, especially in recent years. With reduced high flow in the Mekong mainstream, the decreased flood peak directly reduced flood occurrence (up to 5% or 18 days per year) in the surrounding floodplain areas. However, the increased low flow substantially prolonged the inundation of flooded areas in close proximity of the mainstream by ~36-54 days in some areas. As a result, dams have effectively reduced the typically extensive flooding in the TSL and MD, which could cause unprecedented adverse impacts to the ecological system and local communities. Our results might contain uncertainties caused by the use of basin-wide model, imperfect model parameterizations, uncertainties in input data including dam attributes with the use of a generic dam operation scheme. These uncertainties could have been further amplified by lacking consideration of other human activities such as changes of land use, sand mining and water infrastructure development (e.g., dikes) that have been accelerating in recent times. These aspects could be addressed in future studies. Despite these limitations, this study presents the first results of the changes in natural hydrologic regimes in the MRB over the past eight decades, providing key insights on the role of recent increases in dam construction on changing annual/seasonal flow volumes, maximum flows, minimum flows, and flood occurrence in the TSL and MD areas. The findings are expected to be of use to rethink water resource management, especially in the face of climate change and planning of future dams, and open new avenues for research to address emerging dam-related issues in the MRB.

Chapter 4. Potential changes of the Mekong's flood pulse under future climate change and dam operations

4.1 Introduction

As global temperatures continue to rise, future risks in water stress and flooding will rapidly escalate, exposing more humans and ecosystems to unprecedented extremes (IPCC, 2023, Fischer et al., 2021). Among extreme hydrological mitigation strategies, the construction and operation of dams are known to exert the most extensive influence on water (Oki & Kanae, 2006b; Poff et al., 2007). While directly reducing both the extent and severity of flood and drought risks, dams also bring other benefits in terms of agriculture support and power generation, thus, they are a major component in future development plans. As such, thousands of dams are constructed globally (Zhang & Gu, 2023b), with more planned in the near future. However, flow regulation by dam alters downstream flow regime and dams also act as physical barriers that fragment river systems, fundamentally threaten the integrity of the ecological systems (Dynesius & Nilsson, 1994; Nilsson et al., 2005b; Timpe & Kaplan, 2017b). Thus, there is an urgent need to understand the compound impacts of future climate change and planned dam development on river systems to find a balance between mitigating extreme risks while preserving the environment for a more sustainable future, especially in developing regions.

Mekong River Basin (MRB) in Southeast Asia is one of the developing regions where dozens of mega dams in the mainstream and hundreds of dams in tributaries are being proposed, planned and constructed (Ang et al., 2024; Grumbine & Xu, 2011b; Stone, 2016). The rapid increase in number of dams in just the last decade have led to considerable alterations of the river regime and flood dynamics (M. E. Arias, Piman, et al., 2014; Chua et al., 2021; H. Dang et al., 2022). With the operation of upstream dams, the Tonle Sap River's unique reversal flow is being dampened, reducing its annual exchange with the Mekong mainstream (H. Dang et al., 2022). This dam-induced effect not only causes adverse impact of shrinking the Tonle Sap Lake (H. Dang et al., 2022)and deteriorating its ecology (M. E. Arias et al., 2012) but also increases inundation duration in major agricultural areas of the Mekong Delta (H. Dang & Pokhrel, 2024). Simultaneously, climate variation in recent years has led to several record-breaking droughts in this region with dams having minor roles on mitigating annual water deficit while also further delays the timing of the Mekong flood pulse (H. Dang & Pokhrel, 2024). Additionally, previous studies suggest future climate change will intensify Mekong's hydrological cycle, increasing both magnitude and frequency of extremely high-flow events (Phi Hoang et al., 2016). Considering that more than 60 million people's livelihood and some of most unique ecological system downstream (i.e., Thailand, Laos, Cambodia and Vietnam) are directly relying on the Mekong annual flood pulse (M. E. Arias et al., 2019; MRC, 2010), potential alteration of the Mekong river flow regime under future climate change and planned dams will have profound impacts on livelihoods and ecosystems.

However, despite an increasing body of literature studying the MRB at multiple scales, a holistic assessment of the impacts of future dams under climate change on the flood dynamics over the entire basin has been lacking. Since Mekong is a transboundary river between multiple developing countries, it is relatively difficult to obtain information on dam operation (e.g., operation rules), resulting in disparate and inconsistent information between global and regional dam database (Ang et al., 2024). As such, most dams in the MRB are often overlooked while only a handful of the mainstream dams are considered in many studies for both historical and future periods (Hoang et al., 2019; W. Wang et al., 2017b; J. Yang et al., 2019). Furthermore, even if dams are considered, often time, they are simulated with flood control as the main priority (Hanazaki et al., 2022) while dams in this region are mainly used for hydropower or irrigation. Another major issue is the difficulty and high computational expense in explicitly and accurately simulating the complex fluvial system over the entire MRB at high resolution (Shin et al., 2019). To overcome this limitation, many studies have employed a variety of modelling methods to simulate future climate change impacts, but only over certain portion of the MRB such as the Lancang basin (Bibi et al., 2021; Han et al., 2019), 3S basin (Ngo et al., 2018; Piman et al., 2015), Tonle Sap (M. E. Arias, Piman, et al., 2014; Horton et al., 2021) or the Mekong Delta (Smajgl et al., 2015). Additionally, many studies applied and analyzed only a limited number of global hydrological models (GHMs) and global circulation models (GCMs) for future projection (Yun et al., 2020).

Here, we present a comprehensive assessment of the compounding impacts of dams and climate change on the Mekong River regime, under a framework simulating major operational and planned dams as integral parts of the MRB under multi-model climate change scenarios. This is enabled by combining a river-floodplain-reservoir hydrodynamic model, CaMa-Flood-Dam (CMFD) (H. Dang & Pokhrel, 2024; Shin et al., 2020), and multi-model runoff from the Inter-Sectoral Impact Model Intercomparison Project-Phase 3b (ISIMIP3b; https://www.isimip.org/) for four GHMs, five GCMs, under three climate change scenarios represented as Shared Socioeconomic Pathways (SSP). We will explore how operational and planned dams potentially impact the Mekong's flood pulse as well as extreme hydrological events under each future development scenario. More specifically, this section aims to answer the following scientific questions: (1) How will the MRB flood pulse change under various scenarios of climate? And (2) How effective are dams in mitigating extreme events and supporting water availability during dry episodes?

4.2 Data and Methods

4.2.1 Data

To validate model performance of the applied framework, observed river flow and water level data are obtained from the Mekong River Commission (MRC) for thirteen gauging stations on the Mekong mainstream (Fig. 1). These stations are selected considering (i) broad spatial coverage across the MRB and (ii) availability of at least 5 years of continuous observational data for both river flow and water level. Considering that there are temporal gaps in the observed dataset, model performance metrics were calculated only for periods for which observations are available for each station.

Dam and reservoir specifications including coordinates, status (e.g., operational, planned, cancelled), year of commission, purpose (e.g., hydropower, multipurpose, irrigation, water supply), heights, storage capacity, or installed capacity are obtained from three primary sources: Research Program on Water, Land, and Ecosystem (WLE; https://wle-mekong.cgiar.org), the Stimson Center (https://www.stimson.org/2020/mekong-infrastructure-tracker-tool/) and previous studies (Ang et al., 2024; Shin et al., 2020). Additionally, we have filled any missing values and corrected erroneous records in the merged dam database using publicly available information collected from various resources including published reports from local governments or the MRC, documents from design and construction companies, other peer-reviewed literature as well as news articles. This results in a total of 221 dams (including operational, proposed and planned projects) with enough attributes for simulation. Among those, 83 dams were applied for the historical period (1979-2014). An additional 43 dams were applied for the period between 2015-2023. For the dams recorded as operational by 2024 but not yet observed in satellite and aerial images, they are assumed to start operation in 2030. Considering that planned and proposed projects can unexpectedly change due to many influences, we have decided to conduct two-sets of dam development simulation scenarios where no more dams are built (DAM-A) and all planned and proposed dams are operational by 2030 (DAM-B). While it might not be possible for all proposed projects to be operational by 2023, DAM-B scenarios would still provide a wider range of temporal coverage on the potential impacts of a fully developed basin. As a result, all dams are considered to start operation by 2030.

4.2.2 Model and Simulation Settings

This study employs a one-way coupling of GCMs (GFDL-ESM4, IPSL-CM6A-LR, MPI-ESM1-2-HR, MRI-ESM2-0, and UKESM1-0-LL), GHMs (CWatM, H08, JULES-W2, and WaterGAP2-2e), and a hydrodynamic model (CMFD). Climate simulations by the GCMs provide the meteorological inputs to the GHMs including precipitation, air temperature, short- and long-wave radiations, wind speed, specific humidity, and atmospheric pressure, which are bias-corrected and downscaled to $0.5° \times 0.5°$ spatial resolution. The four terrestrial hydrology models simulate terrestrial hydrological processes from canopy to bedrock (e.g., evapotranspiration, snow melt, infiltration, and groundwater fluctuation). The detailed hydrodynamics in river, reservoir, and floodplain is simulated by the hydrodynamic model at a spatial resolution of 3-arcmin (~5km).

While the GHMs have a capability of simulating river flow and reservoir operation, they are not suitable for the MRB due to the uses of large grids, simplified hydrodynamics, and limited historical and future reservoir information. Hence, the runoff is fed to CMFD to simulate the complex hydrodynamic processes in the MRB. Three modes of CMFD, that is without dams (NAT) and with current dams (DAM-A) and with proposed dams (DAM-B), are independently used for each scenario set of GCM and GHM. In the DAM mode, reservoirs are operated to satisfy downstream irrigation water demand for irrigation dams and to maximize hydropower production A comprehensive description of reservoir operation can be found in the previous literature (Shin et al., 2019, Shin et al., 2020).

4.2.3 Data analysis

Daily time series of each simulation are extracted at each gauging location for model performance validation using statistical indicators such as correlation and standard deviation (SD). Simulation results basin-wide are then analyzed into monthly, annual and long-term average data for further analysis. On the Mekong mainstream, Kratie is downstream to the majority of dams in the MRB while it is still far away from the retention reservoir effect of the Tonle Sap Lake, thus, we have selected this location for further analyses of dam impacts. To analyze the seasonal variation, a simplified season timing of this location was depicted from Dang and Pokhrel, 2024 where the wet season is between April to October. Additionally, while all NAT simulations are completed, due to time and computation limitations, only a set of GCM-GHM simulation (GFDL-ESM4 with JULES-W2) with dams under historical and extreme future climate scenario (SSP5) were completed so far. Therefore, the following results in section 4.3.3 are initial findings from only 1 of 120 possible future scenarios and should be interpreted with caution.

4.3 Preliminary results

4.3.1 Model performance

Results shown in Figure 4-1 suggest that all of the models show relatively good performance in reproducing daily historical water level and discharge of the MRB. In terms of water level, most models have a correlation ratio between 0.6-0.9, which suggests that the models can capture the temporal dynamics of water level compared to observation. Further, the diagram suggests that the models could also capture the range of water level fluctuation where SD values are mostly within 0.5-1.5 range. Similar conclusions can be made for discharge where the correlation ranges between 0.5-0.95 while SD are within the range of 0.5-1.5. However, there are exceptions where water level SD for all stations exceed 1.5 such as Chiang Saen, Stung Treng and Can Tho, while the correlation rates for Can Tho is the lowest, approximately 0.6 for all models. Additionally, many models underperformed in reproducing discharge at Can Tho with correlations at approximately 0.5-0.6. The moderate performance at this station has been noted in previous studies (Shin et al., 2020, Dang and Pokhrel, 2024) and could be attributed to the uncertainties in CMFD's fixed parameters (e.g., channel width and depth) that are not specifically tuned for the Mekong Delta. Additional analysis on long-term seasonal cycle in Figure 4-2 shows that the simulated results can reproduce well both the timing and magnitude of historical river regime with minor discrepancies. Considering that the primary objective of this section is to quantify the long-term variations of the hydrologic regime under future dam operations and climate scenarios, the observed minor discrepancies will have a negligible influence on the key findings. Overall, good performance at daily scale across the MRB for both water level and discharge simulation over a long period (i.e., 35 years) supports the application of these models in further examining the potential hydrological changes of the MRB under future development scenarios.

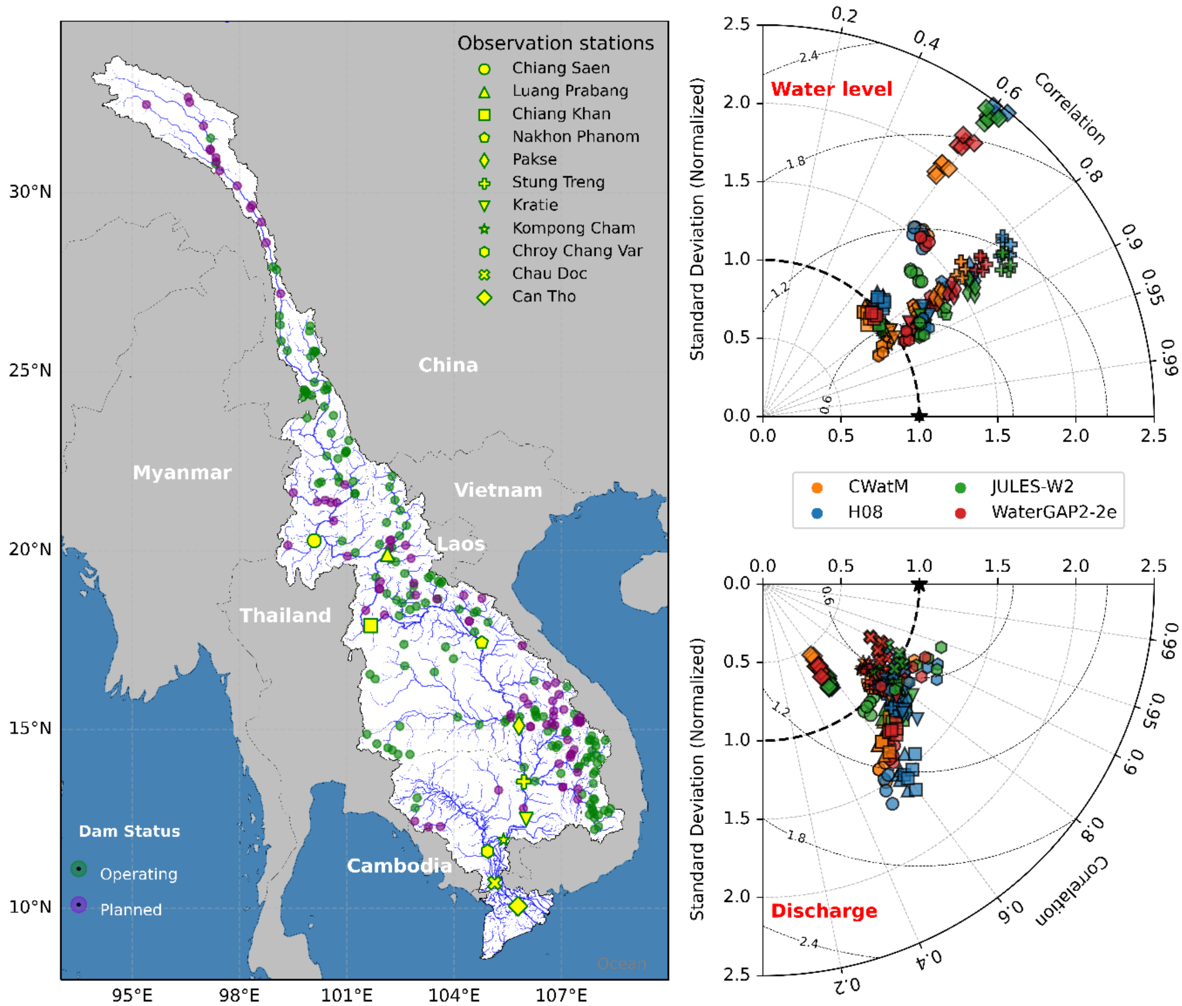

Figure 4-1. The performance of different simulations in capturing daily discharge and water level between 1979-2014 at selected gauging stations. Stations are indicated with markers and GHMs are color coded. The basin map on the left show locations of gauging stations selected for validation and dams applied in simulations. The Taylor diagrams on the left illustrate model performance in simulating water level (top) and discharge (bottom). The normal standard deviation (SD) on the vertical and horizontal axis, and the correlation on the radial axis. The reference point is situated where correlation and normalized SD are both valued as 1.

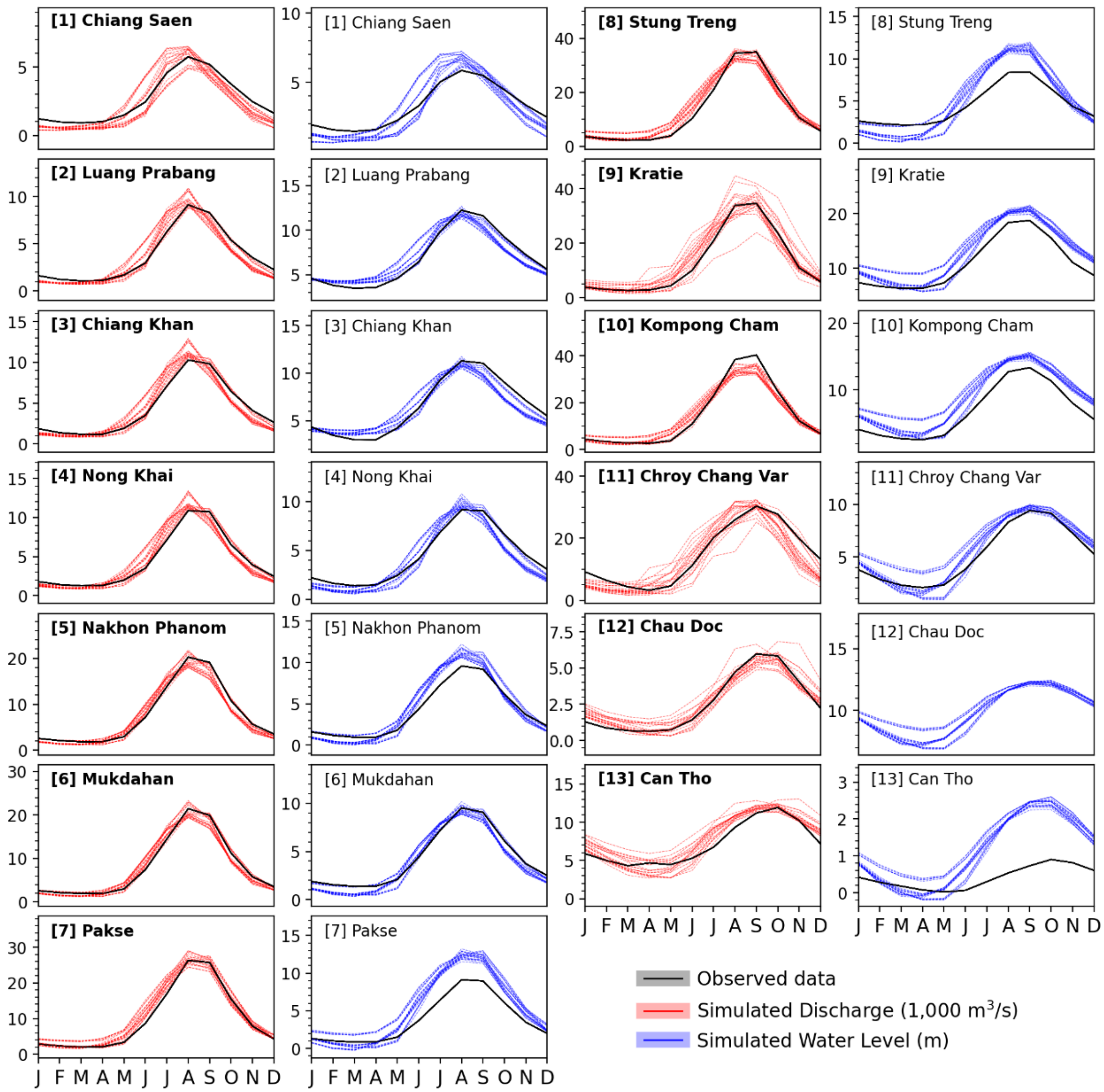

Figure 4-2. Comparison of long-term average seasonal cycle of simulated discharge (red lines) and water level (blue lines) from 20 model combinations with observations (black lines) at gauging stations marked in Fig. 4-1. Each model combination is presented as a dotted color line.

4.3.2 Climate impacts on long-term discharge

Figure 4-3 depicts the impacts of each climate scenario on basin-wide long-term average discharge of the MRB. Initial results suggest that the magnitude of potential change in all scenarios and periods are relatively minor with a maximum of ~250 m^3/s, or 5% compared to historical average. While there are some visible discrepancies, most panels in Figure 4-3 agree that there is an increase of discharge on the Mekong mainstream and its major tributaries. The only period that shows considerable decrease is in the far future under SSP1, where mid to lower Mekong River experiences a reduction long-term discharge.

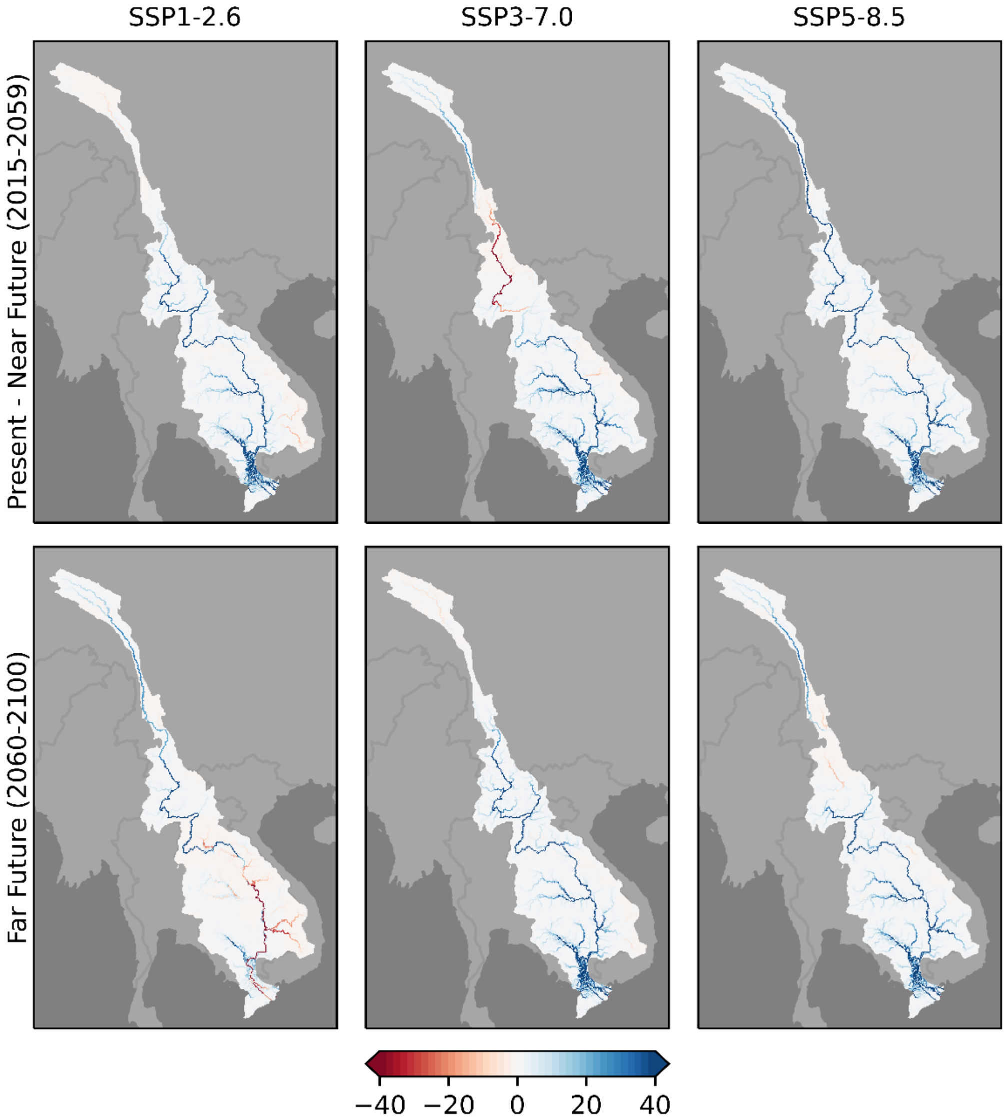

Figure 4-3. Climate-induced changes in long-term average discharge (m^3/s) across the MRB under future climate scenarios without dam impacts (NAT). Top panels illustrate the difference in long-term average discharge between the present – near future period (2015-2059) and the historical periods (1979-2014). Similarly, the bottom panels indicate the potential changes in the far future period (2060-2100).

4.3.3 Dam and climate impacts on annual and seasonal discharge.

Hydrographs in Figure 4-4 further confirm previous findings in Figure 4-3 that even in the most extreme future climate scenarios, there will be only small increases in long-term annual discharge (~260 m^3/s or 5%). Furthermore, the figure suggests that climate is still the driving factor on annual discharge at this location both in the past and in the future, despite the increasing number of dams as there are only minor differences between NAT and DAM simulation results. Additionally, the figure suggests that the lowest annual discharge is ~2,400 m^3/s and is relatively similar to what has been observed in the past. However, there is potentially an increase in the frequency of dry years where only 12 out of 36 historical years (~33%) witness annual discharge below average, while there is 38 out of 86 years (~44%) in the future period. Similarly, when compared to Q25 of the historical period, 32 years (~37%) in the future period have higher annual discharge. Overall, these findings suggest that future annual discharge will only increase slightly, however climate change will substantially increase interannual variability, with potentially more extreme dry and wet years while dams that only optimized for single purpose (hydropower or irrigation) will have little impact on mitigating these extreme hydrological events.

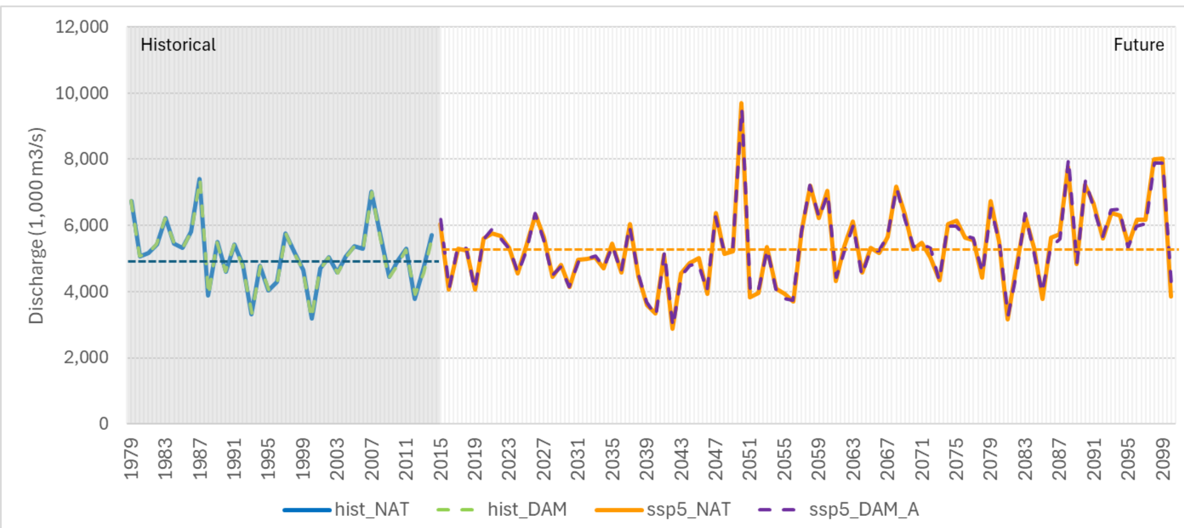

Figure 4-4. Simulated annual discharge at Kratie station in historical (1979-2014) and future period (2015-2100) under NAT and DAM conditions. The illustrated climate change scenario is SSP5. The long-term average discharge of each period is shown as color-coded horizontal dotted line. Simulated discharge of DAM-B is almost identical to DAM-A; thus, DAM-B was not displayed to improve the visibility of other simulations.

In terms of seasonal water availability, Figure 4-5 shows that climate change will increase discharge in both seasons with a more visible change in the dry season (~5-10%). Additionally, the figure also suggests that, historically, dams have only minor impact in increasing the dry season mean discharge (<5%). However, dams are potentially increasing the dry season discharge by 40-75% in both development scenarios (DAM-A or DAM-B) in the future. This substantial increase in percentage can be attributed to the relatively low magnitude of dry season discharge in the Mekong. Similar findings have been noted in Dang and Pokhrel, 2024 where dry season discharge is substantially increased (>20%), especially since 2010 due a rapid increase in the number of dams. However, results in Figure 4-5 suggest that there are almost no differences between DAM-A and DAM-B, which means that there are potentially no changes in overall of the dry season discharge even if more dams are built in the MRB. Additional analysis needs to be done to further explore and confirm these findings.

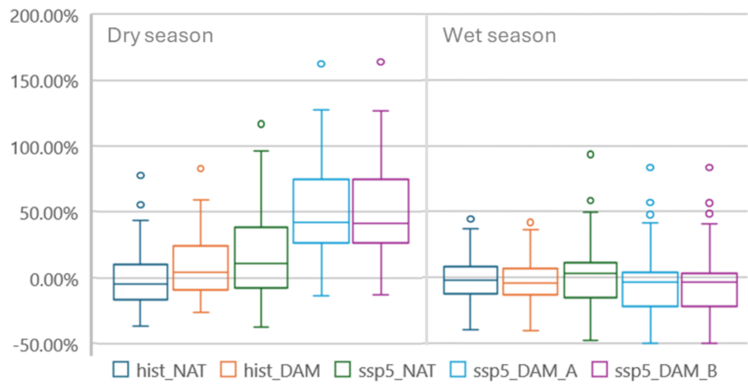

Figure 4-5. Box plot of seasonal water availability changes (%) compared to historical long-term average under historical and future scenarios (color-coded). Within each box, the top and bottom horizontal lines denote the 25th and 75th percentile while the middle line shows the median values. Vertical extending lines denote the most extreme values within 1.5 interquartile range while the dots denote outliers.

Chapter 5. Limitations and future research opportunities

While the CaMa-Flood model applied in this dissertation has many advantages and is extensively used in simulating river regime and flood dynamics at the regional scale, it is not without limitations. Understanding these limitations is crucial for interpreting model outputs and planning for future model development and improvements. In this chapter, I discuss in detail the suitability of CaMa-Flood in this dissertation, model's limitations and avenues for improvements in future studies.

5.1 Representations of physical processes

In hydrodynamic simulations, models can be categorized based on the number of dimensions they consider in calculation (i.e., 1D, 2D, and 3D). Many 1D models are typically designed to utilize simplified equations for unidirectional flow which simulate rivers or channels with a single dominant flow direction that are highly gravity driven. As such, 1D models tend to rely on coarse resolution, predefined and simplified channel characteristics as input. Therefore, these models require the least computational resources and are efficient compared to higher dimension models in many situations. In contrast, 2D models account for multiple flow paths and are generally applied in simulating wide and flat floodplain (Q. Yang et al., 2022) or highly braided rivers/channels system where both water surface elevation and velocities can vary in multiple directions. Owing to the complexity of multi-directional flow, 2D models generally require more detailed topographical data than 1D models, therefore, demanding a higher computational requirement. Lastly, 3D models incorporate three-dimensional flow dynamics, allowing for the representation of vertical variations and complex turbulent interactions, particularly in deep water bodies or environments with significant spatial variations. While 3D models are the most comprehensive, they require significantly more computational power due to the complex inputs, calculations, and time-consuming calibrations (Baracchini et al., 2020), which make them less efficient for extensive simulations. In general, higher dimension models allow for a more accurate representation of physical processes such as flow behavior in rivers or floodplain inundation dynamics, however, their computational and input requirements are also more demanding. Therefore, model selection should depend on the requirements of the scientific question, relevant analyses as well as data availability.

Considering that the scientific questions in this dissertation require analyses from long-term or ensemble simulation results over the entire MRB which is relatively large (~795,000 km^2)

with the lack of readily available high-resolution forcing data for this region, a model that solves the St. Venant momentum equation based on a 1D solution, namely the local inertial flow equation (Bates et al., 2010; Yamazaki et al., 2013), such as in CaMa-Flood would be suitable. In CaMa-Flood simulations, river basins are discretized into gridded unit catchments at a relatively coarse spatial resolution (5km), which have a uniform sub-grid river and floodplain attributes profiled from high-resolution topography data (Yamazaki et al., 2011, 2019). More specifically, rivers are characterized as rectangular channels while the floodplains are represented as slopes that directly guide water into the river channel. The simplified representation of rivers and floodplain allowed the model to quickly run with minimal effort in simulating the river regime and flood dynamics of the MRB over long time periods.

However, the simplified representation of physical processes is also the source of many limitations of the CaMa-Flood model. In reality, there can be ponds or small water bodies that reside for days after flooding due to the flatness of the area and lack of a direct connection to a permanent water body such as a river, or lake where such local storage could drain into. However, due to CaMa-Flood's simplified floodplain representation, the model always assumes continuous and complete drainage during simulation without considering the unconnected inundation areas. Thus, additional analysis on the time lag for complete draining of inundation areas or percentage of each grid cell that contains permanent stagnant water bodies (i.e., lakes or pond that are smaller than 5 x 5 km^2) based on high-resolution topography data and remote sensing-based water occurrence data such as the Global Surface Water (Pekel et al., 2016) or NASA's Surface Water and Ocean Topography (SWOT) mission would help improve CaMa-Flood performance. Furthermore, the model does not consider evaporation, thus, there could be a small amount of excess water in inundation areas, either natural ponds or man-made reservoir. These limitations could be addressed by cull coupling of CaMa-Flood with a hydrological model such as the Community Land Surface (CLM5) or Variable Infiltration Capacity (VIC). While simulated flood depth can be obtained at 90m resolution, the downscale calculation is based on the 5km grid cell simulated water storage, which, in combine with the lack of consideration for unconnected inundation areas, could significantly under or overestimate the flood extent, duration and depth, especially in complex floodplain environments. As such modifications of the model's setup to simulate at higher resolution than 5km could further improve the model. Lastly, water occurrence or flood extent data acquired from satellite images such as SWOT should be used in validation of the CaMa-Flood results to further enhance the credibility of simulations.

Another critical limitation is the challenge of parameterization and calibration. The CaMa-Flood model relies on various parameters (e.g. river channel width, bank height, and Manning's roughness coefficient) to simulate hydrological processes, and these parameters need to be calibrated against observed data to ensure accuracy. Since obtaining high-quality, spatially and temporally consistent data for calibration can be difficult, particularly in regions with sparse monitoring networks such as MRB, bathymetric parameters were empirically decided for each grid cell. However, due to the continuously evolving nature of river systems as well as human activities (e.g., sediment trapping or extraction), these parameters should be calibrated to represent changes of river and floodplain attributes based on more recent remote sensing data, especially in the Mekong Delta areas considering that simulated water level is still substantially different from observation as shown in Fig. 3-4. Similar to river channel parameters, the Manning's roughness coefficient was empirically decided, however, it is assumed to be constant throughout the basin (Yamazaki et al., 2011) as 0.03 for rivers and 0.1 for floodplain. While the assigned values are within reasonable range for most rivers with stable channels and fine bed materials (i.e., sand or gravel), not all sections of the river basin are the same. Therefore, this parameter could be assigned individually for each grid cell and calibrated base on high-resolution land use, land cover and other satellite image products in future model developments.

5.2 Representation of human activities

Originally, CaMa-Flood could only simulate water flow in a main channel following the river network map where each grid cell can have multiple upstream cells, but it only has one downstream cell. While this setup can be a good representation of a regular watershed where flow is driven primarily by gravity and difference in surface elevation, it could not represent flow in multiple directions in flat areas where the channels can divide into smaller streams. Thus, bifurcation channels were incorporated into the model allowing CaMa-Flood to behave as a quasi-2D model by accounting for multi-directional flow (Yamazaki et al., 2014). These channels are alternative routes aside from the main channels, which could transfer water between cells that wasn't assigned a downstream-upstream connection. Flows through bifurcation channels are also calculated by the local inertial equation but are only initiated after calculation for main channel flow is complete. Additionally, the bifurcation channels are only activated when a certain flood depth threshold is met. These bifurcation channels are proven to be essential for realistic hydrodynamic simulation in relatively flat areas such as the Lower Mekong (Yamazaki et al., 2014). However, results in simulated long-term average flow (Fig 3-18) across the Mekong Delta suggests that the complex network of man-made channel in this region is not represented entirely in the model. Fig 3-18 show that the majority of the water still flows in the main channels while in reality, there is a considerable amount of river flow in the channels that connect the entire delta. Thus, additional analysis in the future to improve the efficiency of bifurcation channels in CaMa-Flood is needed.

In terms of human activities, man-made dikes have not been considered in CaMa-Flood. Without representation of dikes in simulations, the extent and duration of flood due to riverbank overflow can be overestimated in major delta areas. Additionally, agriculture and aquaculture activities that require man-made shallow inundation areas such as rice and inland shrimp farming are not considered in CaMa-Flood, which can cause underestimation in flood dynamic simulation since the model does not consider stagnant water in floodplain areas. Therefore, dikes and simplified farming practices should be added in future model development.

Lastly, the inclusion of dams and reservoirs in the CaMa-Flood model introduces additional complexities and limitations. While the model can simulate the impacts of dam operations on river flow and floodplain inundation, it relies on several assumptions and simplifications. For example, the model assumes simplified dam operation rules that focus on a single purpose (i.e., flood control, hydropower, irrigation support) (Hanazaki et al., 2022; Shin et al., 2020), which may not reflect the complex decision-making processes involved in real-world dam management. These simplifications can lead to inaccuracies in predicting the timing and magnitude of reservoir releases, affecting downstream flood dynamics and water availability. Therefore, a more comprehensive dam scheme that considers each dam as multi-purpose, optimizing and cooperating cascade of dams to release water that meet various demands downstream, needs to be developed in the future. Additionally, due to lack of available information on dam attributes and operational rules, studies often neglect smaller or less documented dams, which can further limit their accuracy in regions with numerous water control structures such as the MRB. Thus, applying high-resolution remote sensing products in observing these structures to extract reservoir attributes (i.e., surface extent, surface elevation and storage capacity) as well as their operation patterns to use as input for simulations would substantially increase model performance in future studies.

Chapter 6. Summary and Conclusion

While numerous studies have provided critical insights on the changes of the MRB and its subbasins' hydrological conditions as well as various anthropogenic activities impacts in this region both in the past and future, mechanistic quantifications on the changes of these systems due to natural climate variability with more realistic dam operations is lacking.

In Chapter 2, using a hydrological-hydrodynamic modeling system (i.e., HiGW-MAT and CaMa-Flood-Dam) that includes the major dams in the MRB, we show that while climate variability has been a key driver of inter-decadal variabilities in the lake's water balance, the operation of Mekong dams has exerted a growing influence—especially after 2010—on the Mekong flood pulse, Tonlé Sap River's flow reversal, and the TSL's inundation dynamics. The dam-induced dampening of the Mekong's peak discharge increased from 1-2% during 1979-2009 to ~7% in the 2010s, causing comparable alterations in the peak of inflow from the Mekong into TSL. More crucially, during the 2010s, the dams caused a reduction in annual inflow volume into TSL by 10-25% and shortened the annual inundation duration by up to 15 days in the lake's periphery. Further, seasonally inundated areas decreased (increased) most substantially by ~245 km2 or ~3% (~270 km2 or ~6%) in August (April) during the 2010s. These results demonstrate that Mekong dams have already caused substantial alterations in the hydrologic balance and inundation dynamics of the TSL. Our findings offer critical insights relevant for improved transboundary water management and decision making in light of growing concerns about the adverse impacts of large dams in the MRB.

In Chapter 3, an enhanced river-floodplain hydrodynamic model considering optimized dam operation (CaMa-Flood-Dam) is used in combination with a global climate reanalysis dataset (ERA5-reanalysis). The results include 83-year (1940-2022) daily simulated river flow, water level, and flood depth at ~5km resolution in scenarios with and without 126 major dams operating in the MRB. Results indicate that there are clear significant regional trends in annual volume, flood peak, and low flow over the eight decades period. The detected trend also varies greatly across the basin and could be quantitatively attributed to one of the two major factors including natural climate variation and dam operation. The results also suggest that since 2010, upstream dams' impact has substantially altered the timing of the MRB flood pulse as well as shifting considerable volume of water from the wet season to the dry season. Furthermore, due to dam operations, there have been substantial alteration to the Lower MRB's extreme flows and flood occurrence. This study provides crucial insights on the natural evolution of the MRB’s hydrological condition over the last eight decades as well as in-depth analysis on the impacts of dam operation toward the MRB’s flood pulse and extreme events.

In Chapter 4, runoff from multi-model of ISIMIP3b is used as input for CaMa-Flood-Dam to simulate future hydrology of the MRB under various scenarios of climate change and dam development. The simulation results include the combination of 5 global meteorological models, 4 hydrological models, 3 climate scenarios and 3 basin development conditions (no dam, operation dams and planned dams). The results denote that under future conditions, there is only minimal change in long-term average decadal or annual discharge across the MRB. Additionally, climate variation will continue to be the major driver of inter-annual hydrological changes in this region, exacerbating the annual extremes, despite future dam development. However, it should be noted that dam-induced impact on seasonal discharge will be much higher than climate impacts, substantially increasing the dry season water availability in the Mekong mainstream.

In Chapter 5, in-depth discussion on CaMa-Flood model limitations and future research opportunities are provided. I note that CaMa-Flood is a valuable tool for simulating river flow and floodplain inundation at a macro scale. However, it is essential to recognize its limitations to interpret its outputs accurately and guide future improvements. These limitations include simplified representations of physical processes, parameterization and calibration challenges, assumptions in dam operations, inadequate representation of human activities. Addressing these limitations through enhanced data collection, model development, and integration frameworks will improve the model's accuracy and reliability, ultimately supporting more effective model simulations.

It is expected that the new findings in this study will provide critical insights on how cumulative impact of dam operations have changed and potentially will change the river regime and flood dynamics of the MRB.

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