Science of the Total Environment 831 (2022) 154833

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

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

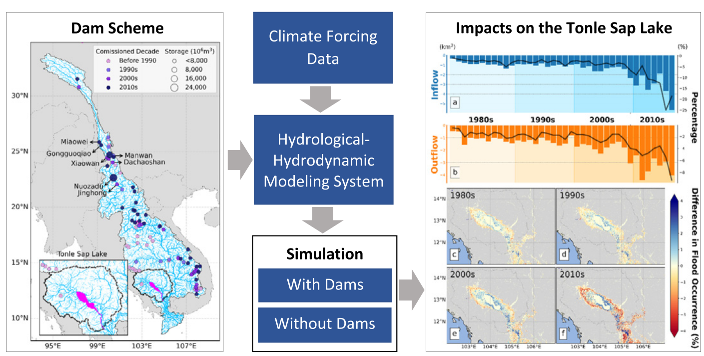
Huy Dang [a], Yadu Pokhrel [a,*], Sanghoon Shin [a,b], Jac Stelly [a], Daniel Ahlquist [c], Duong Du Bui [d]

[a] Department of Civil and Environmental Engineering, Michigan State University, East Lansing, MI, United States
[b] Earth System Science Interdisciplinary Center, University of Maryland, College Park, MD, United States
[c] James Madison College, Michigan State University, East Lansing, MI, United States
[d] National Center for Water Resources Planning and Investigation (NAWAPI), Ministry of Natural Resources and Environment (MONRE), Hanoi, Viet Nam

HIGHLIGHTS

- Hydrologic changes in the Tonle Sap Lake system are attributed to climate variability and Mekong dams.
- The direct effects of dams are quantified by comparing simulations with and without dams.
- Dam operation dampened the peak of flow reversal in the Tonle Sap River.
- Dam operation shrank (expanded) the lake's inundated areas in the wet (dry) season.
- The impacts of Mekong dams on the lake's water balance have increase substantially after year 2010.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 3 January 2022
Received in revised form 21 March 2022
Accepted 22 March 2022
Available online 29 March 2022

Editor: Ashantha Goonetilleke

Keywords:
Mekong River basin
Tonle Sap Lake
Hydropower dams
Flood pulse
Inundation dynamics
Water balance

ABSTRACT

Inland lakes have been increasingly impacted by climate change and human activities, leading to unprecedented environmental consequences. Among many rapidly changing lakes is the Tonlé Sap Lake (TSL) in Cambodia—Southeast Asia's largest inland lake—which is under growing threats from altered flows and inundation dynamics due to compounding effects of climate change and dam construction in the Mekong River basin (MRB). While previous studies have examined the potential causes of recent changes in open water areas, a mechanistic quantification of the lake's shifting hydrologic balance and inundation dynamics due to natural climate variability and dam operations is lacking. Here, using a hydrological-hydrodynamic modeling system 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 km^2 or ~3% (~270 km^2 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.

* Corresponding author.
E-mail address: ypokhrel@msu.edu (Y. Pokhrel).

http://dx.doi.org/10.1016/j.scitotenv.2022.154833

1. Introduction

Inland lakes around the world have been increasingly impacted by climate change and human activities, leading to unprecedented scale 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 ~2500 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 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. Data and methods

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 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 2.3) 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 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). 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).

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 2.3). This is a commonly used approach in the MRB given the lack of open data on hydropower operation (Dang et al., 2020).

2.2. 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).

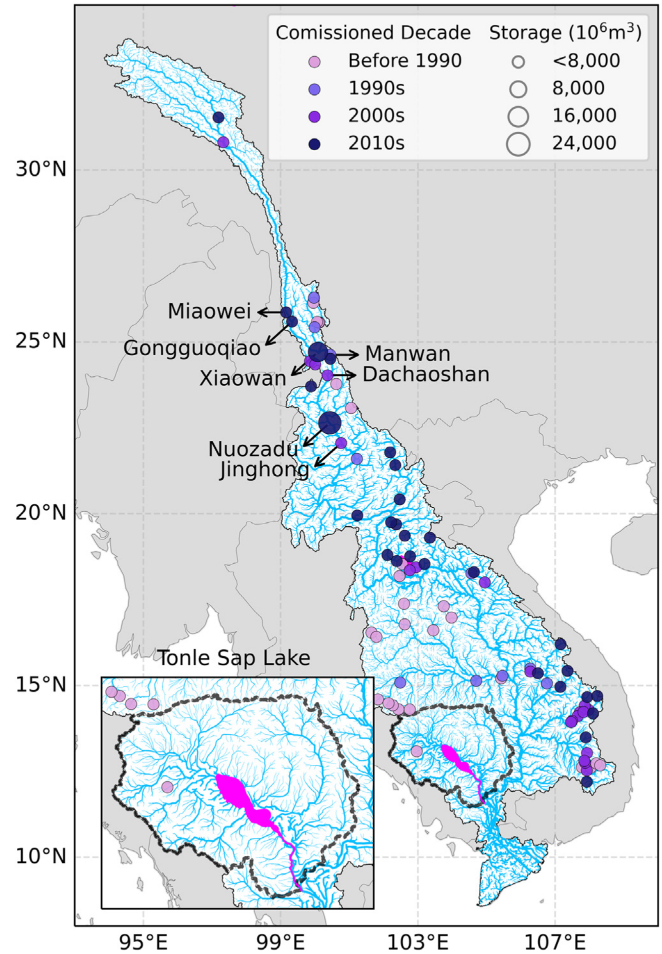


Fig. 1. A spatial map of the MRB depicting the location of the 86 selected dams (color-coded circles) that are included in the model. The color-coding and size of the circles indicate the decade of commissioning and maximum storage capacity, respectively. The dams located in the Mekong mainstream (as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

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 (~90 m) using a 90 m 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. 1).

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. 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.

For irrigation dams, when reservoir storage meets the normal operating condition between the minimum and maximum capacity, a targeted monthly release r_m [L^3/T], is applied, which is calculated based on demand-controlled release ratio R [−], release coefficient k_{rls} [−], provisional monthly release r_m' [L^3/T], and long-term monthly inflow i_m [L^3/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:

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

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.

3. Results

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). 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 is also presented in the supplementary information (Fig. S1). 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. 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. 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. 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. 2e–g), Kompong Luong (KL, Fig. 2h) in the TSL and Prek Kdam (PK, Fig. 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 the 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 scheme.

The long-term average of simulated flood depth for the TSL region is also shown in Fig. 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.

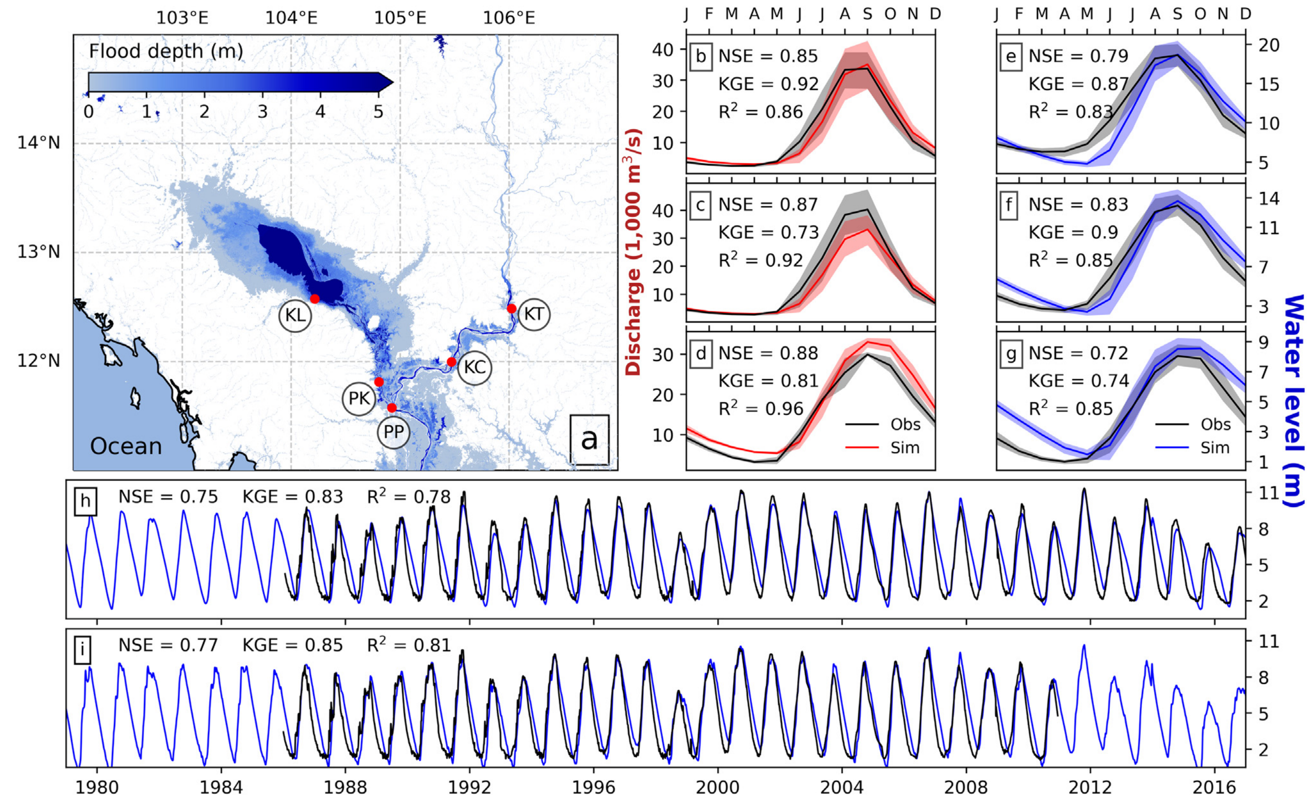


Fig. 2. Long-term (1979–2016) average of simulated flood depth over the TSL area (a). Comparison of the seasonal cycle of simulated river discharge (b-d) and water levels (e-g) with observations at Kratie (KT; b and e), Kompong Cham (KC; c and f), and Phnom Penh Port (PP; d and g) stations. Shadings (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 (R^2) are indicated for each station.

3.2. Effects of climate variability and dams on river discharge and water level

Table 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).

Fig. 3a depicts the decadal average of seasonal water level fluctuation at the KL station (location shown in Fig. 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. 3a). 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. 3b) 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 ~1270 m^3/s in the 2000s (late-October). And from the 2000s to 2010s, this outflow peak dropped by ~1750 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

Table 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. The highest values of reduction in maximum flow and increase in minimum flow are highlighted in pink and green colors, respectively.

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%

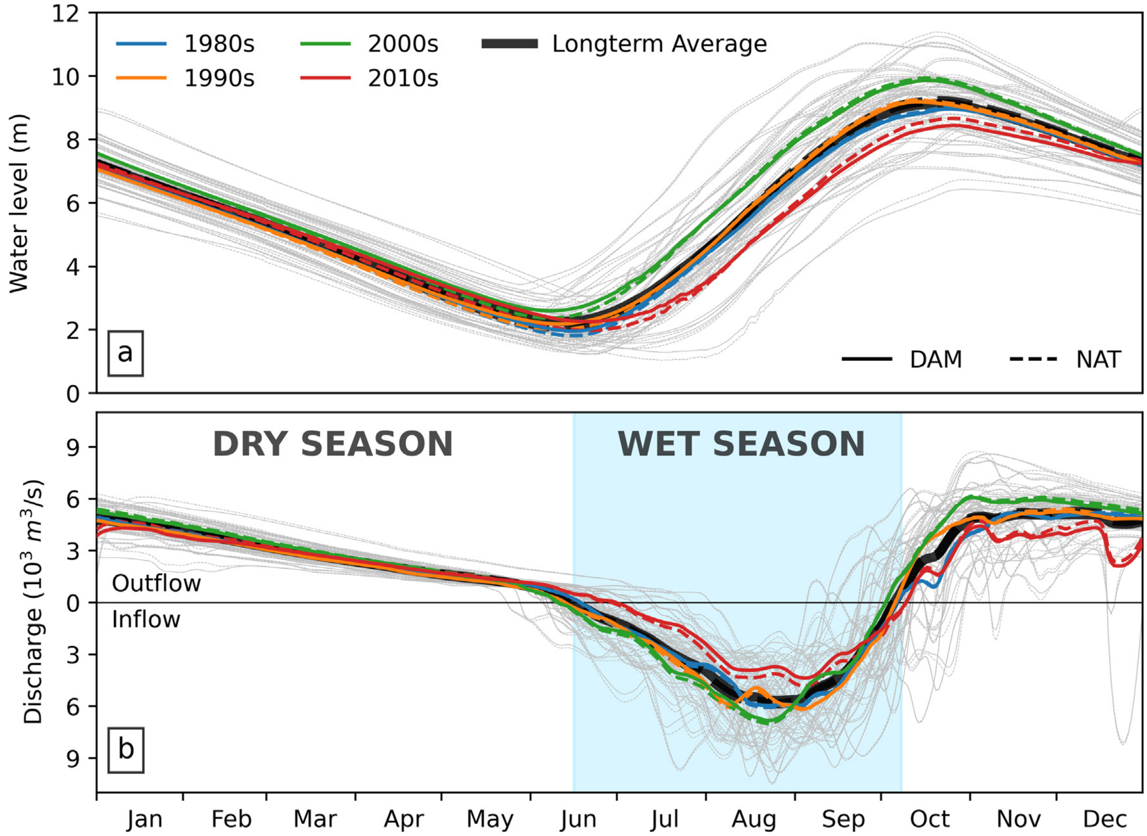


Fig. 3. Decadal (color-coded lines) and long-term (thick black lines; 1979–2016) average of water levels at the KL station in the TSL (a) and river discharge at the PK station in the TSR (b). Solid and dashed lines represent the DAM and NAT simulation results, respectively.

corresponds to a late onset of inflow (Fig. 3a and b). 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. 3b).

Comparison of lake water levels from the NAT and DAM simulations (Table S1) 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., ~8 cm 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., ~8 m), 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.

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 S2) 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 S2).

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 3.2; Table 1), the impacts on TSL water balance are relatively substantial (Fig. 4). In general, and as also discernible in Fig. 3b, the effects of the dam operations manifest as a substantial reduction in both inflow into and outflow from the lake (Fig. 4). 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.

3.4. Effects of climate variability and dams on inundation dynamics

The decadal shift in flood occurrence (Fig. 5) 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. 5b and c). A notable increase in flood occurrence throughout the entire seasonally flooded portion of the lake can be observed in the 2000s (Fig. 5d), 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. 5e), especially in the outer periphery of the lake, ranging from 7.5 to more than 10% (i.e., 27 to more than 40 days).

Fig. 6 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

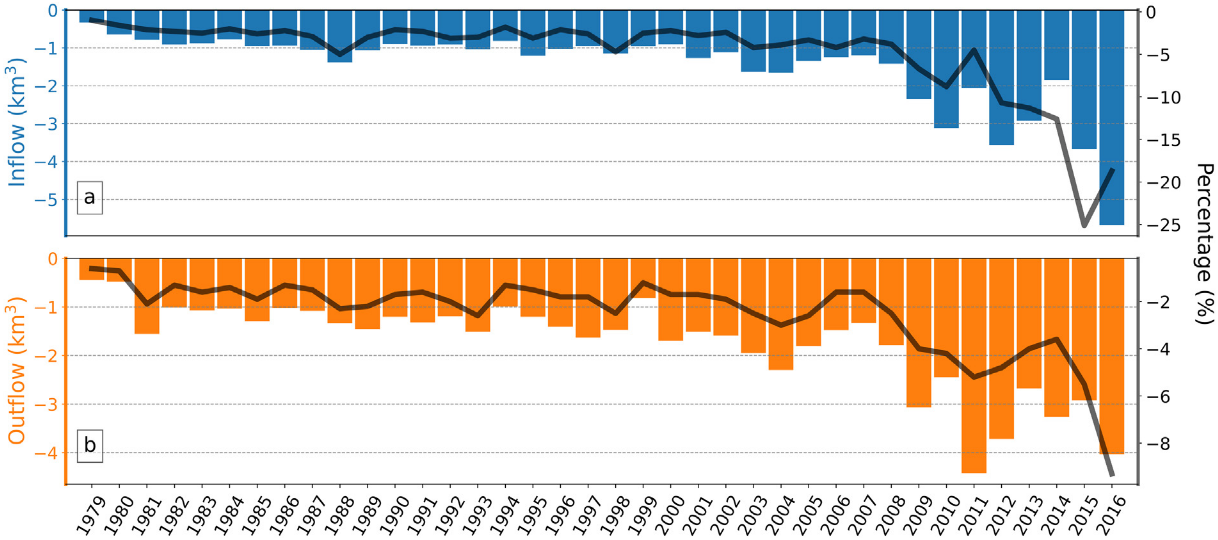


Fig. 4. Difference in annual inflow (a) and outflow (b) volume (bars; left y-axis) between DAM and NAT simulations at the Prek Kdam station in the TSR. Grey lines (right y-axis) show the difference in percentage figures relative to the NAT simulation.

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. 5). 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. 6d) 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.

The dam-induced changes in flood occurrence relate to a substantial alteration in the Lake's surface area (Fig. 7). Consistent with our results on the shift in water levels and inundation dynamics (Figs. 3 and 6), 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 by ~270 km^2 during April, equivalent to ~6% of the lake's surface area in the NAT simulation (Table S4), 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 on lake water levels (Fig. 3).

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 indicate 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 1 and Fig. 3) 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

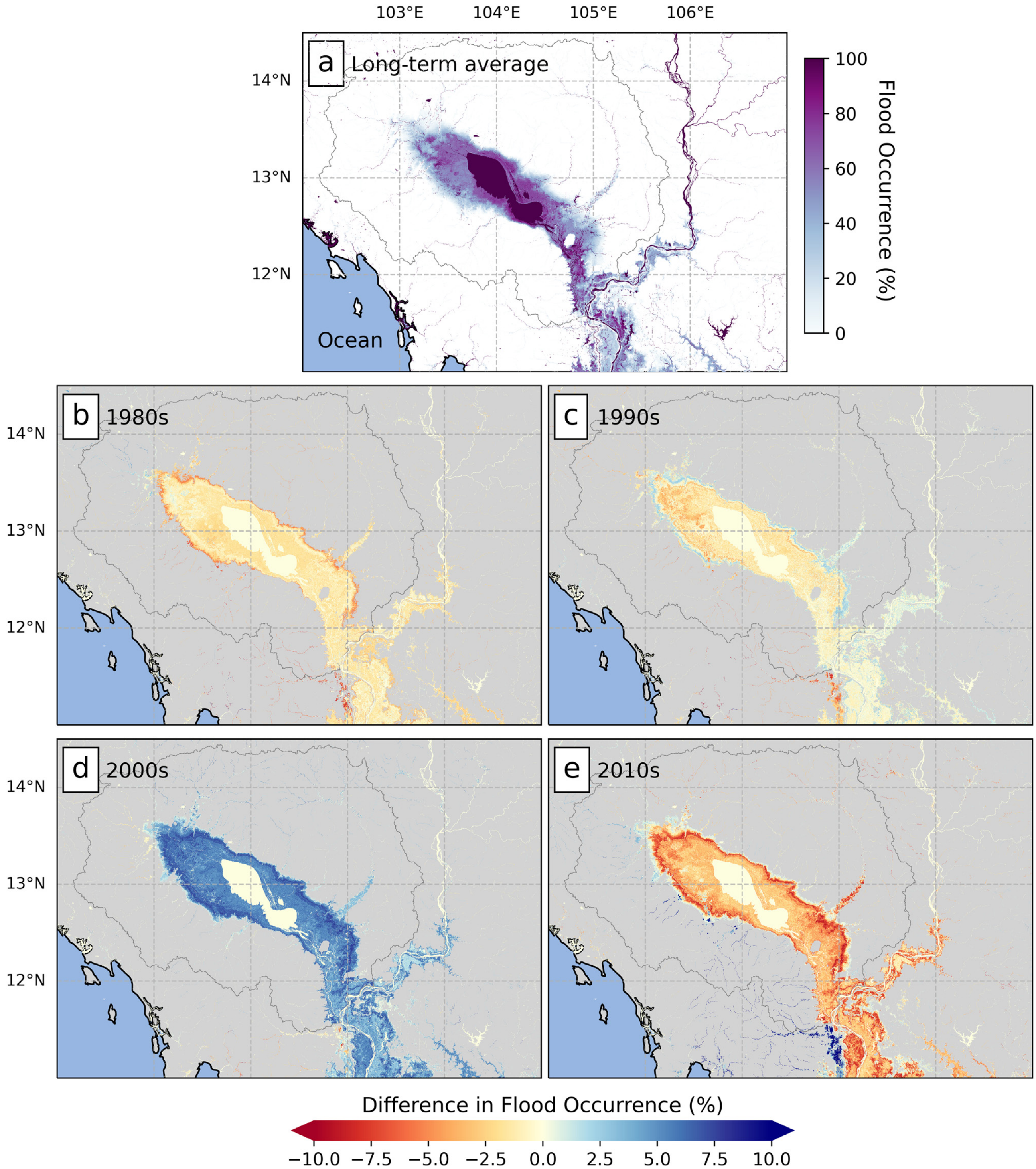


Fig. 5. Long-term (1979–2016) average of flood occurrence (a). Difference between average flood occurrence for each decade and the long-term average in the NAT simulation: 1980s (b), 1990s (c), 2000s (d), and 2010s (e). The bottom color bar applies to panels b–e where results shown are percentage differences 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).

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. 6d), our results are comparable to the dam-induced changes

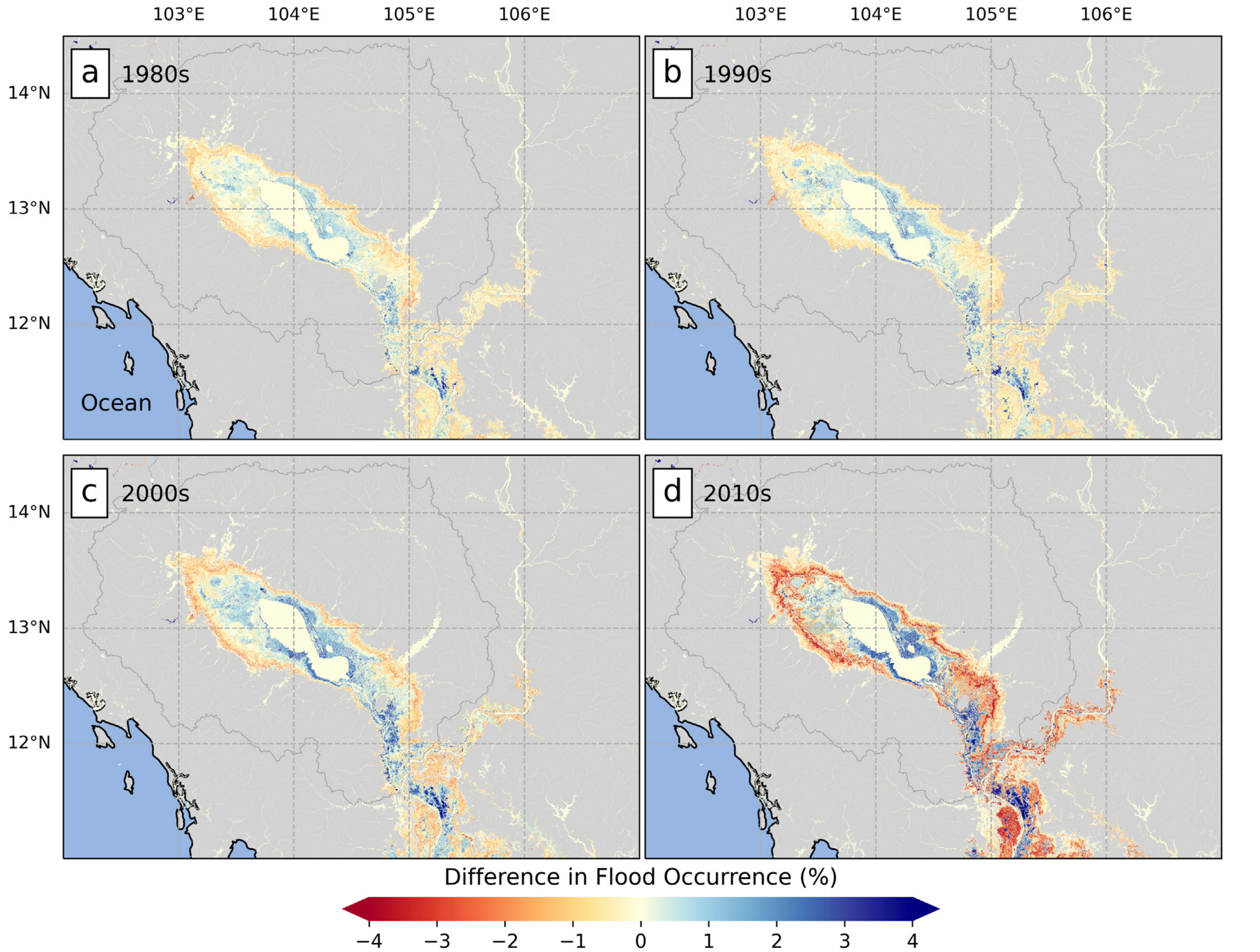


Fig. 6. Differences in decadal-average flood occurrence (in %) between DAM and NAT simulations in the 1980s (a), 1990s (b), 2000s (c), and 2010s (d). Areas with no flood occurrence in both simulations are indicated in grey.

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. 7), 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. 3), 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

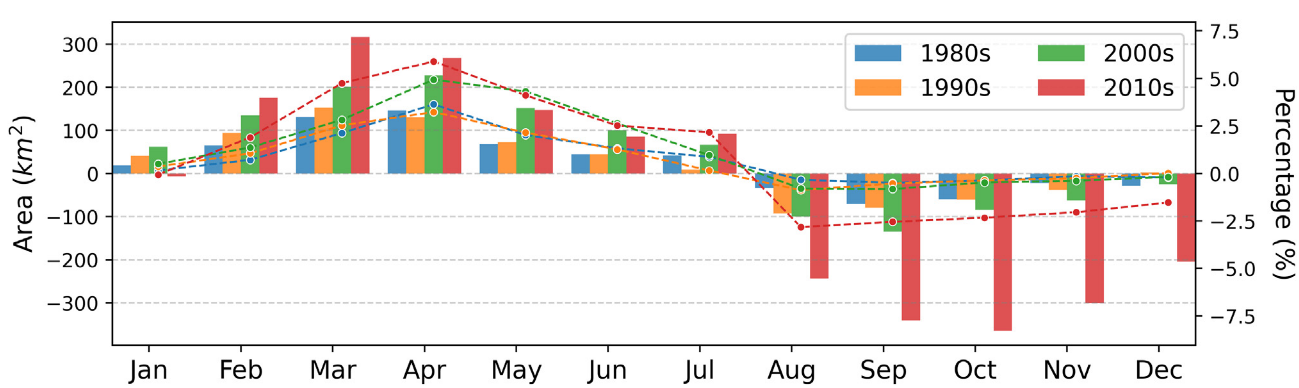


Fig. 7. Differences in decadal-average inundated areas (color-coded bar; left y-axis) between DAM and NAT simulations. Results shown are spatial average for the TSL watershed shown in Fig. 1. Color-coded lines (right y-axis) show the difference in percentage figures relative to the total inundated areas in the NAT simulation.

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). Further, 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 river-bed 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.

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% (~23 cm). 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 such as the Amazon and Congo.

CRediT authorship contribution statement

Huy Dang: Formal analysis, Visualization, Writing – original draft, Writing – review & editing. **Yadu Pokhrel:** Conceptualization, Funding acquisition, Writing – original draft, Writing – review & editing. **Sanghoon Shin:** Data curation, Methodology, Software, Writing – review & editing. **Jac Stelly:** Writing – original draft, Writing – review & editing. **Daniel Ahlquist:** Funding acquisition, Writing – review & editing. **Duong Du Bui:** Writing – review & editing.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Yadu Pokhrel reports financial support was provided by National Science Foundation. Yadu Pokhrel reports financial support was provided by NASA. Yadu Pokhrel reports financial support was provided by Henry Luce Foundation.

Acknowledgments

This research was supported by the National Science Foundation (CAREER Award; Grant #: 1752729), the Henry Luce Foundation (Mekong Culture WELL project), and NASA (Award #: 80NSSC17K0259 and 80NSSC18K1134). D.D.B. received funding from Vingroup Innovation

Foundation (VINIF; project code: VINIF.2019.DA17). We thank Amanda Flaim for comments and suggestions that helped tremendously in improving the manuscript. We are also grateful to Mauricio Arias for providing water level data from prior publications. Simulations were conducted using Cheyenne (https://doi.org/10.5065/D6RX99HX) provided by NCAR's Computational and Information Systems Laboratory, sponsored by the National Science Foundation. Observed river discharge and water level data can be obtained from the Mekong River Commission (http://www.mrcmekong.org/), and dam database is available from the Research Program on Water, Land, and Ecosystem (https://wle-mekong.cgiar.org/).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2022.154833.

References

AghaKouchak, A., Mirchi, A., Madani, K., Di Baldassarre, G., Nazemi, A., Alborzi, A., Anjileli, H., Azarderakhsh, M., Chiang, F., Hassanzadeh, E., Huning, L.S., Mallakpour, I., Martinez, A., Mazdiyasni, O., Moftakhari, H., Norouzi, H., Sadegh, M., Sadeqi, D., Van Loon, A.F., Wanders, N., 2021. Anthropogenic drought: definition, challenges, and opportunities. Rev. Geophys. 59, 1–23. https://doi.org/10.1029/2019RG000683.

Arias, M.E., Cochrane, T.A., Piman, T., Kummu, M., Caruso, B.S., Killeen, T.J., 2012. Quantifying changes in flooding and habitats in the Tonle Sap Lake (Cambodia) caused by water infrastructure development and climate change in the Mekong Basin. J. Environ. Manag. 112, 53–66. https://doi.org/10.1016/j.jenvman.2012.07.003.

Arias, M.E., Cochrane, T.A., Norton, D., Killeen, T.J., Khon, P., 2013. The flood pulse as the underlying driver of vegetation in the largest wetland and fishery of the Mekong basin. Ambio 42, 864–876. https://doi.org/10.1007/s13280-013-0424-4.

Arias, M.E., Cochrane, T.A., Elliott, V., 2014a. Modelling future changes of habitat and fauna in the Tonle Sap wetland of the Mekong. Environ. Conserv. 41, 165–175. https://doi.org/10.1017/S0376892913000283.

Arias, M.E., Piman, T., Lauri, H., Cochrane, T.A., Kummu, M., 2014b. Dams on Mekong tributaries as significant contributors of hydrological alterations to the Tonle Sap Floodplain in Cambodia. Hydrol. Earth Syst. Sci. 18, 5303–5315. https://doi.org/10.5194/hess-18-5303-2014.

Baran, E., Gallego, G., 2015. Cambodia's fisheries: a decade of changes and evolution. Catch Cult. 21, 28–31.

Barlow, C., Baran, E., Halls, A.S., Kshatriya, M., 2008. Migratory fish resources. Catch Cult. 14, 16–21.

Beban, A., So, S., Un, K., 2017. From force to legitimation: rethinking land grabs in Cambodia. Dev. Chang. 48, 590–612. https://doi.org/10.1111/dech.12301.

Binh, D.Van, Kantoush, S., Sumi, T., 2020a. Changes to long-term discharge and sediment loads in the Vietnamese Mekong Delta caused by upstream dams. Geomorphology 353, 107011. https://doi.org/10.1016/j.geomorph.2019.107011.

Binh, D.Van, Kantoush, S.A., Saber, M., Mai, N.P., Maskey, S., Phong, D.T., Sumi, T., 2020b. Long-term alterations of flow regimes of the Mekong River and adaptation strategies for the Vietnamese Mekong Delta. J. Hydrol. Reg. Stud. 32, 100742. https://doi.org/10.1016/j.ejrh.2020.100742.

Bryant, S., Mcgrath, H., Boudreault, M., 2021. Gridded Flood Depth Estimates From Satellite Derived Inundations. 30, pp. 1–21.

Burbano, M., Shin, S., Nguyen, K., Pokhrel, Y., 2020. Hydrologic changes, dam construction, and the shift in dietary protein in the Lower Mekong River Basin. J. Hydrol. 581, 124454. https://doi.org/10.1016/j.jhydrol.2019.124454.

Bussi, G., Darby, S.E., Whitehead, P.G., Jin, L., Dadson, S.J., Voepel, H.E., Vasilopoulos, G., Hackney, C.R., Hutton, C., Berchoux, T., Parsons, D.R., Nicholas, A., 2021. Impact of dams and climate change on suspended sediment flux to the Mekong delta. Sci. Total Environ. 755, 142468. https://doi.org/10.1016/j.scitotenv.2020.142468.

Chanvirak, K., 2020. Fish for prahok running low. Dec. 24, 2020Khmer Times. https://www.khmertimeskh.com/50796693/fish-for-prahok-running-low/.

Chaudhari, S., Felfelani, F., Shin, S., Pokhrel, Y., 2018. Climate and anthropogenic contributions to the desiccation of the second largest saline lake in the twentieth century. J. Hydrol. 560, 342–353. https://doi.org/10.1016/j.jhydrol.2018.03.034.

Chen, A., Liu, J., Kummu, M., Varis, O., Tang, Q., Mao, G., Wang, J., Chen, D., 2021. Multidecadal variability of the Tonle Sap Lake flood pulse regime. Hydrol. Process. https://doi.org/10.1002/hyp.14327.

Chua, S.D.X., Lu, X.X., Oeurng, C., Sok, T., Grundy-warr, C., 2021. Drastic decline of floodpulse in the Cambodian floodplains (the Mekong River and the Tonle Sap system). 1992, pp. 1–28.

Cian, F., Marconcini, M., Ceccato, P., Giupponi, C., 2018. Flood depth estimation by means of high-resolution SAR images and lidar data. Nat. Hazards Earth Syst. Sci. 18, 3063–3084. https://doi.org/10.5194/nhess-18-3063-2018.

Coe, M.T., Foley, J.A., 2001. Human and natural impacts on the water resources of the Lake Chad basin. J. Geophys. Res. Atmos. 106, 3349–3356. https://doi.org/10.1029/2000JD900587.

Cohen, S., Raney, A., Munasinghe, D., Derek Loftis, J., Molthan, A., Bell, J., Rogers, L., Galantowicz, J., Robert Brakenridge, G., Kettner, A., Huang, Y.F., Tsang, Y.P., 2019. The Floodwater Depth Estimation Tool (FwDET v2.0) for improved remote sensing analysis of coastal flooding. Nat. Hazards Earth Syst. Sci. 19, 2053–2065. https://doi.org/10.5194/nhess-19-2053-2019.

Cramb, R., 2020. White gold: the commercialisation of rice farming in the lower Mekong basin. White Gold: The Commercialisation of Rice Farming in the Lower Mekong Basin https://doi.org/10.1007/978-981-15-0998-8.

Dang, T.D., Vu, D.T., Chowdhury, A.F.M.K., Galelli, S., 2020. A software package for the representation and optimization of water reservoir operations in the VIC hydrologic model. Environ. Model. Softw. 126, 104673. https://doi.org/10.1016/j.envsoft.2020.104673.

Delgado, J.M., Apel, H., Merz, B., 2010. Flood trends and variability in the Mekong river. Hydrol. Earth Syst. Sci. 14, 407–418. https://doi.org/10.5194/hess-14-407-2010.

Fox, J., Ledgerwood, J., 1999. Dry-season flood-recession rice in the Mekong Delta: two thousand years of sustainable agriculture? Asian Perspect. 38, 37–50.

Frappart, F., Do Minh, K., L'Hermitte, J., Cazenave, A., Ramillien, G., Le Toan, T., Mognard-Campbell, N., 2006. Water volume change in the lower Mekong from satellite altimetry and imagery data. Geophys. J. Int. 167, 570–584. https://doi.org/10.1111/j.1365-246X.2006.03184.x.

Frappart, F., Biancamaria, S., Normandin, C., Blarel, F., Bourrel, L., Aumont, M., Azemar, P., Vu, P.L., Le Toan, T., Lubac, B., Darrozes, J., 2018. Influence of recent climatic events on the surface water storage of the Tonle Sap Lake. Sci. Total Environ. 636, 1520–1533. https://doi.org/10.1016/j.scitotenv.2018.04.326.

Fung, Z., Pomun, T., Charles, K.J., Kirchherr, J., 2019. Mapping the social impacts of small dams: the case of Thailand's Ing River basin. Ambio 48, 180–191. https://doi.org/10.1007/s13280-018-1062-7.

Gao, H., Bohn, T.J., Podest, E., McDonald, K.C., Lettenmaier, D.P., 2011. On the causes of the shrinking of Lake Chad. Environ. Res. Lett. 6. https://doi.org/10.1088/1748-9326/6/3/034021.

Gernaat, D.E.H.J., Bogaart, P.W., Vuuren, D.P.V., Biemans, H., Niessink, R., 2017. High-resolution assessment of global technical and economic hydropower potential. Nat. Energy 2, 821–828. https://doi.org/10.1038/s41560-017-0006-y.

Grumbine, R.E., Xu, J., 2011. Mekong hydropower development. Science (80-.) 332, 178–179. https://doi.org/10.1126/science.1200990.

Guan, Y., Zheng, F., 2021. Alterations in the water-level regime of Tonle Sap Lake. J. Hydrol. Eng. 26, 05020045. https://doi.org/10.1061/(asce)he.1943-5584.0002013.

Halls, A.S., Hortle, K.G., 2021. Flooding is a key driver of the Tonle Sap dai fishery in Cambodia. Sci. Rep. 11, 3806. https://doi.org/10.1038/s41598-021-81248-x.

Hoes, O.A.C., Meijer, L.J.J., Van Der Ent, R.J., Van De Giesen, N.C., 2017. Systematic high-resolution assessment of global hydropower potential. PLoS One 12, 1–10. https://doi.org/10.1371/journal.pone.0171844.

Hortle, B.K.G., Pengbun, N., Rady, H., Sopha, L., 2004. Trends in the Cambodian dai fishery: floods and fishing pressure. Catch Cult. 10, 7–9.

Intralawan, A., Smajgl, A., McConnell, W., Ahlquist, D.B., Ward, J., Kramer, D.B., 2019. Reviewing benefits and costs of hydropower development evidence from the Lower Mekong River Basin. WIREs Water 6, e1347. https://doi.org/10.1002/wat2.1347.

Ji, X., Li, Y., Luo, X., He, D., 2018. Changes in the lake area of Tonle Sap: possible linkage to runoff alterations in the Lancang River? Remote Sens. 10, 866. https://doi.org/10.3390/rs10060866.

Junk, W.J., 1999. The flood pulse concept of large rivers: learning from the tropics. Large Rivers 11, 261–280. https://doi.org/10.1127/lr/11/1999/261.

Kabir, T., Pokhrel, Y., Felfelani, F., 2022. On the precipitation-induced uncertainties in process-based hydrological modeling in the Mekong River Basin. Water Resour. Res. 58. https://doi.org/10.1029/2021wr030828.

Keskinen, M., Tola, P., Varis, O., 2007. Conflicts With Abundance of Water 2.

Keskinen, M., Kummu, M., Käkönen, M., Varis, O., 2012. Mekong at the crossroads: next steps for impact assessment of large dams. Ambio 41, 319–324. https://doi.org/10.1007/s13280-012-0261-x.

Keskinen, M., Someth, P., Salmivaara, A., Kummu, M., 2015. Water-energy-food nexus in a transboundary river basin: the case of Tonle Sap Lake, Mekong River Basin. Water (Switzerland) 7, 5416–5436. https://doi.org/10.3390/w7105416.

Khan, I., Jack, M.W., Stephenson, J., 2018. Analysis of greenhouse gas emissions in electricity systems using time-varying carbon intensity. J. Clean. Prod. 184, 1091–1101. https://doi.org/10.1016/j.jclepro.2018.02.309.

Kontgis, C., Schneider, A., Ozdogan, M., Kucharik, C., Tri, V.P.D., Duc, N.H., Schatz, J., 2019. Climate change impacts on rice productivity in the Mekong River Delta. Appl. Geogr. 102, 71–83. https://doi.org/10.1016/j.apgeog.2018.12.004.

Kummu, M., Sarkkula, J., 2008. Impact of the Mekong River flow alteration on the Tonle Sap flood pulse. Ambio 37, 185–192. https://doi.org/10.1579/0044-7447(2008)37[185:IOTMRF]2.0.CO;2.

Kummu, M., Tes, S., Yin, S., Adamson, P., Józsa, J., Koponen, J., Richey, J., Sarkkula, J., 2013. Water balance analysis for the Tonle Sap Lake-floodplain system. Hydrol. Process. 28, 1722–1733. https://doi.org/10.1002/hyp.9718.

Lee, D., Lee, G., Kim, S., Jung, S., 2020. Future runoff analysis in the Mekong River basin under a climate change scenario using deep learning. Water (Switzerland) 12, 1–19. https://doi.org/10.3390/W12061556.

Li, D., Long, D., Zhao, J., Lu, H., Hong, Y., 2017. Observed changes in flow regimes in the Mekong River basin. J. Hydrol. 551, 217–232. https://doi.org/10.1016/j.jhydrol.2017.05.061.

Lin, Z., Qi, J., 2017. Hydro-dam – a nature-based solution or an ecological problem: the fate of the Tonlé sap Lake. Environ. Res. 158, 24–32. https://doi.org/10.1016/j.envres.2017.05.016.

Liu, Y., Wu, G., Guo, R., Wan, R., 2016. Changing landscapes by damming: the Three Gorges Dam causes downstream lake shrinkage and severe droughts. Landsc. Ecol. 31, 1883–1890. https://doi.org/10.1007/s10980-016-0391-9.

Lu, X.X., Chua, S.D.X., 2021. River discharge and water level changes in the Mekong River: droughts in an era of mega-dams. Hydrol. Process. 35, 1–9. https://doi.org/10.1002/hyp.14265.

Micklin, P., 2007. The Aral Sea disaster. Annu. Rev. Earth Planet. Sci. 35, 47–72. https://doi.org/10.1146/annurev.earth.35.031306.140120.

Micklin, P., 2016. The future Aral Sea: hope and despair. Environ. Earth Sci. 75, 1–15. https://doi.org/10.1007/s12665-016-5614-5.

Ng, W.X., Park, E., 2021. Shrinking Tonlé Sap and the recent intensification of sand mining in the Cambodian Mekong River. Sci. Total Environ. 777, 146180. https://doi.org/10.1016/j.scitotenv.2021.146180.

Nguyen, N.Y., Ichikawa, Y., Ishidaira, H., 2016. Estimation of inundation depth using flood extent information and hydrodynamic simulations. Hydrol. Res. Lett. 10, 39–44. https://doi.org/10.3178/hrl.10.39.

Orr, S., Pittock, J., Chapagain, A., Dumaresq, D., 2012. Dams on the Mekong River: lost fish protein and the implications for land and water resources. Glob. Environ. Chang. 22, 925–932. https://doi.org/10.1016/j.gloenvcha.2012.06.002.

Phoumin, H., Meas, S., An, H.P., 2021. Understanding quality energy-related infrastructure development in the mekong subregion: key drivers and policy implications. Econ. Law. Institutions Asia Pacific, pp. 303–330 https://doi.org/10.1007/978-981-16-2000-3_13.

Piman, T., Cochrane, T.A., Arias, M.E., Green, A., Dat, N.D., 2013. Assessment of flow changes from hydropower development and operations in Sekong, Sesan, and Srepok Rivers of the Mekong Basin. J. Water Resour. Plan. Manag. 139, 723–732. https://doi.org/10.1061/(asce)wr.1943-5452.0000286.

Pokhrel, Y., Hanasaki, N., Koirala, S., Cho, J., Yeh, P.J.F., Kim, H., Kanae, S., Oki, T., 2012a. Incorporating anthropogenic water regulation modules into a land surface model. J. Hydrometeorol. 13, 255–269. https://doi.org/10.1175/JHM-D-11-013.1.

Pokhrel, Y., Hanasaki, N., Yeh, P.J.F., Yamada, T.J., Kanae, S., Oki, T., 2012b. Model estimates of sea-level change due to anthropogenic impacts on terrestrial water storage. Nat. Geosci. 5, 389–392. https://doi.org/10.1038/ngeo1476.

Pokhrel, Y., Koirala, S., Yeh, P.J.F., Hanasaki, N., Longuevergne, L., Kanae, S., Oki, T., 2015. Incorporation of groundwater pumping in a global Land Surface Model with the representation of human impacts. Water Resour. Res. 51, 78–96. https://doi.org/10.1002/2014WR015602.

Pokhrel, Y., Felfelani, F., Shin, S., Yamada, T.J., Satoh, Y., 2017. Modeling large-scale human alteration of land surface hydrology and climate. Geosci. Lett. 4. https://doi.org/10.1186/s40562-017-0076-5.

Pokhrel, Y., Burbano, M., Roush, J., Kang, H., Sridhar, V., Hyndman, D.W., 2018a. A review of the integrated effects of changing climate, land use, and dams on Mekong river hydrology. Water (Switzerland) 10, 1–25. https://doi.org/10.3390/w10030266.

Pokhrel, Y., Shin, S., Lin, Z., Yamazaki, D., Qi, J., 2018b. Potential disruption of flood dynamics in the lower Mekong River basin due to upstream flow regulation. Sci. Rep. 8, 1–13. https://doi.org/10.1038/s41598-018-35823-4.

Schmitt, R.J.P., Bizzi, S., Castelletti, A., Kondolf, G.M., 2018. Improved trade-offs of hydropower and sand connectivity by strategic dam planning in the Mekong. Nat. Sustain. 1, 96–104. https://doi.org/10.1038/s41893-018-0022-3.

Schoenberger, L., Beban, A., 2018. "They turn us into Criminals": embodiments of fear in Cambodian land grabbing. Ann. Am. Assoc. Geogr. 108, 1338–1353. https://doi.org/10.1080/24694452.2017.1420462.

Shin, S., Pokhrel, Y., Miguez-Macho, G., 2019. High-resolution modeling of reservoir release and storage dynamics at the continental scale. Water Resour. Res. 55, 787–810. https://doi.org/10.1029/2018WR023025.

Shin, S., Pokhrel, Y., Yamazaki, D., Huang, X., Torbick, N., Qi, J., Pattanakiat, S., Ngo-Duc, T., Nguyen, T.D., 2020. High resolution modeling of river-floodplain-reservoir inundation dynamics in the Mekong River basin. Water Resour. Res. 56, 1–23. https://doi.org/10.1029/2019WR026449.

Shin, S., Pokhrel, Y., Talchabhadel, R., Panthi, J., 2021. Spatio-temporal dynamics of hydrologic changes in the Himalayan river basins of Nepal using high-resolution hydrological-hydrodynamic modeling. J. Hydrol. 598, 126209. https://doi.org/10.1016/j.jhydrol.2021.126209.

Siev, S., Paringit, E.C., Yoshimura, C., Hul, S., 2016. Seasonal changes in the inundation area and water volume of the Tonle Sap River and its floodplain. Hydrology 3, 1–12. https://doi.org/10.3390/hydrology3040033.

Soukhaphon, A., Baird, I.G., Hogan, Z.S., 2021. The impacts of hydropower dams in the Mekong River basin: a review. Water (Switzerland) 13, 1–18. https://doi.org/10.3390/w13030265.

Takata, K., Emori, S., Watanabe, T., 2003. Development of the minimal advanced treatments of surface interaction and runoff. Glob. Planet. Chang. 38, 209–222. https://doi.org/10.1016/S0921-8181(03)00030-4.

Teh, L.S.L., Bond, N., KC, K., Fraser, E., Seng, R., Sumaila, U.R., 2019. The economic impact of global change on fishing and non-fishing households in the Tonle Sap ecosystem, Pursat, Cambodia. Fish. Res. 210, 71–80. https://doi.org/10.1016/j.fishres.2018.10.005.

Teng, J., Jakeman, A.J., Vaze, J., Croke, B.F.W., Dutta, D., Kim, S., 2017. Flood inundation modelling: a review of methods, recent advances and uncertainty analysis. Environ. Model. Softw. 90, 201–216. https://doi.org/10.1016/j.envsoft.2017.01.006.

Thilakarathne, M., Sridhar, V., 2017. Characterization of future drought conditions in the lower Mekong River basin. Weather Clim. Extrem. 17, 47–58. https://doi.org/10.1016/j.wace.2017.07.004.

Västilä, K., Kummu, M., Sangmanee, C., Chinvanno, S., 2010. Modelling climate change impacts on the flood pulse in the lower Mekong floodplains. J. Water Clim. Chang. 1, 67–86. https://doi.org/10.2166/wcc.2010.008.

Wang, J., Yun, X., Pokhrel, Y., Yamazaki, D., Zhao, Q., Chen, A., Tang, Q., 2021. Modeling daily floods in the Lancang-Mekong River basin using an improved hydrological-hydrodynamic model. Water Resour. Res. 57, 1–20. https://doi.org/10.1029/2021WR029734.

Wang, W., Lu, H., Ruby Leung, L., Li, H.Y., Zhao, J., Tian, F., Yang, K., Sothea, K., 2017. Dam construction in Lancang-Mekong River basin could mitigate future flood risk from warming-induced intensified rainfall. Geophys. Res. Lett. 44, 10378–10386. https://doi.org/10.1002/2017GL075037.

Wang, Y., Feng, L., Liu, J., Hou, X., Chen, D., 2020. Changes of inundation area and water turbidity of Tonle Sap Lake: responses to climate changes or upstream dam construction? Environ. Res. Lett. 15. https://doi.org/10.1088/1748-9326/abac79.

Weedon, G.P., Balsamo, G., Bellouin, N., Gomes, S., Best, M.J., Viterbo, P., 2018. The WFDEI Meteorological Forcing Data. https://doi.org/10.5065/486N-8109.

Wen, D., Cao, J., Zhao, C., Masiri, I., Buntoung, S., 2021. Interdecadal variation of summer rainfall in the Greater Mekong Subregion and its possible causes. Environ. Res. Lett. 16. https://doi.org/10.1088/1748-9326/ac188b.

Yamazaki, D., Kanae, S., Kim, H., Oki, T., 2011. A physically based description of floodplain inundation dynamics in a global river routing model. Water Resour. Res. 47, 1–21. https://doi.org/10.1029/2010WR009726.

Yamazaki, D., De Almeida, G.A.M., Bates, P.D., 2013. Improving computational efficiency in global river models by implementing the local inertial flow equation and a vector-based river network map. Water Resour. Res. 49, 7221–7235. https://doi.org/10.1002/wrcr.20552.

Yamazaki, D., Sato, T., Kanae, S., Hirabayashi, Y., Bates, P.D., 2014. Regional flood dynamics in a bifurcating mega delta simulated in a global river model. Geophys. Res. Lett. 41, 3127–3135. https://doi.org/10.1002/2014GL059744.

Yamazaki, D., Ikeshima, D., Neal, J.C., O'Loughlin, F., Sampson, C.C., Kanae, S., Bates, P.D., 2017. MERIT DEM: a new high-accuracy global digital elevation model and its merit to global hydrodynamic modeling. AGU Fall Meeting Abstracts, p. H12C-04.

Yoshida, Y., Lee, H.S., Trung, B.H., Tran, H.D., Lall, M.K., Kakar, K., Xuan, T.D., 2020. Impacts of mainstream hydropower dams on fisheries and agriculture in Lower Mekong basin. Sustainability 12, 1–21. https://doi.org/10.3390/su12062408.

Yu, W., Kim, Y., Lee, D., Lee, G., 2019. Hydrological assessment of basin development scenarios: impacts on the Tonle Sap Lake in Cambodia. Quat. Int. 503, 115–127. https://doi.org/10.1016/j.quaint.2018.09.023.

Yun, X., Tang, Q., Wang, J., Liu, X., Zhang, Y., Lu, H., Wang, Y., Zhang, L., Chen, D., 2020. Impacts of climate change and reservoir operation on streamflow and flood characteristics in the Lancang-Mekong River Basin. J. Hydrol. 590, 125472. https://doi.org/10.1016/j.jhydrol.2020.125472.

Yun, X., Tang, Q., Li, J., Lu, H., Zhang, L., Chen, D., 2021. Can reservoir regulation mitigate future climate change induced hydrological extremes in the Lancang-Mekong River Basin? Sci. Total Environ. 785, 147322. https://doi.org/10.1016/j.scitotenv.2021.147322.

Zhang, Y., Ma, H., Zhao, S., 2021. Assessment of hydropower sustainability: review and modeling. J. Clean. Prod. 321, 128898. https://doi.org/10.1016/j.jclepro.2021.128898.

Zhou, Y., Hejazi, M., Smith, S., Edmonds, J., Li, H., Clarke, L., Calvin, K., Thomson, A., 2015. A comprehensive view of global potential for hydro-generated electricity. Energy Environ. Sci. 8, 2622–2633. https://doi.org/10.1039/c5ee00888c.

Ziv, G., Baran, E., Nam, S., Rodríguez-Iturbe, I., Levin, S.A., 2012. Trading-off fish biodiversity, food security, and hydropower in the Mekong River Basin. Proc. Natl. Acad. Sci. U. S. A. 109, 5609–5614. https://doi.org/10.1073/pnas.1201423109.