SPATIOTEMPORAL MODELING OF DAMS AND CONSEQUENT IMPACTS ON THE MEKONG RIVER BASIN ECOSYSTEM

By

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ABSTRACT

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The hydro-dam can help increase adaptation to climate change and meet water, energy, and food needs as a widely adopted water infrastructure. However, it alters and fragments ecosystems, especially at places where hydro-dam constructions are gaining popularity for the sake of more socio-economic benefits. This dissertation examines and characterizes the process and outcomes of ecosystem changes owing to hydro-dams, using the Mekong River Basin as an example. The overarching research question is answered from four angles, including 1) finding new essential properties of dams, 2) determining dams' impact scope on land change, 3) estimating cascade consequences of dams on significant water bodies, and 4) analyzing dams' ripple effect on the atmosphere.

The main body (Chapters 2-4) of this dissertation consists of three articles. In Chapter 2, I achieve the first two research goals by performing time-serial trajectory analyses on 67 working Mekong hydro-dams and the lands surrounding them using long-term geospatial imageries and statistical methods. In Chapter 3, I calculated and analyzed the open water surface area of the Tonle Sap Lake and the changes at a 16-day interval from 2001 to 2015 to assess how upstream hydro-dam proliferation has influenced the largest inland lake in the lower basin. In Chapter 4, the spatial variations of inundation areas in the Tonle Sap Lake floodplain and temporal changes of the greenhouse gas (such as carbon dioxide and nitrous oxide) emissions from the changing lands were modeled and quantified using

geospatial datasets and a biogeochemical model to provide a solution to the fourth research question.

In summary, this dissertation has successfully established a new remote sensing approach that enables hydro-dam characterization and set up a combined framework combining geospatial modeling and biogeochemical modeling. The three studies come to the conclusions that 1) hydro-dams' impact scale on land change is spatially anisotropic at the local level, 2) hydro-dams' cascade consequence on a large water body at a remote place is significant, and 3) hydro-dams' ripple effect on floodplain via water and lands can cause more greenhouse gas emissions into the atmosphere. This dissertation can enrich the current literature regarding human-nature interactions, focusing on hydro-dam's role in the ecosystem. It also broadens the knowledge of hydro-dams' impacts and attracts more relevant studies and environmental protection efforts. More importantly, this dissertation can assist future policy-making, especially for sustainable hydro-dam planning and transboundary water resource management.

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Last but not least, I am extremely thankful to my family, especially my husband, Weichao, who has always been supportive, caring, and understanding. I also want to express my deepest sense of gratitude to my parents. Finally, I'd like to thank my son, Marcus, who was born two weeks before my defense. This little guy started a new chapter of my life and I feel so happy and blessed that he chose us to be his parents and friends in this life-long journey. I wish him a bright future. Again, without the support of my family, it is impossible for me finish this journal.

PREFACE

The three main chapters of this dissertation have been published in or submitted to peer-reviewed journals and have co-authors. According to the copyright policies, these chapters could be reused and quoted in the dissertation as the author retains the copyright. Thus, these chapters are briefly summarized in the main body of this document (Chapters 2-4), followed by an Appendix section with the original published article or manuscript under review attached. The citations for these chapters are below.

Chapter 2: Lin, Z., & Qi, J. (2019). A New Remote Sensing Approach to Enrich Hydropower Dams' Information and Assess Their Impact Distances : A Case Study in the Mekong River Basin. *Remote Sensing*, *11*(24). https://doi.org/10.3390/rs11243016

Chapter 3: Lin, Z., & Qi, J. (2017). Hydro-dam – A nature-based solution or an ecological problem: The fate of the Tonlé Sap Lake. *Environmental Research*, *158*, 24–32. https://doi.org/10.1016/j.envres.2017.05.016

Chapter 4: Lin, Z., Pokhrel, Y., Shin, S., Zhang, F., & Qi, J. Hydro-dam impacts on greenhouse gas emissions of the Tonle Sap Lake Floodplain. *Environmental Research, (In revision)*

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KEY TO ABBREVIATIONS

WEF	Water-Energy-Food
MRB	Mekong River Basin
MR	Mekong River
UMRB	Upper Mekong River Basin
LMRB	Lower Mekong River Basin
WLE	Water, Land, and Ecosystem
LCLUC	Land cover land use change
TSL	Tonle Sap Lake
GHG	Greenhouse Gas
CO2	Carbon dioxide
N2O	Nitrous oxide
MK	Mann-Kendall
DEM	Digital Elevation Model
NDVI	Normalized Difference Vegetation Index
SD	Standard Deviation
CV	Coefficient of Variation
MW	Megawatt
MODIS	Moderate Resolution Imaging Spectroradiometer
DNDC	DeNitrification and DeComposition
GIS	Geographic Information Science

CHAPTER 1

INTRODUCTION

Water, food, and energy and the Mekong River Basin

The past decades have witnessed a rapid socio-economic development accompanied by an unprecedented population boom, especially in the developing countries and regions in Asia, South America, and Africa (de la Croix and Gobbi, 2017). From early 1900 to 2020s, the world's population has increased from less than 10 million to approximately 80 million ("World Population Growth - Our World in Data," n.d.), causing concerning challenges to the planet's *natural resource* capacity (Pimentel et al., 2013). Meanwhile, the more severe climate change and consequent extreme climatic events have trigger uncertainty and severe damage to sustainable development in many places (Getvoldsen et al., 2009; Lu et al., 2019). To meet the escalating demand for more water-energy-food (WEF) from the enlarged population and help adapt to the changing climate, better exploitation and utilization of natural resources become crucial means to maintain and boost social and economic development (Biggs et al., 2015; Simpson and Jewitt, 2019). However, these actions have unintentionally left an undesired ripple effect on the natural environment and ecosystems in some places, making the balance between the need of people and the exploitation of natural resources a concerning status (Lee, 2016; Liu et al., 2017).

The Mekong River Basin (MRB) is one of the regions manifesting the abovementioned human-nature conflicts (Kirmani, 1990; Osborne, 2009). The enormous river basin occupies a large portion of Southeast Asia and is one of the world's largest riverine watersheds breed abundant species and biodiversity (Mekong River Commission (MRC), 2003, 2000). Its total catchment area is approximately 795,000 km^2 and has been the home to millions of people over hundreds of years (Van Zalinge et al., 2004). The entire basin is nourished by the sixth-longest Asian river – Mekong River (MR), which originates from the Tibetan Plateau and flows through six Asian and Southeast Asian countries, including China, Myanmar, Thailand, Laos, Cambodia, and Vietnam (Adamson et al., 2009). The national border between China, Myanmar, and Laos forms a dividing line that separates the MRB into Upper Mekong River Basin (UMRB) and Lower Mekong River Basin (LMRB) (Yang et al., 2019). The UMRB is much smaller (i.e., a quarter of the MRB) and comprises plateaus of southwestern China. For many years, two Asian summer monsoons controls the UMRB (Shi and Chen, 2018), while the climate in the LMRB is typically tropical monsoonal with an apparent two-season cycle (i.e., wet season and dry season) every year ("Mekong River | Facts, Definition, Map, History, & Location | Britannica," n.d.).

A substantial portion of the Mekong population (i.e., ~ 70 million) reside in the LMRB and are mainly engaged in farming activities for livelihoods as agricultural labor (Pech and Sunada, 2008). For many years, wet-season precipitation brought by the Monsoon and year-round river flows provided valuable water resources to lower Mekong agricultural and aquatic food production. Fish and rainfed crops are the primary nutrient sources for the lower Mekong residents. Fishery and agriculture productivity relies heavily on the periodical cycle of the LMRB hydrology and the Monsoon climate (Kirby et al., 2010). However, the rhythm of the watershed hydro-pattern has experienced a significant change because of the varying climate conditions and human responses to negative consequences of climate change in recent decades (Xue et al., 2011).

According to the most widely used world's disaster database called EM-DAT (Guha-Sapir et al., 2016), a total of 203 severe floods and droughts have hit the MRB from 2001 to 2021. More than 119 million population were affected and the Mekong countries have suffered from a $59 billion economic loss (Guha-Sapir et al., 2016). The region becomes one of the most vulnerable regions to climate change, and its inhabitants confront a high risk of reduced WEF sustainability in socio-economic development (Phommasack et al., 2013). Under such circumstances, human interventions have been largely encouraged and developed at the basin-wide scale over the entire MRB to secure the essential living supply and prevent the negative impacts of the frequent floods and droughts (Intralawan et al., 2019; Kubiszewski et al., 2013).

Hydro-dams in the MRB

As one of the most efficient means to buffer human society and industrial and agricultural activities against seasonal and annual climate variability, hydro-dam construction has gained popularity among Mekong countries since the 1950s (Osborne, 2009). Hydro-dams are designed and operated for the purpose of facilitating cropland irrigation, mitigating floods and droughts, generating clean hydropower, and providing recreation places (Brown et al., 2009). According to the WLE Greater Mekong dam database (WLE, 2017), to the late 2017, a total of 320 hydro-dams are functioning in the MRB. Approximately 47% of the commissioned Mekong hydro-dams were established by Thailand, 19.4% and 19.0% by China and Vietnam, respectively (WLE, 2017). The largest Mekong hydro-dam with the highest installed capacity (i.e., 5850 Megawatt (MW)) was initiated and owned by China since 2014 (WLE, 2017).

The MRB has been recognized as one of the most prominent areas where hydro-dam construction is at a surprising pace (Grumbine and Xu, 2011; Winemiller et al., 2016). The number of hydro-dams has kept rising since 1956, and currently, more hydro-dams are under construction or proposed/planned driven by the enormous socio-economic benefits underneath (WLE, 2017). For example, Laos has decided to set up another 56 hydro-dams by 2030 (WLE, 2017). The accelerated and competitive hydro-dam development is mainly driven by the huge amount of economic profit generated by the hydro-dam facilities to local inhabitants.

Although the basin-wide hydro-dam projects positively contribute to settling the conflict between the basin's socio-economic development and the sustainable environment maintenance, they inevitably cause undesirable side effects on the MRB ecosystem, especially in hydrological irregularity, biodiversity loss, and unevenly transboundary water occupation (Soukhaphon et al., 2021; Vaidyanathan, 2011). For instance, after a hydro-dam is completed, its water storage reservoir will become the primary water source for cropland irrigation of the neighboring communities. The improved accessibility to water and enhanced food productivity promotes more natural lands (e.g., wetland and grassland) converted to agricultural fields (Biemans et al., 2011; Jurík et al., 2018; Rufin et al., 2019). Sadly, local inhabitants' need for more water and food is satisfied at the cost of some plants and wildlife losing the home they are dependent on (Siyal et al., 2019). Another example is the hydro-dam's regulation on river flow through turbine and gauge becomes a barrier for fish migration during the reproduction period, making fish biodiversity and fishery productivity confronting a threatening recession (Dudgeon, 2005; Wu et al., 2019; Ziv et al., 2012).

In general, like many other man-made facilities, hydro-dams play a controversial role in the harmonious coexistence of humans and nature. It serves as a bridge in the WEF nexus and inevitably leads to many ecological and environmental issues (Gao et al., 2021; Olawuyi, 2020). Since the last century, with the enhancement of modeling techniques and the emergence of data diversity, research on the impact of hydro-dams on nature has gradually become a multidisciplinary hot spot (Brown et al., 2009), such as hydrology, geography, ecology, and environmental science.

Research overview and research gaps

To date, far more studies have been performed to explore and reveal the role of hydro-dams in the MRB ecosystem and their impacts on different ecosystem services. To the best of my knowledge, most scholars have focused more on the "negative" effects of hydro-dams than on the economic value in terms of electricity generation. In-depth studies of these impacts and ongoing dialectical discussions and debates can provide a more comprehensive perspective on whether the approaches and measures taken to maintain WEF nexus development are effective or not.

It is noticed that a majority of these studies have adopted and applied quantitative models (e.g., hydrologic model, land cover land use change (LCLUC) model, etc.) to assess the impacts of hydro-dams and predict the outcomes of dam removal (Chen and Olden, 2017; Foley et al., 2017). Scholars in engineering, hydrology, geography, environment, and ecology fields often use this approach to conduct specific studies. In contrast, in social science research, field surveys and sampling and subsequent statistical analyses are the most common research workflow used by researchers in sociology and economics (Kirchherr and Charles, 2018). According to current literature, the impacts of hydro-dams' can be classified as short-term and long-term, direct and indirect, quantifiable and non-quantifiable, and foreseeable and unforeseeable.

The most direct impact of a hydro-dam on the natural ecosystem is the hydrological alterations of water bodies in the river network via the regulation of river flow and reservoir volume (Hecht et al., 2019; Pokhrel et al., 2018; Räsänen et al., 2012). Besides, the changes in hydrology combined with the fact that a hydro-dams may act as a physical barrier in fish migration channel have caused a decline in the biodiversity of fish in the MRB (Baran and Myschowoda, 2009; Dugan et al., 2010; Ziv et al., 2012). What's more, Mekong hydro-dams also induce basin-wide LCLUC and downstream sediment accumulation (Kondolf et al., 2014; Kummu and Varis, 2007).These three directions are followed by the majority of studies addressing the effects of the MRB hydro-dams. The remaining studies focus on the another two aspects: the indirect impact of hydro-dams on the MRB ecosystem and the controversial issues of the spatial redistribution of water resources between the LMRB and UMRB regions and among Mekong countries from the political perspective (Bakker, 1999; Hirsch, 2010; Pearse-Smith, 2012).

Although there is a large body of literature assessing hydro-dams and their impacts at multiple scales, perspectives, and levels, there are still some problems that current research has rarely studied. First, our knowledge of the properties of hydro-dams themselves is incomplete (Lin and Qi, 2019). For example, basic information about a particular hydro-dam can be obtained from project records, construction documentaries, and public reports. Yet, information on a large number of hydro-dams at a broad spatial extent can only be extracted from regional or global-scale hydro-dam databases. Often, the data in these databases have not been verified with high accuracy, which leads to systematic errors in the modeling process in some fields. Second, due to data shortage and computational power limitations in the early years, many studies were limited to a specific geographic area and period only. Studies on a larger scale (i.e., time and space) can better help identify hydro-dams' ripple effect. Finally, as mentioned above, some research areas are in full swing. In contrast, others lack targeted in-depth studies, and how the latter can be complemented by available historical data is one of the research topics in this dissertation.

Research questions and summary of three dissertation chapters

This dissertation research addresses three specific science questions in Land, Water, and Atmosphere as follows:

1) **Land**: what are the spatial and temporal characteristics of all working Mekong hydro-dams in terms of LCLUC?
2) **Water**: what are the long-term and cumulative impacts of the Mekong hydro-dam cascade on the Tonle Sap Lake (TSL) hydrological cycle?
3) **Atmosphere**: what is the consequent change trend in the long-term greenhouse gas (GHG) (e.g., carbon dioxide (CO_2) and nitrous oxide (N_2O)) emissions from the Tonle Sap floodplain?

These three research questions can help fill some of the gaps in current studies. In particular, the first research question investigates how Mekong hydro-dams have affected the land use pattern at a basin-wide scale. The results of this study could increase the diversity of information in the current Mekong hydro-dam database. The second research question explores the long-term hydrological impacts of Mekong hydro-dams on a large water body in distant areas. The third question studies how floodplain inundation changes owing to the TSL hydro-pattern variations can alter the GHG change tendency.

The research background, process, and outcomes of studies designed to solve the three research questions are explained and illustrated in the following dissertation chapters (Chapters 2-4). Chapter 2 introduces a new remote sensing-based method that characterizes Mekong hydro-dams spatially and temporally using time-series datasets. The new method can measure the impact distance of any functioning Mekong hydro-dam at the areas above and below the dam site and precisely identify when the project was started and completed. Therefore, it adds new basic hydro-dam properties to a more comprehensive understanding of hydro-dam constructions. Chapter 3 investigates and shows the trajectory of the open water surface area of the TSL (i.e., the largest inland freshwater lake in Southeast Asia) over 15 years. The Mann-Kendall (MK) nonparametric trend test is used to identify the changing trend of this hydro-pattern feature. Compared to the changes in atmospheric conditions (i.e., temperature and precipitation), the driven factor underneath is analyzed and discussed. Chapter 4 takes advantage of geospatial data and techniques and a process-based biogeochemical model to simulate the daily CO_2 and N_2O emissions from the Tonle Sap floodplain under the influence of TSL's inundation variations. A long-term gases emission trajectory, similar to the open water surface area change of the TSL, was produced and used to detect the changing trend in the CO_2 and N_2O emissions from the altered Tonle Sap floodplain inundation area from 2001 to 2015.

CHAPTER 2

A NEW REMOTE SENSING APPROACH TO ENRICH HYDROPOWER DAMS' INFORMATION AND ASSESS THEIR IMPACTS DISTANCES: A CASE STUDY IN THE MEKONG RIVER BASIN

Summary of the published article

Basic information on hydro-dam properties plays a paramount role in the modeling process for hydro-dam evaluations. This data is usually acquired from hydro-dam databases. However, some essential hydro-dams' characteristics are missing, and the comprehensive and in-depth knowledge of dam properties is incomplete. For example, none of the existing dam databases can provide the impact scale of a specific hydro-dam, not to mention many hydro-dams in a large area. Besides, current temporal information of hydro-dam constructions recorded in commonly-used dam databases is inconsistent and inaccurate. The column "year" in different dam databases refers to different time points during the construction process, leading to a gross error when using this property.

This research aims to establish a feasible and reliable quantitative method for obtaining critical construction time points and spatial impact extent of a hydro-dam on LCLUC by taking advantage of geospatial science. Specifically, the proposed method can 1) fill record blanks in the current dam databases (i.e., dam commissioned year) and 2) add new hydro-dam characteristics (e.g., duration of the construction process, radius size of the influential buffer) in any dam database.

The datasets used in this research include a WLE Mekong hydro-dam database, digital elevation model (DEM) data, and a 30-year Landsat Normalized Difference Vegetation Index (NDVI) image collection covering the entire MRB from 1988 to 2017. A total of 67 Mekong

hydro-dams were studied using the proposed new remote sensing method. Their geo-locations and commissioned year records extracted from the WLE database were verified using open-source information (e.g., literature, reports, media news, etc.). The basis for creating the new method is that the hydro-dam construction and operation cause LCLUC surrounding the dam site. Such changes are spatially anisotropic (e.g., different at the area above and below the dam) and obtain stationarity over time. The key steps to realize the method comprise 1) separating the area above the dam and below the dam using DEM and NDVI quantile combination, 2) detecting the changing points in the 30-year trajectory using image entropy mean, standard deviation (SD), and coefficient of variation (CV) calculated using NDVI at different buffer zones with an increment of equal interval centered at the dam site.

The final results were assessed both empirically and statistically. The start and end years of hydro-dam construction generated by this method were correlated to the information on the real timings of constructions using the Pearson correlation test. The hydro-dams' impact scope estimates were compared to relevant findings in other peer-reviewed studies. It can be concluded that 1) the long-term curve of entropy's mean calculated for the above dam area at 400m distance is the most suitable one for determining construction start year (Pearson correlation value = 0.96), 2) similarly, the trajectory of entropy SD calculated for the below dam area at 500m distance is the best to identify construction completion year (Pearson correlation value = 0.90), 3) the impact scale in terms of a buffer radius at the above dam area and below dam area for the majority of Mekong hydro-dams is 4.0km and 2.5km, respectively.

Using the enormous MRB as the study area and 67 commissioned Mekong hydro-dams as study objects, the method set up and realized in this research has been approved to have the capability to be implemented and generalized at any other watershed worldwide by utilizing the long-lasting impacts of hydro-dams on land. This article successfully answers the scientific question of "what are the spatial and temporal characteristics of all working Mekong hydro-dams in terms of LCLUC?" and offers insights to a better understanding of hydro-dam construction itself by filling the current gaps in many dam databases. The findings and conclusions obtained in this study can be further extended to the research focusing on the hydro-dam's impact at a much larger scale.

APPENDIX

The content and information summarized in CHAPTER 2 have been published in an open-source peer-reviewed journal (i.e., *Remote Sensing*) in 2019.According to the journal's copyright policy, the publication could be reused and quoted in the dissertation as the author retains the copyright. The article can be found and viewed using the citation below.

Chapter 2: Lin, Z., & Qi, J. (2019). A New Remote Sensing Approach to Enrich Hydropower Dams' Information and Assess Their Impact Distances : A Case Study in the Mekong River Basin. *Remote Sensing*, *11*(24). https://doi.org/10.3390/rs11243016

CHAPTER 3

HYDRO-DAM – A NATURE-BASED SOLUTION OR AN ECOLOGICAL PROBLEM: THE FATE OF THE TONLE SAP LAKE

Summary of the published article

It is known that the regional proliferation of hydro-dams has a constant and notable impact on the hydrological pattern of the rivers in which they are located. Such influence, when accumulated, can also change the hydro-pattern of water bodies downstream the river network. Among all the water bodies in the LMRB (e.g., lake, river, stream, and pond), the TSL, lying in the lowland of Cambodia, is the most vital one since it is the largest inland freshwater lake in Southeast Asia and functions as a regulating reservoir for the MR mainstream. This great lake feeds over three million people, breeds abundant wildlife species, and attracts millions of tourists worldwide every year. Therefore, the lake also plays a pivotal role in the Cambodian economy.

Previous studies have demonstrated the consequences of Mekong hydro-dam constructions on the lake's hydrology, biodiversity, and sedimentation, particularly on its unique seasonal reverse-pulse pattern. These studies modeled and analyzed the water level change and inflow and outflow fluctuations of the TSL when the hydro-dam boom occurred. But little is known and has been investigated on the lake's open water surface area using continuous observations over decades. However, the lake's size is the most direct and effective indicator of the lake's hydrological change. Due to the limitation of computation and lack of sufficient data support, most analyses were performed by comparing the differences of two-time points (or more). In this study, continuous remote sensing imageries make the close monitoring of the lake's surface area accessible and possible.

Both Landsat images acquired at specific dates of a five-year interval from 1988 to 2016 and Moderate Resolution Imaging Spectroradiometer (MODIS) NDVI time series from 2001 to 2015 obtained at a 16-day interval were used to 1) first confirm the changes of the lake's surface area briefly and roughly, and 2) extract the semi-monthly lake surface area size. The optimal threshold used to separate the lake surface from the surrounding landscape for each image was determined by visualization interpretation and Otsu's method. When estimates from Landsat products showed a noticeable surface area change in the past three decades, MODIS NDVI-derived lake size long-term trajectory was produced every 16 days from 2001 to 2015. Flash flood and drought disturbance on the curve was removed using the forecasting function in Excel 2016, and other types of the statistical anomaly were also eliminated. At last, the nonparametric MK trend test was applied to uncover the underlying change tendency of the TSL's hydrology in the perspective of open water surface area.

A downward changing direction was discovered when all the outliers and bias were cleared, implying a shrinking phenomenon in the TSL. There are multiple drivers for such hydrological loss and can be mainly summarized into two categories, human interventions, climate change, to name them all. Correlation analyses between climatic factors (i.e., regional rainfall accumulation and air temperature) and lake area time series were not significant, thus inferring climate change may not be the primary driver responsible for the identified decline. Then, can we claim that the Mekong hydro-dam cascade should bear the lion's share of the responsibility for the long-term reduction in the great lake's water area? It would be arbitrary to do so. Yet, we can confirm that the construction and operations of the Mekong hydro-dams did have some impacts on changes in the hydrological characteristics of the TSL because the changes occurred during the period when the number of commissioned hydro-dam rose explosively. At the current stage, we need more specific and accurate hydrologic measurements, support of models with high precision, and continuous, long-term observations to establish this fact.

This study has succeeded in indirectly exploring and discovering the hydro-changes in the most significant water body of the LMRB under the shadow of accelerating dam proliferation from the water perspective. It answers the questions of "what are the long-term and cumulative impacts of the Mekong hydro-dam cascade on the TSL's hydrological cycle?" and for the very first time, it provides solid evidence by using long-term, frequent observations on a large water body.

APPENDIX

The content and information summarized in CHAPTER 3 have been published in a peer-reviewed journal (i.e., *Environmental Research*) in 2017.According to the journal's copyright policy, the publication could be reused and quoted in the dissertation as the author retains the copyright. The article can be found and viewed using the citation below.

Chapter 3: Lin, Z., & Qi, J. (2017). Hydro-dam – A nature-based solution or an ecological problem: The fate of the Tonlé Sap Lake. *Environmental Research*, *158*, 24–32. https://doi.org/10.1016/j.envres.2017.05.016

CHAPTER 4

CHANGE TREND ANALYSIS OF GREENHOUSE GAS EMISSIONS FROM THE TONLE SAP FLOODPLAIN, CAMBODIA OVER FIFTEEN YEARS

Summary of the manuscript under review

The concentration of GHG in the atmosphere warms the planet and is the main reason for global warming. Typical GHG include CO_2, N_2O and methane (CH_4). GHG emissions mainly come from industrial and agricultural activities as well as transportation and LCLUC. Among different land cover types, the seasonally inundated floodplain plays an important role. It is perceived as an ecosystem that can act as a GHG sink or source during the different inundation stages. In Southeast Asia, the vast Tonle Sap floodplain dominated by evergreen or deciduous tropical forest is vulnerable to the periodical changes of the Tonle Sap water system and thus leading to the changes of its spatial extents year by year. Sometimes, when there is less drainage into the lake, submerged floodplain land will be exposed to the air and become bare land and vice versa. The floodplain water level change and spatial inundation area loss and gain together affect carbon and nitrogen biogeochemical cycles and constantly alter GHG emissions in this wetland.

So far, there has been no research conducted to simulate this process and assess the potential change and change trend in the floodplain GHG emissions. This article demonstrates a pilot study that quantifies the daily CO_2 and N_2O emission from the altered floodplain lands based on geospatial analyses and a widely adopted biogeochemical model called DeNitrification and DeComposition (DNDC). The findings can be used to reveal the ripple effect of TSL's hydro-variations on the floodplain GHG emission. Model-derived daily emissions accumulate annually throughout 15 years, and the slopes of the linear regression uncover the changing tendency of the regional CO_2 and N_2O emission. Given the size of the study area and the difficulty of field sampling in the wetland rainforest, the model simulation outputs were compared with data obtained from other peer-reviewed work.

The datasets employed in this article consist of long-term daily climatic factors (i.e., precipitation and temperature), soil properties, geo-location centroids of gridded floodplain lands, and vegetative biomass information. In addition to the data support, remote sensing combined with geographic information science (GIS) determines the preliminary modeling process for the spatial extent change detection of the Tonle Sap floodplain. The model was implemented in a regional mode using the remote sensing-based large database and generated a daily CO_2 and N_2O emission estimate for every grid in the study area from 2001 to 2015 using the maximum floodplain spatial extent in 2011 as the reference. These daily estimates were then summarized into annual emission accumulations, and linear regressions were applied to recognize the change tendency in the total amount and yearly rate of CO_2 and N_2O emissions due to the floodplain spatial extent change. It was noted that more floodplains lands were no longer submerged under the seasonal floodwater and regional emission quantity and rate both rose over the 15-year study period.

This article demonstrates a multidisciplinary effort to evaluate cascade consequences of the water body's hydrological change on the atmosphere. The workflow taken here can be generalized to the other floodplains to help disentangle the following myth: how human efforts for a better adaptation to climate change have changed the climate? Considering the magnitude and scale of the Mekong hydro-dams and their impacts, this question urgently needs to be answered and is partially solved by the findings of this research.

APPENDIX

The content and information summarized in CHAPTER 4 have been submitted to a peer-reviewed journal (i.e., *Environmental Research*) in 2021. According to the journal's copyright policy, the publication could be reused and quoted in the dissertation as the author retains the copyright. Here, I attach the submitted manuscript below.

Chapter 4: Lin, Z., Pokhrel, Y., Shin, S., Zhang, F., & Qi, J. Hydro-dam impacts on greenhouse gas emissions of the Tonle Sap Lake Floodplain. *Environmental Research, (In revision)*

Submitted manuscript:

Change trend analysis of greenhouse gas emissions from the Tonle Sap floodplain, Cambodia over fifteen years

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Abstract

Climate change and human activities can have significant impact on floodplain hydrologic patterns and associated greenhouse gas (GHG) emissions. This research, using the Tonle Sap floodplain as a study case, investigates the change trends in the floodplain extents and associated GHG emissions from 2001 to 2015. Specifically, we first used satellite images, topographic data, and model-based water depth information to delineate the maximum spatial extent of Tonle Sap floodplain inundation and the permanent lake each year. Then, we applied the DeNitrification and DeComposition (DNDC) model, driven by local climate data, soil properties, and floodplain vegetation biomass information, to calculate the daily emissions of carbon dioxide (CO_2) and nitrous oxide (N_2O) from the non-inundated floodplain area. Results show that 1) more floodplain lands are no longer submerged due to the hydro-pattern change of the Tonle Sap water system, which is physically connected to the densely dammed Mekong River (MR), 2) the annual total CO_2 and N_2O emissions from the floodplain had increased from 2001 to 2015, and 3) the annual emission rates also increased over the study period. These findings imply that Tonle Sap floodplain could potentially become a big source of GHG if the regional flood pulse is to be removed by the hydro-dam regulations across the Mekong River Basin (MRB). Given the scale and magnitude of global hydro-dam construction, floodplain induced changes in GHG emissions could be significant and may offset the hydropower induced carbon reductions. The approach taken in this study may contribute to environmental and ecological research with a focus on climate change and human influence on watershed ecosystems.

Keywords:

GHG emissions; Floodplain biogeochemical process; DNDC; Remote sensing; Long-term change trend

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1. Introduction

There have been many studies and discussions on global climate change and its causes (Ahmed, 2020; Dessler and Parson, 2019; Khairullina et al., 2019; Knight, 2016). Research indicates that influencing factors of natural processes and anthropogenic processes are the original reasons for this issue (Mikhaylov et al., 2020). A typical and concerning environmental problem of climate change is global warming, a consequence of enhanced GHG concentration in the atmosphere, especially CO_2 (Kumar, 2018; Ritchie and Roser, 2020). In addition to CO_2, methane (CH_4), N_2O, industrial gases, water vapor, and ozone also contribute to the observed global warming trend. Industrial activities (e.g., fossil fuel combustion), transportation, agriculture (e.g., livestock and rice production), and land use change (LUC) (e.g., urbanization and deforestation) are the leading causes for more and more GHG (Cloy and Smith, 2017; Ritchie and Roser, 2020).

Previous LUC-GHG research mainly focused on farmland, forestland, and grassland, because they were perceived as land cover types of high carbon stock (Harris et al., 2015; Kim and Kirschbaum, 2015; Tubiello et al., 2015). Recent studies have shown that periodically inundated floodplain also plays a vital role as a GHG sink or source throughout the drying-wetting phase (Arce et al., 2018; Machado dos Santos Pinto et al., 2020). The characteristics playing a defining role in the floodplain GHG emissions include soil properties, water level, climate (e.g., temperature and precipitation), vegetation composition, and management intervention (if any) (Cronan, 2018). Among all these factors, the water level fluctuates more frequently as a result of combined impacts of climate (e.g., extreme climatic events, ENSO, etc.) (Ilyas et al., 2019; Karim et al., 2016) and human activities (e.g., hydro-damming, water resource management, cropland irrigation, etc.) (Alam et al., 2017; Dang et al., 2016; Wang and Wang, 2016).

The enormous Tonle Sap floodplain, lying in the heart of Cambodia, is one of the world's largest freshwater floodplains receiving significant influences of regional climatic fluctuations and human activities. This lowland floodplain, together with the great Tonle Sap Lake (TSL) have gone through rapid changes in both spatial extents and hydroperiod cycles over the past several decades (Cochrane et al., 2014; Dang et al., 2016; Hecht et al., 2019; Lin and Qi, 2017). The changes of Tonle Sap water system are believed to be related to dampening effects by the intensified upstream hydro-dams in the MRB and a shift in the Asian monsoon climate patterns (Lin and Qi, 2017; Yu et al., 2019). The alterations in the Tonle Sap hydrological dynamics can affect the floodplain's biogeochemical processes and the carbon (C) and nitrogen (N) cycles (de Vicente, 2021), leading to further changes of the GHG generation. However, the trends of GHG emissions from the Tonle Sap floodplain, which is tightly linked to the Mekong hydro-dams' regulation, are unknown.

In this research, we take the Tonle Sap floodplain as a study case and we aim to 1) map the annual geospatial extent of the Tonle Sap floodplain from 2001 to 2015, and 2) uncover potential change trends in the GHG emissions, triggered by the interannual floodplain extent variations. First, we mapped the spatio-temporal dynamics of the Tonle Sap floodplain using long-term remote sensing images and geospatial modeling methods. Then, we employed the process-based DNDC model to simulate daily GHG emissions from the non-inundated floodplain area over the 15-year period. Lastly, based on the simulated results, we analyzed the trends in the GHG emissions to understand how hydroperiod alternations of the Tonle Sap water system could contribute to global warming.

Since the 1970s, remote sensing data and techniques have been widely used because they enable frequent and multi-scale observations of a large area with high efficiency and reliability (Guo et al., 2017; Schultz and Engman, 2012). Previous studies have approved the capabilities of remote sensing and geospatial modeling in monitoring the hydrology and habitat of the Tonle Sap floodplain (Mahood et al., 2020; Siev et al., 2016). The DNDC computer program adopted in this research was initially designed and developed upon a series of C and N biogeochemical reactions (e.g., composition and nitrification) in agroecosystems to predict rice productivity, soil carbon cycling, nitrogen leaching, and trace gas emissions (Li, 2001, 1996; Yin et al., 2020). It was gradually improved to become applicable to other ecosystems (e.g., wetland, rangeland, etc.), and has been successfully engaged in different studies over twenty countries as a supportive ecologically modeling tool (Beheydt et al., 2007; Katayanagi et al., 2012; Li et al., 2017).

2. Materials and methods

2.1. Study area

For thousands of years, the TSL and its floodplain have fed millions of Southeast Asian residents and bred abundant biodiversity as the most productive ecosystem in the MRB (Lamberts, 2006; Olson and Morton, 2018). Initiated in 1950s to meet the increasing demand for more food and energy, Mekong hydro-dam projects proliferate and have experienced an obvious boom especially after 2000 (Figure 1). Connecting to the MR mainstream via the Tonle Sap River (TSR), the lake and its floodplain function as a natural reservoir to regulate seasonal Mekong floodwater. When the wet season arrives, floodwater pours into the lake via the TSR, enlarging the lake up to six times its size of the lowest water level (Kummu et al., 2014; MRC, 2005). During the dry season from November to April, lake water flows back into the TSR and joins the MR at the confluence near Phnom Penh, the capital city of Cambodia. This flow reversal pulse forms a unique pattern in terms of expanding and contracting floodplain, transporting sediment and nutrients from the MR to the Tonle Sap water system. Recent studies have found a reduction in the inflows and outflows of the TSR (Cochrane et al., 2014), resulting in an alteration to the Tonle Sap hydrological cycling (Lin and Qi, 2017; Yu et al., 2019). Regardless of the causes of weakened flood pulses of the TSL, the alterations in the floodplain's hydroperiod offer an opportunity for land use to convert from floodplain to agricultural fields (Arias et al., 2014), while at the same time could trigger changes in the associated biogeochemical processes. As a result, these unintended changes bring a concern to the fate of the lake and sustainability of the local communities.

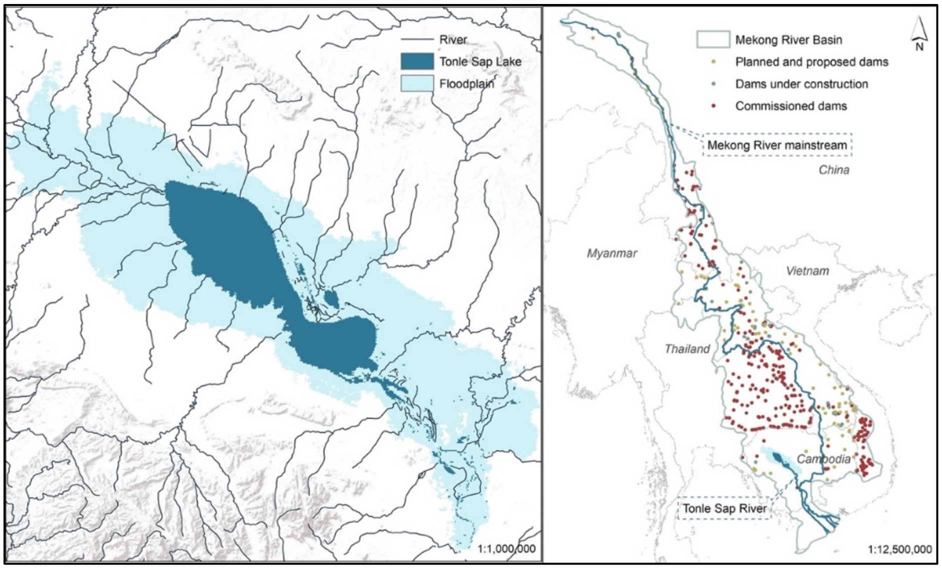

Figure 1. The Tonle Sap Lake and floodplain in the Lower Mekong River Basin with hydro-dams built across the entire Mekong River Basin. The Tonle Sap Lake and floodplain are connected to the Mekong River via the Tonle Sap River.

2.2. Data

2.2.1. Data used for mapping floodplain extent

To map the spatial extent and temporal variations of the Tonle Sap floodplain, we used Landsat 5 TM/8 OLI 8-day Enhanced Vegetation Index (EVI) composites, elevation map, water depth, and periodical TSL surface area data (Table 1) to delineate the annual maximum floodplain area from 2001 to 2015. The elevation information was obtained using a 30-m void-filled Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM). The water depth estimates were produced based on a modeling framework (Shin et al., 2020) that combines a land surface model HiGW-MAT (Pokhrel et al., 2015) and a hydrodynamics model CaMa-Flood (Yamazaki et al., 2011). The open lake surface area data were acquired from (Lin and Qi, 2017) using MODIS time series at a 16-day temporal resolution. The lake surface area data was used to determine the time windows when the Tonle Sap floodplain approached its annual maximum/minimum spatial extent.

2.2.2. Data used for simulating GHG emissions

The process-based DNDC model requires the following parameter sets to enable biogeochemical simulations: geographic attributes (i.e., latitude, longitude, slope, size of specific land cover), soil properties (i.e., pH, bulk density (BLD), soil organic carbon (SOC), clay (%)), climatic information (i.e., rainfall, 2-m air temperature) and vegetation composition and characteristics (i.e., type of plant, plant biomass) (Table 1). The entire input dataset was comprised of satellite images except for the soil and plant type categories.

Table 1. Employed datasets and remote sensing images for geospatial modeling and biogeochemical modeling.

Dataset	Spatial resolution	Temporal range / Temporal resolution
SRTM elevation	30-m	2000
Water depth	90-m	2001-2015 / daily
Tonle Sap Lake surface area		2001 – 2015 / 16-day
Landsat 5 TM/8 OLI Enhanced Vegetation Index (EVI) composite	30-m	Driest month in 2001 – 2015 / 8-day
SoilGrids250m	250-m	
Climate Hazards Group InfraRed Precipitation with Station data (CHIRPS) rainfall collection	0.05°	2001 – 2015 / daily
MODIS 11A1.006 land surface temperature (LST) product	1-km	2001 – 2015 / daily
European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis v5 (ERA5) temperature collection	0.25°	2001 – 2015 / daily
Woods Hole Research Center (WHRC) pantropical national-level carbon stock dataset	500-m	2015

The geographic attributes were generated using elevation information and interannual spatial changes of the maximum floodplain extents. The soil property files were acquired from a global soil information system named SoilGrids, developed by the International Soil Reference Information Centre (ISRIC) at a 250-m spatial resolution (Hengl et al., 2017). All soils content properties were evaluated at a 5-cm depth beneath the ground surface. Due to the shortage of long-term, ground-based meteorological station records for the entire study area, satellite-based daily rainfall and temperature time series were collected from the 0.05° (~5.5-km at the equator) Climate Hazards Group InfraRed Precipitation with Station measurements (CHIRPS) dataset (Funk et al., 2015) and the 1-km MODIS 11A1.006 daily land surface temperature (LST) product (Wan et al., 2015), respectively. To convert the surface temperature to model-required 2-m air temperature, the 0.25° European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis v5 (ERA5) daily temperature was involved (ECMWF, 2017) for temperature calibration. For vegetation characteristics, the plant type information was acquired from peer-reviewed work (Davidson, 2006), and the plant biomass statistics were extracted from the Woods Hole Research Center (WHRC) pantropical national-level carbon stock dataset (Baccini et al., 2012).

2.3. Methods

The brief workflow chart shows how geospatial modeling and biogeochemical model were combined to achieve the research goals (Fig. 2). In this study, procedures to quantify the daily GHG fluxes from Tonle Sap floodplain alteration can be generalized into two sections: 1) identifying the interannual changes of Tonle Sap floodplain maximum extents, and 2) simulating the GHG emissions from the changed floodplain area. Based on the DNDC outputs, trajectories of GHG emission rate and quantity were established to help uncover any change trends. Specific operations are as described below.

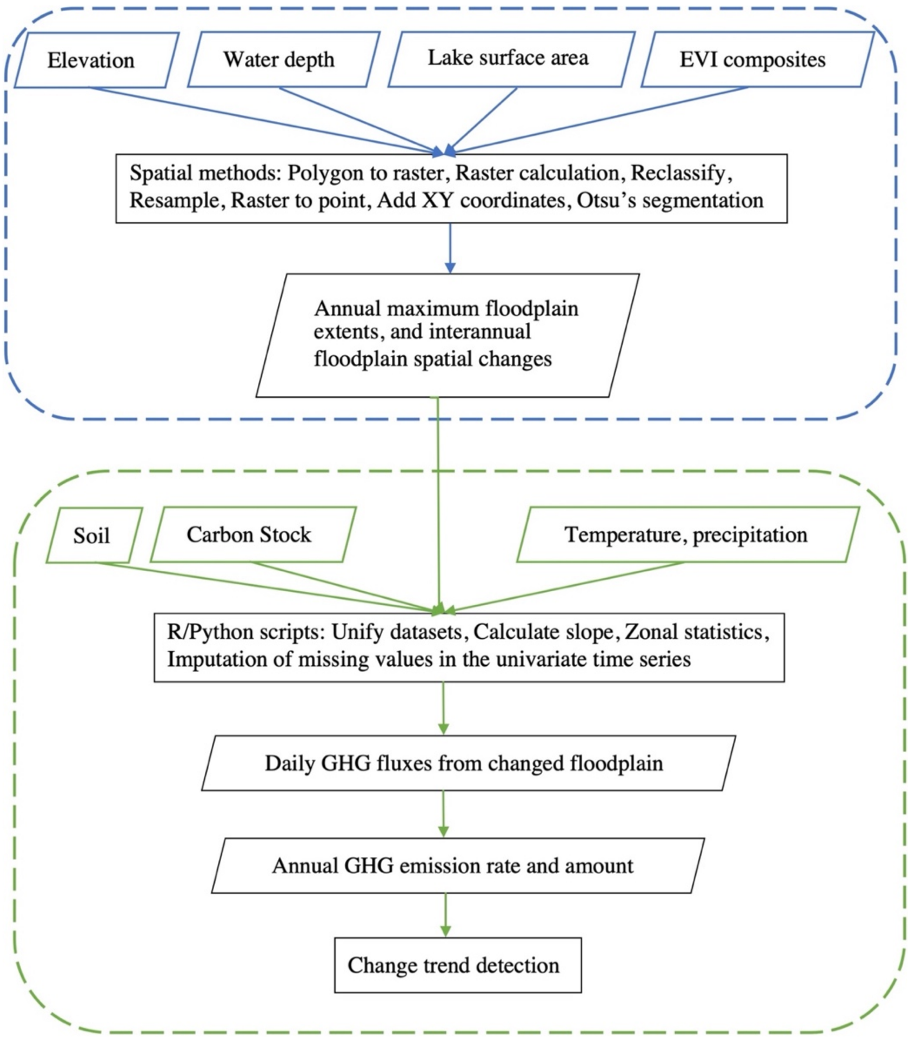

Figure 2. Workflow chart of the study.

2.3.1. Mapping spatio-temporal Tonle Sap floodplain dynamics

Here, we assumed the lake and the floodplain reached their maximum and minimum spatial extent simultaneously. Following this rule, the critical steps in mapping out the annual Tonle Sap floodplain spatial extent were: 1) figuring out the time widows when the floodplain reached its maximum (P_{max}) and minimum (P_{min}) size each year, and 2) removing the permanent lake area from the land cover (floodplain + lake) composites.

First, the 15-year lake surface area time series was used to decide the time windows of P_{max} and P_{min} from 2001 to 2015. Then, the water depth estimation of P_{max} was combined with the elevation data to detect the yearly maximum floodplain inundation area, which also included the permanent lake. Third, Otsu's thresholding method was applied to mosaicked Landsat EVI images acquired during P_{min} to recognize the permanent lake pixels. Otsu's method is a cluster-based image segmentation algorithm that differentiates groups of pixels based on image histogram (Otsu, 1979; Xu et al., 2011). Last, annual permanent lake pixels were removed from the maximum inundation extent map for each year. Consequently, both the maximum yearly floodplain spatial extent and interannual floodplain spatial dynamics were obtained and produced.

More conversions and calculations were carried out to allow outcomes from the geospatial modeling to be usable for future biogeochemical simulations. For example, the areas and geo-coordinates of interannual changed floodplain pixels were computed using ArcGIS. Centroids of interannual changed floodplain pixels were also calculated and applied to extract soil and climate information.

Given that 1) the maximum spatial extent of the Tonle Sap floodplain was different every year, and 2) there was no recognized boundary of the Tonle Sap floodplain, we decided to use the largest spatial extent over the study period to determine the boundary of the floodplain. This decision was made based on a premise that the changes of floodplain hydrology play the most important role in the floodplain spatial extent variation. In this case, the temporal factor doesn't matter too much in the trend change detection but the influence on the hydrology caused by upstream human activities and regional climate change gains the highest weight. Since approximately half of the inflows into the lake and floodplain come from the Mekong tributaries and local rainfall doesn't drain the lake too much, the year when both the lake and the floodplain reached their maximum spatial extent would be the one that received the least impact from the hydro-dams and thus could be set as the reference year.

In this study, the spatial difference between the assumed floodplain boundary and those defined by the extracted annual floodplain maximum extent would represent the spatial changes of the Tonle Sap floodplain in the 15 years.

2.3.2. Modeling CO_2 and N_2O emissions

Establishing a complete DNDC database and parameterizing the model requires these operations: 1) determining the size of a simulation unit and calculating the non-inundated floodplain area in each unit. In this research, given the large area of the study site and the various spatial resolutions of employed remote sensing datasets, ranging from 30-m to 5.5-km, we decided to unify and resample all the inputs using the 5.5-km unit size. The total area of floodplain exposed to the air over the entire year was computed by multiplying the number of 30-m pixels identified as influenced floodplain in the 5.5-km unit with the area of a 30-m pixel, 2) obtaining the above-ground biomass information of identified Tonle Sap floodplain vegetation. We selected random points (a total number of 200) of vegetation in the Tonle Sap floodplain and averaged their corresponding biomass statistics to generate the desired biomass information, 3) computing the soil SOC_{avg}, pH_{avg}, $clay_{avg}$, and BLD_{avg} for every single simulation unit using zonal statistical analysis. Each simulation unit contains 484 soil pixels extracted from the 250-m SoilGrids dataset, 4) filling missing values caused by cloud contamination and observation failure in the MODIS LST time series using an R-based package named "imputeTS", and 5) calibrating the improved MODIS daily LST based on the ERA5 2-m air temperature observations and producing new air temperature time series at a higher spatial resolution. Finally, the DNDC model was run in "No irrigation and Average Soil" mode because there was no human-dominated irrigation intervention in this natural Tonle Sap floodplain ecosystem.

Since this study solely focused on the dry soils, no CH_4 was produced in the study site as CH_4 was usually released during the dry-wet period. That is, we excluded the inundated floodplain soils, then CH_4 should not be considered here. In this case, by summing up the daily CO_2 and N_2O fluxes from the DNDC, we obtained the annual total amount of these two GHG emissions for the entire study area and then divided them using the area of the interannual changed floodplain to acquire the regional emitting rates. Linear regression was applied to reveal any trend in both the CO_2 and N_2O emission quantity and rate from 2001 to 2015.

3. Results

3.1. Intermediate outcomes in spatial modeling and DNDC database establishment

The time windows during which the lake reached its maximum and minimum surface area were identified from 2001 to 2015 (Table 2). Usually, the TSL spread to its largest spatial extent from late August to late October, with the detectable open water surface area growing up to 4413 km^2 as of 2011. P_{max} always occurred in the wet season when heavy rainfall brought by the South Asian monsoon hit the lower MRB. P_{min} showed up in the dry season from late April to mid-June, and the lake area could reduce to 2579 km^2.

Table 2. Annual periods when the Tonle Sap Lake increased/decreased to the maximum/minimum surface area from 2001 to 2015.

Year	P_{max}	P_{min}
2001	29-Aug to 14-Sep	09-May to 25-May
2002	14-Sep to 30-Sep	09-May to 25-May
2003	14-Sep to 30-Sep	09-May to 25-May
2004*	28-Aug to 13-Sep	08-May to 24-May
2005	29-Aug to 14-Sep	25-May to 10-Jun
2006	29-Aug to 14-Sep	09-May to 25-May
2007	17-Nov to 03-Dec	23-Apr to 09-May
2008*	13-Sep to 29-Sep	22-Apr to 08-May
2009	01-Nov to 17-Nov	23-Apr to 09-May

Table 2 (cont'd)

2010	17-Nov to 03-Dec	23-Apr to 09-May
2011	16-Oct to 01-Nov	09-May to 25-May
2012*	15-Oct to 31-Oct	27-Jul to 12-Aug
2013	30-Sep to 16-Oct	23-Apr to 09-May
2014	13-Aug to 29-Aug	25-May to 10-Jun
2015	14-Sep to 30-Sep	10-Jun to 26-Jun

* For leap years, the date of year (DOY) refers to a different date after Feb 29th and will be one day earlier than the one in the non-leap years.

The averaged biomass estimate of the Tonle Sap vegetation was 72923 kg C/ha.

The correlation equation built between daily MODIS LST (x) and daily ERA5 (y) 2-m air temperature was:

$$y = 0.2936x + 18.202 \quad (1)$$

3.2. Changes of floodplain spatial extent

Annual maps of the maximum floodplain spatial extent with the permanent lake removed show how the Tonle Sap floodplain changed across space and over time (Fig. 3). The years 2002, 2007, 2011, and 2013 witnessed inundated floodplain expanded to 17287 km^2, 17262 km^2, 17313 km^2, and 17304 km^2. In 2015, the floodplain inundation area dropped to 11542 km^2, only three-quarters of the previous year's. Another year with contracting floodplain was 2005, and the size of the submerged floodplain was 12991 km^2. It was notable that the total area of the annual maximum inundated floodplain in 2001, 2003, and 2004 was also small. Additionally, we noticed that the northwest part of the Tonle Sap floodplain lost more inundated lands when the Tonle Sap water system's hydro-pattern stability was affected.

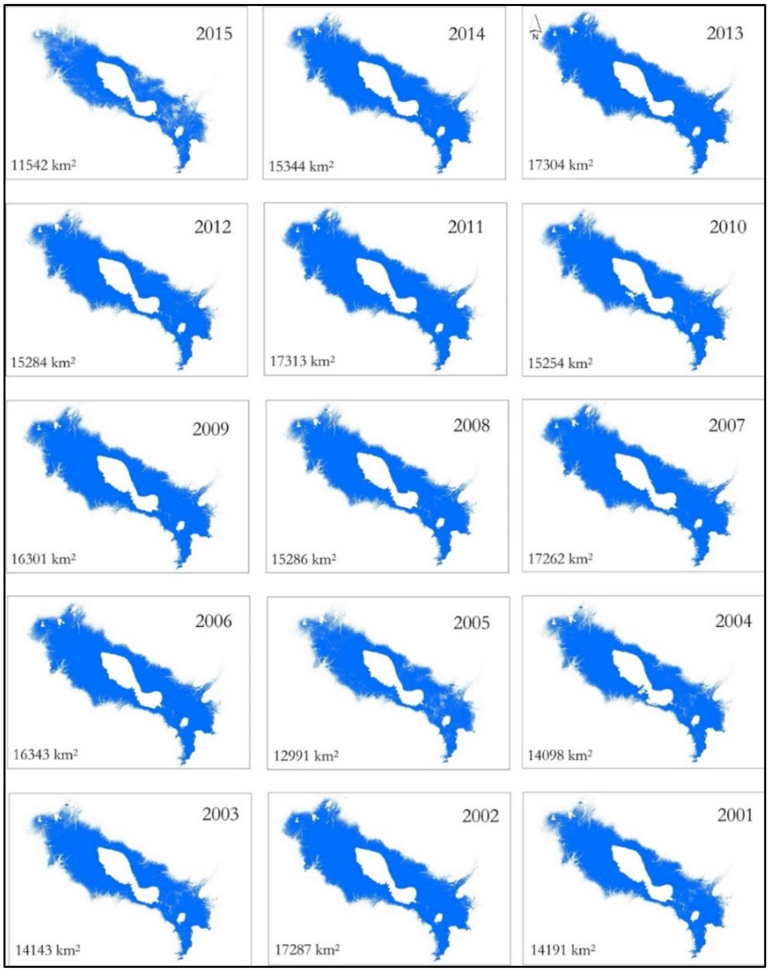

Figure 3. The annual maximum spatial extent of inundated Tonle Sap floodplain (permanent lake removed) from 2001 to 2015, spatial resolution: 30m.

For the entire study period, the maximum floodplain area reached the highest value in 2011. The floodplain boundary of 2011 was adopted as the outermost border of the study site. Using the 2011 floodplain spatial extent as a baseline, the interannual non-inundation lands were identified (Fig. 4). Since the size of the changing area in 2013 was 1 km^2, even smaller than that of a single simulation unit, an empty map was made for this year. In the years when fewer floodplain lands were submerged, e.g., 2001, 2003, 2004, 2005, and 2015 (Fig. 3), more non-inundation pixels appeared (Fig. 4). Moreover, it was evident that lands away from the permanent lake suffered more from the loss of floodplain inundation. It was true that when doing the unit size conversion from 30-m to 5.5-km, a portion of the 30-m pixels in Fig. 3 were lost. It was also worth noting that the only pixel in 2007 was because of high elevations in this 5.5-km area.

Figure 4. The annual non-inundated Tonle Sap floodplain areas from 2001 to 2015, except for 2011 and 2013, spatial resolution: 5.5-km. Inundated floodplain area in 2011 was used as a baseline. The areal difference between 2011 and 2013 was too small to be mapped.

3.3. Spatial patterns of CO_2 and N_2O emission rates

CO_2 and N_2O were the only two major GHG released from the non-inundated floodplain soils according to outcomes of the DNDC model. Spatial heterogeneities were observable in both the annual CO_2 and N_2O emitting rate maps (Fig. 5 and Fig. 6). Using the pattern of 2015 as an instance, we noticed the CO_2 emission rate varied from 454 to 2678 kg C/ha/yr in the non-inundated floodplain area (Fig. 5). Meanwhile, the N_2O emission rate increased from 0.085 to 2.509 kg N/ha/yr (Fig. 6). For the annual CO_2 emission rate, the lowest values changed from 450 to 588 kg C/ha/yr, while the highest one varied from 1815 to 3549 kg C/ha/yr. For the annual N_2O emission rate, the lowest number shifted from 0.077 to 0.131 kg N/ha/yr, and the highest one increased from 0.738 to 2.875 kg N/ha/yr.

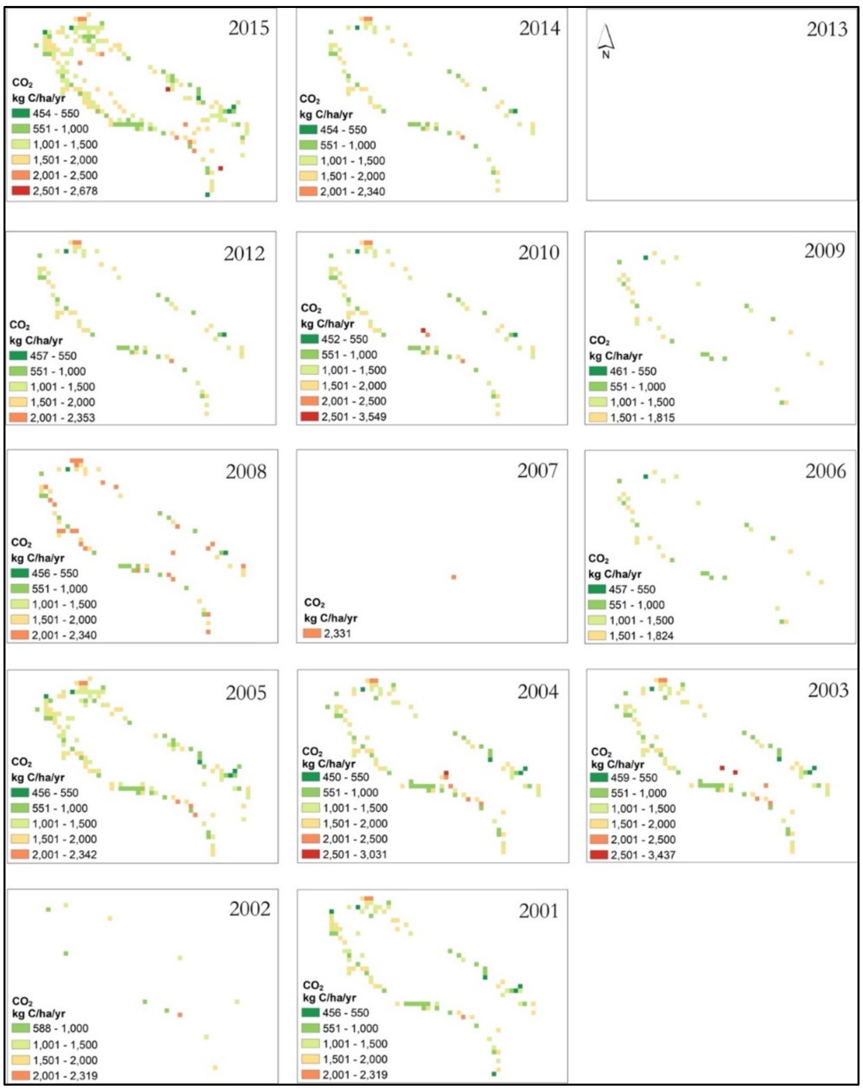

Figure 5. CO_2 emission rate (kg C/ha/yr) from the non-inundated floodplain lands, spatial resolution: 5.5-km.

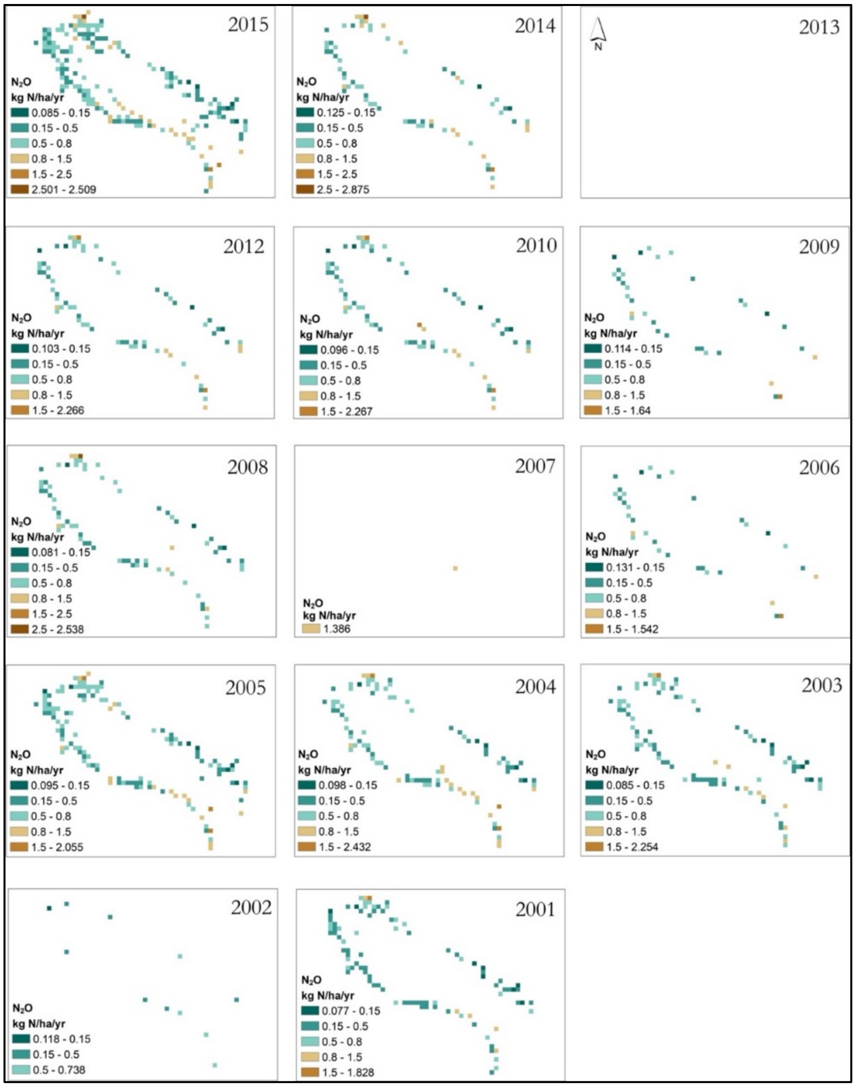

Figure 6. N_2O emission rate (kg N/ha/yr) from the non-inundated floodplain lands, spatial resolution: 5.5-km.

Though the spatial heterogeneities were obvious, there were no hotspot clusters of CO_2 and N_2O emission rates, that is, higher/lower values of gas emission rate intended to aggregate in adjacent lands (Fig. 5 and Fig. 6). Usually, higher N_2O emission rates appeared in the south and the farthest north parts in the non-inundated floodplain, and lower rates showed up in the east region (Fig. 6). What's more, when comparing the annual maps in Fig. 5 and Fig. 6, we didn't find any distinct spatial displacement tendency. To be specific, if a pixel in a map displayed a high (or low) CO_2 and N_2O emission rate, the probability of this pixel remaining at the same high (or low) level in the other years would be high. For example, if a pixel was labeled with a high-level CO_2 emission rate in 2014, it continued to have a high CO_2 efflux rate in 2015 (Fig. 6). Such trends were not significant in both figures.

3.4. Temporal dynamics of floodplain extents and CO_2 and N_2O emissions

In this study, the sums of CO_2 and N_2O emissions from the non-inundated floodplain, the regional gas emission rates, and the total areas of floodplain inundation loss, all presented an upward changing trend over the 15-year period (Fig. 7). Given the extremely low value of non-submerged land size in 2007 (~ size of a simulation unit), another set of graphs were produced by removing the statistics of 2007 for more rigorous trend detections (Fig. 8). Similarly, upwards trends were found again in all graphs. More importantly, such increasing tendencies became more apparent after the spike in 2007 was eliminated.

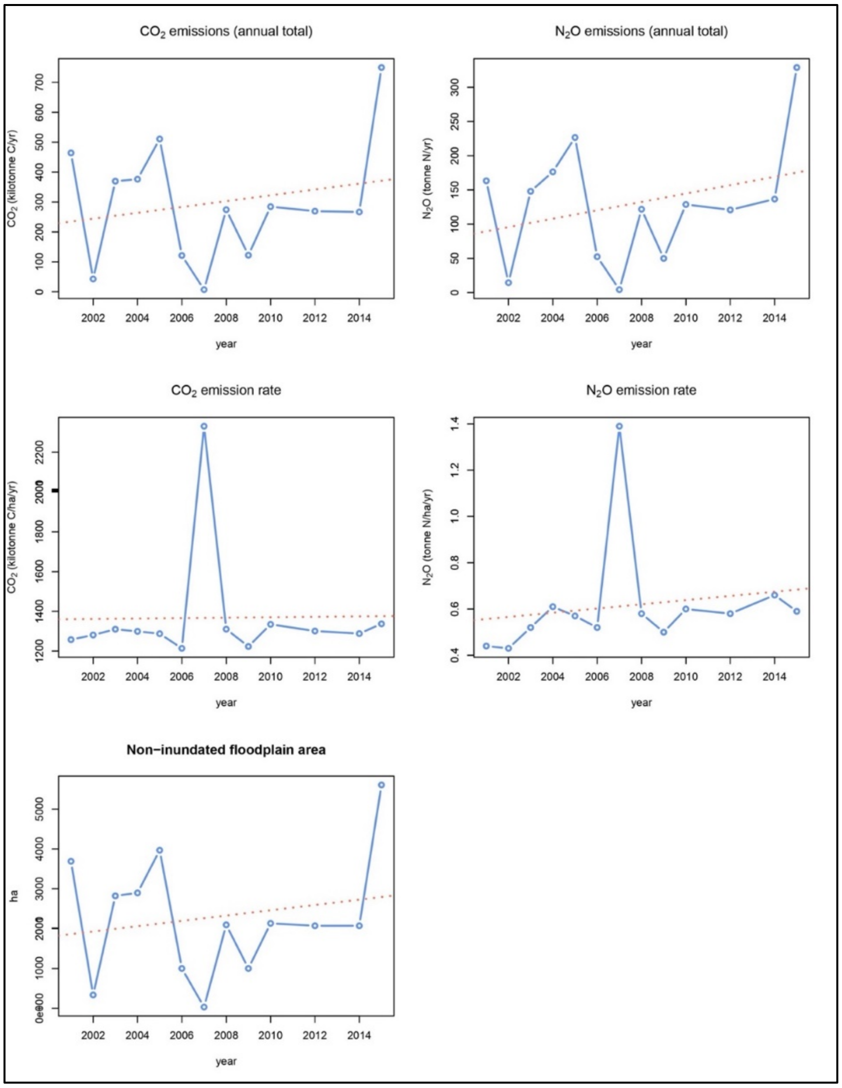

Figure 7. CO_2 and N_2O emissions, emission rates, and non-inundated floodplain areas with trend lines.

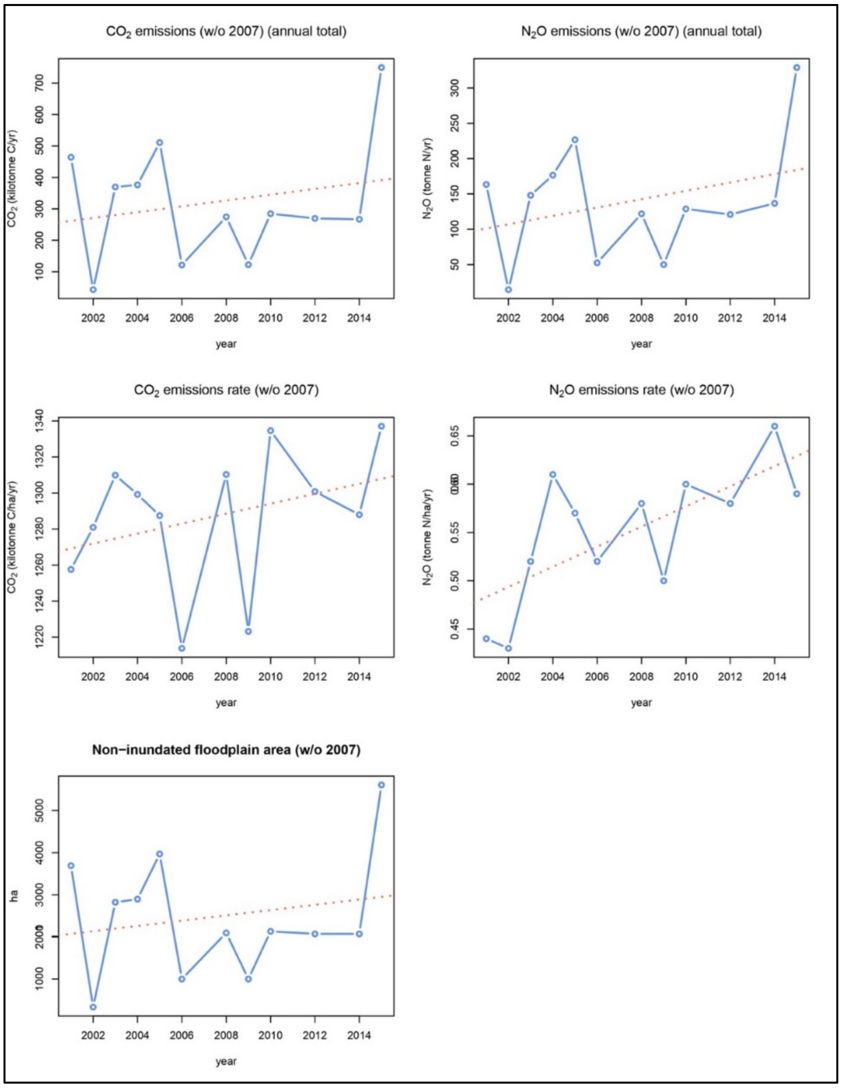

Figure 8. CO_2 and N_2O emissions, emission rates, and non-inundated floodplain areas with trend lines; spikes of 2007 were removed.

4. Discussion

4.1. Causes of floodplain spatial extent change

According to the records in one of the most widely-used disaster databases, Emergency Events Database (EM-DAT), severe floods swept through Cambodia in 2001, 2002, 2011, 2013, with more than six million population affected (Guha-Sapir et al., 2016). This information follows what we found in the outputs of the geospatial modeling, as described in *3.2 Changes of floodplain spatial extent*. Extreme weather results in the expanding/shrinking Tonle Sap floodplain. In addition, the overall increasing trend of non-inundated floodplain areas implies that other factors must be counted for the long-term floodplain extent change.

It is known that a lot of human efforts have been made, especially in the regions facing the heavy burden of climate change and the high demand for resources. In the MRB, a large number of hydro-dams have been built to reduce the harmful effects of extreme climatic events and support local socio-economic development. A boom of hydro-damming took place after the new Millennium (Lin and Qi, 2019). Though Mekong hydro-dams have succeeding in mitigating floods and droughts and generating clean energy, they inevitably alter the hydrology of Mekong water systems by adjusting the river flows of the MR and its tributaries (Hecht et al., 2019; Pokhrel et al., 2018). A majority of Mekong hydro-dams with large installed capacity was aggregated in the upstream countries, and debates regarding the transboundary water resource re-distribution keep attracting attentions (Kuenzer et al., 2013; Xie and Warner, 2021). Our study area is in the lower part of the Mekong watershed and has constantly received the influence and chain effect of hydro-dam's management on MR and TSR. The longstanding alteration of water inflow and outflow into/from the lake and floodplain has led to many consequences; one of them is the upward change trend in the floodplain non-inundated areas revealed by this study.

4.2. Causes of CO_2 and N_2O emission change

First, the total amount of CO_2 and N_2O emission increased as a combined outcome of the enlarged area of the non-inundated floodplain and rising gas emission rates. Second, as mentioned in *3.3. Spatial patterns of CO_2 and N_2O emission rates*, no distinct spatial displacements in CO_2 and N_2O emission rates were discovered. It suggested that among all the factors determining the biogeochemical process of C and N cycling in the Tonle Sap floodplain, only those that didn't change over time but varied across space played a more important role in affecting some GHG emissions. Therefore, changes in CO_2 and N_2O emission rates can be mainly attributed to soil properties, topographic features and the area of non-inundated floodplain within a 5.5-km unit. Here, the only topographic feature used in the simulation process is slope. However, due to the flat topography of the Tonle Sap floodplain, there is not many variations in slope across the study area. Therefore, soil properties and area of influenced floodplain gain more weight in deciding both CO_2 and N_2O emission rates. To verify this conclusion, we checked and compared the soil property data and noticed that the average SOC and pH values were usually larger for the pixels identified with high CO_2 and N_2O emissions. What's more, the non-inundated floodplain area was larger in pixels (spatial resolution: 5.5-km) of higher CO_2 and N_2O emissions.

4.3. Strengths and limitations

Given the large size of the Tonle Sap floodplain and the inaccessibility of its swamp forest, performing field surveys in the dynamic non-inundation areas over 15 years was full of difficulties and hardly possible. Thus, we collected and leveraged information from existing literature as an indirect verification of the results. We compared the CO_2 and N_2O emission outcomes to those found in the article by Li et al. (Li et al., 2004). In their work, the authors used the DNDC model to calculate GHG emission rates from two natural wetlands, one in Minnesota (MN) and one in Florida (FL), USA. Since the FL wetland had similar humid, hot climate and wetland forest ecosystem with the Tonle Sap floodplain, we compared CO_2 and N_2O emission rates of the FL wetland to our findings. Their results showed that the average rates of FL wetland CO_2 and N_2O emission were 5450 kg C/ha/yr and 5.3 kg N/ha/yr when the floodplain transformed to a GHG source, which were in the same magnitude as what we obtain in this study. Despite the lack of direct validation of specific GHG emissions, which would only impact the magnitude of detailed statistics, we focus on and emphasize the change trends of the CO_2 and N_2O emission trajectories over fifteen years. The upward tendency identified in floodplain spatial extent variation and consequent CO_2 and N_2O emissions is valuable for assessing future contributions of the Tonle Sap floodplain ecosystem global warming. Moreover, this study reveals how the floodplain and biogeochemical reactions in the floodplain environments have been influenced by climatic oscillation and human activities spatially and temporally. It delineates the dynamic picture of a vital component in a floodplain ecosystem at a very large scale with high efficiency.

5. Conclusions

This pilot study combines geospatial modeling and biogeochemical modeling to examine long-term change trends of the Tonle Sap floodplain and GHG emissions (e.g., CO_2 and N_2O) from the non-inundated floodplain areas. Climate change and intensification of hydro-dam constructions in the MRB have generated accumulative impacts on the Tonle Sap floodplain ecosystem, especially in the floodplain hydrological patterns. Altered floodplain hydroperiods have further caused the spatial extent change of the floodplain and left more CO_2 and N_2O released into the atmosphere. The approaches developed and applied in this research can be generalized to other large watersheds where the trade-offs between human adaptations to climate change and the environment are concerned. The outcomes and findings are evidence of climate and human influence on a natural floodplain ecosystem. Future studies will focus on the LUC in the Tonle Sap floodplain and explore the GHG emissions from the new lands pattern.

CRediT authorship contribution statement

Zihan Lin: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Software, Validation, Visualization, Writing - Original Draft, Writing - Review &

Editing. **Yadu Pokhrel:** Funding acquisition, Project administration, Resources, Writing - Review & Editing. **Sanghoon Shin:** Resources, Software, Writing - Review & Editing. **Feng Zhang:** Conceptualization, Software, Writing - Review & Editing. **Jiaguo Qi:** Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Resources, Supervision, Writing - Review & Editing.

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References

Ahmed, M., 2020. Introduction to modern climate change. Andrew E. Dessler: Cambridge University Press, 2011, 252 pp, ISBN-10: 0521173159. Sci. Total Environ. 734, 139397. https://doi.org/10.1016/j.scitotenv.2020.139397

Alam, M.J., Humphreys, E., Sarkar, M.A.R., Yadav, S., 2017. Intensification and diversification increase land and water productivity and profitability of rice-based cropping systems on the High Ganges River Floodplain of Bangladesh. F. Crop. Res. 209, 10–26. https://doi.org/10.1016/j.fcr.2017.04.008

Arce, M.I., Von Schiller, D., Bengtsson, M.M., Hinze, C., Jung, H., Alves, R.J.E., Urich, T., Singer, G., 2018. Drying and rainfall shape the structure and functioning of nitrifying microbial communities in riverbed sediments. Front. Microbiol. 9, 1–17. https://doi.org/10.3389/fmicb.2018.02794

Arias, M.E., Cochrane, T.A., Elliott, V., 2014. 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

Baccini, A., Goetz, S.J., Walker, W.S., Laporte, N.T., Sun, M., Sulla-Menashe, D., Hackler, J., Beck, P.S.A., Dubayah, R., Friedl, M.A., 2012. Estimated carbon dioxide emissions from tropical deforestation improved by carbon-density maps. Nat. Clim. Chang. 2, 182–185. https://doi.org/10.1038/nclimate1354

Beheydt, D., Boeckx, P., Sleutel, S., Li, C., Van Cleemput, O., 2007. Validation of DNDC for 22 long-term N2O field emission measurements. Atmos. Environ. 41, 6196–6211. https://doi.org/10.1016/j.atmosenv.2007.04.003

Cloy, J.M., Smith, K.A., 2017. Greenhouse gas sources and sinks, Encyclopedia of the Anthropocene. Elsevier Inc. https://doi.org/10.1016/B978-0-12-809665-9.09961-4

Cochrane, T.A., Arias, M.E., Piman, T., 2014. Historical impact of water infrastructure on water levels of the Mekong River and the Tonle Sap system. Hydrol. Earth Syst. Sci. 18, 4529–4541. https://doi.org/10.5194/hess-18-4529-2014

Cronan, C.S., 2018. Ecosystem Biogeochemistry, in: Ecosystem Biogeochemistry: Element Cycling in the Forest Landscape. Springer, pp. 31–40.

Dang, T.D., Cochrane, T.A., Arias, M.E., Van, P.D.T., de Vries, T.T., 2016. Hydrological alterations from water infrastructure development in the Mekong floodplains. Hydrol. Process. 30, 3824–3838. https://doi.org/10.1002/hyp.10894

Davidson, P.J.., 2006. The biodiversity of the Tonle Sap Biosphere Reserve - 2005 status review.

de Vicente, I., 2021. Biogeochemistry of mediterranean wetlands: A review about the effects of water-level fluctuations on phosphorus cycling and greenhouse gas emissions. Water 13. https://doi.org/10.3390/w13111510

Dessler, A.E., Parson, E.A., 2019. The science and politics of global climate change: A guide to the debate. Cambridge University Press.

ECMWF, 2017. Copernicus Climate Change Service (C3S): ERA5: Fifth generation of ECMWF atmospheric reanalyses of the global climate. Copernicus Climate Change Service Climate Data Store (CDS).

Funk, C., Peterson, P., Landsfeld, M., Pedreros, D., Verdin, J., Shukla, S., Husak, G., Rowland, J., Harrison, L., Hoell, A., Michaelsen, J., 2015. The climate hazards infrared precipitation with stations—a new environmental record for monitoring extremes. Sci. Data 2, 150066. https://doi.org/10.1038/sdata.2015.66

Guha-Sapir, D., Below, R., Hoyois, P., 2016. EM-DAT: the CRED/OFDA international disaster database. http://www.emdat.be/.

Guo, M., Li, J., Sheng, C., Xu, J., Wu, L., 2017. A review of wetland remote sensing. Sensors 17, 1–36. https://doi.org/10.3390/s17040777

Harris, Z.M., Spake, R., Taylor, G., 2015. Land use change to bioenergy: A meta-analysis of soil carbon and GHG emissions. Biomass and Bioenergy 82, 27–39. https://doi.org/10.1016/j.biombioe.2015.05.008

Hecht, J.S., Lacombe, G., Arias, M.E., Dang, T.D., Piman, T., 2019. Hydropower dams of the Mekong River basin: A review of their hydrological impacts. J. Hydrol. 568, 285–300. https://doi.org/10.1016/j.jhydrol.2018.10.045

Hengl, T., de Jesus, J.M., Heuvelink, G.B.M., Gonzalez, M.R., Kilibarda, M., Blagotić, A., Shangguan, W., Wright, M.N., Geng, X., Bauer-Marschallinger, B., others, 2017. SoilGrids250m: Global gridded soil information based on machine learning. PLoS One 12. https://doi.org/10.1371/journal.pone.0169748

Ilyas, S., Xu, X., Jia, G., Zhang, A., 2019. Interannual variability of global wetlands in response to El Niño Southern Oscillations (ENSO) and land-use. Front. Earth Sci. 7, 1–14.

https://doi.org/10.3389/feart.2019.00289

Karim, F., Petheram, C., Marvanek, S., Ticehurst, C., Wallace, J., Hasan, M., 2016. Impact of climate change on floodplain inundation and hydrological connectivity between wetlands and rivers in a tropical river catchment. Hydrol. Process. 30, 1574–1593. https://doi.org/10.1002/hyp.10714

Katayanagi, N., Furukawa, Y., Fumoto, T., Hosen, Y., 2012. Validation of the DNDC-rice model by using CH4 and N2O flux data from rice cultivated in pots under alternate wetting and drying irrigation management. Soil Sci. Plant Nutr. 58, 360–372. https://doi.org/10.1080/00380768.2012.682955

Khairullina, E.R., Bogdanova, V.I., Slepneva, E. V., Nizamutdinova, G.F., Fatkhullina, L.R., Kovalenko, Y.A., Skutelnik, O.A., 2019. Global climate change: Cyclical nature of natural and permanent nature of man-made processes. EurAsian J. Biosci. 13, 2311–2316.

Kim, D.G., Kirschbaum, M.U.F., 2015. The effect of land-use change on the net exchange rates of greenhouse gases: A compilation of estimates. Agric. Ecosyst. Environ. 208, 114–126. https://doi.org/10.1016/j.agee.2015.04.026

Knight, K.W., 2016. Public awareness and perception of climate change: a quantitative cross-national study. Environ. Sociol. 2, 101–113. https://doi.org/10.1080/23251042.2015.1128055

Kuenzer, C., Campbell, I., Roch, M., Leinenkugel, P., Tuan, V.Q., Dech, S., 2013. Understanding the impact of hydropower developments in the context of upstream–downstream relations in the Mekong river basin. Sustain. Sci. 8, 565–584. https://doi.org/10.1007/s11625-012-0195-z

Kumar, A., 2018. Global warming, climate change and greenhouse gas mitigation, in: Biofuels:

Greenhouse Gas Mitigation and Global Warming. Springer, pp. 1–16.

Kummu, M., Tes, S., Yin, S., Adamson, P., Józsa, J., Koponen, J., Richey, J., Sarkkula, J., 2014. Water balance analysis for the Tonle Sap Lake-floodplain system. Hydrol. Process. 28, 1722–1733. https://doi.org/10.1002/hyp.9718

Lamberts, D., 2006. The Tonle Sap Lake as a productive ecosystem. Int. J. Water Resour. Dev. 22, 481–495. https://doi.org/10.1080/07900620500482592

Li, C., 2001. Biogeochemical concepts and methodologies: Development of the DNDC model. Quat. Sci. 2, 89-99 (in Chinese).

Li, C., 1996. The DNDC model, in: Evaluation of Soil Organic Matter Models. Springer, pp. 263–267.

Li, C., Cui, J., Sun, G., Trettin, C., 2004. Modeling impacts of management on carbon sequestration and trace gas emissions in forested wetland ecosystems. Environ. Manage. 33, 176–186. https://doi.org/10.1007/s00267-003-9128-z

Li, Z., Yang, J.Y., Drury, C.F., Yang, X.M., Reynolds, W.D., Li, X., Hu, C., 2017. Evaluation of the DNDC model for simulating soil temperature, moisture and respiration from monoculture and rotational corn, soybean and winter wheat in Canada. Ecol. Modell. 360, 230–243. https://doi.org/10.1016/j.ecolmodel.2017.07.013

Lin, Z., Qi, J., 2019. A new remote sensing approach to enrich hydropower dams' information and assess their impact distances: A case study in the Mekong River Basin. Remote Sens. 11. https://doi.org/10.3390/rs11243016

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/0.1016/j.envres.2017.05.016

Machado dos Santos Pinto, R., Weigelhofer, G., Diaz-Pines, E., Guerreiro Brito, A., Zechmeister-Boltenstern, S., Hein, T., 2020. River-floodplain restoration and hydrological effects on GHG emissions: Biogeochemical dynamics in the parafluvial zone. Sci. Total Environ. 715, 136980. https://doi.org/10.1016/j.scitotenv.2020.136980

Mahood, S.P., Poole, C.M., Watson, J.E.M., MacKenzie, R.A., Sharma, S., Garnett, S.T., 2020. Agricultural intensification is causing rapid habitat change in the Tonle Sap Floodplain, Cambodia. Wetl. Ecol. Manag. 28, 713–726. https://doi.org/10.1007/s11273-020-09740-1

Mikhaylov, A., Moiseev, N., Aleshin, K., Burkhardt, T., 2020. Global climate change and greenhouse effect. Entrep. Sustain. Issues 7, 2897–2913. https://doi.org/10.9770/jesi.2020.7.4(21)

MRC, 2005. Overview of the hydrology of the Mekong Basin. https://doi.org/1728 3248

Olson, K.R., Morton, L.W., 2018. Tonle Sap Lake and River and confluence with the Mekong River in Cambodia. J. Soil Water Conserv. 73, 60A-66A. https://doi.org/10.2489/jswc.73.3.60A

Otsu, N., 1979. A threshold selection method from gray-level histograms. IEEE Trans. Syst. Man. Cybern. 9, 62–66. https://doi.org/10.1109/TSMC.1979.4310076

Pokhrel, Y., Shin, S., Lin, Z., Yamazaki, D., Qi, J., 2018. Potential disruption of flood dynamics in the Lower Mekong River Basin due to upstream flow regulation. Sci. Rep. 8, 17767. https://doi.org/10.1038/s41598-018-35823-4

Pokhrel, Y.N., Koirala, S., Yeh, P.J., 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

Ritchie, H., Roser, M., 2020. CO_2 and greenhouse gas emissions. Our world data.

https://doi.org/https://ourworldindata.org/co2-and-other-greenhouse-gas-emissions

Schultz, G.A., Engman, E.T., 2012. Remote sensing in hydrology and water management. Springer, New York.

Shin, S., Pokhrel, Y., Yamazaki, D., Huang, X., Torbick, N., Qi, J., Pattanakiat, S., Ngo-Duc, T., 2020. High resolution modeling of river-floodplain-reservoir inundation dynamics in the Mekong River Basin. Water Resour. Res. 56, e2019WR026449. https://doi.org/10.1029/2019WR026449

Siev, S., Paringit, E., Yoshimura, C., Hul, S., 2016. Seasonal changes in the inundation area and water volume of the Tonle Sap River and its floodplain. Hydrology 3, 33. https://doi.org/10.3390/hydrology3040033

Tubiello, F., Salvatore, M., Ferrara, A., Rossi, S., Biancalani, R., Golec, R., Federici, S., Jacobs, H., Flammini, A., Prosperi, P., Cardenas, P., Schmidhuber, J., Sanz-Sanchez, M.-J., Smith, P., House, J., Srivastava, N., 2015. The contribution of agriculture, forestry and other land use activities to global warming, 1990-2012. Glob. Chang. Biol. 21, 2655–2660. https://doi.org/10.1111/gcb.12865

Wan, Z., Hook, S., Hulley, G., 2015. MOD11A1 MODIS/Terra Land Surface Temperature/Emissivity Daily L3 Global 1km SIN Grid V006. 2015, distributed by NASA EOSDIS Land Processes DAAC.

Wang, H.-Z., Wang, H., 2016. The Yangtze River floodplain: Threats and rehabilitation. Am. Fish. Soc. Symp. 84 263–291.

Xie, L., Warner, J., 2021. The politics of securitization: China's competing security agendas and their impacts on securitizing shared rivers. Eurasian Geogr. Econ. 1–30. https://doi.org/10.1080/15387216.2020.1870516

Xu, X., Xu, S., Jin, L., Song, E., 2011. Characteristic analysis of Otsu threshold and its applications. Pattern Recognit. Lett. 32, 956–961. https://doi.org/10.1016/j.patrec.2011.01.021

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, n/a-n/a. https://doi.org/10.1029/2010WR009726

Yin, S., Zhang, X., Lyu, J., Zhi, Y., Chen, F., Wang, L., Liu, C., Zhou, S., 2020. Carbon sequestration and emissions mitigation in paddy fields based on the DNDC model: A review. Artif. Intell. Agric. 4, 140–149. https://doi.org/10.1016/j.aiia.2020.07.002

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

CHAPTER 5

CONCLUSIONS

Main research conclusions

This dissertation study was undertaken to design a new approach and framework and characterize hydro-dams and their influence on different aspects of ecosystems (i.e., Land, Water, and Atmosphere) using the MRB as an example.

The first article, *A new remote sensing approach to enrich hydropower dams' information and assess their impacts distances: a case study in the Mekong River Basin*, can be considered a methodological study examining the scale of the impact caused by a hydro-dam on the landscape in its neighboring regime. Engaging with the time-series model and analyses, this article comes to the main conclusions as follows. First, it approves that the adjacent influence is spatially asymmetric: the impact at the area above the hydro-dam is generally more significant than that at the area below the site. Second, changing points in the trajectory derived from a land change indicator reflect the key timings in the hydro-dam construction process, such as project start year and commission year. As the first study to obtain a hydro-dam's spatial and temporal characteristics, the findings of this study offer a statistical supplement to the existing dam databases. Meanwhile, as a pilot study in figuring out the spatial extent of hydro-dams' impact on land perspective, it parallels several existing research in the influential distance of a dam and enlarges the capacity to perform the impact scale analyses.

Comparatively, the second article, *Hydro-dam – A nature-based solution or an ecological problem: The fate of the Tonlé Sap Lake*, is a geospatial study focusing on tracking the cascade consequences of UMRB hydro-dam proliferation on the distant largest inland water body in the LMRB. Taking advantage of long-term spatial observations over the TSL's water surface area, this study, for the very first time, estimates the lake surface area at a 16-day interval over 15 years and eventually reveals how the lake has changed from a hydrologic perspective. It concludes that the climatic impact is not the major contributor to the lake's phenological pattern change. Moreover, it provides indirect evidence that hydro-dams' regulation on river flow and volume can be accumulated to trigger undesired outcomes throughout the water system.

The first two articles explain MRB hydro-dams' impact from land and water perspectives, respectively. More importantly, they examine these influences at both local and regional scales. The third study, *Change trend analysis of greenhouse gas emissions from the Tonle Sap floodplain, Cambodia over fifteen years*, as a multidisciplinary endeavor combining geographical and ecological modeling, has complemented the impact investigation of hydro-dams, particularly from an atmospheric perspective at a regional level. Supported by geospatial and biogeochemical models, the third article concludes that the inundation changes in the Tonle Sap floodplain will affect the carbon and nitrogen cycling process and lead to consequent GHG emissions in a changing status. The changing trend has been uncovered to be an upward one and might unintentionally exacerbate global warming. This study is designed and carried out from a fresh view among the current research on MRB hydro-dams.

Intellectual contribution

This dissertation has contributed to our understanding of human-nature interactions in terms of hydro-dams, mainly in three aspects. First, for environmental, geographical, ecological, and biological research, it fills existing knowledge gaps regarding the role of hydro-dams in the ecosystem by figuring out answers to the three specific research questions. Theoretically, the findings of hydro-dams' impacts on Mekong land, water, and atmosphere can further help enhance understanding the WEF nexus concept structured by human needs and interventions.

Second, methodologically, this dissertation develops and manifests 1) a new remote sensing approach and 2) a combined spatial and biogeochemical modeling framework that can be promoted and employed to quantify and interpret 1) hydro-dams' construction dates and impact magnitude on surrounding land and 2) disturbance in the GHG emissions accompanied by floodplain inundation area change. The contributions in establishing and verifying innovative methods and tools can offer new opportunities that enable scholars to sort out the complex relationships behind human-nature interactions at multi-scale and multi-resolution.

Third, the dissertation enriches the literature and discussions on the role of human-nature interactions in the WEF nexus. Such contribution is especially essential for the rational utilization and transboundary re-allocation of water resources while seeking perpetual maintenance of ecosystem stability. Particularly, the first article presents quantitative assessments of hydro-dams' influence on LCLUC, and the second article exhibits a qualitative evaluation of hydro-dams' impacts on the TSL's hydro-patterns. The third article measures both quantitative and qualitative hydro-dams' ripple effect on the atmosphere via land and water. Notably, the first article, performed at a local level (i.e., area encompassing the hydro-dam) on the adjacency effect, has found and enumerated the influential scale and timing information of every commissioned dam in the selected dam list. This work largely enriches the data support for the modeling process in many disciplines. The second article, carried out at a distant region over a spacious watershed, has uncovered the change tendency of the TSL and the underlying relationship among climate change, expanded human interventions, and the lake. This study considerably deepens the comprehension of dams' indirect and cumulative impact at places far away. The third research, which solves the floodplain inundation variations and the accompanying GHG emissions changes, has provided quantitative clues to enhancing insights into the dams' impacts for the first time.

Practical implications

The insights gained from this dissertation may assist human-nature interaction study and provide implications for natural resource management and policy-making. First, the new remote sensing method in Chapter 2 is easy to be adopted and will benefit research that needs the essential information of a hydro-dam construction. Such research includes but is not limited to modeling in hydrology, environment, and ecology fields and the quantitative analyses of hydro-dams' influence. Second, the interdisciplinary framework set up in Chapter 4 has shown its capacity and feasibility and can encourage more multidisciplinary studies to investigate more in the human-nature interactions from brand new views.

More importantly, this dissertation research facilitates better MRB hydro-dam planning and administration for the sake of sustainable water resource exploitation. Specifically, the analyses and findings of Mekong hydro-dams' impacts undertaken in Chapters 2, 3 and 4, have extended our knowledge of dam planning and will promote the development of an environmentally-friendly strategy on land use transition and water resource utilization. For example, the first article reveals the spatial heterogeneity of a hydro-dam's changing ability on surrounding LCLUC, i.e., more significant influence at the area above the dam. Therefore, when rural residents plan cropland cultivation, they can be advised to allocate more irrigated crops upstream of the dam for a sufficient water supply. Another example is that when Mekong policymakers discuss where to propose new hydro-dam projects, they should put more weight on the potential cascade consequences of the water infrastructure in ecosystems at a distant place.

By following this rule, they can reduce the transboundary water resource competition and conflict by making optimal decisions on the dam design.

Last but not least, this dissertation is of practical significance for the production of agriculture and fishery. In other words, the enhancement of optimal planning for land transition and hydro-dam establishment mentioned above is beneficial to addressing the existing environmental problems in the MRB. For instance, rational crop rotation and installed dam capacity can maximize irrigation water exploitation and increase rivers' elasticity to extreme climatic events. An annually stable water flow helps to reduce the soil sedimentation in the confluence of rivers and lakes. On top of that, a good selection of dam sites can lower the risks of hindering fish migration and maintain aquatic biodiversity.

Future research

The investigation on Mekong hydro-dam's characteristics and dams' impact on the Mekong ecosystem in different aspects has provided a deeper insight into the general question of whether human interventions on climate change have produced the expected effect. Moving forward from this dissertation, four directions are proposed for future research given the limitations on current work.

First, due to the limited access to sufficient hydro-data and lack of knowledge of major Mekong hydro-dams' operations, this research does not involve specific and comprehensive analyses on the water level and volume changes in the Mekong River mainstream and inflow and outflow volume into/from the TSL. Future research should collect long-term hydrological observations at the dam sites and use hydro-models to identify the ripple effect of hydro-dams' proliferation on the TSL. Under such circumstances, more hydrological characteristics of the great lake can be explored.

Second, more efforts are needed to determine the new land use pattern in the MRB region on account of the hydro-dam boom in recent decades, using multi-level and multi-scale analysis to understand the WEF nexus trade-off in the MRB better. I believe this can be a fruitful area for future work: Specifically, I assessed the hydro-dam's influence scale on adjacent lands but did not explore the rearrangement of land use patterns within the impact regime. Is it true that more agricultural lands are emerging due to the construction of dams? Which type of land is more likely to be converted into agricultural land if the former hypothesis holds true? Is this phenomenon widespread over the entire basin or only limited to certain areas (e.g., close to human settlement)? Besides, in Chapter 4, I found out more Tonle Sap floodplain lands were no longer submerged under floodwater. Then, what would be the new usage for these lands? I believe continued studies on Mekong LCLUC caused by the hydro-dam increment can help with a unique insight into the evaluation of hydro-dam-related gains (e.g., clean energy induced carbon reduction) and loss (e.g., sacrifice of certain land use type).

Third, the current study of hydro-dams' impact on adjacent LCLUC should be extended to a larger scale. Combination of investigations on local dam impact and regional dam impact could depict a more comprehensive picture of how hydro-dams affect the landscape. This has been partially realized in the collaboration with Dr. Peilei Fan on a project checking the hydro-dams' influence on economy, population and greenness globally. In this work, we use geospatial datasets and geo-analytical techniques to investigate the changes of GDP, urban land area, population density, nighttime light and NDVI in the areas of distances changing from 5km, 20km, and 50km from 2001 to 2015. We found that small and medium (i.e., installed capacity) hydro-dams had significant decrease in population and urban land area while medium and large ones had far less nighttime light in the study zones. Since the number of hydro-dams labelled as

Mekong dam in the global database was much smaller than that of the WLE Greater Mekong dam database, a future study can be carried out by replacing the global one using the WLE database to explore the hydro-dams influence at a much larger spatial scale on multi-perspectives.

Forth, more broadly, research using controlled trials and comparative analysis can offer a good source for adding new knowledge toward an improved understanding of the dynamics of human-nature interactions. So far, I have studied hydro-dams characteristics and dams' influence on the land, water, and atmosphere in the MRB. Yet, the changing processes studied were complicated since they all received the impact of the dams and other human-induced alterations on the environment. For a more accurate separation between the effects of dams and other human activities or naturally induced changes, more studies should be repeated in the regions where hydro-dam constructions are not present or rare. The results should be compared to those found in this dissertation to confirm the ratio of hydro-dams' impact among the effects of human interventions on climate change and water resource management.

BIBLIOGRAPHY

BIBLIOGRAPHY

Adamson, P.T., Rutherfurd, I.D., Peel, M.C., Conlan, I.A., 2009. The hydrology of the Mekong River, in: The Mekong. Elsevier, pp. 53–76.

Bakker, K., 1999. The politics of hydropower: Developing the Mekong. Polit. Geogr. 18, 209–232. https://doi.org/10.1016/S0962-6298(98)00085-7

Baran, E., Myschowoda, C., 2009. Dams and fisheries in the Mekong Basin. Aquat. Ecosyst. Health Manag. 12, 227–234.

Biemans, H., Haddeland, I., Kabat, P., Ludwig, F., Hutjes, R.W.A., Heinke, J., von Bloh, W., Gerten, D., 2011. Impact of reservoirs on river discharge and irrigation water supply during the 20th century. Water Resour. Res. 47.

Biggs, E.M., Bruce, E., Boruff, B., Duncan, J.M.A., Horsley, J., Pauli, N., McNeill, K., Neef, A., Van Ogtrop, F., Curnow, J., 2015. Sustainable development and the water–energy–food nexus: A perspective on livelihoods. Environ. Sci. Policy 54, 389–397.

Brown, P.H., Tullos, D., Tilt, B., Magee, D., Wolf, A.T., 2009. Modeling the costs and benefits of dam construction from a multidisciplinary perspective. J. Environ. Manage. 90, S303–S311.

Chen, W., Olden, J.D., 2017. Designing flows to resolve human and environmental water needs in a dam-regulated river. Nat. Commun. 8, 1–10.

de la Croix, D., Gobbi, P.E., 2017. Population density, fertility, and demographic convergence in developing countries. J. Dev. Econ. 127, 13–24. https://doi.org/10.1016/j.jdeveco.2017.02.003

Dudgeon, D., 2005. River rehabilitation for conservation of fish biodiversity in monsoonal Asia. Ecol. Soc. 10.

Dugan, P.J., Barlow, C., Agostinho, A.A., Baran, E., Cada, G.F., Chen, D., Cowx, I.G., Ferguson, J.W., Jutagate, T., Mallen-Cooper, M., 2010. Fish migration, dams, and loss of ecosystem services in the Mekong basin. Ambio 39, 344–348.

Foley, M.M., Bellmore, J.R., O'Connor, J.E., Duda, J.J., East, A.E., Grant, G.E., Anderson, C.W., Bountry, J.A., Collins, M.J., Connolly, P.J., 2017. Dam removal: Listening in. Water Resour. Res. 53, 5229–5246.

Gao, J., Zhao, J., Wang, H., 2021. Dam-Impacted Water–Energy–Food Nexus in Lancang-Mekong River Basin. J. Water Resour. Plan. Manag. 147, 4021010.

Getvoldsen, K.S., Butt, T.E., House, C., Ferreira, F., 2009. Sustainable development and climate change. Int. Aff. 85, 1117–1228. https://doi.org/10.1007/978-3-319-63007-6_27

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

Guha-Sapir, D., Below, R., Hoyois, P., 2016. EM-DAT: the CRED/OFDA international disaster database. http://www.emdat.be/.

Hecht, J.S., Lacombe, G., Arias, M.E., Dang, T.D., Piman, T., 2019. Hydropower dams of the Mekong River basin: A review of their hydrological impacts. J. Hydrol. 568, 285–300.

Hirsch, P., 2010. The Changing Political Dynamics of Dam Building on the Mekong. Water Altern. 3.

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. Wiley Interdiscip. Rev. Water 6, e1347.

Jurík, Ľ., Zeleňáková, M., Kaletová, T., Arifjanov, A., 2018. Small water reservoirs: sources of water for irrigation, in: Water Resources in Slovakia: Part I. Springer, pp. 115–131.

Kirby, M., Krittasudthacheewa, C., Mainuddin, M., Kemp-Benedict, E., Swartz, C., de la Rosa, E., 2010. The Mekong: a diverse basin facing the tensions of development. Water Int. 35, 573–593.

Kirchherr, J., Charles, K., 2018. Enhancing the sample diversity of snowball samples: Recommendations from a research project on anti-dam movements in Southeast Asia. PLoS One 13, e0201710.

Kirmani, S.S., 1990. Water, peace and conflict management: the experience of the Indus and Mekong river basins. Water Int. 15, 200–205.

Kondolf, G.M., Rubin, Z.K., Minear, J.T., 2014. Dams on the Mekong: Cumulative sediment starvation. Water Resour. Res. 50, 5158–5169. https://doi.org/10.1002/2013WR014651

Kubiszewski, I., Costanza, R., Paquet, P., Halimi, S., 2013. Hydropower development in the lower Mekong basin: alternative approaches to deal with uncertainty. Reg. Environ. Chang. 13, 3–15. https://doi.org/10.1007/s10113-012-0303-8

Kummu, M., Varis, O., 2007. Sediment-related impacts due to upstream reservoir trapping, the Lower Mekong River. Geomorphology 85, 275–293.

Lee, S., 2016. Natural resource security in an uncertain world, in: The Water, Food, Energy and Climate Nexus. Routledge, pp. 164–172.

Lin, Z., Qi, J., 2019. A New Remote Sensing Approach to Enrich Hydropower Dams ' Information and Assess Their Impact Distances : A Case Study in the Mekong River Basin. Remote Sens. 11. https://doi.org/10.3390/rs11243016

Liu, J., Yang, H., Cudennec, C., Gain, A.K., Hoff, H., Lawford, R., Qi, J., Strasser, L. de, Yillia, P.T., Zheng, C., 2017. Challenges in operationalizing the water–energy–food nexus. Hydrol. Sci. J. 62, 1714–1720.

Lu, S., Bai, X., Zhang, X., Li, W., Tang, Y., 2019. The impact of climate change on the sustainable development of regional economy. J. Clean. Prod. 233, 1387–1395.

Mekong River | Facts, Definition, Map, History, & Location | Britannica [WWW Document], n.d. URL https://www.britannica.com/place/Mekong-River (accessed 10.31.21).

Mekong River Commission (MRC), 2003. State of the Basin report. Mekong River Commission.

Mekong River Commission (MRC), 2000. Annual report 2000. Annu. Rep. 2000.

Olawuyi, D., 2020. Sustainable development and the water-energy-food nexus: Legal challenges and emerging solutions. Environ. Sci. Policy 103, 1–9.

Osborne, M., 2009. The Mekong: river under threat. Lowy Institute for International Policy.

Pearse-Smith, S.W.D., 2012. 'Water war'in the Mekong Basin? Asia Pac. Viewp. 53, 147–162.

Pech, S., Sunada, K., 2008. Population growth and natural-resources pressures in the Mekong River Basin. AMBIO A J. Hum. Environ. 37, 219–224.

Phommasack, B., Jiraphongsa, C., Ko Oo, M., Bond, K.C., Phaholyothin, N., Suphanchaimat, R., Ungchusak, K., Macfarlane, S.B., 2013. Mekong Basin Disease Surveillance (MBDS): a trust-based network. Emerg. Health Threats J. 6, 19944.

Pimentel, D., Huang, X., Cordova, A., Pimentel, M.H., 2013. Impact of a growing population on natural resources: The challenge for environmental management. Environ. Manag. Pract. Instruments Environ. Manag. 1, 6–21. https://doi.org/10.36366/frontiers.v3i1.48

Pokhrel, Y., Burbano, M., Roush, J., Kang, H., Sridhar, V., Hyndman, D., 2018. A review of the integrated effects of changing climate, land use, and dams on Mekong river hydrology. Water 10, 266.

Räsänen, T.A., Koponen, J., Lauri, H., Kummu, M., 2012. Downstream hydrological impacts of hydropower development in the Upper Mekong Basin. Water Resour. Manag. 26, 3495–3513. https://doi.org/10.1007/s11269-012-0087-0

Rufin, P., Gollnow, F., Müller, D., Hostert, P., 2019. Synthesizing dam-induced land system change. Ambio 48, 1183–1194.

Shi, H., Chen, J., 2018. Characteristics of climate change and its relationship with land use/cover change in Yunnan Province, China. Int. J. Climatol. 38, 2520–2537. https://doi.org/10.1002/joc.5404

Simpson, G.B., Jewitt, G.P.W., 2019. The development of the water-energy-food nexus as a framework for achieving resource security: A review. Front. Environ. Sci. 7, 1–9. https://doi.org/10.3389/fenvs.2019.00008

Siyal, A.A., Bhatti, A.M., Babar, M.M., Ansari, K., Saher, R., Ahmed, S., 2019. Environmental impact of conversion of natural wetland into reservoir: a case study of Chotiari Reservoir in Pakistan, in: World Environmental and Water Resources Congress 2019: Watershed Management, Irrigation and Drainage, and Water Resources Planning and Management. American Society of Civil Engineers Reston, VA, pp. 15–27.

Soukhaphon, A., Baird, I.G., Hogan, Z.S., 2021. The impacts of hydropower dams in the Mekong River Basin: A review. Water 13, 265.

Vaidyanathan, G., 2011. Dam controversy: remaking the Mekong. Nat. News 478, 305–307.

Van Zalinge, N., Degen, P., Pongsri, C., Nuov, S., Jensen, J.G., Nguyen, V.H., Choulamany, X., FAO Regional Office for Asia and the Pacific Phnom Penh(Cambodia), B.M.R.C., 2004. The Mekong river system. RAP Publ.

Winemiller, K.O., McIntyre, P.B., Castello, L., Fluet-Chouinard, E., Giarrizzo, T., Nam, S., Baird, I.G., Darwall, W., Lujan, N.K., Harrison, I., 2016. Balancing hydropower and biodiversity in the Amazon, Congo, and Mekong. Science (80-.). 351, 128–129.

WLE, 2017. Dataset on the Dams of the Irrawaddy, Mekong, Red and Salween River Basins.

World Population Growth - Our World in Data [WWW Document], n.d. URL https://ourworldindata.org/world-population-growth?source=post_page-----d904819ea029---------------------- (accessed 10.31.21).

Wu, H., Chen, J., Xu, J., Zeng, G., Sang, L., Liu, Q., Yin, Z., Dai, J., Yin, D., Liang, J., 2019. Effects of dam construction on biodiversity: A review. J. Clean. Prod. 221, 480–489.

Xue, Z., Liu, J.P., Ge, Q., 2011. Changes in hydrology and sediment delivery of the Mekong River in the last 50 years: connection to damming, monsoon, and ENSO. Earth Surf. Process. Landforms 36, 296–308.

Yang, R., Zhang, W.-K., Gui, S., Tao, Y., Cao, J., 2019. Rainy season precipitation variation in the Mekong River basin and its relationship to the Indian and East Asian summer monsoons. Clim. Dyn. 52, 5691–5708.

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. 201201423.