Advancing understanding of development policy impacts on transboundary river basins: Integrated watershed modelling of the Lower Mekong Basin.

Author:
Ly, Kongmeng

Publication Date:
2021

DOI:
https://doi.org/10.26190/unsworks/1621

Advancing understanding of development policy impacts on transboundary river basins: Integrated watershed modelling of the Lower Mekong Basin.

Kongmeng Ly

A thesis in fulfilment of the requirements for the degree of
Doctor of Philosophy

SCHOOL OF BIOLOGICAL, EARTH AND ENVIRONMENTAL SCIENCES
FACULTY OF SCIENCES

7 January 2022

Thesis Title

Advancing understanding of development policy impacts on transboundary river basins: Integrated watershed modelling of the Lower Mekong Basin.

Thesis Abstract

The management of transboundary river basins across developing countries, such as the Lower Mekong River Basin (LMB), is frequently challenging given the developme nt and conservation divergences of the basin countries. Driven by needs to sustain economic performance and reduce poverty, the LMB countries are embarking on signif icant land use changes in the form hydropower dams, to fulfill their energy requirements. This pathway could lead to irreversible changes to the ecosystem of the Mekong River, if not properly managed. This thesis aims to explore the potential effects of changes in land use —with a focus on current and projected hydropower operations— on the Lower Mekong river network streamflow and instream water quality. To achieve this aim, this thesis first examined the relationships between the basin land use/lan d cover attributes, and streamflow and instream water quality dynamics of the Mekong River, using total suspended solids and nitrate as proxies for water quality. Finding s from this allowed framing challenges of integrated water management of transboundary river basins. These were used as criteria for selecting eWater's Source modellin g framework as a management tool that can support decision-making in the socio-ecological context of the LMB. Against a combination of predictive performance metrics and hydrologic signatures, the model's application in the LMB was found to robustly simulate streamflow, TSS and nitrate time series. The model was then used for analy sing four plausible future hydropower development scenarios, under extreme climate conditions and operational alternatives. This revealed that hydropower operations on either tributary or mainstream could result in annual and wet season flow reduction while increasing dry season flows compared to a baseline scenario. Conversely, hydro power operation on both tributary and mainstream could result in dry season flow reduction. Both instream TSS and nitrate loads were predicted to reduce under all three scenarios compared to the baseline. These effects were found to magnify under extreme climate conditions, but were less severe under improved operational alternative s. In the LMB where hydropower development is inevitable, findings from this thesis provide an enhanced understanding on the importance of operational alternatives as an effective transboundary cooperation and management pathway for balancing electricity generation and protection of riverine ecology, water and food security, and peop le livelihoods.

Thesis submission for the degree of Doctor of Philosophy

ORIGINALITY STATEMENT

☑ I hereby declare that this submission is my own work and to the best of my knowledge it contains no materials previously published or written by another person, or substantial proportions of material which have been accepted for the award of any other degree or diploma at UNSW or any other educational institution, except where due acknowledgement is made in the thesis. Any contribution made to the research by others, with whom I have worked at UNSW or elsewhere, is explicitly acknowledged in the thesis. I also declare that the intellectual content of this thesis is the product of my own work, except to the extent that assistance from others in the project's design and conception or in style, presentation and linguistic expression is acknowledged.

COPYRIGHT STATEMENT

AUTHENTICITY STATEMENT

☑ I certify that the Library deposit digital copy is a direct equivalent of the final officially approved version of my thesis.

Publications can be used in the candidate's thesis in lieu of a Chapter provided:

- The candidate contributed **greater than 50%** of the content in the publication and are the "primary author", i.e. they were responsible primarily for the planning, execution and preparation of the work for publication.
- The candidate has obtained approval to include the publication in their thesis in lieu of a Chapter from their Supervisor and Postgraduate Coordinator.
- The publication is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in the thesis.

☑ The candidate has declared that **their thesis has publications - either published or submitted for publication - incorporated into it in lieu of a Chapter/s. Details of these publications are provided below.**.

Publication Details #1

Full Title:	Linking Changes in Land Cover and Land Use of the Lower Mekong Basin to Instream Nitrate and Total Suspended Solids Variations
Authors:	Ly, Kongmeng; Metternicht, Graciela; Marshall, Lucy
Journal or Book Name:	Sustainability
Volume/Page Numbers:	12/2992
Date Accepted/Published:	2 April 2020/8 April 2020
Status:	published
The Candidate's Contribution to the Work:	This study was conceptualised by Kongmeng Ly in close consultation with Professor Graciela Metternicht and Professor Lucy Marshall, both of whom provided guidance on the available methods that can be applied to achieve the study objectives. Data collection and analyses were carried out by Kongmeng Ly, who also drafted and finalized the manuscript with the review and editing supports of Professors Metternicht and Marshall in their roles of academic supervisors.
Location of the work in the thesis and/or how the work is incorporated in the thesis:	Chapter 2 of my thesis.

Publication Details #2

Full Title:	Transboundary river catchment areas of developing countries: Potential and limitations of watershed models for the simulation of sediment and nutrient loads. A review
Authors:	Ly, Kongmeng; Metternicht, Graciela; Marshall, Lucy
Journal or Book Name:	Journal of Hydrology: Regional Studies
Volume/Page Numbers:	24/100605
Date Accepted/Published:	22 May 2019/05 June 2019
Status:	published
The Candidate's Contribution to the Work:	This study was conceptualised by Kongmeng Ly in close consultation with Professor Graciela Metternicht and Professor Lucy Marshall, both of whom provided guidance on the available methods that can be applied to achieve the study objectives. The identification and review of relevant publications were carried out by Kongmeng Ly, who also drafted and finalized the manuscript with the review and editing supports of Professors Metternicht and Marshall in their roles of academic supervisors.
Location of the work in the thesis and/or how the work is incorporated in the thesis:	Chapter 3 of my thesis.

Publication Details #3

Full Title:	Simulation of streamflow and instream loads of total suspended solids and nitrate in a large transboundary river basin using Source model and geospatial analysis.
Authors:	Ly, Kongmeng; Metternicht, Graciela; Marshall, Lucy
Journal or Book Name:	Science of The Total Environment
Volume/Page Numbers:	744/140656
Date Accepted/Published:	29 June 2020/6 July 2020
Status:	published
The Candidate's Contribution to the Work:	This study was conceptualised by Kongmeng Ly in close consultation with Professor Graciela Metternicht and Professor Lucy Marshall, both of whom provided guidance on the available methods that can be applied to achieve the study objectives. Pre-experimental data collection and analyses were carried out by Kongmeng Ly. He also assembled and conducted the experiments and analysed the results of the experiment. Professional personnel of eWater's Limited provided supports during the experiment set up. Kongmeng Ly drafted and finalised the manuscript with the review and editing supports of Professors Metternicht and Marshall in their roles of academic supervisors.
Location of the work in the thesis and/or how the work is incorporated in the thesis:	Chapter 4 of my thesis.

Publication Details #4

Full Title:	Exploring and evaluating the effects of transboundary river basin hydropower development and operation under extreme climate conditions
Authors:	Kongmeng Ly, Graciela Metternicht, Lucy Marshall
Journal or Book Name:	Science of the Total Environment
Volume/Page Numbers:	803/149828
Date Accepted/Published:	18 August 2021/10 January 2022
Status:	published
The Candidate's Contribution to the Work:	This study was conceptualised by Kongmeng Ly in close consultation with Professor Graciela Metternicht and Professor Lucy Marshall, both of whom provided guidance on the available methods that can be applied to achieve the study objectives. Pre-experimental data and information collection, reviews and analyses were carried out by Kongmeng Ly. He formulated plausible future development narratives, conducted experiments, analysed experimental results, and drafted and finalised the manuscript with the review and editing supports of Professors Metternicht and Marshall in their roles of academic supervisors.
Location of the work in the thesis and/or how the work is incorporated in the thesis:	Chapter 5 of my thesis

Candidate's Declaration

I confirm that where I have used a publication in lieu of a chapter, the listed publication(s) above meet(s) the requirements to be included in the thesis. I also declare that I have complied with the Thesis Examination Procedure.

Acknowledgements

This thesis would not have been possible without the immense love and support of my family and the guidance and support of several individuals and organizations who has provided me with knowledge, skills, and resources, allowing the possible completion of this research.

While there are too many to be acknowledged by names, it goes without saying that without the dedicated guidance, support and encouragement from my supervisor, Prof. Graciela Metternicht, my research would have been abandoned following the onset of COVID-19 pandemic. The skills and knowledge gained during my research under your supervision have truly been valuable for my professional development and extremely importance for the management of the Lower Mekong Basin. I am truly grateful for your commitment in seeing me through to the submission of this thesis.

I also owe a huge amount of gratitude to Prof. Lucy Marshall, my co-supervisor, for the time and technical guidance that made my research experiment scientifically sound. Yours and Prof. Metternich's supports, particularly during this past year, have been instrumental for the completion of this thesis.

A special thank you to eWater Limited and its professional staff for providing access to the Source Model, as well as training and continuous technical guidance throughout the modelling portion of my research. I would also like to thank the Mekong River Commission Secretariat and their staff for providing data integral for the success of this research.

My life journey to Sydney, Australia, would not have been possible without the generous support provided by the people and the Government of Australia, via the prestigious DFAT's Australia Awards. I would especially like to thank the staff of UNSW DFAT and Lao Australia Institute for their supports in preparing my life in Australia and ensuring the safe return of my family and I to the Lao PDR, during the difficult travel restrictions of COVID-19.

To my parents, I am thankful to have been born as your son. Your unconditional love and teaching have made me the man that I am today. To my sisters, thank you for all your advice and emotional supports.

Most importantly, I am deeply indebted to my beautiful wife, Yer Vue, and daughters, Mackenzie and Charlize, who have always stood by me and dealt with all of my absences from many family occasions with a smile. For your loves, I dedicate this thesis to you.

Preface

This thesis consists of six chapters with Chapters 2 to 5 written as separate manuscripts for publication and containing separate appendices and references. At the current juncture, Chapters 2 to 4 have been published in peer-review journals while Chapter 5 has been submitted for publication. Specific details of each manuscript publication that makes up this thesis and their authorships are summarised below, with details of my contribution to each manuscript presented at the beginning of each chapter within this thesis.

Chapter 2. Ly, Kongmeng, Graciela Metternicht, and Lucy Marshall. "Linking changes in land cover and land use of the lower Mekong Basin to instream nitrate and total suspended solids variations." Sustainability 12, no. 7 (2020): 2992. Journal impact factor: 2.075. https://doi.org/10.3390/su12072992

Chapter 3. Ly, K., Metternicht, G. and Marshall, L., 2019. Transboundary river catchment areas of developing countries: Potential and limitations of watershed models for the simulation of sediment and nutrient loads. A review. Journal of Hydrology: Regional Studies, 24, p.100605. Journal impact factor: 3.65. https://doi.org/10.1016/j.ejrh.2019.100605.

Chapter 4. Ly, K., Metternicht, G. and Marshall, L., 2020. Simulation of streamflow and instream loads of total suspended solids and nitrate in a large transboundary river basin using Source model and geospatial analysis. *Science of The Total Environment*, *744*, p.140656. Journal impact factor: 6.55. https://doi.org/10.1016/j.scitotenv.2020.140656.

Chapter 5. Ly, K., Metternicht, G. and Marshall, L., 2021. Exploring and evaluating the effects of transboundary river basin hydropower development and operation under extreme climate condition. Manuscript submitted to *Science of the Total Environment*. Journal impact factor: 6.55.

Abstract

The management of transboundary river basins across developing countries, such as the Lower Mekong River Basin (LMB), is frequently challenging given the development and conservation divergences of the basin countries. Driven by needs to sustain economic performance and reduce poverty, the LMB countries are embarking on significant land use changes in the form hydropower dams, to fulfill their energy requirements. This pathway could lead to irreversible changes to the ecosystem of the Mekong River, if not properly managed. This thesis aims to explore the potential effects of changes in land use —with a focus on current and projected hydropower operations— on the Lower Mekong River network streamflow and instream water quality. To achieve this aim, this thesis first examined the relationships between the basin land use/land cover attributes, and streamflow and instream water quality dynamics of the Mekong River, using total suspended solids and nitrate as proxies for water quality. Findings from this allowed framing challenges of integrated water management of transboundary river basins. These were used as criteria for selecting eWater's Source modelling framework as a management tool that can support decision-making in the socio-ecological context of the LMB. Against a combination of predictive performance metrics and hydrologic signatures, the model's application in the LMB was found to robustly simulate streamflow, TSS and nitrate time series. The model was then used for analysing four plausible future hydropower development scenarios, under extreme climate conditions and operational alternatives. This revealed that hydropower operations on either tributary or mainstream could result in annual and wet season flow reduction while increasing dry season flows compared to a baseline scenario. Conversely, hydropower operation on both tributary and mainstream could result in dry season flow reduction. Both instream TSS and nitrate loads were predicted to reduce under all three scenarios compared to the baseline. These effects were found to magnify under extreme climate conditions, but were less severe under improved operational alternatives. In the LMB where hydropower development is

inevitable, findings from this thesis provide an enhanced understanding on the importance of operational alternatives as an effective transboundary cooperation and management pathway for balancing electricity generation and protection of riverine ecology, water and food security, and people livelihoods.

List of Abbreviations

Acronym	Definition
ADB	Asian Development Bank
AEC	ASEAN Economic Community
AGLCTS	Annual global land cover time series
AGNPS	Agricultural Non-Point Source Pollution model
AnnAGNPS	Annualised Agricultural Non-Point Source Pollution model
ASEAN	Association of Southeast Asian Nations
CN	Curve Number
CREAMS	Chemicals, Runoff, and Erosion from Agricultural Management System model
DDTs	Dichlorodiphenyltrichloroethane
DPSIR	Drivers, Pressure, State, Impact, Response
DTM	Digital terrain model
DWC	Dry Weather Concentration
EMC	Event Mean Concentration
ESA	European Space Agency
FAO	The Food and Agricultural Organization of United Nations
FDC	Flow duration curve
FI	Flashiness Index
FNP	Nakhone Phanom Gauging Station
FPS	Pakse Gauging Station
FST	Stung Treng Gauging Station
FU	Functional Unit
GDP	Gross Domestic Products
GIS	Geographic Information Systems

GLEAMS	Groundwater Loading Effects of Agricultural Management System model
GRDs	Generation and removal dynamics
HRCs	Hydrological response characteristics
HRUs	Hydrological response units
HSPF	Hydrological Simulation Program - Fortran
HUSLE	Hydro-geomorphic Universal Soil Loss Equation
IHACRES – CMD	Identification of unit Hydrographs and Component flows from Rainfall, Evaporation and Streamflow data based on Catchment Moisture Deficit
IWRM	Integrated Water Resource Management
LB	Lancang River Basin
LCCS	Land cover classification system
LMB	Lower Mekong Basin
LMR	Lower Mekong River
LR	Lancang River
LULC	Land use/land cover
MD	Mekong Delta
MRC	The Mekong River Commission
MSE	Mean square error
MUSLE	Modified Universal Soil Loss Equation
NSE	Nash-Sutcliffe Efficiency
OCs	Oganochlorine compounds
PCBs	Polychlorinated biphenyls
PDIES	Procedures for Data, Information Exchange and Sharing
PMFM	Procedures for Maintenance of Flows on the Mainstream

PNPCA	Procedures for Notification, Prior consultation and Agreement
PPMs	Predictive Performance Metrics
PWQ	Procedures for Water Quality
PWUM	Procedures for Water Use Monitoring
Rc	Runoff ratio
RI	Reliability index
RQs	Research questions
RSI	Relative spread index
RUSLE	Revised Universal Soil Loss Equation
SDGs	Sustainable Development Goals
SI	Supplementary Information
SMK	Seasonal Mann-Kendall
STL	Seasonal and Trend decomposition Loess algorithm
SWAT	Soil Water Assessment Tool model
SWM	Storm Water Management Model
TSS	Total suspended solids
UMB	Upper Mekong River Basin
UMR	Upper Mekong River
UNDP	United Nations Development Programme
WB	World Bank
WEAP	Water Evaluation and Planning model
WMs	Watershed models
WQMN	Water Quality Monitoring Network

List of Figures

List of Tables

Contents

List of Appendices

Chapter 1. Thesis general introduction

Kongmeng Ly

Chapter 1. Introduction

1.1 Research background

1.1.1 Significance of the Mekong River

Located in Southeast Asia and made of land areas of Lao PDR, Thailand, Cambodia, and Viet Nam, the Lower Mekong River Basin (LMB) is one of the most important and significant transboundary river basins in the world. With the Mekong River as its backbone, the basin river network systems and its riparian ecosystems are biodiversity rich and have historically provided resources that support the livelihoods of over 60 million people who called it home (Mekong River Commission, 2018). Originating from the mountain ranges of the Himalaya, this transboundary river runs through the Peoples Republic of China (PRC) and Myanmar forming the Upper Mekong River Basin (UMB) (also known as the Lancang River Basin, LB) before flowing through the LMB. The river discharges about 457 km^3 annually into the South China Seas, also known as the East Sea (Chen et al., 2020) at the southern part of Viet Nam (Olson and Morton, 2018) (Figure 1.1). Together, the URB and LMB has a total land area of 810,000 km^2 and the entire river length extends over 4,800 km, making it the 10th longest river in the world (Mekong River Commission, 2018). In terms of discharge, the river is the 8th largest in the world with 35% of its discharge contributed by the 202,000 km^2 of drainage within Lao PDR (Table 1.1) (Mekong River Commission, 2009).

Topographically, the LMB and UMB are made up of diverse landforms. The UMB is predominately mountainous with steep valleys, narrow river channel, and high elevation drop giving it over 40,000 MW of theoretical hydropower potential (Geheb and Suhardiman, 2019). As such, this section of the Mekong River has been recognized as important water resources for hydropower development (Cosslett and Cosslett, 2018) and has been rapidly exploited since 1993 when the Manwan Hydropower became operational on the mainstream of the River (Fan et al., 2015).

Figure 1.1: The Upper and Lower Mekong River Basin (Mekong River Commission, 2018) and flow contribution from each Member Countries (Mekong River Commission, 2009).

On the other hand, the LMB (with a total land area of 624,000 km^2) is more topographically diverse with complex draining patterns and elevations ranging from 0 to 2800 m above sea level (Mekong River Commission, 2009). These characteristics allow the basin to be subdivided into four broad physiographic regions. Located in the upper part of the basin is the Northern Highland where mountain ranges and steep valleys dominate the landscape encompassing Northern Thailand and Northern Lao PDR. In the western part of the basin, where the Khorat Plateau formed, the landscape is dominated by areas of rolling hills and alluvial plains. Further south, the Tonle Sap Basin forms the largest freshwater lake in Southeast Asia and provides a unique ecosystem with enormous hydrological, biological, nutritional and cultural values to the region (Arias et al., 2014; Chan et al., 2020; Halls and Hortle, 2021). In the Delta Region, where the Mekong River splits into two main channels, the landscape is mostly flat, with low-gradient drainage river, wide floodplains, and network of canals (Mekong River Commission, 2011).

Due to its diverse topography and landform, the LMB is endowed with a wide variety of terrestrial and aquatic natural resources. The Mekong River Commission (2018) estimated that the river network system is home to 1,148 fish species making it one of the most bio-diverse river in the world. Its annual flood pulse caused by the monsoon rain during the wet season has allowed for productive inland wild capture fisheries (Kummu and Sarkkula, 2008; Cosslett and Cosslett, 2018; Halls and Hortle, 2021), an important source of dietary protein of the basin population (Chan et al., 2020). On land, the basin is rich with largely unexploited mineral resources including goal, copper, potash, zinc, coal, and oil and gas (Pech and Sunada, 2008; Mekong River Commission, 2011; Wu, 2021). With a broad variety of ecosystems that include diverse forest types providing habitats to many important wildlife species and non-timber forest products to support income generation, the LMB has been identified as one of the most biological important regions of the world (CEPF, 2012; Yasmi et al., 2017; Schweikhard et al., 2019; Brewer et al., 2020).

Table 1.1: Drainage area and discharge contributions of the Upper and Lower Mekong Basin (Mekong River Commission, 2009)

	Drainage area				
Countries	**Total (km2)**	**% of UMB**	**% of LMB**	**% of Country Area**	**% of flow contribution**
PRC	165,000.0	21	-	2	16

Myanmar	24,000.0	3	-	4	2
Lao PDR	202,000.0	25	33	85	35
Thailand	184,000.0	23	30	36	18
Cambodia	161,000.0	20	26	86	18
Viet Nam	65,000.0	8	11	20	11

With the LMB countries having up to 86% of their land located within the basin (Table 1.1), the Mekong River and its resources are vital for the countries' economic development, and water and food security. Despite the abundance of these resources, the LMB is still considered as one of the poorest region in the world with wide ranging socioeconomic disparities among its four countries (Cosslett and Cosslett, 2018). These disparities have led to a divergence of economic development priorities among the LMB countries. For example, the Lao PDR, a landlocked country that is dominated by mountains and steep valleys, has fundamentally linked its economic development and poverty alleviation pathways with hydropower development (Chattranond, 2018; ADB, 2019). Conversely, downstream countries such as Viet Nam prioritises economic development of the Mekong Delta on agriculture and fisheries, and thus places its focus on maintaining the river natural flow and sediment transport capacity to sustain functions of the delta river system (Dang et al., 2018; Trung et al., 2018).

1.1.2 Water management legal and cooperative frameworks

Given the divergence in economic development and conservation priorities of the LMB countries, the management of the Mekong River and its water resources has been challenging for national and regional water resource planners. To manage water resources within their national boundaries, the LMB Countries have individually established national legal frameworks aiming at managing and protecting water and its related resources (Table 1.2). These frameworks have allowed the countries to manage and maintain water quality and quantity within their national respective boundaries under a framework of integrated watershed management. They also set out legal mandates for individuals exploiting large scale water and its resources to include the monitoring, management, and conservation of water quality and quantity during planning, development, and operation phases.

Table 1.2: Key national water resources management frameworks of the LMB countries

Tittle	Year of Issued	Countries	Functions and Aims of the Frameworks
Law on Water Resources Management of the Kingdom of Cambodia (The Royal Government of Cambodia, 2007)	2007	Cambodia	Aimed at fostering the effective and sustainable management of water resources within Cambodia, this framework establishes mandates for the exploitation and management of water and its related resources including the protection of water quality and flow of waterbodies within the country boundary.
Law on Water and Water Resources (National Assembly, 2017)	1996	Lao PDR	This framework (which was revised in 2017) sets out necessary principles, regulations, and measures relating to the management, utilization and development of water and its resources, aiming at maintaining their sustainability. Specifically, the framework establishes provisions for watershed management and the protection of water resources including water quality and hydrology.
Water Resources Act (The Royal Thai Government, 2018)	2018	Thailand	The act sets out principles for the development, management, conservation, and rehabilitation of water resources. Management measures stipulated in the framework includes the preservation of water resources for public uses and prevention of flood and drought.
Law on Water Resources (Government of Socialist Republic of Viet Nam, 1998)	1998	Viet Nam	The framework has in its objectives to strengthen the efficiency of government water resources and to increase the responsibility of organizations and individuals in the protection and utilization of water. Specifically, the framework stipulates provisions for the management, protection, and mitigation of any adverse effects on water resources, including water quality and quantity protection and maintenance.

In addition to the their national legal frameworks, the LMB countries also have a long history of cooperation in relation to the development of the basin, with the establishment of the Mekong Committee for the coordination of investigations on the LMB in the early 1950s (Mekong River Commission, 2020). This committee would later be known the Mekong River Commission (MRC) following the adoption of the 1995 Mekong Agreement on the Cooperation for the Sustainable Development of the Mekong River Basin (MRC, 1995). With the 1995 Mekong Agreement (MRC, 1995), the LMB countries agreed *"to cooperate in all fields of sustainable development, utilisation, management and conservation of water and related resources of the LMB"*, and tasked the MRC with promoting the coordination of all fields of sustainable development, utilisation, management, and conservation of the Mekong River and its resources (MRC, 1995). Under this agreement, cooperation is enabled through the agreement's five Procedural Rules (Table 1.3).

Table 1.3: A summary of LMB Countries' cooperative commitment under the 1995 Mekong Agreement and its procedural rules (Mekong River Commission, 2020).

Procedures	Cooperation commitments
Procedures for Notification, Prior Consultation and Agreement (PNPCA)	• Reasonable and equitable use of waters of the Mekong River network system. • Notification, prior consultation and agreement on proposed water uses as follows: o Notification is required for all uses on the Mekong tributaries that may result in significant impact on the mainstream. o Prior consultation is required for all dry season intra-basin uses on the mainstream and all wet season inter-basin uses of the mainstream. o Prior agreement is required for all dry season inter-basin diversions and uses that could substantially impacts on flows of the mainstream.
Procedures for Water Use Monitoring (PWUM)	• Sharing data and information on water uses • Protection of existing water users and ensuring that existing uses are in accordance with agreed operating rules.

Procedures for the Maintenance of Flows on the Mainstream (PMFM)	• Maintenance of minimum flow in the mainstream to support downstream water use and maintain the integrity of the mainstream ecosystems.
Procedures for Water Quality (PWQ)	• Monitor and report the status of water quality of the Mekong River and its tributaries. • Framework for notification of and jointly response to water quality emergency situation. • Sharing information on water quality condition of the Mekong River and its tributaries.
Procedures for Data, Information Exchange and Sharing (PDIES)	• Sharing of data and information vital for the sustainable development and management of the Mekong River and its resources. • Establishment of the LMB data repository that can be used for assessment of potential impacts of future development

For the management of water quality, the Procedures for Water Quality (PWQ, Table 1.3) provide guidelines for the maintenance of acceptable/good water quality of the Mekong River, whereas the Procedures for the Maintenance of Flow on the Mainstream (PMFM, Table 1.3) provide a cooperative framework for maintaining a mutually acceptable hydrological flow regime of the Mekong River. These procedures allow the establishment of a number of joint environmental monitoring programs across the LMB to monitor the status and establish long term trends of environmental quality.

Among the many monitoring programs implemented at regional levels, hydrological monitoring and a water quality monitoring network are two key environmental monitoring programs that have provided long-term observations of hydrological and water quality indicators (Mekong River Commission, 2009; Mekong River Commission, 2014). For example, under the MRC Water Quality Monitoring Network (WQMN), 18 water quality indicators were routinely monitored in 48 stations across the LMB as of 2015. The data generated by the network has provided necessary baseline information for not only academic research (Li and Bush, 2015; Campbell, 2016; Ratha et al., 2016; Ly et al., 2020b) but also for assessing potential impacts of inland and instream development activities (Fan et al., 2015; Dang et al., 2018; Hoang et al., 2019).

1.1.3 Factors driving changes in LULC and influencing streamflow and water quality of the Mekong River

While existing national and regional water resources legal frameworks are available to guide decision making, pressures to reduce poverty and increase economic development continue to drive how countries utilize the Mekong River (Sithirith, 2021). In many parts of the basin, the improvement of road networks has connected rural communities to the market economy, putting further pressure on the land use and transforming forest areas for commercial agricultural production (Sithong and Yayoi, 2006). As the LMC becomes more integrated into the ASEAN Economic Community (AEC), drivers such as population growth, international trade, and technology change are expected to further alter land use in the basin (Rutten et al., 2014).

Streamflow and water quality of the Mekong River are influenced by a number of factors. Using the Drivers-Pressure-State-Impact-Response (DPSIR) framework adopted by the European Environment Framework (Kristensen, 2004) this research identified cause-effect relationships among drivers, pressures, states, impacts and responses associated with water quality and quantity of the Mekong River (Figure 1.2).

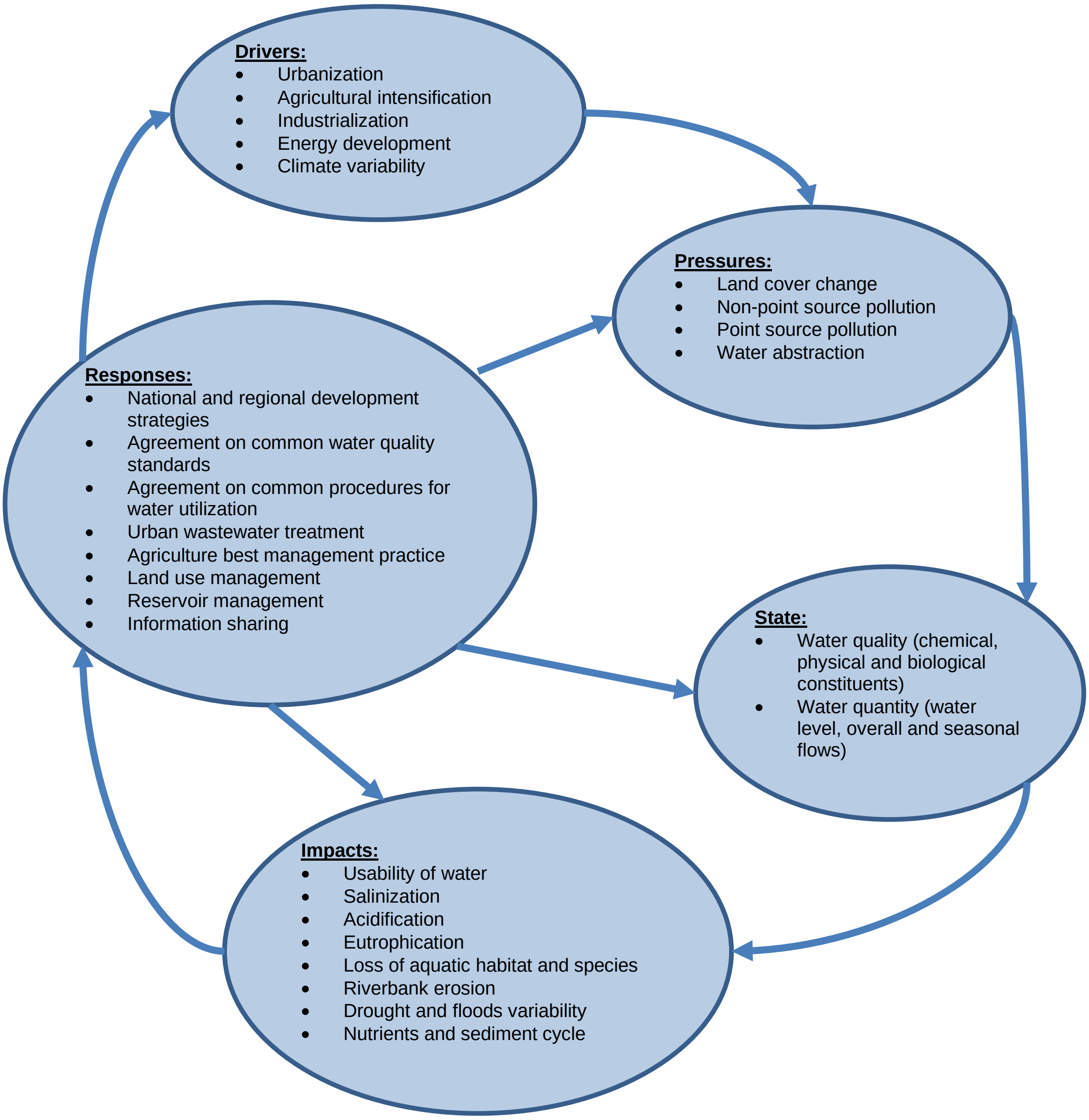


Figure 1.2: A conceptual model of the Drivers-Pressures-State-Impact and Responses driving water quality and quantity of the Mekong River, compiled from relevant literature of the area.

Figure 1.2 evidence that in the LMB, the pursuing of higher economic performance and improving livelihood conditions have led to increased industrialization, urban expansion, increased energy generation and agricultural intensification, driving water quality and quantity of the Mekong River. Along with climatic variability, these drivers are likely to increase and alter patterns of point and non-point sources pollution in the basin.

Demands of food and energy production for a growing population and high rates of economic growth (World Bank Group, 2015) have unleashed significant LULC changes over the entire LMB, causing degradation of land and water resources (Arias et al., 2019; Sridhar et al., 2019). Pressures for delivering food security have led to the expansion of agricultural areas and intensive agricultural production (Crews-Meyer, 2004; Edmonds, 2004; Brewer et al., 2020), while globalisation and cheap labour cost have driven expansion of industrial and urban areas (Homesana, 2019; Lwin, 2019; Vu et al., 2019). These expansion activities are largely at the expense of grassland (Okamoto et al., 2014; Ly et al., 2020a) and forest areas (Pham et al., 2015; Oeurng et al., 2016; Trang et al., 2017), reducing the natural buffer capacity of the basin to control non-point source pollution runoff (Lerch et al., 2017; Cui et al., 2019; Valera et al., 2019a; Walton et al., 2020).

National efforts to sustain economic growth, meet the growing energy demand of urban population, and extend electricity coverage to rural communities, have led a cascade of dams operating or under development across the Mekong River mainstream and its tributaries, altering cross-border river morphology and threatening the basin water security (Trang et al., 2017; Pokhrel et al., 2018; Gunawardana et al., 2021). Such water abstraction for energy generation and agricultural purposes have impacted water levels of the LMB, altering aquatic habitats, triggering further intrusion of seawater in the delta area, and exacerbating eutrophication in certain areas of the river, including the Tonle Sap Lake. Consequently, the integrity of the Mekong River to maintain its functions of supporting and sustaining diverse ecosystems is under threat.

Many studies conducted in the LMB have concluded that streamflow and water quality of the Mekong River are changing (Fan et al., 2015; Li and Bush, 2015; Chea et al., 2016; Hecht et al., 2019; Ly et al., 2020a), with changes in streamflow and sediment regimes being linked to hydropower operation (Hecht et al., 2019; Yu et al., 2019; Binh et al., 2020) and increasing nutrients levels being linked to the expansion of urban and agricultural areas (Oeurng et al., 2016; Yadav et al., 2019; Ly et al., 2020a; Bridhikitti et al., 2021). Heavy metals and nutrients monitored in the Mekong Delta have been detected at levels exceeding guidelines for drinking and domestic use purposes (Wilbers et al., 2014; Chea et al., 2016). In other areas, organochlorine compounds (OCs), such as PCBs and DDTs, have been recorded at elevated levels (Sudaryanto et al., 2011).

1.2 Research rationale and objectives

1.2.1 Rationale

If not properly managed, the effects of development and land use change on water quality are expected to exacerbate in the LMB, as countries continue to increase their development activities to improve economic performance. Under uncertain future climate variability, these impacts could be even more profound affecting the basin's energy, food, and water security.

As the river continues to function as a lifeline for the entire basin, balancing competing interests is the main challenge for the basin water resources managers (Molle et al., 2009; Wild et al., 2019; Williams, 2019; Chen et al., 2020). With the LMB countries continuing to embark on divergent development and conservation pathways, it is essential that potential consequences of activities for the Mekong River across a range of temporal and spatial scales are well understood. The transboundary nature of the Mekong River requires consideration of potential cross-border impacts of development plans for better regional cooperation and management (Kauffman, 2015; Olson and Morton, 2018; Sithirith, 2021).

While there have been an abundance of studies examining the status of water scarcity and pollutants in the LMB (Cenci and Martin, 2004; Sudaryanto et al., 2011; Guédron et al., 2014; Wilbers et al., 2014; Chea et al., 2016), these tend to focus on the influences of a single development factor. Based on the review of literature, none has been carried out to examine the effects of LULC changes stemming from increased economic development and population growth. Furthermore, research on the potential effects of different future development pathways on streamflow and water quality of the Lower Mekong River has been non-existent.

1.2.2 Research objectives

Against these backgrounds, this research aimed to explore and evaluate the effects of current and future development of the LMB on the streamflow and water quality of the Mekong River. To achieve the overall objectives of the research, the following research questions (RQs) were formulated and explored during the course of the research:

RQ1: Have there been significant changes in streamflow and water quality of the Mekong River? If so, what appear to be the drivers of these changes?

RQ2: Is there an available tool that has been successfully used to assess the effects of development on streamflow and water quality of a large transboundary river basin such as the LMB?

RQ3: How will the identified tool perform when applying in the LMB considering its management challenges?

RQ4: What are the national and regional development priorities of the LMB and what are the environmental consequences of the implementation of these priorities?

1.3 Research approach

Figure 1.3 illustrates the approach applied for this study where the exploration and evaluation of potential consequences of future development pathways on streamflow and water quality of the Mekong River required collation of available development and environmental monitoring data. This information served as a foundation for understanding the relationships between watershed behaviours of the LMB and the dynamics of instream hydrology and water quality of the Mekong River. These relationships aided in the performance evaluation for identifying suitable management tool for the LMB, a large-scale transboundary river basin with limited environmental data. Likewise, the basin development information was used for the establishment of plausible of future development pathways and consequently aided in the exploring how planned development strategies could affect streamflow and water quality of the Mekong River (Section 1.2.2). Through this approach, each RQ (Section 1.2.2) was conceptually explored and answered by different methodology (Sections 1.3.1 to 1.3.4), but with an overall aim of achieving the research objectives.

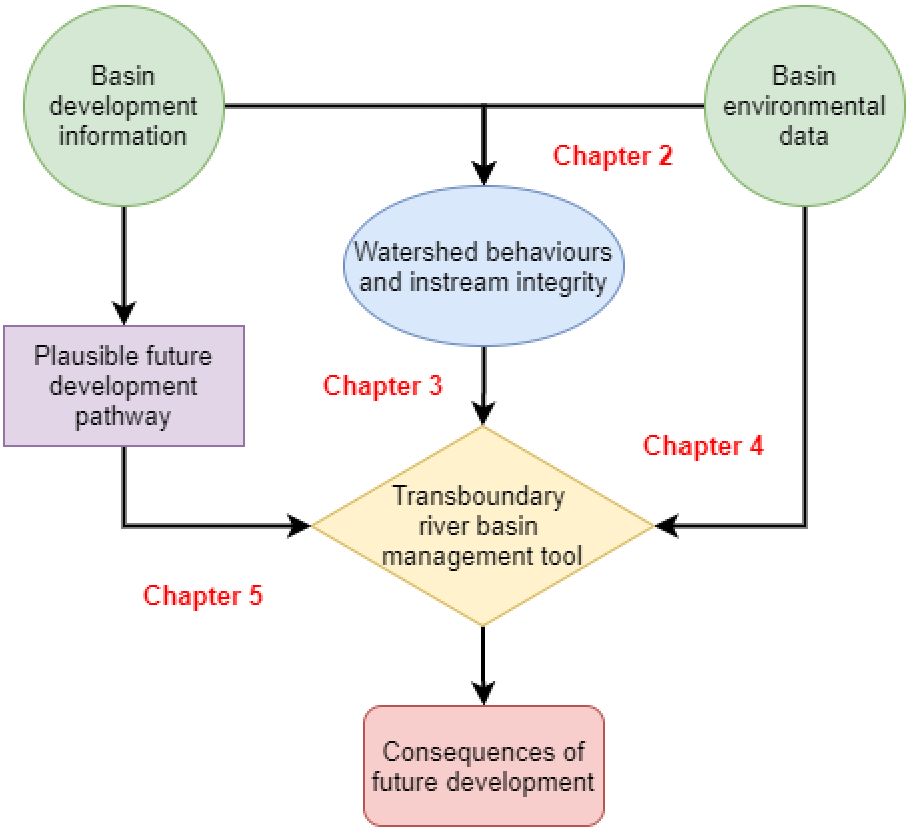


Figure 1.3: Approach applied for answering RQs and achieving research objectives

1.3.1 Have there been significant changes in streamflow and water quality of the Mekong River? If so, what are the drivers of these changes? (Chapter 2)

Approach: To answer this RQ, historical streamflow and water quality monitoring data of the Mekong River from 1985 to 2015 were analysed. Total suspended solids (TSS) and nitrate were used as proxies for water quality due to their documented ecological importance for sustaining the Mekong River functions (Trung et al., 2018; Intralawan et al., 2019; Wild et al., 2019). Any significant changes in streamflow and instream TSS and nitrate levels were assessed using a combination of Seasonal and Trend decomposition Loess algorithm (STL) (Cleveland et al., 1990) to remove the influences of seasonal influences and outliers and seasonal Mann-Kendall test (Hirsch et al., 1982) to determine the statistical significance of changes. Through the review of literature, these methods were recommended and widely used for the assessment of the monotonic trends of environmental monitoring data (Johnson et al., 2009; Abell et al., 2011; Fu and Wang, 2012; Ai et al., 2015; Gu et al., 2019).

As development and increasing population have been documented as the main cause for LULC changes (Bin and Alounsavath, 2016; Ribolzi et al., 2017; Huang et al., 2020), temporal assessment of LULC changes in the LMB from 1993 to 2015 was carried out and used for explaining the detected changes in streamflow and instream TSS and nitrate levels. Relationships between LULC and streamflow and instream TSS and nitrate were established at both spatial and temporal scale by Pearson's correlation analysis (Benesty et al., 2009). Results from this study were compared with prior studies from other regions and any relationships deviated from expected norms were explained by the evidence-based unique natural (e.g. soil types, forest types, topography, etc.) and anthropogenic (e.g. land use practices, instream disturbance, deforestation, etc.) characteristics of the LMB. Understanding the underlying factors influencing changes in streamflow and instream water quality of the Mekong River is crucial for identifying appropriate tools to support the effective management of the LMB.

1.3.2 Is there an available tool that has been successfully used to assess the effects of development on streamflow and water quality of a large transboundary river basin such as the LMB? (Chapter 3)

Approach: With RQ1 resulting in a better understanding of factors influencing streamflow and instream TSS and nitrate dynamics (Section 1.3.1), we established a set of criteria associated with the management challenges of transboundary river basin of developing countries such as the LMB. These criteria were separated into two groups and ranked based on their perceived important to water resources planners of the LMB and applied to evaluate and identify the most suitable watershed management tool. A list of 12 watershed models (WMs) were identified as having potential to be used for the management of the LMB from a review of over 250 peer-review publications. Each WM was first assessed against a group of the initial assessment criteria, where any WMs found not to meet any of the criteria were eliminated from consideration. The remaining WMs were then further scrutinised against a group of final selection criteria, where the Source modelling framework (Carr and Podger, 2012; eWater, 2019) was found to have a comparative advantage to support the management of the LMB.

1.3.3 How will the identified tool perform when applying in the LMB considering its management challenges? (Chapter 4)

Approach: With the Source modelling framework identified as having comparative advantage compared to other watershed management tools when exploring answer to RQ2, the modelling framework was applied to establish the *LMB-Source* model using available basin data that include LULC, digital elevation model (DEM) and meteorological data. As part of the requirements for the *LMB-Source* model set up (eWater, 2019), we estimated parameter values for the LMB specific hydrologic response characteristics (HRCs) and overland TSS and nitrate generation and removal dynamics (GRDs). To ascertain that the LMB-Source model can simulate runoff behaviours of the LMB, the simulated streamflow and instream TSS and nitrate time series were compared against their counterpart time series of the same time period. A combination of predictive performance metrics (PPMs) (Moriasi et al., 2015) and the novice application of hydrologic signatures (McMillan, 2020) were used to diagnose the model performance of different streamflow segments and to optimise parameter values of HRCs and GRDs.

1.3.4 What are the national and regional development priorities of the LMB and what are the environmental consequences of the implementation of these priorities? (Chapter 5)

Approach: To answer this RQ, we reviewed and analysed national and regional development plans and identified hydropower development as the main development priority in the basin. Using exploratory scenario development approach (Rounsevell and Metzger, 2010; Gorgoglione et al., 2019), we constructed three plausible future hydropower development scenarios in addition to the baseline scenario, where development narrative evolving around the preservation of current streamflow and water quality condition. Using the LMB-Source model, future streamflow and instream TSS and nitrate loads were predicted for each scenario under normal, extreme wet, and extreme dry climate conditions from 2016 to 2050. Predicted streamflow and instream TSS and nitrate loads time series of each scenario under different climate conditions were compared to their counterparts of the baseline scenarios, where a set of indicators of changes were used to quantify the scale of impacts. Operational alternatives were also explored to determine their mitigation potentials as measures for sustainable management and development of transboundary river basin.

1.4 Thesis structure

Along with this introduction chapter (Chapter 1) and conclusion chapter (Chapter 6), this thesis consists of four chapters representing four different manuscripts that have either been published in peer-reviewed journals or have been submitted to peer-reviewed journals. As a collection of manuscripts, Chapters 2 to 5 of this thesis have their separate Abstract, Introduction, Methodology, Result, Discussion, Conclusion, Reference, and Supplementary Information or Appendix Sections. While these manuscripts are interconnected (Figure 1.4), and were designed to specifically answer research questions formulated following the conceptualisation of the overall research objectives (Section 1.2.2), they are designed to be read as separate body of work and have referencing formats that reflect the requirements of the peer-reviewed journals of which they were published. The specific details of each manuscripts that make up this thesis and their authorships are summarised below.

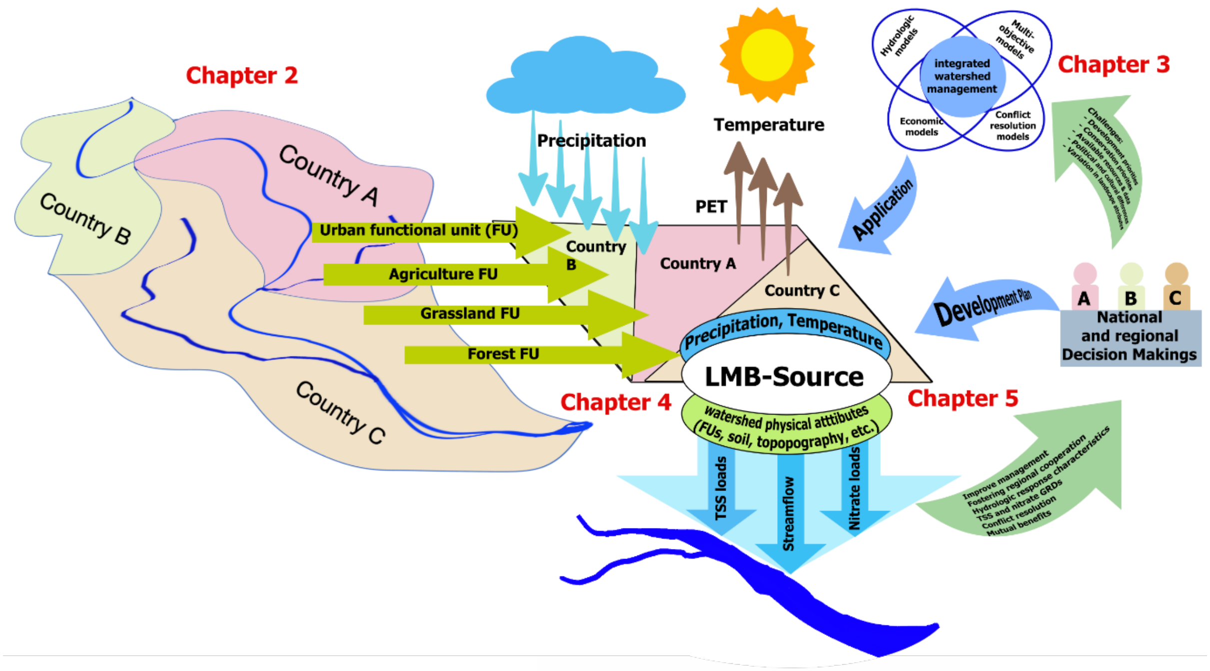


Figure 1.4: Graphical illustration of the interconnectivity of the manuscripts making up this thesis (modified from the graphical abstract of my manuscript that was published in *Science of the Total Environment* (Ly et al., 2020b)).

Chapter 1 serves as an overall introduction chapter to my thesis, outlining my research background and motivation. Specifically, the chapter provides an overview of the ecological, cultural, and economical values of the Mekong River and its resources. It highlights important findings from prior research on the conditions of the Mekong River water quality and quantity to support the functioning of the river. Knowledge gaps drawn from these studies served as a motivation for exploring answer to my research questions. (Section 1.2)

Chapter 2 provides answers to RQ1 of this thesis using the approach describes in Section 1.3.1. Findings from this chapter help enhanced understanding of spatiotemporal relationships between LULC and streamflow and instream dynamics of TSS and nitrate levels. This understanding allowed for the identification of management challenges specific to the LMB and served as a foundation for the development of criteria to be used in Chapter 3. This chapter is published in *Sustainability* which can be found at https://doi.org/10.3390/su12072992.

Chapter 3 provides results of my evaluation of available watershed management tools from a review of over 250 peer-reviewed journals against a set of management criteria developed based on findings from Chapter 2. Against these criteria, the eWater Source modelling framework was identified to have a comparative advantage for the management of large-scale transboundary river basin of developing countries such as the LMB. The findings from this chapter is published in the *Journal of Hydrology: Regional Studies* which can be found at https://doi.org/10.1016/j.ejrh.2019.100605.

Chapter 4 evaluates the capability of the eWater Source modelling framework, previously identified in Chapter 3, in simulating watershed behaviours, hydrological processes and instream water quality dynamics of the LMB. The evaluation was carried out using the approach described in Section 1.3.3 with the findings presented in Chapter 4 of this thesis and published in Science of the Total Environment which can be found at https://doi.org/10.1016/j.scitotenv.2020.140656.

Chapter 5 explores and evaluates the potential effects of future development on streamflow and instream TSS and nitrate loads of the LMB. Building on findings from Chapter 4 and using the approach described in Section 1.3.4, this chapter does not only quantify the magnitudes of impacts associated with plausible future hydropower development pathways under climatic extreme conditions, but also explore hydropower operational alternative as an effective mitigation option. The manuscript of this chapter has been submitted to *Science of the Total Environment*.

Chapter 6 provides an overall discussion and conclusion of my thesis integrating key findings from Chapter 2 to 5 in relation the RQs and overall thesis aim. Implications of my research for the sustainable development and management of the Mekong River are highlighted, as well as recommendation for future research in this field.

1.5 References

ABBASPOUR, K. C., ROUHOLAHNEJAD, E., VAGHEFI, S., SRINIVASAN, R., YANG, H. & KLØVE, B. 2015. A continental-scale hydrology and water quality model for Europe: Calibration and uncertainty of a high-resolution large-scale SWAT model. *Journal of Hydrology,* 524**,** 733-752.

ABBOTT, M. B., BATHURST, J. C., CUNGE, J. A., O'CONNELL, P. E. & RASMUSSEN, J. 1986. An introduction to the European Hydrological System — Systeme Hydrologique Europeen, “SHE”, 1: History and philosophy of a physically-based, distributed modelling system. *Journal of Hydrology,* 87**,** 45-59.

ABELL, J. M., ÖZKUNDAKCI, D., HAMILTON, D. P. & MILLER, S. D. 2011. Relationships between land use and nitrogen and phosphorus in New Zealand lakes. *Marine and Freshwater Research,* 62**,** 162-175.

ADB 2019. Lao People’s Democratic Republic Engergy Sector Assessment, Strategy, and Road Map. *Country Sector and Thematic Assessments.* The Asian Development Bank.

ADU, J. T. & KUMARASAMY, M. V. 2018. Assessing Non-Point Source Pollution Models: a Review. *Polish Journal of Environmental Studies,* 27**,** 1913-1922.

AFZAL, M., BATTILANI, A., SOLIMANDO, D. & RAGAB, R. 2016. Improving water resources management using different irrigation strategies and water qualities: Field and modelling study. *Agricultural Water Management,* 176**,** 40-54.

AGARWAL, A., DELOS ANGELES, M. S., BHATIA, R., CHÉRET, I., DAVILA-POBLETE, S., FALKENMARK, M., VILLARREAL, F. G., JØNCH-CLAUSEN, T., KADI, M. A. & KINDLER, J. 2000. *Integrated water resources management*, Global water partnership.

AHMADI, S. H., AMIN, S., REZA KESHAVARZI, A. & MIRZAMOSTAFA, N. 2006. Simulating Watershed Outlet Sediment Concentration using the ANSWERS Model by applying Two Sediment Transport Capacity Equations. *Biosystems Engineering,* 94**,** 615-626.

AI, L., SHI, Z. H., YIN, W. & HUANG, X. 2015. Spatial and seasonal patterns in stream water contamination across mountainous watersheds: Linkage with landscape characteristics. *Journal of Hydrology,* 523**,** 398-408.

AL-ABED, N. & AL-SHARIF, M. 2008. Hydrological Modeling of Zarqa River Basin – Jordan Using the Hydrological Simulation Program – FORTRAN (HSPF) Model. *Water Resources Management,* 22**,** 1203-1220.

AL BAKRI, D., RAHMAN, S. & BOWLING, L. 2008. Sources and management of urban stormwater pollution in rural catchments, Australia. *Journal of Hydrology,* 356**,** 299-311.

ALLAN, D., ERICKSON, D. & FAY, J. 1997. The Influence of Catchment Land Use on Stream Integrity Across Multiple Spatial Scales. *Freshwater Biology,* 37**,** 149-161.

AMMANN, L., FENICIA, F. & REICHERT, P. 2019. A likelihood framework for deterministic hydrological models and the importance of non-stationary autocorrelation. *Hydrology and Earth System Sciences,* 23**,** 2147-2172.

ANG, R. & OEURNG, C. 2018. Simulating streamflow in an ungauged catchment of Tonlesap Lake Basin in Cambodia using Soil and Water Assessment Tool (SWAT) model. *Water Science,* 32**,** 89-101.

ARHEIMER, B. & LIDÉN, R. 2000. Nitrogen and phosphorus concentrations from agricultural catchments—influence of spatial and temporal variables. *Journal of Hydrology,* 227**,** 140-159.

ARIAS, M. E., COCHRANE, T. A., KUMMU, M., LAURI, H., HOLTGRIEVE, G. W., KOPONEN, J. & PIMAN, T. 2014. Impacts of hydropower and climate change on drivers of ecological productivity of Southeast Asia's most important wetland. *Ecological Modelling,* 272**,** 252-263.

ARIAS, M. E., HOLTGRIEVE, G. W., NGOR, P. B., DANG, T. D. & PIMAN, T. 2019. Maintaining perspective of ongoing environmental change in the Mekong floodplains. *Current Opinion in Environmental Sustainability,* 37**,** 1-7.

ARNOLD, J. G., MORIASI, D. N., GASSMAN, P. W., ABBASPOUR, K. C., WHITE, M. J., SRINIVASAN, R., SANTHI, C., HARMEL, R. D., VAN GRIENSVEN, A., VAN LIEW, M. W., KANNAN, N. & JHA, M. K. 2012. SWAT: Model use, calibration, and validation. *Transactions of the ASABE,* 55**,** 1491-1508.

BAGINSKA, B., MILNE-HOME, W. & CORNISH, P. S. 2003. Modelling nutrient transport in Currency Creek, NSW with AnnAGNPS and PEST. *Environmental Modelling & Software,* 18**,** 801-808.

BAKER, A. 2003. Land use and water quality. *Hydrological Processes,* 17**,** 2499-2501.

BAKER, D. B., RICHARDS, R. P., LOFTUS, T. T. & KRAMER, J. W. 2004. A NEW FLASHINESS INDEX: CHARACTERISTICS AND APPLICATIONS TO MIDWESTERN RIVERS AND STREAMS. *Journal of the American Water Resources Association,* 40**,** 503-522.

BARLOW, K., WEEKS, A., F., G., CHRISTY, B. & CHENG, X. 2011. A Source model of the Ovens River Catchment in Victoria - Northen Victoria Project. eWater CRC Application Report: eWater.

BAUER, S., OLSON, J., COCKRILL, A., VAN HATTEM, M., MILLER, L., TAUZER, M. & LEPPIG, G. 2015. Impacts of Surface Water Diversions for Marijuana Cultivation on Aquatic Habitat in Four Northwestern California Watersheds. *PLOS ONE,* 10**,** e0120016.

BEASLEY, D. B., HUGGINS, L. F. & MONKE, E. J. 1980. ANSWERS: A Model for Watershed Planning. *Transactions of the ASAE,* 23**,** 938.

BENESTY, J., CHEN, J., HUANG, Y. & COHEN, I. 2009. Pearson correlation coefficient. *Noise reduction in speech processing.* Springer.

BERGMAN, M. J., GREEN, W. & DONNANGELO, L. J. 2002. Calibration of Storm Loads in the South Prong Watershed, Florida, Using BASINS/HSPF1. *JAWRA Journal of the American Water Resources Association,* 38**,** 1423-1436.

BETRIE, G. D., MOHAMED, Y. A., VAN GRIENSVEN, A. & SRINIVASAN, R. 2011. Sediment management modelling in the Blue Nile Basin using SWAT model. *Hydrology and Earth System Sciences,* 15**,** 807.

BHUYAN, S. J., KOELLIKER, J. K., MARZEN, L. J. & HARRINGTON, J. A. 2003. An integrated approach for water quality assessment of a Kansas watershed. *Environmental Modelling & Software,* 18**,** 473-484.

BICKNELL, B., IMHOFF, J., KITTLE, J., JOBES, T. & DONIGIAN, A. 2001. HSPF, Version 12, User's Mannual. Athens, GA: U.S. Environmental Protection Agency.

BIN, K. S. & ALOUNSAVATH, O. 2016. Factors influencing the increase of forest cover in Luang Prabang Province, Northern Laos. *Forest Science and Technology,* 12**,** 98-103.

BINGNER, R. L., THEURER, F. D. & YUAN, Y. 2009. *AnnAGNPS Technical Processes: Documentation Version 5* [Online]. Available: ftp://199.133.90.201/pub/outgoing/AGNPS/AGNPS_Web_Files/pdf_files/AnnAGNPS_Technical_Documentation.pdf [Accessed 3 December 2009].

BINH, D. V., KANTOUSH, S. & SUMI, T. 2020. Changes to long-term discharge and sediment loads in the Vietnamese Mekong Delta caused by upstream dams. *Geomorphology,* 353**,** 107011.

BLEVINS, R., LAL, R., DORAN, J., LANGDALE, G. & FRYE, W. 2018. Conservation tillage for erosion control and soil quality. *Advances in soil and water conservation.* Routledge.

BOONSONG, K., PIYATIRATITIVORAKUL, S. & PATANAPONPAIBOON, P. 2003. Potential use of mangrove plantation as constructed wetland for municipal wastewater treatment. *Water Sci Technol,* 48**,** 257-66.

BORAH, D. K. 2011. Hydrologic procedures of storm event watershed models: a comprehensive review and comparison. *Hydrological Processes,* 25**,** 3472-3489.

BORZÌ, I., BONACCORSO, B. & FIORI, A. 2018. A Modified IHACRES Rainfall–Runoff Model for Predicting Hydrologic Response of a River Basin System with a Relevant Groundwater Component. *Proceedings,* 7**,** 24.

BREWER, J., LANGSTON, J. D., FERRETTI-GALLON, K., INNES, J. L., XIN, S., ZHAI, H. & WANG, G. 2020. Alleviating forest degradation in the Lancang-Mekong Region requires closing management—measurement gaps. *Journal of Forestry Research,* 31**,** 2033-2051.

BRIDHIKITTI, A., PRABAMROONG, T., GAOHUAN, L. & GUO-AN, Y. 2021. Best management practices for mitigating agricultural nutrient pollution in the Mun River Basin, Thailand. *Soil and Water Research,* 16**,** 121-128.

BROWNE, D., DELETIC, A., MUDD, G. M. & FLETCHER, T. D. 2008. A new saturated/unsaturated model for stormwater infiltration systems. *Hydrological Processes,* 22**,** 12.

BRUN, S. E. & BAND, L. E. 2000. Simulating runoff behavior in an urbanizing watershed. *Computers, Environment and Urban Systems,* 24**,** 5-22.

BUCK, O., NIYOGI, D. K. & TOWNSEND, C. R. 2004. Scale-dependence of land use effects on water quality of streams in agricultural catchments. *Environmental Pollution,* 130**,** 287-299.

CAMPBELL, I. C. 2016. Integrated management in the Mekong River Basin. *Ecohydrology & Hydrobiology,* 16**,** 255-262.

CARR, R. & PODGER, G. eWater source - Australia's next generation IWRM modelling platform. Water Resources Symposium, 2012 Barton, ACT. Engineers Australia, 742-749.

CENCI, R. M. & MARTIN, J. M. 2004. Concentration and fate of trace metals in Mekong River Delta. *Science of The Total Environment,* 332**,** 167-182.

CEPF 2012. Ecosystem profile: Indo-Burma biodiversity hotspot. Critical Ecosystem Partnership Fund.

CHAHOR, Y., CASALÍ, J., GIMÉNEZ, R., BINGNER, R. L., CAMPO, M. A. & GOÑI, M. 2014. Evaluation of the AnnAGNPS model for predicting runoff and sediment yield in a small Mediterranean agricultural watershed in Navarre (Spain). *Agricultural Water Management,* 134**,** 24-37.

CHAN, B., BROSSE, S., HOGAN, Z. S., NGOR, P. B. & LEK, S. 2020. Influence of Local Habitat and Climatic Factors on the Distribution of Fish Species in the Tonle Sap Lake. *Water,* 12**,** 786.

CHANG, H. 2008. Spatial analysis of water quality trends in the Han River basin, South Korea. *Water Research,* 42**,** 3285-3304.

CHAPLOT, V., KHAMPASEUTH, X., VALENTIN, C. & BISSONNAIS, Y. L. 2007. Interrill erosion in the sloping lands of northern Laos subjected to shifting cultivation. *Earth Surface Processes and Landforms,* 32**,** 415-428.

CHATTRANOND, O. Battery of Asia? The Rise of Regulatory Regionalism and Transboundary Hydropower Development in Laos. 2018.

CHEA, R., GRENOUILLET, G. & LEK, S. 2016. Evidence of Water Quality Degradation in Lower Mekong Basin Revealed by Self-Organizing Map. *PLoS One,* 11.

CHEN, X., ZHENG, Y., XU, B., WANG, L., HAN, F. & ZHANG, C. 2020. Balancing competing interests in the Mekong River Basin via the operation of cascade hydropower reservoirs in China: Insights from system modeling. *Journal of Cleaner Production,* 254**,** 119967.

CHEREMISINOFF, N. P. 1997. 2 - Relationship Between Groundwater and Surface Water. *In:* CHEREMISINOFF, N. P. (ed.) *Groundwater Remediation and Treatment Technologies.* Westwood, NJ: William Andrew Publishing.

CHIEW, F., SCANLON, P., VERTESSY, R. & WATSON, F. 2002. Estimation of pollutant concentrations for EMSS modelling of the South-East Queensland region. *Technical Report* [Online], Report 02/1. Available: https://ewater.org.au/archive/crcch/archive/pubs/pdfs/technical200201.pdf [Accessed 15 June 2019].

CHINYAMA, A., OCHIENG, G. M., NHAPI, I. & OTIENO, F. A. 2014. A simple framework for selection of water quality models. *Reviews in Environmental Science and Biotechnology,* 13**,** 109-119.

CHONG, L. 2010. Nattai River Catchment Source Catchments Application Project. *eWater Technical Report*.

CHU, X. & STEINMAN, A. 2009. *Event and continuous modeling with HEC_HMS*.

CLEVELAND, R. B., CLEVELAND, W. S., MCRAE, J. E. & TERPENNING, I. 1990. STL: A seasonal-trend decomposition. *Journal of official statistics,* 6**,** 3-73.

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.

COHEN, A. & DAVIDSON, S. 2011. The watershed approach: Challenges, antecedents, and the transition from technical tool to governance unit. *Water alternatives,* 4**,** 1.

CONNOLLY, N. M., PEARSON, R. G., LOONG, D., MAUGHAN, M. & BRODIE, J. 2015. Water quality variation along streams with similar agricultural development but contrasting riparian vegetation. *Agriculture, Ecosystems & Environment,* 213**,** 11-20.

COOPER, R. J., BATTAMS, Z. M., PEARL, S. H. & HISCOCK, K. M. 2019. Mitigating river sediment enrichment through the construction of roadside wetlands. *Journal of Environmental Management,* 231**,** 146-154.

COSSLETT, T. L. & COSSLETT, P. D. 2018. The Lower Mekong Basin: Rice Production, Climate Change, ENSO, and Mekong Dams. *In:* COSSLETT, T. L. & COSSLETT, P. D. (eds.) *Sustainable Development of Rice and Water Resources in Mainland Southeast Asia and Mekong River Basin.* Singapore: Springer Singapore.

COX, B. A. 2003. A review of currently available in-stream water-quality models and their applicability for simulating dissolved oxygen in lowland rivers. *Science of The Total Environment,* 314-316**,** 335-377.

CRAWFORD, N. H. & LINSLEY, R. K. 1966. Digital Simulation in Hydrology'Stanford Watershed Model 4.

CREWS-MEYER, K. A. 2004. Agricultural landscape change and stability in northeast Thailand: historical patch-level analysis. *Agriculture, Ecosystems & Environment,* 101**,** 155-169.

CROKE, B. F., ANDREWS, F., JAKEMAN, A., CUDDY, S. & LUDDY, A. Redesign of the IHACRES rainfall-runoff model. 29th Hydrology and Water Resources Symposium: Water Capital, 20-23 February 2005, Rydges Lakeside, Canberra, 2005. Engineers Australia, 333.

CROKE, B. F. W. & JAKEMAN, A. J. 2004. A catchment moisture deficit module for the IHACRES rainfall-runoff model. *Environmental Modelling & Software,* 19**,** 1-5.

CROSSETTE, E., PANUNTO, M., KUAN, C. & MOHAMOUD, Y. 2015. Application of BASINS/HSPF to Data Scarce Watersheds. *In:* AGENCY, U. S. E. P. (ed.). Washington, DC: EPA/600/R-15/007.

CUI, Y., FANG, L., GUO, X., HAN, F., JU, W., YE, L., WANG, X., TAN, W. & ZHANG, X. 2019. Natural grassland as the optimal pattern of vegetation restoration in arid and semi-arid regions: Evidence from nutrient limitation of soil microbes. *Science of the total environment,* 648**,** 388-397.

DANG, T. D., COCHRANE, T. A., ARIAS, M. E. & TRI, V. P. D. 2018. Future hydrological alterations in the Mekong Delta under the impact of water resources development, land subsidence and sea level rise. *Journal of Hydrology: Regional Studies,* 15**,** 119-133.

DANIELS, R. B. & GILLIAM, J. W. 1996. Sediment and Chemical Load Reduction by Grass and Riparian Filters. 60**,** 246-251.

DAS, G. G. 2015. Why some countries are slow in acquiring new technologies? A model of trade-led diffusion and absorption. *Journal of Policy Modeling,* 37**,** 65-91.

DEPARTMENT OF FOREIGN AFFAIRS AND TRADE 2016. Final Evaluation of the MRC Integrated Capacity Building Programme (ICBP). Canberra: DFAT.

DEVIA, G. K., GANASRI, B. & DWARAKISH, G. 2015. A review on hydrological models. *Aquatic Procedia,* 4, 1001-1007.

DUAN, Q., SOROOSHIAN, S. & GUPTA, V. 1992. Effective and efficient global optimization for conceptual rainfall-runoff models. *Water Resources Research,* 28, 1015-1031.

DUTTA, D., HUGHES, J., VAZE, J., KIM, S., YANG, A. & PODGER, G. A daily river system model for the Murray-Darling basin: Development, testing and implementation. Hydrology and Water Resources Symposium, 2012 Barton, ACT. Engineers Australia, 1057-1066.

EDMONDS, C. 2004. Rice Production, Land Use Dynamics, and Infrastructure Development in Viet Nam's Mekong River Delta. *Asian Development Review,* 21, 57-78.

EL-KHOURY, A., SEIDOU, O., LAPEN, D. R., QUE, Z., MOHAMMADIAN, M., SUNOHARA, M. & BAHRAM, D. 2015. Combined impacts of future climate and land use changes on discharge, nitrogen and phosphorus loads for a Canadian river basin. *Journal of Environmental Management,* 151, 76-86.

ELLIS, R. & SEARLE, R. 2013. An Integrated Water Quality Modelling Framework for Reporting on Great Barrier Reef Catchments. *20th International Congress on Modelling and Simulation.* Adelaide, Australia.

ESEN, E. & USLU, O. 2008. Assessment of the effects of agricultural practices on non-point source pollution for a coastal watershed: A case study Nif Watershed, Turkey. *Ocean & Coastal Management,* 51, 601-611.

EVANS, J. P. & JAKEMAN, A. J. 1998. Development of a simple, catchment-scale, rainfall-evapotranspiration-runoff model. *Environmental Modelling & Software,* 13, 385-393.

EWATER 2019. Source User Guide 4.7. *In:* DAVIS, G. (ed.).

EWATER LTD. 2018. Source User Guide 4.7. Available: https://wiki.ewater.org.au/display/SD47/Source+User+Guide+4.7 [Accessed 03 November 2018].

FAN, H., HE, D. & WANG, H. 2015. Environmental consequences of damming the mainstream Lancang-Mekong River: A review. *Earth-Science Reviews,* 146**,** 77-91.

FORTIN, J.-P., TURCOTTE, R., MASSICOTTE, S., MOUSSA, R., FITZBACK, J. & VILLENEUVE, J.-P. 2001. Distributed Watershed Model Compatible with Remote Sensing and GIS Data. I: Description of Model. *Journal of Hydrologic Engineering,* 6**,** 91-99.

FOX, J., VOGLER, J. B., SEN, O. L., GIAMBELLUCA, T. W. & ZIEGLER, A. D. 2012. Simulating Land-Cover Change in Montane Mainland Southeast Asia. *Environmental Management,* 49**,** 968-979.

FRANCESCONI, W., SRINIVASAN, R., PÉREZ-MIÑANA, E., WILLCOCK, S. P. & QUINTERO, M. 2016. Using the Soil and Water Assessment Tool (SWAT) to model ecosystem services: A systematic review. *Journal of Hydrology,* 535**,** 625-636.

FRERE, M. H., ONSTAD, C. A. & HOLTAN, H. 1975. ACTMO, an agricultural chemical transport model. Washington, DC.: USDA.

FU, L. & WANG, Y.-G. 2012. *Statistical Tools for Analyzing Water Quality Data* [Online]. InTech. Available: https://www.intechopen.com/books/water-quality-monitoring-and-assessment/statistical-tools-for-analyzing-water-quality-data [Accessed 11 November 2017].

GAN, T. Y. & BIFTU, G. F. 1996. Automatic Calibration of Conceptual Rainfall-Runoff Models: Optimization Algorithms, Catchment Conditions, and Model Structure. *Water Resources Research,* 32**,** 3513-3524.

GARCIA, L. E. 2008. Integrated water resources management: a 'small'step for conceptualists, a giant step for practitioners. *International Journal of Water Resources Development,* 24**,** 23-36.

GARRICK, D., ANDERSON, G., CONNELL, D. & PITTOCK, J. 2014. *Federal rivers: Managing water in multi-layered political systems*.

GEHEB, K. & SUHARDIMAN, D. 2019. The political ecology of hydropower in the Mekong River Basin. *Current Opinion in Environmental Sustainability,* 37**,** 8-13.

GHARARI, S., CLARK, M., MIZUKAMI, N., WONG, J. S., PIETRONIRO, A. & WHEATER, H. 2019. Improving the representation of subsurface water movement in land models. *Journal of Hydrometeorology*.

GOHARIAN, E. & BURIAN, S. J. 2018. Developing an integrated framework to build a decision support tool for urban water management. *Journal of Hydroinformatics,* 20**,** 708.

GORGOGLIONE, A., CRISCI, M., KAYSER, R. H., CHRETIES, C. & COLLISCHONN, W. 2019. A New Scenario-Based Framework for Conflict Resolution in Water Allocation in Transboundary Watersheds. *Water,* 11**,** 1174.

GOVERNMENT OF SOCIALIST REPUBLIC OF VIET NAM 1998. Law on Water Resources. *In:* DEVELOPMENT, M. O. A. A. R. (ed.). Hanoi, Viet Nam.

GU, Q., HU, H., MA, L., SHENG, L., YANG, S., ZHANG, X., ZHANG, M., ZHENG, K. & CHEN, L. 2019. Characterizing the spatial variations of the relationship between land use and surface water quality using self-organizing map approach. *Ecological Indicators,* 102**,** 633-643.

GUÉDRON, S., TISSERAND, D., GARAMBOIS, S., SPADINI, L., MOLTON, F., BOUNVILAY, B., CHARLET, L. & POLYA, D. A. 2014. Baseline investigation of (methyl)mercury in waters, soils, sediments and key foodstuffs in the Lower Mekong Basin: The rapidly developing city of Vientiane (Lao PDR). *Journal of Geochemical Exploration,* 143**,** 96-102.

GUNAWARDANA, S. K., SHRESTHA, S., MOHANASUNDARAM, S., SALIN, K. R. & PIMAN, T. 2021. Multiple drivers of hydrological alteration in the transbounndary Srepok River Basin of the Lower Mekong Region. *Journal of Environmental Management,* 278, 111524.

GUPTA, H. V., SOROOSHIAN, S. & YAPO, P. O. 1999. Status of Automatic Calibration for Hydrologic Models: Comparison with Multilevel Expert Calibration. *Journal of Hydrologic Engineering,* 4, 135-143.

GUPTA, H. V., WAGENER, T. & LIU, Y. 2008. Reconciling theory with observations: elements of a diagnostic approach to model evaluation. *Hydrological Processes,* 22, 3802-3813.

HALLS, A. S. & HORTLE, K. G. 2021. Flooding is a key driver of the Tonle Sap dai fishery in Cambodia. *Scientific Reports,* 11, 1-4.

HE, C. 2003. Integration of geographic information systems and simulation model for watershed management. *Environmental Modelling & Software,* 18, 809-813.

HE, H., ZHOU, J. & ZHANG, W. 2008. Modelling the impacts of environmental changes on hydrological regimes in the Hei River Watershed, China. *Global and Planetary Change,* 61, 175-193.

HEALD, C. L. & SPRACKLEN, D. V. 2015. Land Use Change Impacts on Air Quality and Climate. *Chemical Reviews,* 115, 4476-4496.

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. *Journal of Hydrology,* 568, 285-300.

HER, Y., CHAUBEY, I., FRANKENBERGER, J. & JEONG, J. 2017. Implications of spatial and temporal variations in effects of conservation practices on water management strategies. *Agricultural Water Management,* 180, 252-266.

HEY, D. L., KENIMER, A. L. & BARRETT, K. R. 1994. Water quality improvement by four experimental wetlands. *Ecological Engineering,* 3, 381-397.

HIRSCH, R., R. SLACK, J. & SMITH, R. 1982. Techniques of Trend Analysis for Monthly Water Quality Data. *Water Resources Research,* 18, 107-121.

HJELMFELT ALLEN, T. 1991. Investigation of Curve Number Procedure. *Journal of Hydraulic Engineering,* 117, 725-737.

HOANG, L. P., VAN VLIET, M. T. H., KUMMU, M., LAURI, H., KOPONEN, J., SUPIT, I., LEEMANS, R., KABAT, P. & LUDWIG, F. 2019. The Mekong's future flows under multiple drivers: How climate change, hydropower developments and irrigation expansions drive hydrological changes. *Science of The Total Environment,* 649**,** 601-609.

HOBBIE, S. E., FINLAY, J. C., JANKE, B. D., NIDZGORSKI, D. A., MILLET, D. B. & BAKER, L. A. 2017. Contrasting nitrogen and phosphorus budgets in urban watersheds and implications for managing urban water pollution. *Proceedings of the National Academy of Sciences*.

HOLLAND, J. H. 1975. Adaptation in natural and artificial systems. An introductory analysis with applications to biology, control, and artificial intelligence. Ann Arbor, Michigan: University of Michigan Press.

HOMESANA, C. 2019. Understanding the urban livelihoods and wellbeing of migrant women working in garment factories in Vientiane, Laos.

HOWARTH, R. W., BOYER, E. W., PABICH, W. J. & GALLOWAY, J. N. 2002. Nitrogen Use in the United States from 1961-2000 and Potential Future Trends. *Ambio,* 31**,** 88-96.

HUANG, Y., HUANG, J., ERVINIA, A. & DUAN, S. 2020. Tracking riverine nitrate sources under changing land use pattern and hydrologic regime. *Marine Pollution Bulletin,* 152**,** 110884.

IM, S., KIM, H., KIM, C. & JANG, C. 2008. Assessing the impacts of land use changes on watershed hydrology using MIKE SHE. *Environmental Geology,* 57**,** 231.

INTRALAWAN, A., SMAJGL, A., MCCONNELL, W., AHLQUIST, D. B., WARD, J. & KRAMER, D. B. 2019. Reviewing benefits and costs of hydropower development evidence from the Lower Mekong River Basin. *WIREs Water,* 6**,** e1347.

JABER, F. H. & SHUKLA, S. 2012. MIKE SHE: Model Use, Calibration, and Validation. *Transactions of the ASABE,* 55**,** 1479-1489.

JANTZ, S. M., BARKER, B., BROOKS, T. M., CHINI, L. P., HUANG, Q., MOORE, R. M., NOEL, J. & HURTT, G. C. 2015. Future habitat loss and extinctions driven by land-use change in biodiversity hotspots under four scenarios of climate-change mitigation. *Conservation Biology,* 29**,** 1122-1131.

JAYAKRISHNAN, R., SRINIVASAN, R., SANTHI, C. & ARNOLD, J. G. 2005. Advances in the application of the SWAT model for water resources management. *Hydrological Processes,* 19**,** 749-762.

JEON, J. H., YOON, C. G., JUNG, K. W. & JANG, J. H. 2007. HSPF-Paddy simulation of water flow and quality for the Saemangeum watershed in Korea. *Water Science and Technology,* 56**,** 123.

JIANCHANG, L., ZHANG, L., ZHANG, Y., HUASHENG, H. & HONGBING, D. 2008. Validation of an agricultural non-point source (AGNPS) pollution model for a catchment in the Jiulong River watershed, China. *Journal of Environmental Sciences,* 20**,** 599-606.

JOHNSON, H. O., GUPTA, S. C., VECCHIA, A. V. & ZVOMUYA, F. 2009. Assessment of Water Quality Trends in the Minnesota River using Non-Parametric and Parametric Methods. *Journal of Environmental Quality,* 38**,** 1018-30.

JUNG, K.-W., YOON, C.-G., JANG, J.-H. & KONG, D.-S. 2008. Estimation of pollutant loads considering dam operation in Han River Basin by BASINS/Hydrological Simulation Program-FORTRAN. *Water Science and Technology,* 58**,** 2329.

KANNAN, N., SANTHI, C. & ARNOLD, J. G. 2008. Development of an automated procedure for estimation of the spatial variation of runoff in large river basins. *Journal of Hydrology,* 359**,** 1-15.

KARAKUS, C. B., CERIT, O. & KAVAK, K. S. 2015. Determination of Land Use/Cover Changes and Land Use Potentials of Sivas City and its Surroundings Using Geographical Information Systems (GIS) and Remote Sensing (RS). *Procedia Earth and Planetary Science,* 15**,** 454-461.

KARKI, R., TAGERT, M. L. M., PAZ, J. O. & BINGNER, R. L. 2017. Application of AnnAGNPS to model an agricultural watershed in East-Central Mississippi for the evaluation of an on-farm water storage (OFWS) system. *Agricultural Water Management,* 192**,** 103-114.

KAUFFMAN, G. J. 2015. Governance, Policy, and Economics of Intergovernmental River Basin Management. *Water Resources Management,* 29**,** 5689-5712.

KELLY, R. A., JAKEMAN, A. J., BARRETEAU, O., BORSUK, M. E., ELSAWAH, S., HAMILTON, S. H., HENRIKSEN, H. J., KUIKKA, S., MAIER, H. R., RIZZOLI, A. E., VAN DELDEN, H. & VOINOV, A. A. 2013. Selecting among five common modelling approaches for integrated environmental assessment and management. *Environmental Modelling & Software,* 47**,** 159-181.

KING, M. D. 2018. Nutrient trading credits: best management practices and policy hurdles for non-point source polluters in the Chesapeake Bay. *Environmental Policy and the Pursuit of Sustainability.* Routledge.

KITE, G. 2001. Modelling the Mekong: hydrological simulation for environmental impact studies. *Journal of Hydrology,* 253**,** 1-13.

KNISEL, W. G. 1980. CREAMS: A field-scale model for chemicals, runoff, and erosion from agricultural management systems. Washington, D.C.: USDA National Resources Conservation Service.

KOKKONEN, T. S., JAKEMAN, A. J., YOUNG, P. C. & KOIVUSALO, H. J. 2003. Predicting daily flows in ungauged catchments: model regionalization from catchment descriptors at the Coweeta Hydrologic Laboratory, North Carolina. *Hydrological Processes,* 17**,** 2219-2238.

KRISTENSEN, P. The DPSIR Framework. Comprehensive/detailed assessment of the vlnerability of water resources to enviornmental change in Africa using river basin approach, 2004 UNEP Headquarters, Nairobi, Kenya.

KRULL, E., HAYNES, D., GELL, P., MCGOWAN, J. & LAMONTAGNE, S. 2008. Changes in organic matter chemistry in the Coorong Lagoons over space and time. *Biogeochemistry*.

KUMMU, M. & SARKKULA, J. 2008. Impact of the Mekong River Flow Alteration on the Tonle Sap Flood Pulse. *AMBIO - A Journal of the Human Environment,* 37**,** 185-192.

KUMMU, M. & VARIS, O. 2007. Sediment-related impacts due to upstream reservoir trapping, the Lower Mekong River. *Geomorphology,* 85**,** 275-293.

LACOMBE, G., DOUANGSAVANH, S., VOGEL, R. M., MCCARTNEY, M., CHEMIN, Y., REBELO, L.-M. & SOTOUKEE, T. 2014. Multivariate power-law models for streamflow prediction in the Mekong Basin. 2**,** 35-48.

LACOMBE, G., RIBOLZI, O., DE ROUW, A., PIERRET, A., LATSACHAK, K., SILVERA, N., PHAM DINH, R., ORANGE, D., JANEAU, J. L., SOULILEUTH, B., ROBAIN, H., TACCOEN, A., SENGPHAATHITH, P., MOUCHE, E., SENGTAHEUANGHOUNG, O., TRAN DUC, T. & VALENTIN, C. 2016. Contradictory hydrological impacts of afforestation in the humid tropics evidenced by long-term field monitoring and simulation modelling. *Hydrol. Earth Syst. Sci.,* 20**,** 2691-2704.

LACOMBE, G., VALENTIN, C., SOUNYAFONG, P., DE ROUW, A., SOULILEUTH, B., SILVERA, N., PIERRET, A., SENGTAHEUANGHOUNG, O. & RIBOLZI, O. 2018. Linking crop structure, throughfall, soil surface conditions, runoff and soil detachment: 10 land uses analyzed in Northern Laos. *Science of The Total Environment,* 616-617**,** 1330-1338.

LAWNICZAK, A. E., ZBIERSKA, J., NOWAK, B., ACHTENBERG, K., GRZEŚKOWIAK, A. & KANAS, K. 2016. Impact of agriculture and land use on nitrate contamination in groundwater and running waters in central-west Poland. *Environmental Monitoring and Assessment,* 188**,** 172.

LE, T. N., BREGT, A. K., VAN HALSEMA, G. E., HELLEGERS, P. J. G. J. & NGUYEN, L.-D. 2018. Interplay between land-use dynamics and changes in hydrological regime in the Vietnamese Mekong Delta. *Land Use Policy,* 73, 269-280.

LEE, J., KIM, J., JANG, W. S., LIM, K. J. & ENGEL, B. A. 2018. Assessment of Baseflow Estimates Considering Recession Characteristics in SWAT. *Water,* 10, 371.

LEE, S.-B., YOON, C.-G., JUNG, K. W. & HWANG, H. S. 2010. Comparative evaluation of runoff and water quality using HSPF and SWMM. *Water Science and Technology,* 62, 1401.

LERCH, R., LIN, C., GOYNE, K., KREMER, R. & ANDERSON, S. 2017. Vegetative buffer strips for reducing herbicide transport in runoff: Effects of buffer width, vegetation, and season. *JAWRA Journal of the American Water Resources Association,* 53, 667-683.

LÉVESQUE, É., ANCTIL, F., VAN GRIENSVEN, A. N. N. & BEAUCHAMP, N. 2008. Evaluation of streamflow simulation by SWAT model for two small watersheds under snowmelt and rainfall. *Hydrological Sciences Journal,* 53, 961-976.

LI, S. & BUSH, R. T. 2015. Rising flux of nutrients (C, N, P and Si) in the lower Mekong River. *Journal of Hydrology,* 530, 447-461.

LI, Y., ZHANG, Q., LIU, X. & YAO, J. 2020. Water balance and flashiness for a large floodplain system: A case study of Poyang Lake, China. *Science of The Total Environment,* 710, 135499.

LI, Z., LUO, C., XI, Q., LI, H., PAN, J., ZHOU, Q. & XIONG, Z. 2015. Assessment of the AnnAGNPS model in simulating runoff and nutrients in a typical small watershed in the Taihu Lake basin, China. *CATENA,* 133, 349-361.

LIAO, H., SARVER, E. & KROMETIS, L.-A. H. 2018. Interactive effects of water quality, physical habitat, and watershed anthropogenic activities on stream ecosystem health. *Water Research,* 130, 69-78.

LICCIARDELLO, F., A. ZEMA, D., M. ZIMBONE, S. & L. BINGNER, R. 2007. Runoff and Soil Erosion Evaluation by the AnnAGNPS Model in a Small Mediterranean Watershed. *Transactions of the ASABE,* 50**,** 1585.

LIU, J., SHEN, Z. & CHEN, L. 2018. Assessing how spatial variations of land use pattern affect water quality across a typical urbanized watershed in Beijing, China. *Landscape and Urban Planning,* 176**,** 51-63.

LIU, J., ZHANG, L., ZHANG, Y., HONG, H. & DENG, H. 2008. Validation of an agricultural non-point source (AGNPS) pollution model for a catchment in the Jiulong River watershed, China. *Journal of Environmental Sciences,* 20**,** 599-606.

LIU, S. A., LI, X., CHEN, D., DUAN, Y., JI, H., ZHANG, L., CHAI, Q. & HU, X. 2020. Understanding Land use/Land cover dynamics and impacts of human activities in the Mekong Delta over the last 40 years. *Global Ecology and Conservation,* 22**,** e00991.

LIU, Z. & TONG, S. T. Y. 2011. Using HSPF to Model the Hydrologic and Water Quality Impacts of Riparian Land-Use Change in a Small Watershed. *Journal of Environmental Informatics,* 17**,** 1-14.

LONERGAN, S. C. 2018. Water and conflict: Rhetoric and reality. *Environmental conflict.* Routledge.

LÓPEZ-MORENO, J. I., ZABALZA, J., VICENTE-SERRANO, S. M., REVUELTO, J., GILABERTE, M., AZORIN-MOLINA, C., MORÁN-TEJEDA, E., GARCÍA-RUIZ, J. M. & TAGUE, C. 2014. Impact of climate and land use change on water availability and reservoir management: Scenarios in the Upper Aragón River, Spanish Pyrenees. *Science of The Total Environment,* 493**,** 1222-1231.

LU, H. & XIE, H. 2018. Impact of changes in labor resources and transfers of land use rights on agricultural non-point source pollution in Jiangsu Province, China. *Journal of Environmental Management,* 207**,** 134-140.

LUO, C., LI, Z., LI, H. & CHEN, X. 2015. Evaluation of the AnnAGNPS model for predicting runoff and nutrient export in a typical small watershed in the hilly region of Taihu Lake. *International journal of environmental research and public health,* 12**,** 10955-10973.

LWIN, M. T. 2019. LABOUR MARKET IN MAE SOT 1990–2017 AND THAILAND'S NEW SPECIAL ECONOMIC ZONE POLICY. *Hue University Journal of Science: Economics and Development,* 128**,** 95–109-95–109.

LY, K., METTERNICHT, G. & MARSHALL, L. 2019. Transboundary river catchment areas of developing countries: Potential and limitations of watershed models for the simulation of sediment and nutrient loads. A review. *Journal of Hydrology: Regional Studies,* 24**,** 100605.

LY, K., METTERNICHT, G. & MARSHALL, L. 2020a. Linking Changes in Land Cover and Land Use of the Lower Mekong Basin to Instream Nitrate and Total Suspended Solids Variations. *Sustainability,* 12**,** 2992.

LY, K., METTERNICHT, G. & MARSHALL, L. 2020b. Simulation of streamflow and instream loads of total suspended solids and nitrate in a large transboundary river basin using Source model and geospatial analysis. *Science of The Total Environment***,** 140656.

MA, L., HE, C., BIAN, H. & SHENG, L. 2016. MIKE SHE modeling of ecohydrological processes: Merits, applications, and challenges. *Ecological Engineering,* 96**,** 137-149.

MANH, N. V., DUNG, N. V., HUNG, N. N., KUMMU, M., MERZ, B. & APEL, H. 2015. Future sediment dynamics in the Mekong Delta floodplains: Impacts of hydropower development, climate change and sea level rise. *Global and Planetary Change,* 127**,** 22-33.

MANNIK, R., BORONKAY, A., JORDAN, P., CHURCH, T., HUGHES, D. & BLOCKWELL, S. 2012. Applying eWater source as the catchment model for the Hawkesbury-Nepean water quality model system. *Hydrology and Water Resources Symposium 2012.* Barton, ACT: Engineers Australia.

MARANDA, B. & ANCTIL, F. 2015. SWAT Performance as Influenced by Potential Evapotranspiration Formulations in a Canadian Watershed. *Transactions of the ASABE,* 58**,** 1585.

MARTÍNEZ-MENA, M., CARRILLO-LÓPEZ, E., BOIX-FAYOS, C., ALMAGRO, M., GARCÍA FRANCO, N., DÍAZ-PEREIRA, E., MONTOYA, I. & DE VENTE, J. 2019. Long-term effectiveness of sustainable land management practices to control runoff, soil erosion, and nutrient loss and the role of rainfall intensity in Mediterranean rainfed agroecosystems. *CATENA***,** 104352.

MATHWORKS. R2010a. *MATLAB version 7.10.0*

MCMILLAN, H. 2020. Linking hydrologic signatures to hydrologic processes: A review. *Hydrological Processes,* 34**,** 1393-1409.

MEHDI, B., LUDWIG, R. & LEHNER, B. 2015. Evaluating the impacts of climate change and crop land use change on streamflow, nitrates and phosphorus: A modeling study in Bavaria. *Journal of Hydrology: Regional Studies,* 4**,** 60-90.

MEKONG RIVER COMMISSION 2009. The flow of the Mekong. *In:* BURNHILL, T. (ed.) *MRC management informantion booklet series.* Vientiane, Lao PDR: MRC Secretariat.

MEKONG RIVER COMMISSION 2010. Land use and land cover lower Mekong Basin parts in Laos, Thailand, Cambodia and Vietnam. *In:* COMMISSION, M. R. (ed.). Vientiane, Laos.

MEKONG RIVER COMMISSION 2011. Planning Atlas of the Lower Mekong River Basin. Vientiane, Lao PDR: Mekong River Commission.

MEKONG RIVER COMMISSION 2014. Multi-media (water, sediment, biota) monitoring and assessment report. *In:* KONGMENG LY, H. L., NGUYEN VAN DUYEN (ed.) *MRC Technical Paper.* Vientiane, Lao PDR: The Mekong River Commission Secretariat.

MEKONG RIVER COMMISSION 2018. State of the Basin Report 2018. Vientiane, Lao PDR: The Mekong River Commission Secretariat.

MEKONG RIVER COMMISSION 2020. Understanding the 1995 Mekong Agreement and the MRC Procedures: A handbook. Vientiane, Lao PDR: The Mekong River Commission Secretariat.

MIRCHI, A., WATKINS, D. J. & MADANI, K. 2009. Modeling for watershed planning, management, and decision making. *In:* VAUGHN, J. C. (ed.) *Watersheds: Management, Restoration and Environmental Assessment.* Nova Science Publishers, Inc.

MIRZAEI, M., JAFARI, A., GHOLAMALIFARD, M., AZADI, H., SHOOSHTARI, S. J., MOGHADDAM, S. M., GEBREHIWOT, K. & WITLOX, F. 2019. Mitigating environmental risks: Modeling the interaction of water quality parameters and land use cover. *Land Use Policy***,** 103766.

MISIGO, A. W. & SUZUKI, S. 2018. Spatial-Temporal Sediment Hydrodynamics and Nutrient Loads in Nyanza Gulf, Characterizing Variation in Water Quality. *World Journal of Engineering and Technology,* 6**,** 98.

MITCHELL, B. 2005. Integrated water resource management, institutional arrangements, and land-use planning. *Environment and Planning A,* 37**,** 1335-1352.

MOHER, D., LIBERATI, A., TETZLAFF, J., ALTMAN, D. G. & THE, P. G. 2009. Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA Statement. *PLOS Medicine,* 6**,** e1000097.

MOLLE, F., FORAN, T. & KÄKÖNEN, M. 2009. *Contested Waterscapes in the Mekong Region: Hydropower, Livelihoods and Governance*.

MONAGHAN, R. M., WILCOCK, R. J., SMITH, L. C., TIKKISETTY, B., THORROLD, B. S. & COSTALL, D. 2007. Linkages between land management activities and water quality in an intensively farmed catchment in southern New Zealand. *Agriculture, Ecosystems & Environment,* 118**,** 211-222.

MOORE, R. 2006. Watershed Models. Edited by VP Singh and DK Frevert. Boca Raton, FL, USA: CRC Press,(2006), pp. 653,£ 79.99. ISBN 0-8493-3609-0. *Experimental Agriculture,* 42**,** 370.

MORÁN-TEJEDA, E., ZABALZA, J., RAHMAN, K., GAGO-SILVA, A., LÓPEZ-MORENO, J. I., VICENTE-SERRANO, S., LEHMANN, A., TAGUE, C. L. & BENISTON, M. 2015. Hydrological impacts of climate and land-use changes in a mountain watershed: uncertainty estimation based on model comparison. *Ecohydrology,* 8**,** 1396-1416.

MORIASI, D. N., GITAU, M. W., PAI, N. & DAGGUPATI, P. 2015. Hydrologic and Water Quality Models: Performance Measures and Evaluation Criteria. *Transactions of the ASABE,* 58**,** 1763.

MORITZ, S. & BARTZ-BEIELSTEIN, T. 2017. imputeTS: Time Series Missing Value Imputation in R. *R Jounal 9.1*.

MOTEW, M., CHEN, X., CARPENTER, S. R., BOOTH, E. G., SEIFERT, J., QIU, J., LOHEIDE, S. P., TURNER, M. G., ZIPPER, S. C. & KUCHARIK, C. J. 2019. Comparing the effects of climate and land use on surface water quality using future watershed scenarios. *Science of The Total Environment,* 693**,** 133484.

MOURI, G., TAKIZAWA, S. & OKI, T. 2011. Spatial and temporal variation in nutrient parameters in stream water in a rural-urban catchment, Shikoku, Japan: Effects of land cover and human impact. *Journal of Environmental Management,* 92**,** 1837-1848.

MRC 1995. Agreement on the Cooperation for the Sustainable Development of the Mekong River Basin. *In:* COMMISSION, T. M. R. (ed.). Vientiane, Lao PDR.

NASH, J. E. & SUTCLIFFE, J. V. 1970. River flow forecasting through conceptual models part I — A discussion of principles. *Journal of Hydrology,* 10**,** 282-290.

NATIONAL ASSEMBLY 2017. Law on Water and Water Resources. *In:* DEPARTMENT OF WATER RESOURCES, M. O. N. R. A. E. (ed.). Vientiane Lao PDR.

NDOMBA, P., MTALO, F. & KILLINGTVEIT, A. 2008. SWAT model application in a data scarce tropical complex catchment in Tanzania. *Physics and Chemistry of the Earth, Parts A/B/C,* 33**,** 626-632.

NEEF, A., HAGER, J., WIRTH, T., SCHWARZMEIER, R. & HEIDHUES, F. 2018. Land tenure and water rights in Thailand and Vietnam: Challenges for ethnic minorities in mountainous forest regions. *Geographica Helvetica,* 61**,** 255-265.

NELDER, J. A. & MEAD, R. 1965. A Simplex Method for Function Minimization. *The Computer Journal,* 7**,** 308-313.

NELSON, E. J. & BOOTH, D. B. 2002. Sediment sources in an urbanizing, mixed land-use watershed. *Journal of Hydrology,* 264**,** 51-68.

NGUYEN, H. H., RECKNAGEL, F., MEYER, W., FRIZENSCHAF, J. & SHRESTHA, M. K. 2017. Modelling the impacts of altered management practices, land use and climate changes on the water quality of the Millbrook catchment-reservoir system in South Australia. *Journal of Environmental Management,* 202**,** 1-11.

NGUYEN, H. H., RECKNAGEL, F., MEYER, W., FRIZENSCHAF, J., YING, H. & GIBBS, M. S. 2019. Comparison of the alternative models SOURCE and SWAT for predicting catchment streamflow, sediment and nutrient loads under the effect of land use changes. *Science of The Total Environment,* 662**,** 254-265.

NOBRE, R. L. G., CALIMAN, A., CABRAL, C. R., ARAÚJO, F. D. C., GUÉRIN, J., DANTAS, F. D. C. C., QUESADO, L. B., VENTICINQUE, E. M., GUARIENTO, R. D., AMADO, A. M., KELLY, P., VANNI, M. J. & CARNEIRO, L. S. 2020. Precipitation, landscape properties and land use interactively affect water quality of tropical freshwaters. *Science of the Total Environment,* 716.

OEURNG, C., COCHRANE, T. A., ARIAS, M. E., SHRESTHA, B. & PIMAN, T. 2016. Assessment of changes in riverine nitrate in the Sesan, Srepok and

Sekong tributaries of the Lower Mekong River Basin. *Journal of Hydrology: Regional Studies,* 8, 95-111.

OKAMOTO, K., SHARIFI, A. & CHIBA, Y. 2014. The Impact of Urbanization on Land Use and the Changing Role of Forests in Vientiane. *In:* YOKOYAMA, S., OKAMOTO, K., TAKENAKA, C. & HIROTA, I. (eds.) *Integrated Studies of Social and Natural Environmental Transition in Laos.* Tokyo: Springer Japan.

OLSON, K. R. & MORTON, L. W. 2018. Water rights and fights: Lao dams on the Mekong River. *Journal of Soil and Water Conservation,* 73, 35A.

PANAGOPOULOS, Y., MAKROPOULOS, C. & MIMIKOU, M. 2012. Decision support for diffuse pollution management. *Environmental Modelling & Software,* 30, 57-70.

PARISI, D., TAQUINO, M., GRICE, S. M. & DUANE, G. A. 2003. Promoting Enviornmental Democracy Using GIS as a Means to Integrate Community into the EPA-BASINS Approach. *Society and Natural resources,* 16,, 205-219.

PEASE, L. M., ODUOR, P. & PADMANABHAN, G. 2010. Estimating sediment, nitrogen, and phosphorous loads from the Pipestem Creek watershed, North Dakota, using AnnAGNPS. *Computers & Geosciences,* 36, 282-291.

PECH, S. & SUNADA, K. 2008. Population Growth and Natural-Resources Pressures in the Mekong River Basin. *Ambio,* 37, 219-224.

PETERSEN, C. M., RIFAI, H. S., VILLARREAL, G. C. & STEIN, R. 2011. Modeling <i>Escherichia Coli</i> and Its Sources in an Urban Bayou with Hydrologic Simulation Program—FORTRAN. *Journal of Environmental Engineering,* 137, 487-503.

PETERSON, H. M., NIEBER, J. L. & KANIVETSKY, R. 2011. Hydrologic regionalization to assess anthropogenic changes. *Journal of Hydrology,* 408, 212-225.

PHAM, H. T., MIYAGAWA, S. & KOSAKA, Y. 2015. Distribution patterns of trees in paddy field landscapes in relation to agro-ecological settings in northeast Thailand. *Agriculture, Ecosystems & Environment,* 202, 42-47.

PHUNG, D., HUANG, C., RUTHERFORD, S., DWIRAHMADI, F., CHU, C., WANG, X., NGUYEN, M., NGUYEN, N. H., DO, C. M., NGUYEN, T. H. & DINH, T. A. D. 2015. Temporal and spatial assessment of river surface water quality using multivariate statistical techniques: a study in Can Tho City, a Mekong Delta area, Vietnam. *Environmental Monitoring and Assessment,* 187**,** 229.

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.

POST, D. A. 2009. Regionalizing rainfall–runoff model parameters to predict the daily streamflow of ungauged catchments in the dry tropics. 40**,** 433.

POTTER, C. & HIATT, S. 2009. Modeling river flows and sediment dynamics for the Laguna de Santa Rosa watershed in Northern California. *Journal of Soil and Water Conservation,* 64**,** 383.

PRICE, W. L. 1987. Global optimization algorithms for a CAD workstation. *Journal of Optimization Theory and Applications,* 55**,** 133-146.

PROSSER, P., RUSTOMJI, P., YOUNG, B., MORAN, C. & HUGHES, A. 2001. Constructing river basin sediment budgets for the National Land and Water Resources Audit. *CSIRO Land and Water.*

PUSHPALATHA, R., PERRIN, C., MOINE, N. L. & ANDRÉASSIAN, V. 2012. A review of efficiency criteria suitable for evaluating low-flow simulations. *Journal of Hydrology,* 420-421**,** 171-182.

RATHA, C., GRENOUILLET, G. & LEK, S. 2016. Evidence of Water Quality Degradation in Lower Mekong Basin Revealed by Self-Organizing Map. *PLoS One,* 11.

RENARD, K. G., FOSTER, G. R., WEESIES, G. A., MCCOOL, D. K. & YODER, D. C. 1996. *Predicting soil erosion by water: a guide to conservation planning with the Revised Universal Soil Loss Equation (RUSLE).*

RIBAROVA, I., NINOV, P. & COOPER, D. 2008. Modeling nutrient pollution during a first flood event using HSPF software: Iskar River case study, Bulgaria. *Ecological Modelling,* 211**,** 241-246.

RIBOLZI, O., EVRARD, O., HUON, S., DE ROUW, A., SILVERA, N., LATSACHACK, K. O., SOULILEUTH, B., LEFÈVRE, I., PIERRET, A., LACOMBE, G., SENGTAHEUANGHOUNG, O. & VALENTIN, C. 2017. From shifting cultivation to teak plantation: effect on overland flow and sediment yield in a montane tropical catchment. *Scientific Reports,* 7**,** 3987.

RICHTER, B. D., BAUMGARTNER, J. V., POWELL, J. & BRAUN, D. P. 1996. A Method for Assessing Hydrologic Alteration within Ecosystems. *Conservation Biology,* 10**,** 1163-1174.

ROEBELING, P., ALVES, H., ROCHA, J., BRITO, A., ALMEIDA, P. & MAMEDE, J. 2014. Gains from trans-boundary water quality management in linked catchment and coastal socio-ecological systems: A case study for the Minho region. *Water Resources and Economics,* 8**,** 32-42.

ROLLE, K., GITAU, M. W., CHEN, G. & CHAUHAN, A. 2012. Assessing fecal coliform fate and transport in a coastal watershed using HSPF. *Water Science and Technology,* 66**,** 1096.

ROMERO-ZALIZ, R. & REINOSO-GORDO, J. F. 2018. An Updated Review on Watershed Algorithms. *In:* CRUZ CORONA, C. (ed.) *Soft Computing for Sustainability Science.* Cham: Springer International Publishing.

ROSSI, C. G. 2009. Hydrologic evaluation of the lower Mekong River basin with the soil and water assessment tool model. *International agricultural engineering journal,* v. 18**,** pp. 1-13-2009 v.18 no.1-2.

ROSSMAN, L. A. 2004. SWMM (Storm Water Management Model). *User Mannual.* Washington , DC.: Environmental Protection Angency.

ROUNSEVELL, M. D. A. & METZGER, M. J. 2010. Developing qualitative scenario storylines for environmental change assessment. *WIREs Climate Change,* 1**,** 606-619.

RUTTEN, M., VAN DIJK, M., VAN ROOIJ, W. & HILDERINK, H. 2014. Land Use Dynamics, Climate Change, and Food Security in Vietnam: A Global-to-local Modeling Approach. *World Development,* 59**,** 29-46.

SACHS, J. D. 2012. From Millennium Development Goals to Sustainable Development Goals. *The Lancet,* 379**,** 2206-2211.

SAFEEQ, M. & HUNSAKER, C. T. 2016. Characterizing Runoff and Water Yield for Headwater Catchments in the Southern Sierra Nevada. *JAWRA Journal of the American Water Resources Association,* 52**,** 1327-1346.

SALEH, A. & GALLEGO, O. 2007. Application of SWAT and APEX Using the SWAPP (SWAT-APEX) Program for the Upper North Bosque River Watershed in Texas. *Transactions of the ASABE,* 50**,** 1177.

SALEH, D. K., KRATZER, C. R., GREEN, C. H. & EVANS, D. G. 2009. Using the Soil and Water Assessment Tool (SWAT) to simulate runoff in Mustang Creek Basin, California. *U.S. Geological Survey Scientific Investigations Report 2009-5031.*

SALVIA-CASTELLVÍ, M., FRANÇOIS IFFLY, J., VANDER BORGHT, P. & HOFFMANN, L. 2005. Dissolved and particulate nutrient export from rural catchments: A case study from Luxembourg. *Science of The Total Environment,* 344**,** 51-65.

SANDU, M.-A. & VIRSTA, A. 2015. Applicability of MIKE SHE to Simulate Hydrology in Argesel River Catchment. *Agriculture and Agricultural Science Procedia,* 6**,** 517-524.

SARANGI, A., COX, C. A. & MADRAMOOTOO, C. A. 2007. Evaluation of the AnnAGNPS Model for prediction of runoff and sediment yields in St Lucia watersheds. *Biosystems Engineering,* 97**,** 241-256.

SAWICZ, K., WAGENER, T., SIVAPALAN, M., TROCH, P. A. & CARRILLO, G. 2011. Catchment classification: empirical analysis of hydrologic similarity based on catchment function in the eastern USA. *Hydrology and Earth System Sciences,* 15**,** 2895-2911.

SCHALTEGGER, S. & SYNNESTVEDT, T. 2002. The link between 'green' and economic success: environmental management as the crucial trigger between environmental and economic performance. *Journal of Environmental Management,* 65**,** 339-346.

SCHILLING, K. E. 2002. Chemical transport from paired agricultural and restored prairie watersheds. *Journal of Environmental Quality,* 31**,** 1184-93.

SCHWEIKHARD, J., KASPER, K., EBERT, C., LEHMANN, M., ERBE, P. & ZIEGLER, T. 2019. Investigations into the illegal wildlife trade in central Lao PDR. *Traffic Bulletin,* 31**,** 19-25.

SEARCHINGER, T., HEIMLICH, R., HOUGHTON, R. A., DONG, F., ELOBEID, A., FABIOSA, J., TOKGOZ, S., HAYES, D. & YU, T.-H. 2008. Use of U.S. Croplands for Biofuels Increases Greenhouse Gases Through Emissions from Land-Use Change. *Science,* 319**,** 1238.

SHAW, M., SILBURN, D. M., ELLIS, R., R., S., BIGGS, J., THORBURN, P. & WHISH, G. Paddock scale modelling to assess effectiveness of agricultural management practice in improving water quality in the Great Barrier Reef Catchments. 10th International Congress on Modelling and Simulation, 1-6 December 2013 2013 Adelaide, Australia.

SHRESTHA, B., BABEL, M., MASKEY, S., VAN GRIENSVEN, A., UHLENBROOK, S., GREEN, A. & AKKHARATH, I. 2013. Impact of climate change on sediment yield in the Mekong River basin: a case study of the Nam Ou basin, Lao PDR. *Hydrology and Earth System Sciences,* 17**,** 1.

SHRESTHA, B., COCHRANE, T. A., CARUSO, B. S., ARIAS, M. E. & PIMAN, T. 2016. Uncertainty in flow and sediment projections due to future climate scenarios for the 3S Rivers in the Mekong Basin. *Journal of Hydrology,* 540**,** 1088-1104.

SHRESTHA, B., MASKEY, S., BABEL, M. S., VAN GRIENSVEN, A. & UHLENBROOK, S. 2018. Sediment related impacts of climate change and reservoir development in the Lower Mekong River Basin: a case study of the Nam Ou Basin, Lao PDR. *Climatic Change,* 149**,** 13-27.

SINGH, R., TIWARI, K. N. & MAL, B. C. 2006. Effect of spatial resolution on watershed characteristics and the ANSWERS model hydrological simulations for a small watershed. *In:* KULIGOWSKI, R. J., PARIHAR, J. S. & SAITO, G. (eds.) *Agriculture and Hydrology Applications of Remote Sensing.* Bellingham: Spie-Int Soc Optical Engineering.

SINGH, V. P. & WOOLHISER, D. A. 2002. Mathematical Modeling of Watershed Hydrology. *Journal of Hydrologic Engineering,* 7**,** 270-292.

SITHIRITH, M. 2021. Transboundary River Basin Governance: A Case of the Mekong River Basin. *River Basin Management-Sustainability Issues and Planning Strategies*.

SITHONG, T. & YAYOI, F. 2006. Recent Land Use and Livelihoods Transitions in Northern Laos. *Mountain Research and Development,* 26**,** 237-244.

SOKOLOV, V. 2011. Integrated Water Resources Management. *Water and Food Security in Central Asia.* Springer.

SOLAR, R. R. D. C., BARLOW, J., ANDERSEN, A. N., SCHOEREDER, J. H., BERENGUER, E., FERREIRA, J. N. & GARDNER, T. A. 2016. Biodiversity consequences of land-use change and forest disturbance in the Amazon: A multi-scale assessment using ant communities. *Biological Conservation,* 197**,** 98-107.

SPERA, S. A., GALFORD, G. L., COE, M. T., MACEDO, M. N. & MUSTARD, J. F. 2016. Land-use change affects water recycling in Brazil's last agricultural frontier. *Global Change Biology,* 22**,** 3405-3413.

SRIDHAR, V., KANG, H. & ALI, S. A. 2019. Human-Induced Alterations to Land Use and Climate and Their Responses for Hydrology and Water Management in the Mekong River Basin. *Water,* 11**,** 1307.

SUDARYANTO, A., ISOBE, T., TAKAHASHI, S. & TANABE, S. 2011. Assessment of persistent organic pollutants in sediments from Lower Mekong River Basin. *Chemosphere,* 82**,** 679-686.

SUIF, Z., FLEIFLE, A., YOSHIMURA, C. & SAAVEDRA, O. 2016. Spatio-temporal patterns of soil erosion and suspended sediment dynamics in the Mekong River Basin. *Science of The Total Environment,* 568**,** 933-945.

SUTTLES, B. J., VELLIDIS, G., BOSCH, D. D., LOWRANCE, R., SHERIDAN, M. J. & USERY, L. E. 2003. Watershed-Scale Simulation of Sediment and Nutrient Loads in Georgia Coastal Plain Streams Using the Annualized AGNPS Model. *Transactions of the ASAE,* 46**,** 1325.

TAS, E. 2013. Integrated water resources management. *Aerul si Apa. Componente ale Mediului***,** 217.

TAYLOR, S. D., HE, Y. & HISCOCK, K. M. 2016. Modelling the impacts of agricultural management practices on river water quality in Eastern England. *Journal of Environmental Management,* 180**,** 147-163.

THE ROYAL GOVERNMENT OF CAMBODIA 2007. Law on water resources management of the Kingdom of Cambodia. *In:* METEOROLOGY, M. O. W. R. A. (ed.). Phnom Penh, Cambodia.

THE ROYAL THAI GOVERNMENT 2018. Water Resources Act. *In:* COMMISSION, N. W. R. (ed.). Bangkok, Thailand.

THEURER, F. D. & CLARKE, C. D. Wash load component for sediment yield modeling. The Fifth Federal Interagency Sedimentation Conference, 1991.

TIAN, Y., HUANG, Z. & XIAO, W. 2010. Reductions in non-point source pollution through different management practices for an agricultural watershed in the Three Gorges Reservoir Area. *Journal of Environmental Sciences,* 22**,** 184-191.

TRAMBAUER, P., MASKEY, S., WINSEMIUS, H., WERNER, M. & UHLENBROOK, S. 2013. A review of continental scale hydrological models and their suitability for drought forecasting in (sub-Saharan) Africa. *Physics and Chemistry of the Earth, Parts A/B/C,* 66**,** 16-26.

TRANG, N. T. T., SHRESTHA, S., SHRESTHA, M., DATTA, A. & KAWASAKI, A. 2017. Evaluating the impacts of climate and land-use change on the hydrology and nutrient yield in a transboundary river basin: A case study in the 3S River Basin (Sekong, Sesan, and Srepok). *Science of The Total Environment,* 576**,** 586-598.

TROCH, P. A., CARRILLO, G., SIVAPALAN, M., WAGENER, T. & SAWICZ, K. 2013. Climate-vegetation-soil interactions and long-term hydrologic partitioning: signatures of catchment co-evolution. 17**,** 2209-2217.

TRUNG, L. D., DUC, N. A., NGUYEN, L. T., THAI, T. H., KHAN, A., RAUTENSTRAUCH, K. & SCHMIDT, C. 2018. Assessing cumulative impacts of the proposed Lower Mekong Basin hydropower cascade on the Mekong River floodplains and Delta – Overview of integrated modeling methods and results. *Journal of Hydrology*.

TU, J. 2013. Spatial Variations in the Relationships between Land Use and Water Quality across an Urbanization Gradient in the Watersheds of Northern Georgia, USA. *Environmental Management,* 51**,** 1-17.

ULÉN, B., STENBERG, M. & WESSTRÖM, I. 2016. Use of a flashiness index to predict phosphorus losses from subsurface drains on a Swedish farm with clay soils. *Journal of Hydrology,* 533**,** 581-590.

UNEP-DHI & UNEP 2016. Transboundary River Basins: Status and Trends. Nairobi: United Nations Environment Programme (UNEP).

USDA 1972. National Engineering Handbook. Washington, DC: Soil Conservation.

USEPA 2015. Application of BASINS/HSPF to Data-scarce Watersheds. Washington, DC: Office of Research and Development.

VALERA, C. A., PISSARRA, T. C. T., FILHO, M. V. M., VALLE JÚNIOR, R. F. D., OLIVEIRA, C. F., MOURA, J. P., SANCHES FERNANDES, L. F. & PACHECO, F. A. L. 2019. The Buffer Capacity of Riparian Vegetation to Control Water Quality in Anthropogenic Catchments from a Legally

Protected Area: A Critical View over the Brazilian New Forest Code. *Water,* 11, 549.

VAN DER STERREN, M., RAHMAN, A. & RYAN, G. 2014. Modeling of a lot scale rainwater tank system in XP-SWMM: A case study in Western Sydney, Australia. *Journal of Environmental Management,* 141, 177-189.

VASILIADES, L., SARAILIDIS, G. & LOUKAS, A. 2017. Hydrological modelling of low flows for operational water resources management.

VU, T. T. H., TIAN, G., KHAN, N., ZADA, M., ZHANG, B. & NGUYEN, T. V. 2019. Evaluating the International Competitiveness of Vietnam Wood Processing Industry by Combining the Variation Coefficient and the Entropy Method. *Forests,* 10, 901.

WALTON, C. R., ZAK, D., AUDET, J., PETERSEN, R. J., LANGE, J., OEHMKE, C., WICHTMANN, W., KREYLING, J., GRYGORUK, M. & JABŁOŃSKA, E. 2020. Wetland buffer zones for nitrogen and phosphorus retention: impacts of soil type, hydrology and vegetation. *Science of the Total Environment,* 727, 138709.

WANG, X. & YIN, Z.-Y. 1997. Using GIS to assess the relationship between land use and water quality at a watershed level. *Environment International,* 23, 103-114.

WATERS, D., CARROLL, C., ELLIS, R., MCCLOSKEY, G., HATELEY, L., DOUGALL, C. & FENTIE, B. 2013. Catchment modelling scenarios to inform GBR water quality targets. *20th Internation Congress on Modelling and Simulation.* Adelaide, Australia.

WATERS, D. K., JIAO, F., CHEN, M., YNG, J., PAPE, S., ZHANG, H., LI, J. & NASH, D. 2012. Application of Source to investigate nutrient management options for the Dongshan Peninsula, Suzhou China. eWater Cooperative Research Centre.

WELSH, W. D., VAZE, J., DUTTA, D., RASSAM, D., RAHMAN, J. M., JOLLY, I. D., WALLBRINK, P., PODGER, G. M., BETHUNE, M., HARDY, M. J., TENG, J.

& LERAT, J. 2013. An integrated modelling framework for regulated river systems. *Environmental Modelling & Software,* 39, 81-102.

WESSTRÖM, I., JOEL, A. & MESSING, I. 2014. Controlled drainage and subirrigation – A water management option to reduce non-point source pollution from agricultural land. *Agriculture, Ecosystems & Environment,* 198, 74-82.

WHEELER, K. G., ROBINSON, C. J. & BARK, R. H. 2018. Modelling to bridge many boundaries: the Colorado and Murray-Darling River basins. *Regional Environmental Change,* 18, 1607-1619.

WILBERS, G.-J., BECKER, M., NGA, L. T., SEBESVARI, Z. & RENAUD, F. G. 2014. Spatial and temporal variability of surface water pollution in the Mekong Delta, Vietnam. *Science of The Total Environment,* 485–486, 653-665.

WILD, T. B., REED, P. M., LOUCKS, D. P., MALLEN-COOPER, M. & JENSEN, E. D. 2019. Balancing Hydropower Development and Ecological Impacts in the Mekong: Tradeoffs for Sambor Mega Dam. *Journal of Water Resources Planning and Management,* 145, 05018019.

WILLIAMS, J. M. 2019. The hydropower myth. *Environmental Science and Pollution Research*.

WILLIAMS, J. R. & BERNDT, H. D. 1997. Sediment yield prediction based on watershed hydrology. *Trans. ASAE,* 20, 1100-1104.

WILLIAMS, J. R., NICKS, A. D. & ARNOLD, J. G. 1985. Simulator for Water Resources in Rural Basins. *Journal of Hydraulic Engineering,* 111, 970-986.

WORLD BANK GROUP 2015. World Bank Open Data.

WU, J. C. 2021. Asia and the Pacific. *USGS minerals yearbook 2017-2018.* USGS National Minerals and Information Center.

XIE, M. Integrated water resources management (IWRM)–introduction to principles and practices. Africa Regional Workshop on IWRM, Nairobi, Oct, 2006.

XU, T. & VALOCCHI, A. J. 2015. Data-driven methods to improve baseflow prediction of a regional groundwater model. *Computers & Geosciences,* 85**,** 124-136.

XU, Z. X., PANG, J. P., LIU, C. M. & LI, J. Y. 2009. Assessment of runoff and sediment yield in the Miyun Reservoir catchment by using SWAT model. *Hydrological Processes,* 23**,** 3619-3630.

YADAV, S., BABEL, M. S., SHRESTHA, S. & DEB, P. 2019. Land use impact on the water quality of large tropical river: Mun River Basin, Thailand. *Environmental Monitoring and Assessment,* 191.

YAEGER, M. A., SIVAPALAN, M., MCISAAC, G. F. & CAI, X. 2013. Comparative analysis of hydrologic signatures in two agricultural watersheds in east-central Illinois: legacies of the past to inform the future. 17**,** 4607-4623.

YAN, Q., LEI, T., YUAN, C., LEI, Q., YANG, X., ZHANG, M., SU, G. & AN, L. 2015. Effects of watershed management practices on the relationships among rainfall, runoff, and sediment delivery in the hilly-gully region of the Loess Plateau in China. *Geomorphology,* 228**,** 735-745.

YASMI, Y., DURST, P., HAQ, R. U. & BROADHEAD, J. 2017. Forest change in the Greater Mekong Subregion (GMS): An overview of negative and positive drivers. Bangkok, Thailand: The Food and Agriculture Organization of the United Nations (FAO).

YILMAZ, K. K., GUPTA, H. V. & WAGENER, T. 2008. A process-based diagnostic approach to model evaluation: Application to the NWS distributed hydrologic model. *Water Resources Research,* 44**,** n/a-n/a.

YOUNG, R. A., ONSTAD, C. A., BOSCH, D. D. & ANDERSON, W. P. 1989. AGNPS: A nonpoint-source pollution model for evaluating agricultural watersheds. *J. SOIL WATER CONSERVAT.,* 44**,** 168-173.

YOUNG, R. A. & SHEPHERD, R. G. AGNPS - Agricultural Nonpoint Source Model. Workshop on Computer Applications in Water Management, 1995 Fort Collins, Colorado.

YU, D., SHI, P., LIU, Y. & XUN, B. 2013. Detecting land use-water quality relationships from the viewpoint of ecological restoration in an urban area. *Ecological Engineering,* 53, 205-216.

YU, S., XU, Z., WU, W. & ZUO, D. 2016. Effect of land use types on stream water quality under seasonal variation and topographic characteristics in the Wei River basin, China. *Ecological Indicators,* 60, 202-212.

YU, Y., ZHAO, J., LI, D. & WANG, Z. 2019. Effects of Hydrologic Conditions and Reservoir Operation on Transboundary Cooperation in the Lancang–Mekong River Basin. *Journal of Water Resources Planning and Management,* 145, 04019020.

ZHOU, T., HU, W. & YU, S. 2019. Characterizing interactions of socioeconomic development and environmental impact at a watershed scale. *Environmental Science and Pollution Research*.

Chapter 2. Linking changes in land cover and land use of the Lower Mekong Basin to instream nitrate and total suspended solids variations

Kongmeng Ly, Graciela Metternicht, Lucy Marshall

Published Journal: Ly, K., Metternicht, G., and Marshall, L. "Linking changes in land cover and land use of the lower Mekong Basin to instream nitrate and total suspended solids variations." Sustainability 12, no. 7 (2020): 2992. https://doi.org/10.3390/su12072992.

Keywords: Land use; land cover; spatial variation, temporal variation; streamflow; water quality; transboundary river basin; Mekong River; Lower Mekong River Basin

Contribution: This study was conceptualised by Kongmeng Ly in close consultation with Professor Graciela Metternicht and Professor Lucy Marshall, both of whom provided guidance on the available methods that can be applied to achieve the study objectives. Data collection and analyses were carried out by Kongmeng Ly, who also drafted and finalized the manuscript with the review and editing supports of Professors Metternicht and Marshall in their roles of academic supervisors.

Thesis relevancy: it describes factors influencing streamflow and water quality of the Mekong River. Unlike previous studies which focused on influences of specific factor or factors on water scarcity or river integrity, this chapter highlights the fundamental importance of understanding spatiotemporal relationships between watershed characteristics and streamflow and instream water quality to support the sustainable development and management of large-scale transboundary river basins, such as the LMB. Using TSS and nitrate as proxies for water quality, I identified spatiotemporal trends of streamflow, instream TSS and nitrate concentrations using data recorded from 1985 to 2015. The results were analysed to ascertain whether changes in LULC affect the river streamflow and instream TSS and nitrate levels. Furthermore, ancillary information on land management practice and soil types is used to further explain the observed trends.

Research highlights and innovations:

- Significant temporal changes were detected for streamflow and instream TSS and nitrate levels of the Mekong River.
- First ever research to establish spatiotemporal relationships between LULC and instream TSS and nitrate concentrations.
- Changes in LULC influenced instream TSS and nitrate level differently over time and space.
- In contrary to prior studies in other regions, increase forest land cover was found to increase instream TSS and nitrate levels of the Mekong River reflecting basin specific characteristics of other natural (e.g. topography, soil composition, forest composition, etc.) and anthropogenic (e.g. land use practices, deforestation, instream disturbances, etc.) influences.

2.1 Abstract

Population growth and economic development are driving changes in land use/land cover (LULC) of the transboundary Lower Mekong River Basin (LMB), posing a serious threat to the integrity of the river system. Using data collected on a monthly basis over 30 years (1985–2015) at 14 stations located along the Lower Mekong River, this study explores whether spatiotemporal relationships exist between LULC changes and instream concentrations of total suspended solids (TSS) and nitrate—as proxies of water quality. The results show seasonal influences where temporal patterns of instream TSS and nitrate concentrations mirror patterns detected for discharge. Changes in LULC influenced instream TSS and nitrate levels differently over time and space. The seasonal Mann–Kendall (SMK) confirmed significant reduction of instream TSS concentrations at six stations ($p < 0.05$), while nitrate levels increased at five stations ($p < 0.05$),

predominantly in stations located in the upper section of the basin where forest areas and mountainous topography dominate the landscape. Temporal correlation analyses point to the conversion of grassland (r = −0.61, $p < 0.01$) to paddy fields (r = 0.63, $p < 0.01$) and urban areas (r = 0.44, $p < 0.05$) as the changes in LULC that mostly impact instream nitrate contents. The reduction of TSS appears influenced by increased forest land cover (r = −0.72, $p < 0.01$) and by the development and operation of hydropower projects in the upper Mekong River. Spatial correlation analyses showed positive associations between forest land cover and instream concentrations of TSS (r = 0.64, $p = 0.01$) and nitrate (r = 0.54, $p < 0.05$), indicating that this type of LULC was heavily disturbed and harvested, resulting in soil erosion and runoff of nitrate rich sediment during the Wet season. Our results show that enhanced understanding of how LULC changes influence instream water quality at spatial and temporal scales is vital for assessing potential impacts of future land and water resource development on freshwater resources of the LMB.

2.2 Introduction

Increasing development pressures have altered land use/land cover (LULC) patterns in many river basins around the world. The expansion of agricultural, industrial, and urban areas and the reduction of once pristine forest areas have the potential to affect river water quality, and present a real challenge for water resource managers. Understanding freshwater quality changes through space and time is important for sustainable use and exploitation of this finite resource and for anticipating future impact of land development on aquatic ecosystems. The interactions between LULC changes and stream integrity have been well documented [1–5]; previous studies have examined their impacts spatially [6–9] and temporally [8–10]. Specifically, studies have shown the highest instream sediment concentrations in agricultural areas [11,12], while correlations between instream nitrate concentrations and the proportion of agricultural and urban areas have been documented [10,13,14].

While studies on the effects of LULC on water quality have been explored in many river basins, we found a lack of such studies for large transboundary river basins, such as the Lower Mekong Basin (LMB), where differences exist between countries that make up the basin in terms of topography, LULC compositions, human–environmental interactions, and priorities for development and conservation policies. Despite these differences, rapid economic development is undertaken in many parts of the basin, driving LULC change and pressuring the integrity of the basin environment. Already, studies (Figure 2.1a) have evidenced that the improved road access and the integration of the countries into the Association of Southeast Asian Nations (ASEAN) Economic Community have resulted in the conversion of areas traditionally used for subsistence agricultural practices to areas of intensified agricultural activities and commercial cash crop production [15]. Similarly, intensification of paddy rice cultivation for global export has led to the expansion of agricultural areas at the expense of forest areas in the eastern part of the basin [16,17]. Additionally, changes in the economy have led to the expansion of urban and agricultural areas within the 3S (Sekong, Sesan, and Srepok) sub-basin, affecting its environment and water resources [18]. Improvement of the socioeconomic status of the population living in the Mekong Delta (MD) has been cited as the factor for the increased industrial and urban areas at the expense of forest and agricultural areas, which pose a serious threat to the region’s biodiversity and food security [19].

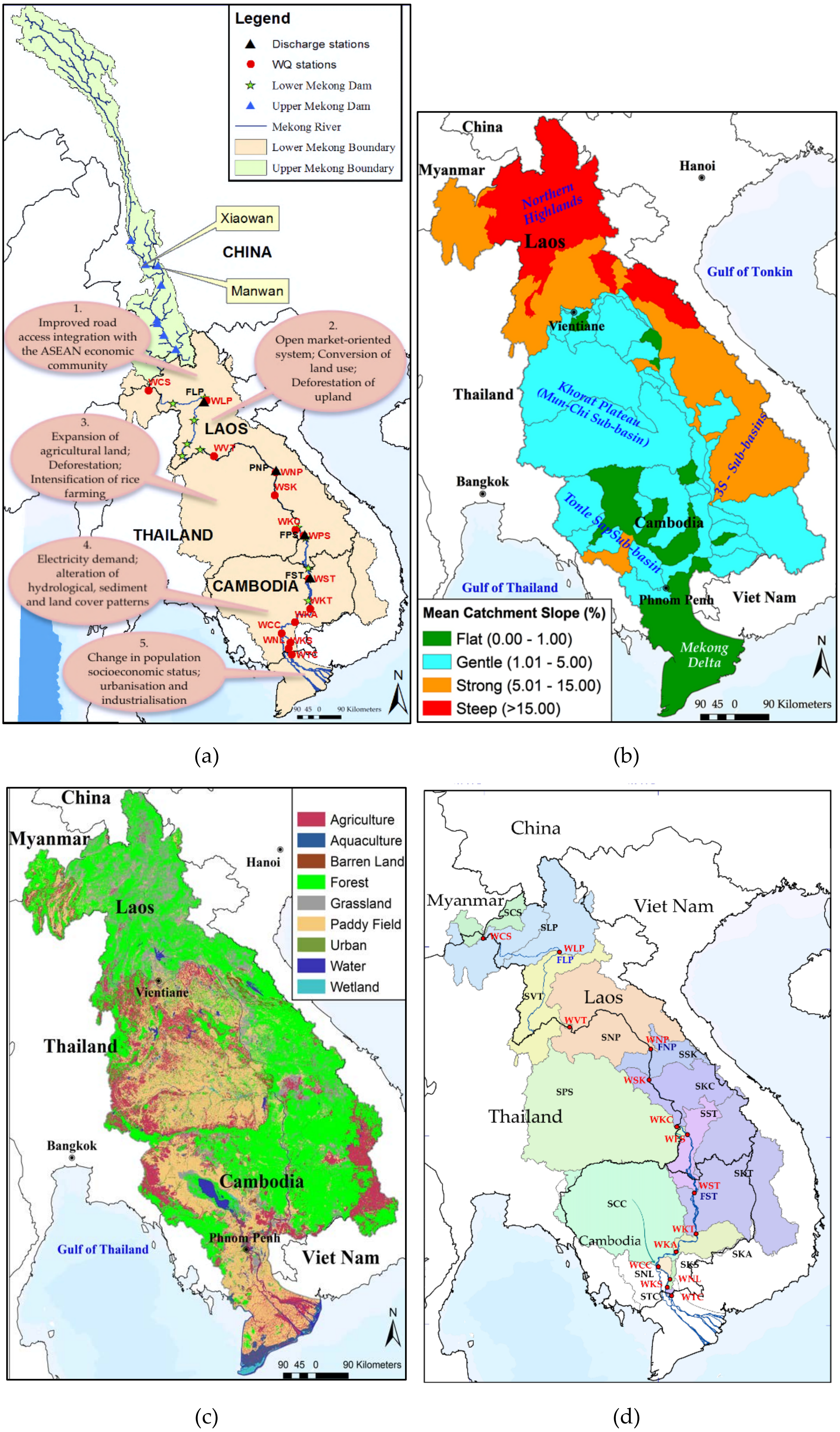


Figure 2.1: The study area of the Lower Mekong Basin (LMB) displaying (**a**) water quality and flow monitoring stations as well as drivers and pressures of land use

change [15–21], (**b**) variation of mean slopes (%), (**c**) a 2010 land use/land cover (LULC) map, and (**d**) delineated sub-basins (Table 2.1 provides a list of acronyms displayed in the figures and further discussions of the analysis results).

Table 2.1: Acronyms of water quality and quality monitoring stations as well as the delineated sub-basins for this study.

River Sections	Station No.	Station Names	Acronyms		
			Water Quality Monitoring Station	Corresponding Sub-Basins	Flow Stations
Upper	**2**	Chiang Sean	WCS	SCS	
	3	Luang Prabang	WLP	SLP	
	4	Vientiane	WVT	SVT	
	5	Nakhon Phanom	WNP	SNP	FNP
	6	Savannakhet	WSK	SSK	
	7	Khong Chiam	WKC	SKC	
	8	Pakse	WPS	SPS	
Lower	9	Stung Treng	WST	SST	FST
	10	Kratie	WKT	SKT	
	11	Kampong Cham	WKA	SKA	
	12	Chrouy Changvar	WCC	SCC	
	13	Neak Loung	WNL	SNL	
	14	Kraorm Samnor	WKS	SKS	
	15	Tan Chau	WTC	STC	

Alongside these drivers, the undergoing and planned development of hydropower projects are threatening to further damage the river ecosystem, causing irreversible change to LULC and destroying habitats of local aquatic and terrestrial animals. Hydropower development (Figure 2.1a) has been highlighted as one of the key drivers influencing hydrological and sediment patterns of the Lower Mekong River (LMR) [22,23]. The operations of the mainstream dams located in the Upper Mekong River (UMR) (also known as the Lancang River (LR)), for example, have proven to be efficient in trapping suspended sediment with estimations according to [24] that about 32–42 Mt of sediments were trapped annually, leading to a reduction of sediment levels in the MD by about 43% [25]. Furthermore, floodplain sedimentation of the MD could be further decreased by 40%, according to [23], with a possibility of diminishing about half of the current sediment load entering the South China Sea if all planned projects become operational. The effects could be even more profound in areas upstream of the delta, with research by [22] projecting that the annual sediment load of the Tonle Sap Lake is likely to be reduced by nearly 60% as a direct result of the changing wet and dry season flow regimes due to hydropower operation.

Therefore, understanding how these LULC change drivers influence instream water quality at spatial and temporal scales is vital for assessing potential impacts of future land and water resource development on freshwater sources. Addressing this knowledge gap, this paper presents a research undertaken in the LMB, a transboundary river basin undergoing major changes in LULC, with the objectives of (1) conducting a spatiotemporal exploratory analysis of how these changes affected water quality indicators (total suspended solids (TSS) and nitrate) using records gathered between 1985 and 2015 at 14 monitoring stations located along the Lower Mekong River (LMR), and (2) identifying trends and observed seasonality of historical TSS and nitrate concentrations. The results are analyzed to ascertain whether changes in LULC affect the river instream TSS and nitrate levels. Furthermore, ancillary information on land management practice and soil types is used to further explain the observed trends.

2.3 Material and Methods

2.3.1 Study Area Characterization

Located in Southeast Asia, the Mekong River is one of the most important rivers in the world, and is ranked as the 8th largest in terms of mean annual flow when discharging into the South China Sea at 14,500 m^3/s [26]. Originating on the Tibetan Plateau, the river passes through six countries (China, Myanmar, Lao PDR, Thailand, Cambodia, and Viet Nam) occupying an area of approximately 795,000 km^2, and it is divided into upper and lower basins. The upper basin is located mainly in China. The lower basin, which is the study area of this research, covers approximately 571,000 km^2, and encompasses land area made up of Lao PDR, Thailand, Cambodia, and Viet Nam [26]. Therefore, the LMR refers to the length of the river from the point it enters Lao PDR to where it discharges into the South China Sea.

Due to its size, the LMB is characterized by four physiographic regions with an elevation range from 0 to about 2800 m above sea level [26]. The highest elevations are found in the upper part of the basin where mountain ranges and steep valleys dominate the landscape (Figure 2.1b). In the eastern part, where the Khorat Plateau formed, the landscape is mostly flat, with low-gradient draining rivers and wide floodplains. Further south, the Tonle Sap Basin forms the largest freshwater lake in Southeast Asia and provides a unique ecosystem with enormous hydrological, biological, nutritional, and cultural values to the region [22,27]. As it enters the delta region, the Mekong River splits into two main channels before discharging into the South China Sea [28].

The distributions of rainfall over these regions are highly variable, ranging from less than 1000 mm in the western part to more than 3000 mm in the northern and eastern parts of the basin [26]. Between May and September, the climate is influenced by the southwest monsoon, which generates much of the precipitation over the basin. From October to April, the climate over the basin becomes drier due the effects of the cold air from the Himalayas.

About 60% of the basin is dominated by clay-rich soils of high acidity and low fertility [26], which poses limitations for agriculture; therefore, these areas are commonly forested (Figure 2.1c). Most forested areas, which in the definition of the Mekong River Commission (MRC) include evergreen, deciduous, coniferous, bamboo, and plantation forests, occur in the mountain ranges of Lao PDR and Cambodia. However, in recent years, acid-tolerant cash crops (e.g., corn, cassava) have been introduced in these areas [29], resulting in the loss of forest area at the annual rate of about 0.4%, according to [30]. Government incentives to limit shifting cultivation have led to an increase of teak, rubber, and biofuel tree plantations in many parts of the basin [31]. In the lowland areas of the Khorat Plateau, Tonle Sap sub-basin, and central to southern parts of Lao PDR, the availability of fertile soil allows a permanent form of agriculture. Therefore, these areas are dominated by paddy rice fields.

Due to the diverse topography and variability in soil types and climatology, the LMB is subject to varying intensities of soil erosion, with mountainous areas of Lao PDR being highly erosive [32]. In particular, areas with slopes of more than 25% have been found to experience mean annual soil erosion of 13 to 32.2 t/ha/year, while areas with slopes between 0% and 6% have been found to have a mean annual soil erosion of about 0.0 to 4.4 t/ha/year [32].

Population distribution and density vary greatly over the basin, with the largest human concentrations occurring in the MD and urban areas, such as Phnom Penh and Vientiane. The population density at these areas ranges from 200 to 700 persons per km^2. In comparison, rural areas in the northern part of Lao PDR have population densities of 20 persons per km^2 [26].

2.3.2 Data and Method

Figure 2.2 illustrates the methodological framework designed for this study and associated techniques, with each step being detailed hereafter.

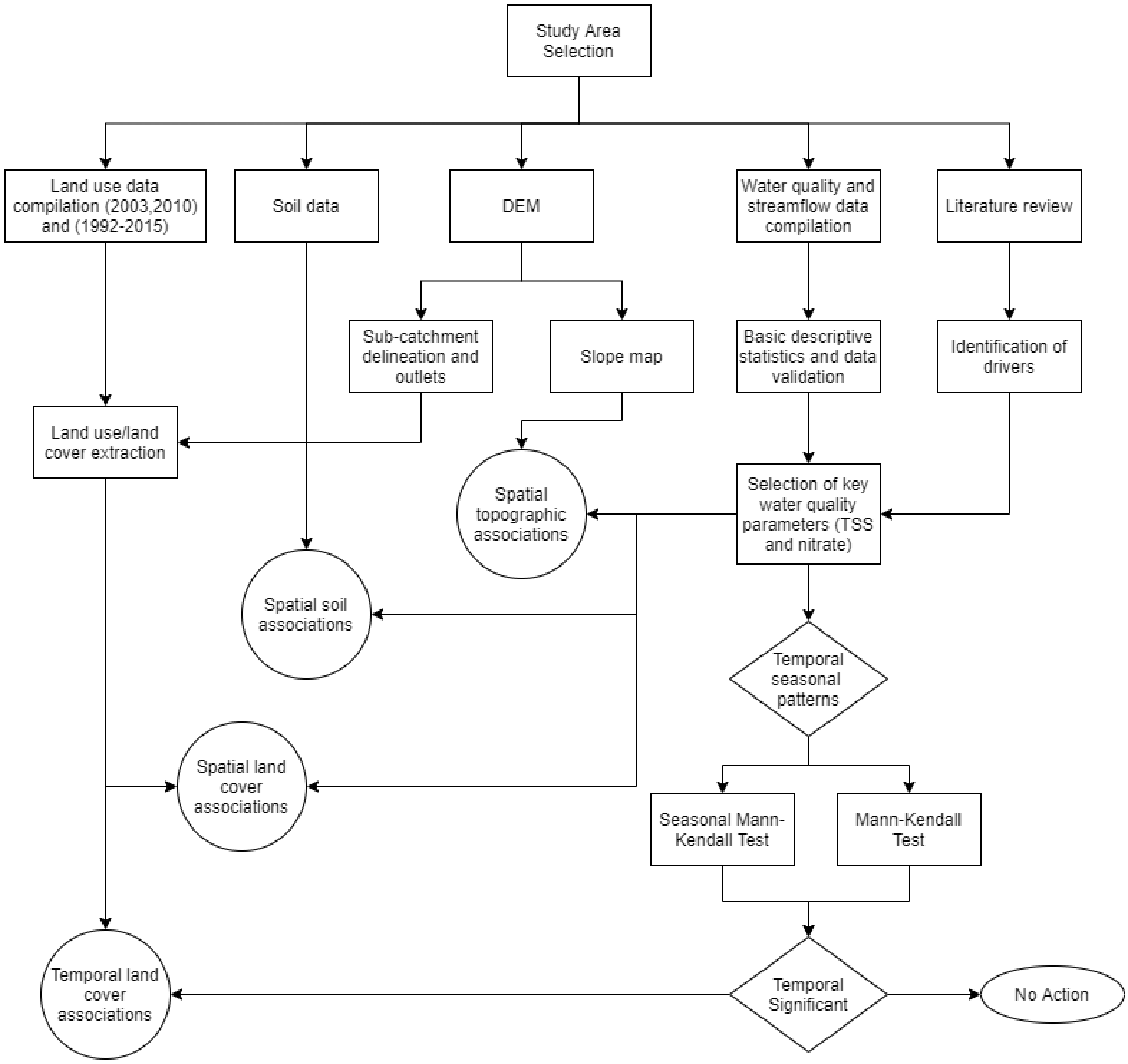


Figure 2.2: Methodological framework of this study.

2.3.3 LULC and Watershed Data

LULC data were compiled from two different sources: A 2010 MRC land use map (Figure 2.1c) and the European Space Agency (ESA) Annual Global Land Cover Time Series (AGLCTS) from 1993 to 2015. The 2010 MRC land cover data were used for spatial association of LULC and water quality indicators, while the ESA 1993–2015 land cover time series were used to explore temporal associations between changes in LULC and water quality (refer to Section 2.3.6). The MRC 2010 land cover data were produced using Landsat-5 Thematic Mapper images with 30 m spatial resolution, complemented with field surveys. The Food and Agricultural

Organization of the United Nations (FAO)'s Land Cover Classification System (LCCS) [33] guided the selection of the 19 land cover type classes.

The ESA annual global land cover time series uses images from five different satellite missions (NOAA-AVHRR HRPT, SPOT-Vegetation, ENVISAT-MERIS FR and RR, ENVISAT-ASAR, and PROBA-V), and is provided at a spatial resolution of 300 m. The annual land cover maps contain 22 main categories also based on the LCCS [33]. The LMB boundary was used to extract a subset of 23 annual land cover datasets (i.e., 1993–2015) for further analysis. To facilitate statistical analysis, classes for both the MRC and ESA datasets were aggregated into nine main LULC types, including forest, paddy field, urban, grassland, barren land, wetland, water, and aquaculture (Appendix 2.A).

Elevation data were sourced from the MRC Digital Terrain Model (DTM), available at 50 m spatial resolution for the entire river basin. The ArcGIS 10.3 spatial analyst toolbox [34] was used to delineate stream networks and sub-basin boundaries using the water quality monitoring stations as the outlets. Detailed methods used for deriving flow direction and accumulation are described in [35]. The lack of vertical precision in flat areas precluded the generation of sub-catchments for the region of the MD, and only 14 sub-catchments were generated as a consequence (Figure 2.1d). Only land cover data generated from these sub-catchments were used to further explore and better understand the behavior of the selected water quality indicators over time and space. Spatiotemporal information of LULC (types and percentages) for each delineated sub-basin was extracted from the 2010 MRC land use data (Figure 2.3) and the ESA landcover dataset (1993–2015) (Appendix 2.B) by overlaying boundaries of each sub-basin on the LULC maps.

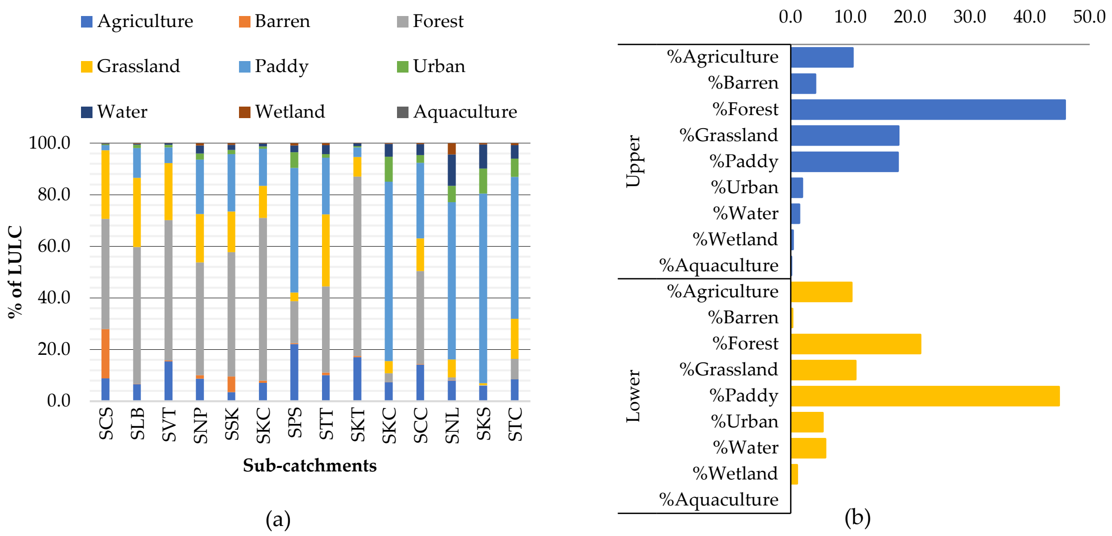


Figure 2.3: The 2010 LULC compositions and their proportions within the sub-basins in the (**a**) LMB and (**b**) upper and lower sections of the basin.

To facilitate the analysis and discussion of the results, the basin was divided into two sections (upper and lower) based on their topographic differences (Table 2.1): The upper section was characterized by the mountain ranges and plateaus of Lao PDR and Thailand, and the lower section by the mostly flat areas of Cambodia and Viet Nam.

2.3.4 Data on Water Quality and Quantity

Data on water quality and quantity were obtained from the MRC Water Quality Monitoring Network (WQMN). Water quality data were sourced from 14 mainstream stations expanding across four countries. Nine of these 14 stations have records dating back to 1985, three began recording observations in the early 1990s, and records of two stations date back to the early 2000s. Water quality data contain time series of more than 20 water quality parameters. The time series collected under the MRC WQMN are not continuous, and measurements for each parameter are collected monthly. Measurement and analysis of each water quality parameter are carried out in accordance with the methods outlined in the *Standard Methods for the Examination of Water and Wastewater* [36]. A total of 72,230 records of all parameters were available for this study. Of those, 8712 points contain information on TSS and nitrate, the proxies that this study adopts to assess water quality.

Data on water quantity, in the form of water level, were sourced from the MRC at Nakhone Phanom (FNP) and Stung Treng (FST) for the period of 1985–2015. Discharge data were also recorded at these stations, but only from 1985 to 2005. Using the available data, the MRC has developed rating curves representing the relationship between discharge and water level of the LMR, enabling the estimation of discharge as a function of recorded water levels.

2.3.5 Statistical Analysis of Water Quality Data

2.3.5.1 Data Pre-Processing and Statistics Summarization

The quality of the collected data was assessed using MATLAB (R2010a) [37]. A total of 4270 and 4442 data points for TSS and nitrate, respectively, were found suitable for further analysis. Descriptive statistics (i.e., mean, maximum, minimum, and standard deviation) were applied on these data to quantitatively describe the main characteristics. Furthermore, time-series analysis using box-and-whisker plots was carried out for TSS and nitrate datasets for all stations to allow comparisons of their levels, ranges, and distributions. In addition, the strength and direction of the relationship between instream TSS and nitrate concentrations and river discharge were evaluated using Pearson's correlation to help explain any patterns detected during the analysis.

2.3.5.2 Decomposition of TSS and Nitrate Time Series

Similarly to other long-term environmental monitoring time series, historical data on water quality often exhibit seasonal patterns, non-normal distribution, and missing data points. As such, analysis of seasonal variability and long-term trends for each dataset was conducted using the Seasonal and Trend decomposition Loess algorithm (STL) [38]. The use of STL for decomposition of water quality time series has been discussed extensively by [38,39], including the internal circulation process of STL [40].

STL has been reported as robust to outliers and missing data values in addition to the ability to handle a large of number of time series [41]. These are attractive attributes given the characteristics of the available TSS and nitrate data in the LMB.

The open source R Studio statistical package [42] was used for time series decomposition and identification of trends. TSS and nitrate time series for each station were filtered into trend, seasonal, and remainder components, using a locally weighted regression approach [43]. Trends were identified by removing the influence of seasonal and reminder components from the time series [39].

2.3.5.3 Seasonal Mann–Kendall Trend Analysis

Ref. [44] summarized statistical tools available for analyzing water quality data, ranging from graphical methods to provide visual summarization of time series to computationally-driven methods for analyzing and forecasting trends of large dataset. Given the characteristics of long-term water quality monitoring data (Section 2.3.5.2), the seasonal Mann–Kendall test (SMK) [45] was used to determine the monotonic trends of TSS and nitrate time series at each station. SMK is a nonparametric method that can be used to detect trends in time series with seasonal variation and missing values. Furthermore, the test was developed specifically for analyzing trends of water quality data collected on a monthly basis [45]. This is an attractive feature of the test considering that TSS and nitrate data obtained for this study are available on a monthly time scale. In a dataset where X is the entire sample consisting of monthly subsamples from January to December [$X = (X_1, X_2, \ldots, X_{12})$], and each monthly subsample (X_i) contains n_j annual values such that, for January, subsample $X_1 = (x_{11}, x_{12}, \ldots, x_{1n})$, the null hypothesis ($H_0$) is that there is no monotonic trend in time for a dataset where X is a sample of independent variables (x_{ij}) in an evenly distributed X_i. Therefore, the alternative hypothesis H_1 is that the monthly random subsample (X_i) is not identically distributed and monotonic trends exist in time. The detailed statistical analysis for SMK can be found in [45]. In this study, the *p*-value of 0.05 defined statistical significance. Z statistics were also used to determine the upward (positive Z value) and downward (negative Z value) trends of TSS and nitrate levels.

2.3.6 Spatial and Temporal Association of LULC and Water Quality Indicators

The relationships between LULC and water quality indicators were explored temporally and spatially. To explore spatial relationships, the proportion of individual LULC types extracted from the MRC 2010 land cover data (see Section 2.3.3) was correlated with the mean concentrations of TSS and nitrate collected in 2010. The year 2010 was selected due to the available MRC data for LULC, TSS, and nitrate. The Pearson's correlation analyses were carried out for the delineated sub-basins (Section 2.3.3 and Figure 2.1d) to describe the overall correlations between LULC and water quality indicators.

Analyses of temporal association of LULC and water quality indicators were undertaken for a station which exhibited significant change in both TSS and nitrate trends, as shown by SMK. Percentages of LULC types extracted from the European Space Agency land cover maps (1993–2015) (see Section 2.3.3 and Appendix 2.B) were used for the analyses. Temporal analyses were carried out at a sub-catchment scale by Pearson's correlation analysis, allowing the association of the mean annual concentrations of TSS and nitrate with the percentages of individual LULC types within the selected sub-catchment. In addition, Factor Analysis [46] was used to further explain the underlying temporal relationships between LULC and water quality indicators.

2.4 Results and Discussion

2.4.1 Summary of Statistics of Water Quality Indicators

Descriptive statistics for water quality indicators at the 14 water quality monitoring stations (Table 2.2) show that mean concentrations for TSS range from 67.4 to 314.9 mg/L, which indicates a sign of spatial variation. On average, the highest TSS levels occurred in the upper part of the basin with the maximum mean concentration recorded at Vientiane (WVT). TSS levels decrease as the river traverses from the upper part of the basin to the MD. Nitrate levels were less variable, with concentrations fluctuating from non-detectable to 1.17 mg/L. Similarly to the patterns obtained for TSS, nitrate levels were also highest in the upper part of the river, with the mean concentration calculated to be as high as 0.34 mg/L at Chiang Sean (WCS).

Table 2.2: Descriptive statistics of total suspended solids (TSS) and nitrate data in the Lower Mekong River (LMR) stations ([a] 0.00 refers to non-detectable level).

Section	Stations (See Table 2.1)	TSS (mg/L)				Nitrate (mg/L)			
		Max	Mean	Min	Std. Dev	Max	Mean	Min [a]	Std. Dev
Upper	WCS	2372.0	294.4	1.6	356.6	0.79	0.34	0.10	0.11
	WLP	3328.0	254.6	2.0	400.0	1.10	0.22	0.00	0.15
	WVT	5716.0	314.9	1.0	591.1	0.99	0.23	0.00	0.15
	WNP	1566.0	169.7	2.0	203.3	0.74	0.29	0.02	0.13
	WSK	649.0	105.1	1.0	109.5	0.65	0.25	0.00	0.14
	WKC	1675.0	160.5	1.3	204.7	0.93	0.26	0.00	0.13
	WPS	1526.0	159.1	1.0	215.0	0.77	0.16	0.00	0.12
Lower	WST	590.0	70.3	1.0	88.8	0.53	0.17	0.00	0.11
	WKT	680.0	80.6	2.0	90.7	1.17	0.16	0.00	0.13
	WKA	546.0	83.3	0.3	100.8	0.90	0.16	0.00	0.12
	WCC	536.0	81.1	1.0	98.8	0.74	0.16	0.00	0.12
	WNL	596.0	80.4	0.4	93.4	0.54	0.16	0.00	0.11
	WKS	293.0	67.4	1.3	63.5	0.60	0.15	0.00	0.11
	WTC	551.2	110.6	0.3	123.0	1.02	0.18	0.00	0.16

2.4.2 Spatial Relationships between LULC and Water Quality Indicators

2.4.2.1 Characteristics of the 2010 LULC

In 2010, forest and paddy rice were the dominant LUCL types in the studied sub-basins (Figure 2.3). Forest land accounted for about 33% of the total land area, while paddy fields accounted for about 31%. However, the proportions of individual LULC types varied greatly between each sub-basin (Figure 2.3a). In the upper section, where topography is characterized by hilly terrains and steep slopes (see Section 2.3.1), forest was the main LULC, accounting for approximately 46% of the total surface area that makes up the section (Figure 2.3b). The mosaic of plains and plateaus intertwined with mountains in this part of the LMB facilitates conversion of forest areas to paddy fields and other forms of agriculture (18 and 10%, respectively). On the other hand, the lower part of the basin is characterized by large areas of plains and low rises suitable for permanent forms of agricultural activities. Therefore, this section of the basin is dominated by paddy field areas (45%), with the exception of the Kratie (SKT) sub-basin, where 70% of its area remained forested. In the MD, which includes the Neak Loung (SNL), Kraorm Samnor (SKS), and Tan Chau (STC) sub-basins, 63% of the LULC were paddy fields, with forest areas covering merely 3% of the total land area (Figure 2.3b).

2.4.2.2 Spatial Association between LULC and Water Quality Indicators

The Pearson's analysis of spatial correlation among LULC parameters and water quality indicators over the entire LMB (Figure 2.4) showed a strong positive association (p = 0.01) between TSS levels and forest areas with a correlation coefficient (r) of 0.64, whereas the association between TSS and paddy fields was strongly negative (r = −0.61, p = 0.02), as it was with urban areas (r = −53, p = 0.05). While correlation existed between TSS and areas covered by grassland (r = 0.42), these relationships were not statistically significant (p > 0.05).

Legend:
Pearson's correlation: 1 to -1
Statistical significance: $p \leq 0.01$; $p \leq 0.05$

		% LULC parameters								Water Quality Indicators	
		Agriculture	Barren land	Forest	Grassland	Paddy field	Urban	Wetland	Aquaculture	TSS (mg/L)	Nitrate (mg/L)
% LULC parameters	Agriculture	1.00	-0.19	0.13	-0.19	-0.17	-0.12	-0.13	0.02	-0.06	-0.11
	Barren land	0.52	1.00	0.20	0.42	-0.40	-0.36	-0.20	0.93	0.09	0.58
	Forest	0.65	0.50	1.00	0.51	-0.94	-0.92	-0.52	0.11	0.64	0.54
	Grassland	0.51	0.14	0.07	1.00	-0.70	-0.71	-0.27	0.36	0.42	0.66
	Paddy field	0.57	0.15	0.00	0.00	1.00	0.98	0.46	-0.34	-0.61	-0.67
	Urban	0.69	0.20	0.00	0.00	0.00	1.00	0.32	-0.28	-0.53	-0.60
	Wetland	0.66	0.50	0.06	0.36	0.10	0.26	1.00	-0.19	-0.31	-0.34
	Aquaculture	0.96	0.00	0.71	0.20	0.23	0.34	0.52	1.00	0.09	0.56
Water quality indicators	TSS (mg/L)	0.84	0.77	0.01	0.13	0.02	0.05	0.28	0.77	1.00	0.68
	Nitrate (mg/L)	0.70	0.03	0.05	0.01	0.01	0.02	0.23	0.04	0.01	1.00

Pearson's correlation matrix (upper triangle); Statistical significance matrix (lower triangle)

Figure 2.4: Pearson's correlation matrix (**upper triangle**) and statistical significance matrix (**lower triangle**) among different land use parameters and water quality indicators.

Statistically significant relationships ($p < 0.05$) were observed between nitrate levels and seven LULC parameters (Figure 2.4). Positive associations were noted with forest land cover (r = 0.54), grassland (r = 0.66), aquaculture areas (r = 0.56), and barren land (r = 0.58). Among these four LULC parameters, the strongest association ($p = 0.01$) was with grassland. The three LULC parameters negatively associated with nitrate were paddy fields (r = −0.67) and urban areas (r = −0.60). These results appear to contradict outcomes of previous studies, including those described in Section 2.2, where their outcomes revealed that catchments dominated by agricultural land use export higher nitrate levels to their receiving water [47], while catchments with high vegetation cover tend to reduce erosion and, therefore, reduce sediment runoff [2,48].

From the analysis of Figure 2.4, it seems that sub-basins of the LMB with greater proportions of forest land cover tend to yield higher TSS and nitrate concentrations, whereas the opposite occurs in sub-catchments with higher proportions of paddy fields. A plausible explanation to support these findings is that in the LMB, traditional land use management (see Section 2.4.2.2.1), soil composition (Appendix 2.C), and topography (Section 2.4.2.2.2) influence the proxy indicators selected to assess water quality. More to the point, while about 33% of the basin (46% in the upper section) was forested in 2010, prior research [49] evidenced the impact of human disturbances—shifting cultivation, logging, and poor infrastructure development—within this land cover. These activities tend to reduce ground vegetation cover, exposing the topsoil to increased sediment detachment and transport during the wet season. For example, many road networks have been constructed through forested areas, applying low engineering standards that failed to account for the easily erodible conditions of the soil, which in turn increases sediment production [50]. Where forest areas are subject to intensive logging, soil erosion in connection with road networks is even more extreme, with a soil loss rate of close to 80% [51]. With few little sustainable land management practices occurring in the area, sediment transportation to the stream network can be exacerbated by natural hazards, i.e., landslides caused by high-intensity rainfall during the monsoon months [52]. These disturbances, along with the effects of hydropower dams (Section 2.2 and Figure 2.1a) operating in the upper part of the catchment, can explain the observed positive relationship between forest land cover and instream TSS and nitrate levels of the LMR.

2.4.2.2.1 Land Management Influencing TSS and Nitrate Deposition

Time series analysis reveals that TSS and nitrate levels were consistently highest in the upper part of the river where sub-basins are dominated by forest land cover and hilly topography with strong to steep slopes (mean slope greater than 15% (see Section 2.3.1 and Figure 2.1b)). Traditional shifting cultivation practiced in hillsides and sloping lands requires no fertilizer inputs, but involves vegetation clearance and burning to provide nutrients for crops [53,54], and has led to the degradation of the forest ecosystem in the upper part of the LMB [55], exposing land to increased soil erosion during rainfall events. As mentioned in Section 2.3.1, croplands in steep slopes are subject to high rainfall–runoff factors (7986 to 12,599 MJ.mm/ha^2) becoming highly erosive (mean annual soil erosion of about 13 to 32.2 t/ha/year) [32]. Areas of high soil erosion are also susceptible to soil nutrient displacement that can lead to increased eutrophication and sedimentation of the river system [49].

Shifting cultivation practices cause erosion (i.e., approximately 5.7 Mg/ha/year of topsoil are lost during cultivation, and about 0.7 Mg/ha/year during fallow years, according to [12], though they are not the only land use practice to be blamed for soil erosion in the LMB. Incentives for eliminating shifting cultivation (see Section 2.3.1) have led to a conversion of upland rice areas to tears, maizes, and tree plantations (teak, rubber, palm trees) [31,49,56]. Changes from upland rice to maizes and job’s tears, for example, have been found to almost double the rate of sediment production, from about 6 to about 11 Mg/ha/year [12]. Along with the conversion of upland rice farming to other types of cash crops, tree plantations have become more prominent in the mountainous region of the LMB. Increased areas of tree plantations, particularly in connection with teak plantation, have also been found to increase overland flow and sediment yield due to the increased throughfall kinetic energy created by their high canopies and large leaves [57].

2.4.2.2.2 Impact of Topography and Soil Type

An assessment of whether landscape variables such as topography (using slope percentage) and soil types influence instream concentrations of TSS and nitrates (Figure 2.5) shows that both were positively associated with the mean slope percentage values of the sub-basins. The highest nutrient and TSS levels were recorded at Luang Prabang (WLP) (2), WVT (3), and Nakhon Phanom (WNP) (4), which are located in the upper part of the basin, where the topography is dominated by steep slopes (mean slope greater than 15%). As the river flows further downstream, lower concentrations of TSS and nitrate were recorded. As previously mentioned (see Section 2.3.1), these areas of the Khorat Plateau, Tonle Sap Basin, and MD are mostly flat land with low-gradient draining rivers and wide floodplains. In these areas, and more so in the MD region, sediment deposition reduces the concentrations of suspended sediment due to the low river gradient, decreasing instream TSS levels [58].

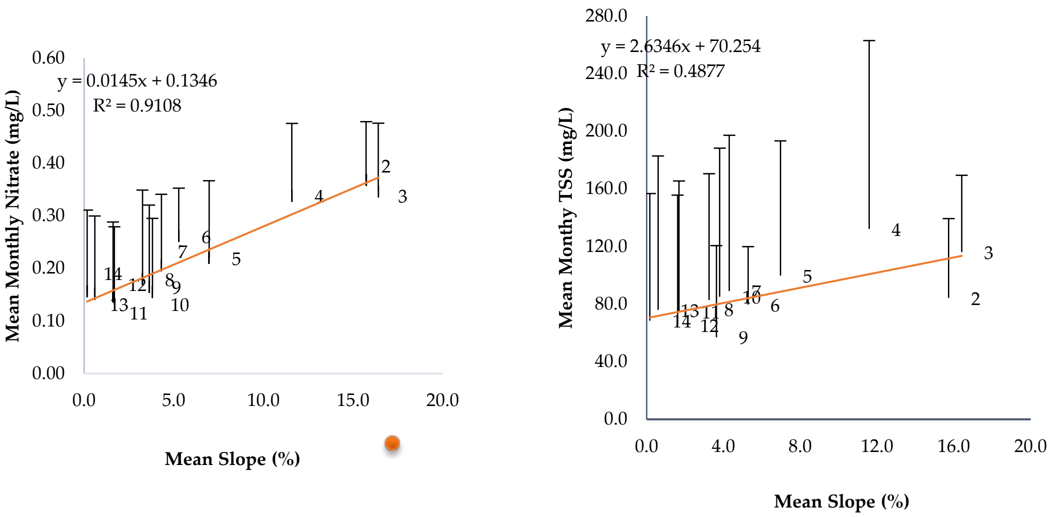


Figure 2.5: Relationships between mean slope of the sub-catchments and 2010 mean monthly TSS and nitrate concentrations (red dots and numbers represent stations). Data label: Red dots represent water quality monitoring stations where: 2—WCS; 3—WLP; 4—WVT; 5—WNP; 6—WSK; 7—WKC; 8—WPS; 9—WST; 10—WKT; 11—WKA; 1—WCC; 13—WNL; 14—WKS; 15—WTC.

An examination of the soil characteristics (Appendix 2.C) reveals that the LMB is dominated by Acrisol soils of low natural fertility, which are acidic and susceptible to erosion once vegetation clearance is carried out [59]. Triangulation of our results with prior research conducted in the study area points to soil characteristics, along with steep slopes and agricultural practices, as the primary drivers of the high TSS and nitrate levels observed in the upper part of the basin.

2.4.3 Seasonal Decomposition of Water Quality Time Series

Results of the decomposition of the water quality time series for the 14 monitoring stations are presented in Appendix 2.D. Figure 2.6 and Figure 2.7 show results of the decomposition of TSS and nitrate time series at WCS, WLP, Kampong Cham (WKA), and WTC by the STL (Section 2.3.5.2). These stations represent typical characteristics of stations located in the upper and lower sections of the basin, respectively. The STL decomposition of the water quality time series shows that seasonal factors strongly influence TSS and nitrate levels in the LMR (Figure 2.6 and Figure 2.7 and Appendix 2.D).

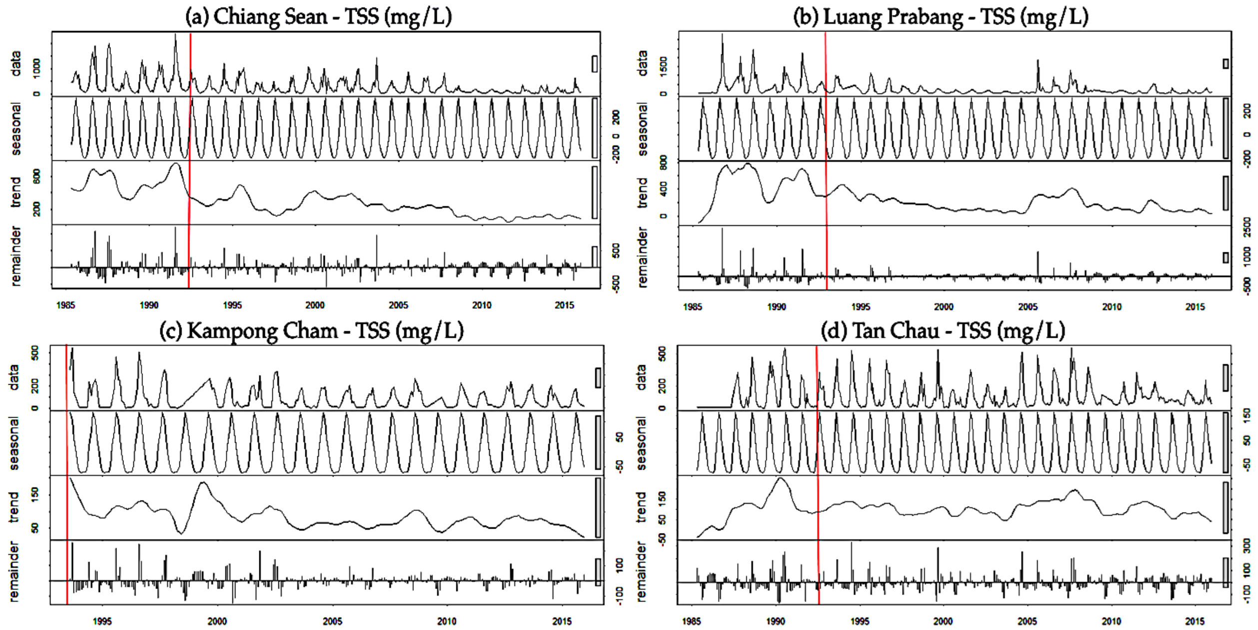


Figure 2.6: Decomposition of TSS time series at (**a**) Chiang Sean (WCS), (**b**) Luang Prabang (WLP), (**c**) Kampong Cham (WKA), and (**d**) Tan Chau (WTC). The red vertical line represents the date the Manwan dam became operational.

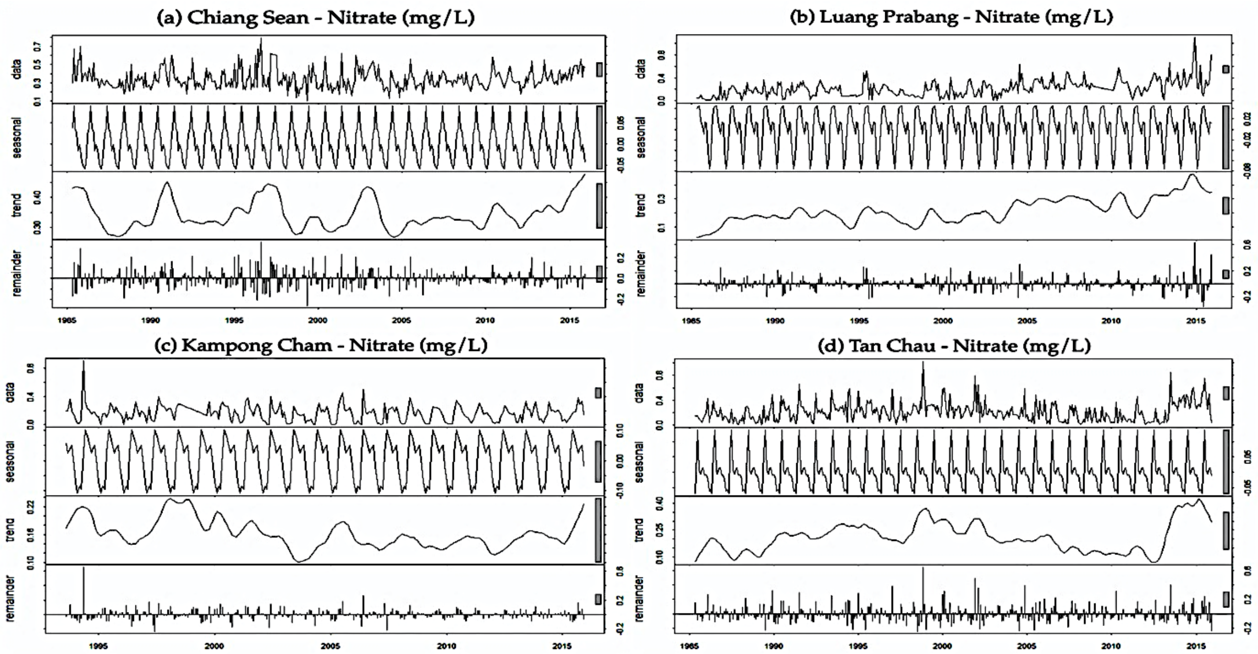
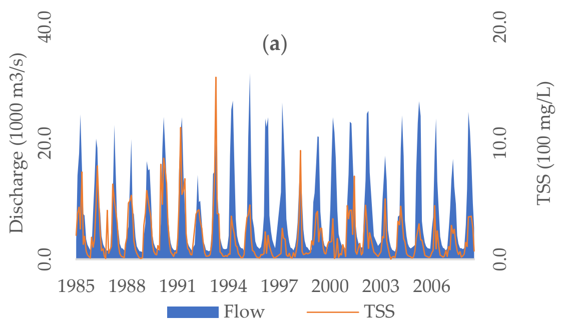


Figure 2.7: Decomposition of nitrate time series at (**a**) Chiang Sean (WCS), (**b**) Luang Prabang (WLP), (**c**) Kampong Cham (WKA), and (**d**) Tan Chau (WTC).

2.4.3.1 Seasonal Decomposition of TSS Time Series

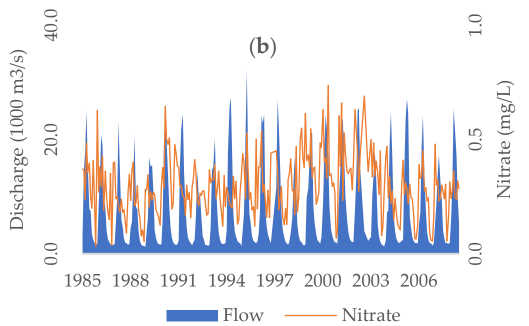
Long-term trends of TSS levels in the upper section of the LMB (represented by WCS and WLP in Figure 2.6(a and b) displayed decreasing patterns over the period monitored. In addition to being influenced by factors discussed in Section 2.4.2, a closer examination of the trend component at these stations reveals reversal patterns in their overall trends, increasing from 1985 to 1993 and reaching their highest peak during this period. These were followed by sharp decreasing patterns from 1993 to 1994, and then increasing again from 1994 to 1995, before gradually decreasing to the level observed in 2015. The patterns appear to coincide with the completion and operation periods of the Manwan Dam, located in the LR (Figure 2.1a). Since 1993, TSS levels recorded at stations located in the upper section of the river have been less variable, with the mean annual concentration at WCS reduced by over 300%. The reduction appears to have been influenced by factors independent from those operating on seasonal time scales. More to the point, studies have shown that damming of the LR has decreased sediment transport through the river, and that the decline in sediment concentrations at stations located in the LMR occurred following the Manwan Dam development in 1993 [22,25,28]. Since it became operational, approximately 60% of TSS originating in the Upper Mekong Basin (UMB) were lost due to sediment trapping [60]. A recent study by [25] found that the Manwan Dam lost approximately 17% of its storage capacity (10.6×10^8 cubic meters) between 1993 and 2009. In addition, this same study reported a reduction in suspended sediment loads of about 83%, 50%, and 43% in the upper, middle, and lower parts of the LMR following the construction of the Xiaowan Dam [25].

In the lower section of the basin, where the topography is flatter (Figure 2.1b), TSS levels were less variable (Table 2.2). Visual examination of temporal trends at these stations did not show obvious patterns, though a number of patterns of reversal are observed throughout the trend component of the STL, as shown in Figure 2.6(c and d) for WKA and WTC, respectively. Since the time series data for WKA and all stations located in Cambodia started in 1995, it is unclear whether the completion of the Manwan Dam affected TSS levels in this section. The seasonal component of the STL in all stations shows a cyclic pattern of sinusoidal behavior, which confirms the seasonality of their time series. Furthermore, temporal patterns of TSS and nitrate times series of all 14 stations followed those of discharge, exhibiting rising and falling concentration levels. Figure 2.8(a–d) provide examples of the cyclic variation obtained from the analysis of discharge, TSS, and nitrate time series at FNP/WNP (flow/water quality stations in the upper section) and FST/WST (flow/water quality stations in the lower section). Pearson's correlation analysis of the three water quality and quantity indicators (TSS, nitrate, and flow) revealed strong relationships. In particular, the results of the analysis suggest that flow was a dominant factor influencing instream TSS and nitrate concentration levels. Positive correlations between discharge and TSS and nitrate levels (r = 0.79, $p < 0.01$ and r = 0.74, $p < 0.01$, respectively) were obtained at WNP (Figure 2.8(a and b)). Similar relationships were also obtained further downstream at WST, with strong correlation values for both TSS and nitrate in relation to discharge (Figure 2.8(c and d)). These relationships further confirm the seasonality of the two water quality indicators, particularly when considering the two distinct seasons (Wet and Dry seasons) of the region and the annual rising and falling periods of the Mekong water levels.



Correlation Matrix (r)

	Discharge	TSS	Nitrate
Discharge	1.00	0.79	0.74

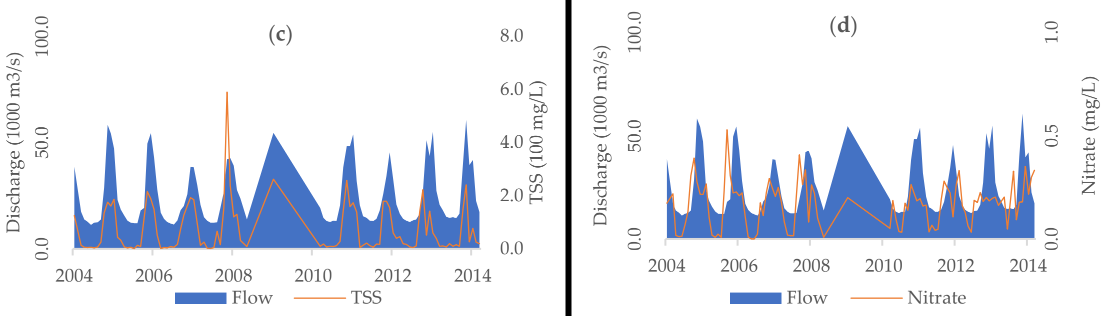


Significance Matrix (*p*-values)

	Discharge	TSS	Nitrate
Discharge	-		

TSS		1.000	0.67
Nitrate			1.00

TSS	<0.01	-	
Nitrate	<0.01	<0.01	-



Correlation Matrix (r)

	Discharge	TSS	Nitrate
Discharge	1.00	0.732	0.39
TSS		1.000	0.38
Nitrate			1.00

Significance Matrix (*p*-values)

	Discharge	TSS	Nitrate
Discharge	-		
TSS	<0.01	-	
Nitrate	<0.01	<0.01	-

Figure 2.8: Comparisons of temporal patterns and relationships of the Mekong River's discharge and instream TSS and nitrate concentrations at WNP (**a** and **b**) and WST (**c** and **d**). These two stations representing the upper and lower sections of the LMR, respectively.

2.4.3.2 Seasonal Decomposition of Nitrate Time Series

Unlike patterns detected for TSS, historical trends for nitrate do not appear to be driven by geography. Results of the decomposition show no increasing or decreasing trend patterns. Figure 2.7(a and b) shows trends detected for nitrate in the upper part of the basin, where patterns of reversal were displayed during the monitoring period. While Figure 2.8 reveals a strong correlation of nitrate levels to both discharge (WNP (r = 0.74, $p < 0.01$) and WST (r = 0.39, $p < 0.01$)) and TSS (WNP (r = 0.67, $p < 0.01$) and WST (r = 0.38, $p < 0.01$)), their historical trends following the removal of seasonal influence do not mirror those detected for TSS (Section 2.4.3.1). This evidences the complexity of instream nitrate transport processes in the LMR. Previous studies on the dynamics of instream nitrate processes have shown a dependence of instream concentration on factors such as LULC and their management, nitrogen input and output ratio, characteristics of local meteorology and geohydrology, and nitrification processes [61].

In the lower part of the basin, the average mean annual concentration of nitrate was 0.1 mg/L, but the concentrations were highly variable, ranging from non-detectable to over 1 mg/L. This section of the basin is dominated by paddy fields and urban areas (Figure 2.3), the two types of LULC that have been linked to significant levels of instream nitrate concentration in this study (Section 2.4.2.2) and other studies (Section 2.2). Across the lower part of the river, temporal trends vary from station to station (Figure 2.7(c and d) and Appendix 2.D) and appear to be influenced by different LULC types and agricultural practices. The most notorious increasing trend occurred at Kraorm Samnor (WKS) (Appendix 2.D), where approximately 90% of the sub-basin is dominated by paddy fields (Figure 2.3). The finding is consistent with other studies, where catchments dominated by agricultural land use and subjected to agricultural intensification are known to yield high instream nitrate concentration [47].

Seasonality appears to be one of the main factors influencing instream nitrate levels in the LMR. Similar to TSS, the seasonal component shows equal intervals of cyclic behavior of the time series, with distinct annual increasing and decreasing patterns coinciding with the beginnings of the Wet and Dry seasons, respectively. The seasonality of the nitrate time series is also confirmed by its strong statistical correlation with those of discharge and TSS (Figure 2.8), the two main indicators of seasonality.

2.4.4 Seasonal Mann–Kendall Analysis of Historical Water Quality Time Series

With the confirmed seasonality of the TSS and nitrate time series (Section 2.4.3), temporal trend analyses were carried out by SMK at the 14 stations, where downward trends of TSS were detected at all but one station located in the upper part of the LMB, from 1985 to 2015 (Table 2.3). The only upward trend obtained in this section of the basin was at Savannakhet (WSK) (z-value of 0.01), though not statistically significant ($p = 0.88$). For the other six stations where downward trends were detected, their *p*-values (<0.05) indicate that the changes observed were statistically significant. The results provided by the SMK further support the outcomes of the STL analysis in Section 2.4.3.1, and confirm that changes in TSS levels in the upper part of the basin were statistically significant. The results of the SMK analysis appear to confirm that the dams operating in the UMB have not affected TSS levels in the lower part of the basin. Of the seven stations included in this study, four displayed no change or upward historical trends. Significant upward trends were detected at WTC ($p < 0.01$), located in the MD. The patterns observed also suggest that suspended sediments generated in the UMB, while important to the instream sediment dynamics of the LMR, rarely reached the lower part of the basin, and had very little influence on instream TSS concentrations in the delta area. Rather, instream TSS levels in the lower part of the river are likely influenced by the interaction between LULC, rainfall–runoff factors, and human activities within the basin (discussed in Sections 2.4.2 and 2.4.3). The results are consistent with prior research [62], which reported high TSS levels in the MD due to accumulated upstream sedimentation and localized erosion caused by agricultural activities.

Of the downward trends detected, two were not statistically significant. The historical trend at WKT was the only significant downward trend ($p < 0.01$). Despite being located in the lower section of the basin, the catchment area of this station exhibited environmental and physical characteristics similar to those of the upper part of the basin, including forest-dominated land cover, hilly topography with strong slopes, and exposure to high-intensity rainfall events during the Wet season. These features, along with human disturbance through LULC practices, have led to an increased sediment runoff, affecting instream TSS concentrations (Section 2.4.2).

While temporal trends for TSS differ between stations located in the upper and the lower parts of the river (Table 2.3), changes detected for nitrate levels vary from station to station. Between 1985 and 2015, nitrate levels increased at nine stations, with the biggest increasing trend detected at WLP. The trends observed at this station are likely due to the increase of intensive agricultural activities upstream of the station (See Figure 2.1a). This region has experienced a change in land use patterns, with areas previously used for subsistence agricultural activities, such as upland rice farming, being converted to intensive agriculture for cash crops, such as banana, maize, and sugar canes [15]. While there is no information on the use of fertilizer in the region, nitrogen-based fertilizers have been known as necessary input for these cash crops to optimize yield [63]. Of the nine stations showing increasing nitrate trends, changes at six stations were statistically significant ($p < 0.05$), including the one detected at WLP. Similar patterns of elevated nitrate levels were also revealed at stations located downstream of densely populated areas, including WVT and WTC [62], and can therefore be attributed to increased urbanization. Downward trends, though not statistically significant ($p > 0.05$), were observed at five stations.

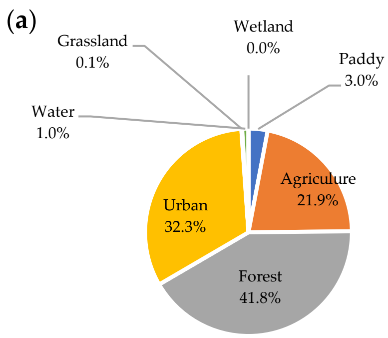
Table 2.3: Results of the Seasonal Mann–Kendall (SMK) analysis on TSS and nitrate time series data (red box represents $p < 0.01$, orange represents $p < 0.05$).

Water Quality Indicators	Statistical tests	Upper Section							Lower Section						
		WCS	WLP	WVT	WNP	WSK	WKC	WPS	WST	WKT	WKA	WCC	WNL	WKS	WTC
TSS	z-values	−0.35	−0.23	−0.1	−0.24	0.01	−0.13	−0.2	0.0	−0.1	−0.03	−0.02	0.08	0.0	0.16
	p-value	0.00	0.00	0.02	0.00	0.88	0.00	0.00	1.0	0.00	0.55	0.66	0.29	0.92	0.00
Nitrate	z-values	0.06	0.35	0.25	−0.02	0.28	−0.07	0.23	0.08	0.03	−0.09	−0.05	0.16	−0.07	0.03
	p-value	0.13	0.00	0.00	0.56	0.00	0.07	0.00	0.27	0.55	0.04	0.28	0.00	0.15	0.42

2.4.5 Temporal Relationships between Land Use Change and Proxies of Water Quality

To ascertain whether temporal changes in LULC influenced TSS and nitrate levels, Pearson's correlation analyses were carried out at Vientiane Sub-basin (SVT) using available data from 1993 to 2015. SVT was selected as the representative of the LMB dynamics due to the rapid changes of LULC composition stemming from its increased economic growth, with an average annual GDP growth rate of 7.1% (highest among the four Lower Mekong Countries) during the time period analyzed [64]. Moreover, the main land cover types of the sub-basin were forest, grassland, and agricultural areas (Figure 2.9a), though their proportions changed from 1993 to 2015. Grasslands were reduced by 13.7% from 1993 to 2015, whereas areas of agriculture, paddy fields, forest, and urban expanded during the same period. Urban growth was the most significant, with a 600% increase with respect to the area recorded in 1993. This is consistent with prior research [65], that found an 11% annual growth rate (2005 to 2015) of Vientiane's population was prompted by the change in the government anti-urban policy, and this instigated a new economic mechanism that promoted international trade and free market, resulting in an increase of industrialized activities and in-migration [65]. Despite the rapid growth of the urban population, the results of the Pearson's correlation analysis show that urbanization was not detrimental to agricultural land, paddy fields, and forest areas. Urban expansion appears to mainly affect grasslands ($p < 0.01$ and $r > -0.70$) (Figure 2.9b), and it confirms the findings of a prior study, which cited rapid urbanization as the cause for the reduction of grassland areas in the SVT [66].

(a)



(b)

		Agriculture	Paddy fields	Forest	Grassland	Urban	Wetland	TSS (mg/L)	Nitrate (mg/L)
		% LULC parameters						Water quality Indicators	
		Pearson's correlation matrix							
% LULC parameters	Agriculture	1.00	0.92	0.51	−0.98	0.75	0.55	−0.54	0.70
	Paddy fields	0.00	1.00	0.49	−0.87	0.71	−0.91	−0.49	0.63
	Forest	0.01	0.02	1.00	−0.67	0.20	0.45	−0.72	0.05
	Grassland	0.00	0.00	0.00	1.00	−0.70	−0.57	0.63	−0.61
	Urban	0.00	0.00	0.36	0.00	1.00	0.00	−0.27	0.44
	Wetland	0.01	0.01	0.03	0.00	0.98	1.00	−0.42	0.50
Water Quality Indicators	TSS (mg/L)	0.01	0.01	0.00	0.00	0.22	0.05	1.00	−0.08
	Nitrate (mg/L)	0.00	0.00	0.81	0.00	0.04	0.02	0.72	1.00
		Statistical significance matrix							

Figure 2.9: (**a**) Mean proportion of LULC in SVT from 1993 to 2015 [33] and (**b**) their relationships with one another and with water quality indicators (see Figure 2.4 for the legend).

The Pearson's analysis revealed positive correlations (r > 0.44) between instream nitrate concentrations and agriculture, paddy field, urban, and wetland land use types, while negatively associated with grassland (r = −0.61) (Figure 2.9b). With $p < 0.01$, these relationships were significant, suggesting these LULC types as the contributors to the nitrate levels observed at WVT (located in the Vientiane sub-basin, see Table 2.1). Specifically, the increase of urban (+ 615%) and agriculture areas (+17.5%) at the expense of grasslands (-13.7%) has led to increased instream nitrate levels. The association of nitrate levels with agriculture and urban land covers is consistent with findings from prior research [66–69]. Furthermore, rapid urbanization has been known to increase instream nutrient levels, particularly in areas with poor sewage treatment [70]. During the study period, mean annual concentrations of nitrate were 0.25 mg/L, with the minimum and maximum ranging from 0.06 to 0.39 mg/L, respectively. Factor analysis of the time series data revealed different clusters of concentrations (Appendix 2.E). Specifically, from 1993 to 1998, nitrate levels were lower than average, and that coincided with a higher percentage of grassland cover, which can prevent nitrate runoff to the river [71]. As the areas of grassland decreased, instream concentrations of nitrate increased (Appendix 2.E). From 2004 onwards, nitrate concentrations became positively correlated with agriculture, paddy fields, and urban areas (Appendix 2.E). During this period, mean annual concentrations of nitrate increased, reaching the maximum value at 0.39 mg/L in 2012. In 2013, the government issued a Strategic Framework for the Development of the Urban Water Supply and Sanitation Sector 2013–2030 [72], which may explain the negative association between the extension of urban areas and nitrate levels between 2012 and 2015. Of note is that, in the 1990s, Vientiane had an annual population growth rate of 3.1%, yet this annual growth rate translated into an increase in areal extent of urban land cover of only 6% over the same time period [73]. This suggests densely populated areas as characteristic of urban development of Vientiane, which prior research [72] found had poor sewerage coverage. The latter may explain the temporal association observed between nitrate levels and urban land use during the 1990s (Appendix 2.E).

The temporal relationships between LULC and TSS at WVT are shown in Figure 2.9b; from 1993 to 2015, TSS exhibited significant negative associations ($p < 0.01$) with forest (r = -0.72), agricultural (r = -54), and paddy field areas (r = −0.49), while a positive association was observed between TSS and grassland (r = 0.63 and $p < 0.01$). The results suggest that changes in forest, grassland, and agricultural areas were the driving forces of the changes observed in TSS levels during this period. The temporal relationship detected between forest and TSS aligns with results from previous studies, which argued that increases in vegetation cover can generally lead to a decrease in soil erosion [74–76]. While the relationship between urban land cover and TSS is very weak (p = 0.36), it nonetheless support findings of previous research [77] where urban land cover yielded less TSS than other land cover types. Urbanization tends to increase impervious surface area and, consequently, to reduce erosion and sediment runoff during rainfall events [78]. However, in the LMB, urbanization does not necessarily increase impervious surface, as unpaved roads and bare land continue to exist in many cities including Vientiane, as illustrated in Appendix 2.F. This could be a factor weakening the relationship between urban land cover and TSS in SVT.

2.5 Conclusions

This research set out to explore the spatiotemporal relationships between LULC and water quality of the LMR using TSS and nitrate as proxies for water quality indicators. This information is vital to assess the impact of socioeconomic drivers and pressures on freshwater sources of the region.

Historical time series of TSS and nitrate at 14 water quality monitoring stations and their associations with multi-temporal information on LULC evidence that the water quality of the LMB is influenced differently by LULC types over time and space. At the temporal scale, the analysis of 30 years of data revealed that instream TSS concentrations exhibited decreasing trends at nine of the 14 stations considered, while an increasing trend was detected at one station. For instream nitrate concentrations, temporal changes varied from station to station, with significant increasing trends detected at five stations of the upper section of the LMB. Instream concentrations of nitrate and TSS were highly correlated with the river discharge and exhibited clear seasonality patterns, and their historical trends appear to be related to the distinctive wet and dry seasons of the region. In contrast, the primary drivers of change appear to be human disturbance through land use practices and instream infrastructure development. Our results evidence, for example, that decreases in TSS levels at stations located in the upper section of the LMR coincided with the operation of the Manwan Hydropower. The operational influences of the mainstream dams located in the UMB on TSS appear to be less profound at stations located in the MD, as these stations exhibited increasing trends during the same time period.

Temporal analyses of the time series data for the Vientiane sub-catchment (SVT in Section 2.4.5) further confirmed the influence of land use practices. At the SVT, the proportion of forest, agriculture, and urban land cover types increased from 1993 to 2015, while the opposite trend occurred with grasslands. These dynamics of LULC change coincided with decreased instream TSS levels, and our analysis shows a positive relationship between instream TSS and grassland, but significant negative relationships with agriculture, forest, and urban land use types. Conversely, the historic trend of instream nitrate concentration increased, suggesting that the increased level was driven by the expansion of urban and agricultural areas at the expenses of grasslands. These changes appear to increase nitrate-laden runoff in the basin, while, at the same time, reducing the basin's natural filtering capacity.

At a spatial level, the values of year 2010 for the proxies representing water quality were compared with the 2010 LULC surface areas. The results (Section 2.4.2.2) suggest that as the proportion of forest areas increased, instream concentrations for both TSS and nitrate also increased. For nitrate, its instream concentrations also increased as the proportion of grassland increased. These results contradict findings from other studies and suggest that water quality of the LMR is influenced by LULC and other factors, such as soil, topography, hydropower development, and land cultivation practices. TSS and nitrate levels were highest in sub-catchments dominated by forest land cover, steep slopes, and easily erodible soil types, as well as those exposed to intensive shifting cultivation practices involving vegetation clearance at the onset of the Wet season.

The strong relationships found between mean slope percentages of sub-catchments and instream concentration of TSS and nitrate suggest that the detachment and runoff of sediment-laden nutrients from forest-dominated areas led to increases of instream concentrations of these water quality indicators. These results confirmed that a combination of landform, topography, and human disturbances through land use practices influenced the instream levels of TSS and nitrate.

Identifying factors influencing changes in the condition of water quality is vital for sustaining development of land and water resources, particularly in the context of the LMB, where development is undertaken at an unprecedentedly rapid pace. This study has enhanced understanding of spatiotemporal dynamics and relationships between LULC and water quality in the LMB, and can advance knowledge on how water quality of the LMR may be protected through appropriate land use planning and development interventions.

2.6 Author Contributions

Conceptualization, K.L., G.M., and L.M.; methodology, K.L. and G.M.; validation and formal analysis, K.L. and L.M.; investigation, resources, and data curation, K.L.; writing—original and revised draft preparation, K.L.; review and editing, G.M. and L.M. All authors have read and agreed to the published version of the manuscript.

2.7 Funding

This research received no external funding.

2.8 Acknowledgements

This research is supported by an Australian Award Scholarship for Kongmeng Ly.

2.9 Conflict of Interest

The authors declare no conflict of interest.

2.10 References

1. Tu, J. Spatial Variations in the Relationships between Land Use and Water Quality across an Urbanization Gradient in the Watersheds of Northern Georgia, USA. *Environ. Manag.* **2013**, *51*, 1–17.
2. Connolly, N.M.; Pearson, R.G.; Loong, D.; Maughan, M.; Brodie, J. Water quality variation along streams with similar agricultural development but contrasting riparian vegetation. *Agric. Ecosyst. Environ.* **2015**, *213*, 11–20.
3. Yu, D.; Shi, P.; Liu, Y.; Xun, B. Detecting land use-water quality relationships from the viewpoint of ecological restoration in an urban area. *Ecol. Eng.* **2013**, *53*, 205–216.
4. Lawniczak, A.E.; Zbierska, J.; Nowak, B.; Achtenberg, K.; Grześkowiak, A.; Kanas, K. Impact of agriculture and land use on nitrate contamination in groundwater and running waters in Central-West Poland. *Environ. Monit. Assess.* **2016**, *188*, 172.
5. Monaghan, R.M.; Wilcock, R.J.; Smith, L.C.; Tikkisetty, B.; Thorrold, B.S.; Costall, D. Linkages between land management activities and water quality in an intensively farmed catchment in Southern New Zealand. *Agric. Ecosyst. Environ.* **2007**, *118*, 211–222.
6. Adams, V.M.; Pressey, R.L.; Stoeckl, N. Navigating trade-offs in land-use planning: Integrating human well-being into objective setting. *Ecol. Soc.* **2014**, *19*, 53.
7. Vandeberg, G.; Dixon, C.; Vose, B.; Fisher, M. Spatial assessment of water quality in the vicinity of Lake Alice National Wildlife Refuge, Upper Devils Lake Basin, North Dakota. *Environ. Monit. Assess.* **2015**, *187*, 1–19.
8. Johnson, H.O.; Gupta, S.C.; Vecchia, A.V.; Zvomuya, F. Assessment of Water Quality Trends in the Minnesota River using Non-Parametric and Parametric Methods. *J. Environ. Qual.* **2009**, *38*, 1018–1030.
9. Barril, C.R.; Tumlos, E.T. Water quality trends and trophic state assessment of Laguna de Bay, Philippines. *Aquat. Ecosyst. Health Manag.* **2002**, *5*, 115–126.

10. Mouri, G.; Takizawa, S.; Oki, T. Spatial and temporal variation in nutrient parameters in stream water in a rural-urban catchment, Shikoku, Japan: Effects of land cover and human impact. *J. Environ. Manag.* **2011**, *92*, 1837–1848.
11. Allan, D.; Erickson, D.; Fay, J. The Influence of Catchment Land Use on Stream Integrity Across Multiple Spatial Scales. *Freshw. Biol.* **1997**, *37*, 149–161.
12. Valentin, C.; Agus, F.; Alamban, R.; Boosaner, A.; Bricquet, J.P.; Chaplot, V.; de Guzman, T.; de Rouw, A.; Janeau, J.L.; Orange, D.; et al. Runoff and sediment losses from 27 upland catchments in Southeast Asia: Impact of rapid land use changes and conservation practices. *Agric. Ecosyst. Environ.* **2008**, *128*, 225–238.
13. Kim, H.; Jeong, H.; Jeon, J.; Bae, S. The Impact of Impervious Surface on Water Quality and Its Threshold in Korea. *Water* **2016**, *8*, 111.
14. Chang, H. Spatial analysis of water quality trends in the Han River basin, South Korea. *Water Res.* **2008**, *42*, 3285–3304.
15. Sithong, T.; Yayoi, F. Recent Land Use and Livelihoods Transitions in Northern Laos. *Mt. Res. Dev.* **2006**, *26*, 237–244.
16. Pham, H.T.; Miyagawa, S.; Kosaka, Y. Distribution patterns of trees in paddy field landscapes in relation to agro-ecological settings in northeast Thailand. *Agric. Ecosyst. Environ.* **2015**, *202*, 42–47.
17. Crews-Meyer, K.A. Agricultural landscape change and stability in northeast Thailand: Historical patch-level analysis. *Agric. Ecosyst. Environ.* **2004**, *101*, 155–169.
18. Takamatsu, M.; Kawasaki, A.; Rogers, P.; Malakie, J. Development of a land-use forecast tool for future water resources assessment: Case study for the Mekong River 3S Sub-basins. *Sustain. Sci.* **2014**, *9*, 157–172.
19. Rutten, M.; van Dijk, M.; van Rooij, W.; Hilderink, H. Land Use Dynamics, Climate Change, and Food Security in Vietnam: A Global-to-local Modeling Approach. *World Dev.* **2014**, *59*, 29–46.

20. Laungaramsri, P. Frontier capitalism and the expansion of rubber plantations in southern Laos. *J. Southeast Asian Stud.* **2012**, *43*, 463–477.
21. Manivong, V.; Cramb, R.A. Economics of smallholder rubber expansion in Northern Laos. *Agrofor. Syst.* **2008**, *74*, 113–125.
22. Arias, M.E.; Cochrane, T.A.; Kummu, M.; Lauri, H.; Holtgrieve, G.W.; Koponen, J.; Piman, T. Impacts of hydropower and climate change on drivers of ecological productivity of Southeast Asia's most important wetland. *Ecol. Model.* **2014**, *272*, 252–263.
23. Manh, N.V.; Dung, N.V.; Hung, N.N.; Kummu, M.; Merz, B.; Apel, H. Future sediment dynamics in the Mekong Delta floodplains: Impacts of hydropower development, climate change and sea level rise. *Glob. Planet. Chang.* **2015**, *127*, 22–33.
24. Pokhrel, Y.; Burbano, M.; Roush, J.; Kang, H.; Sridhar, V.; Hyndman, D. A Review of the Integrated Effects of Changing Climate, Land Use, and Dams on Mekong River Hydrology. *Water* **2018**, *10*, 266.
25. Hecht, J.S.; Lacombe, G.; Arias, M.E.; Dang, T.D.; Piman, T. Hydropower dams of the Mekong River basin: A review of their hydrological impacts. *J. Hydrol.* **2019**, *568*, 285–300.
26. Mekong River Commission. *Planning Atlas of the Lower Mekong River Basin*; Mekong River Commission: Vientiane, Laos, 2011.
27. Kummu, M.; Sarkkula, J. Impact of the Mekong River Flow Alteration on the Tonle Sap Flood Pulse. *AMBIO J. Hum. Environ.* **2008**, *37*, 185–192.
28. Lap Nguyen, V.; Ta, T.K.O.; Tateishi, M. Late Holocene depositional environments and coastal evolution of the Mekong River Delta, Southern Vietnam. *J. Asian Earth Sci.* **2000**, *18*, 427–439.
29. IUSS Working Group. WRB World Reference Base for Soil Resources 2014. Available online: http://www.fao.org/3/i3794en/I3794en.pdf (accessed on 18 January 2020).

30. Leinenkugel, P.; Wolters, M.L.; Oppelt, N.; Kuenzer, C. Tree cover and forest cover dynamics in the Mekong Basin from 2001 to 2011. *Remote Sens. Environ.* **2015**, *158*, 376–392.
31. Lacombe, G.; Valentin, C.; Sounyafong, P.; de Rouw, A.; Soulileuth, B.; Silvera, N.; Pierret, A.; Sengtaheuanghoung, O.; Ribolzi, O. Linking crop structure, throughfall, soil surface conditions, runoff and soil detachment: 10 land uses analyzed in Northern Laos. *Sci. Total Environ.* **2018**, *616–617*, 1330–1338.
32. Suif, Z.; Fleifle, A.; Yoshimura, C.; Saavedra, O. Spatio-temporal patterns of soil erosion and suspended sediment dynamics in the Mekong River Basin. *Sci. Total Environ.* **2016**, *568*, 933–945.
33. European Space Agency. *Land Cover Newsletter*; European Space Agency: Paris, France, 2017; Volume 7.
34. ESRI. *ArcGIS Desktop*, Environmental Systems Research Institute: Redlands, CA, USA, 2014.
35. Jenson, S.K.; Domingue, J.O. Extracting Topographic Structure from Digital Elevation Data for Geographic Information-System Analysis. *Photogramm. Eng. Remote Sens.* **1988**, *54*, 1593–1600.
36. American Public Health Association. *Standard Methods for the Examination of Water and Wastewater*; APHA-AWWA-WEF: Washington, DC, USA, 2005.
37. MathWorks. *MATLAB version 7.10. 0 (R2010a)*; The MathWorks: Natick, MA, USA, 2010.
38. Cleveland, R.B.; Cleveland, W.S.; Terpenning, I. STL: A Seasonal-Trend Decomposition Procedure Based on Loess. *J. Off. Stat.* **1990**, *6*, 3.
39. Wan, Y.; Wan, L.; Li, Y.; Doering, P. Decadal and seasonal trends of nutrient concentration and export from highly managed coastal catchments. *Water Res.* **2017**, *115*, 180–194.

40. Wan, L.; Li, Y.C. Time series trend analysis and prediction of water quality in a managed canal system, Florida (USA). In *IOP Conference Series: Earth and Environmental Science, Proceedings of the The 4th International Conference on Water Resource and Environment (WRE 2018)*, Kaohsiung City, Taiwan, 17–21 July 2018; IOP Publishing: Bristol, UK, 2018; Volume 191, p. 012013.
41. Hyndman, R.J.; Athanasopoulos, G. *Forecasting: Principles and Practice*; OTexts: Melbourne, Australia, 2018.
42. R Development Core Team. *R: A Language and Environment for Statistical Computing*; R Foundation for Statistical Computing: Vienna, Austria, 2008.
43. Cleveland, W.S.; Devlin, S.J. Locally Weighted Regression: An Approach to Regression Analysis by Local Fitting. *J. Am. Stat. Assoc.* **1988**, *83*, 596–610.
44. Fu, L.; Wang, Y.-G. Statistical Tools for Analyzing Water Quality Data. Available online: https://www.intechopen.com/books/water-quality-monitoring-and-assessment/statistical-tools-for-analyzing-water-quality-data (accessed on 11 November 2017).
45. Hirsch, R.; Slack, J.R.; Smith, R. Techniques of Trend Analysis for Monthly Water Quality Data. *Water Resour. Res.* **1982**, *18*, 107–121.
46. Xu, G.; Li, P.; Lu, K.; Tantai, Z.; Zhang, J.; Ren, Z.; Wang, X.; Yu, K.; Shi, P.; Cheng, Y. Seasonal changes in water quality and its main influencing factors in the Dan River basin. *CATENA* **2019**, *173*, 131–140.
47. Aquilina, L.; Vergnaud-Ayraud, V.; Labasque, T.; Bour, O.; Molénat, J.; Ruiz, L.; de Montety, V.; De Ridder, J.; Roques, C.; Longuevergne, L. Nitrate dynamics in agricultural catchments deduced from groundwater dating and long-term nitrate monitoring in surface- and groundwaters. *Sci. Total Environ.* **2012**, *435–436*, 167–178.
48. Wang, C.; Zheng, S.-S.; Wang, P.-F.; Hou, J. Interactions between vegetation, water flow and sediment transport: A review. *J. Hydrodyn. Ser. B* **2015**, *27*, 24–37.

49. Chaplot, V.; Khampaseuth, X.; Valentin, C.; Bissonnais, Y.L. Interrill erosion in the sloping lands of Northern Laos subjected to shifting cultivation. *Earth Surf. Process. Landf.* **2007**, *32*, 415–428.
50. Sidle, R.C.; Ziegler, A.D.; Negishi, J.N.; Nik, A.R.; Siew, R.; Turkelboom, F. Erosion processes in steep terrain—Truths, myths, and uncertainties related to forest management in Southeast Asia. *For. Ecol. Manag.* **2006**, *224*, 199–225.
51. Wemple, B.C.; Browning, T.; Ziegler, A.D.; Celi, J.; Chun, K.P.; Jaramillo, F.; Leite, N.K.; Ramchunder, S.J.; Negishi, J.N.; Palomeque, X.; et al. Ecohydrological disturbances associated with roads: Current knowledge, research needs, and management concerns with reference to the tropics. *Ecohydrology* **2018**, *11*, e1881.
52. Rijsdijk, A.; Sampurno Bruijnzeel, L.A.; Sutoto, C.K. Runoff and sediment yield from rural roads, trails and settlements in the upper Konto catchment, East Java, Indonesia. *Geomorphology* **2007**, *87*, 28–37.
53. Chaplot, V.; Poesen, J. Sediment, soil organic carbon and runoff delivery at various spatial scales. *CATENA* **2012**, *88*, 46–56.
54. Inoue, Y.; Qi, J.; Olioso, A.; Kiyono, Y.; Horie, T.; Asai, H.; Saito, K.; Ochiai, Y.; Shiraiwa, T.; Douangsavanh, L. Reflectance characteristics of major land surfaces in slash-and-burn ecosystems in Laos. *Int. J. Remote Sens.* **2008**, *29*, 2011–2019.
55. Fujisaka, S. A diagnostic survey of shifting cultivation in Northern Laos: Targeting research to improve sustainability and productivity. *Agrofor. Syst.* **1991**, *13*, 95–109.
56. Fox, J.; Vogler, J.B.; Sen, O.L.; Giambelluca, T.W.; Ziegler, A.D. Simulating Land-Cover Change in Montane Mainland Southeast Asia. *Environ. Manag.* **2012**, *49*, 968–979.
57. Ribolzi, O.; Evrard, O.; Huon, S.; de Rouw, A.; Silvera, N.; Latsachack, K.O.; Soulileuth, B.; Lefèvre, I.; Pierret, A.; Lacombe, G.; et al. From shifting cultivation to teak plantation: Effect on overland flow and sediment yield in a montane tropical catchment. *Sci. Rep.* **2017**, *7*, 3987.

58. Fleifle, A.E. Suspended Sediment Load Monitoring Along the Mekong River from Satellite Images. *J. Earth Sci. Clim. Chang.* **2013**, *4*, 160.
59. Dahlgren, R.A.; Macías, F.; Arbestain, M.C.; Chesworth, W.; Robarge, W.P.; Macías, F. Acrisols. In *Encyclopedia of Soil Science*; Chesworth, W., Ed.; Springer: Dordrecht, The Netherlands, 2008; pp. 22–24.
60. Kummu, M.; Varis, O. Sediment-related impacts due to upstream reservoir trapping, the Lower Mekong River. *Geomorphology* **2007**, *85*, 275–293.
61. Schuetz, T.; Gascuel-Odoux, C.; Durand, P.; Weiler, M. Nitrate sinks and sources as controls of spatio-temporal water quality dynamics in an agricultural headwater catchment. *Hydrol. Earth Syst. Sci.* **2016**, *20*, 843–857.
62. Chea, R.; Grenouillet, G.; Lek, S. Evidence of Water Quality Degradation in Lower Mekong Basin Revealed by Self-Organizing Map. *PLoS ONE* **2016**, *11*, e0145527.
63. Poffenbarger, H.J.; Sawyer, J.E.; Barker, D.W.; Olk, D.C.; Six, J.; Castellano, M.J. Legacy effects of long-term nitrogen fertilizer application on the fate of nitrogen fertilizer inputs in continuous maize. *Agric. Ecosyst. Environ.* **2018**, *265*, 544–555.
64. World Bank Group. (Ed.) GDP per capita growth (annual %)-Lao PDR. In *Data Catolog*; World Bank National Accounts Data, and OECD National Accounts Data Files; World Bank Group: Washington, DC, USA, 2019.
65. Epprecht, M.; Bosoni, N.; Hayward, D. *Urbanization Processes in the Lao PDR*; Centre for Development and Environment: Vientiane, Laos, 2018.
66. Okamoto, K.; Sharifi, A.; Chiba, Y. The Impact of Urbanization on Land Use and the Changing Role of Forests in Vientiane. In *Integrated Studies of Social and Natural Environmental Transition in Laos*; Yokoyama, S., Okamoto, K., Takenaka, C., Hirota, I., Eds.; Springer: Tokyo, Japan, 2014; pp. 29–38.
67. Salvia-Castellví, M.; François Iffly, J.; Vander Borght, P.; Hoffmann, L. Dissolved and particulate nutrient export from rural catchments: A case study from Luxembourg. *Sci. Total Environ.* **2005**, *344*, 51–65.

68. Schilling, K.E. Chemical transport from paired agricultural and restored prairie watersheds. *J. Environ. Qual.* **2002**, *31*, 1184–1193.
69. Buck, O.; Niyogi, D.K.; Townsend, C.R. Scale-dependence of land use effects on water quality of streams in agricultural catchments. *Environ. Pollut.* **2004**, *130*, 287–299.
70. Tromboni, F.; Dodds, W. Relationships between Land Use and Stream Nutrient Concentrations in a Highly Urbanized Tropical Region of Brazil: Thresholds and Riparian Zones. *Environ. Manag.* **2017**, *60*, 30–40.
71. Arheimer, B.; Lidén, R. Nitrogen and phosphorus concentrations from agricultural catchments—Influence of spatial and temporal variables. *J. Hydrol.* **2000**, *227*, 140–159.
72. World Bank Group. *Water Supply and Sanitation in Lao PDR: Turning Finance into Services for the Future*; Water and Sanitation Program; World Bank Group: Washington, DC, USA, 2014.
73. JICA. Vientiane Capital Urban Development Master Plan-Proposal. Available online: https://www.jica.go.jp/project/english/laos/009/materials/pdf/pamphlet_01.pdf (accessed on 20 January 2020).
74. Morgan, R.P.C.; McIntyre, K.; Vickers, A.W.; Quinton, J.N.; Rickson, R.J. A rainfall simulation study of soil erosion on rangeland in Swaziland. *Soil Technol.* **1997**, *11*, 291–299.
75. Rey, F. Influence of vegetation distribution on sediment yield in forested marly gullies. *CATENA* **2003**, *50*, 549–562.
76. Snelder, D.J.; Bryan, R.B. The use of rainfall simulation tests to assess the influence of vegetation density on soil loss on degraded rangelands in the Baringo District, Kenya. *CATENA* **1995**, *25*, 105–116.
77. Mallin, M.A.; Johnson, V.L.; Ensign, S.H. Comparative impacts of stormwater runoff on water quality of an urban, a suburban, and a rural stream. *Environ. Monit. Assess.* **2009**, *159*, 475–491.

78. Shuster, W.D.; Bonta, J.; Thurston, H.; Warnemuende, E.; Smith, D.R. Impacts of impervious surface on watershed hydrology: A review. *Urban Water J.* **2005**, *2*, 263–275.

Appendix 2 – Chapter 2's Supplementary Information (SI)

Appendix 2.A – Land use classifications

LULC categories as defined by the MRC and ESA, and their aggregation into nine LULC types for this study (LULC classified as others (category number 10) was not used in this study).

Table A1. Land use classifications.

Category No.	LULC types (Parameters)	MRC 2010 LULC Data	ESA Global Land Cover Data (1993–2015)
1	Agriculture	Annual crop	Cropland (rainfed)
		Industrial plantation	
		Orchard	Mosaic cropland/vegetation
		Shifting cultivation	Mosaic vegetation/cropland
2	Paddy fields	Paddy rice	Cropland (irrigated)
3	Aquaculture	Aquaculture	-
4	Barren Land	Bare soil	Bare area
5	Forest	Bamboo forest	Broadleaved evergreen
		Coniferous forest	Broadleaved deciduous
		Deciduous forest	Needle-leaved evergreen
		Evergreen forest	Needle-leaved deciduous
		Flooded forest	Mixed leaf type
		Forest plantation	Mosaic tree, shrub/HC
		-	Mosaic HC/tree shrub
6	Grassland	Grassland	Shrubland
		Shrubland	Grassland
7	Urban	Urban area	Urban area
8	Water	Water body	Water bodies
9	Wetland	Mangrove	Tree flooded, fresh water
		Marsh/Swamp area	Tree flooded, saline water
		-	Shrub or herbaceous flooded
10*	Others*	-	Lichens and mosses
		-	Permanent snow and ice
		-	No data

Appendix 2.B – Temporal changes of LULC composition in the LMB

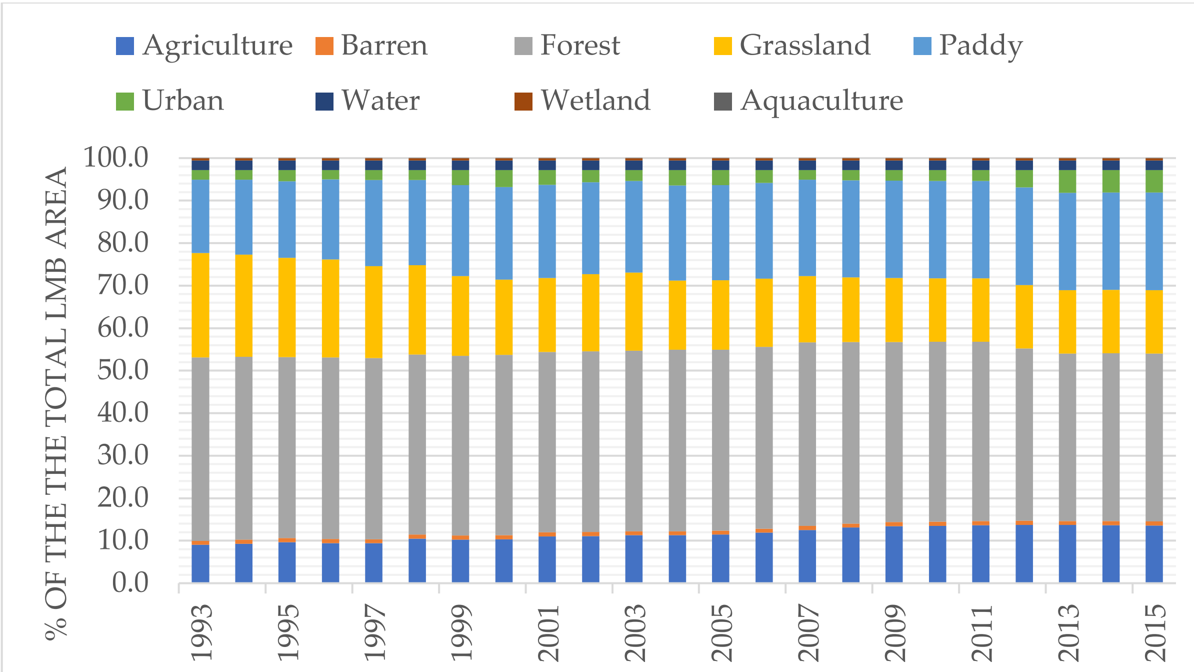


Figure A1. Proportion of annual land use/land cover of the entire LMB from 1993 to 2015.

Appendix 2.C – Types of soil in the LMB

The percentages of each soil type in the defined sub-basin are shown in Table A2.

Table A2. Soil characteristics of each sub-basin of the Lower Mekong Basin.

Sub-basins	Acrisol	Cambisol	Gleysol	Leptosol	Luvisol	Water	Others	total	Characteristic of the Dominant Soil Type
SCS	49%	25%	1%	2%	11%	0%	12%	100%	Low fertility; susceptible to significant erosion once vegetation cover is removed; very acidic, especially on the surface horizons
SLP	66%	16%	-	1%	3%	0%	14%	100%	
SVT	60%	18%	0%	0%	4%	1%	17%	100%	
SNP	80%	10%	2%	0%	1%	1%	6%	100%	
SSK	50%	16%	1%	8%	7%	1%	17%	100%	
SKC	70%	13%	0%	3%	2%	1%	10%	100%	
SPS	64%	1%	4%	0%	7%	2%	24%	100%	
SST	49%	31%	3%	2%	4%	3%	9%	100%	
SKT	68%	8%	4%	4%	1%	1%	14%	100%	
SKA	29%	-	3%	15%	17%	22%	15%	100%	
SCC	50%	14%	10%	9%	5%	4%	9%	100%	
SNL	55%	28%	7%	-	-	8%	3%	100%	
SKS	65%	14%	5%	-	-	6%	10%	100%	
STC	47%	16%	17%	6%	-	3%	12%	100%	

Appendix 2.D. TSS and Nitrate Time Series Decomposition

Appendix 2.D.1. TSS Time Series Decomposition

The decompositions of TSS time series at the 14 water quality monitoring stations in the Lower Mekong River are shown in Figures A2–A15.

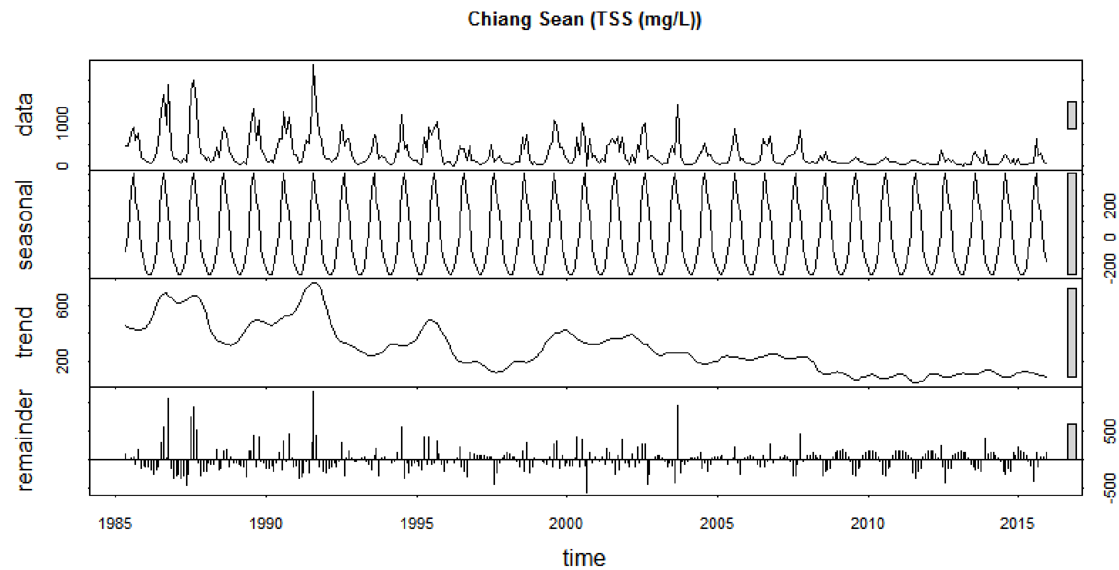


Figure A2. Decomposition of TSS time series at Chiang Sean Water Quality Monitoring Station (WCS).

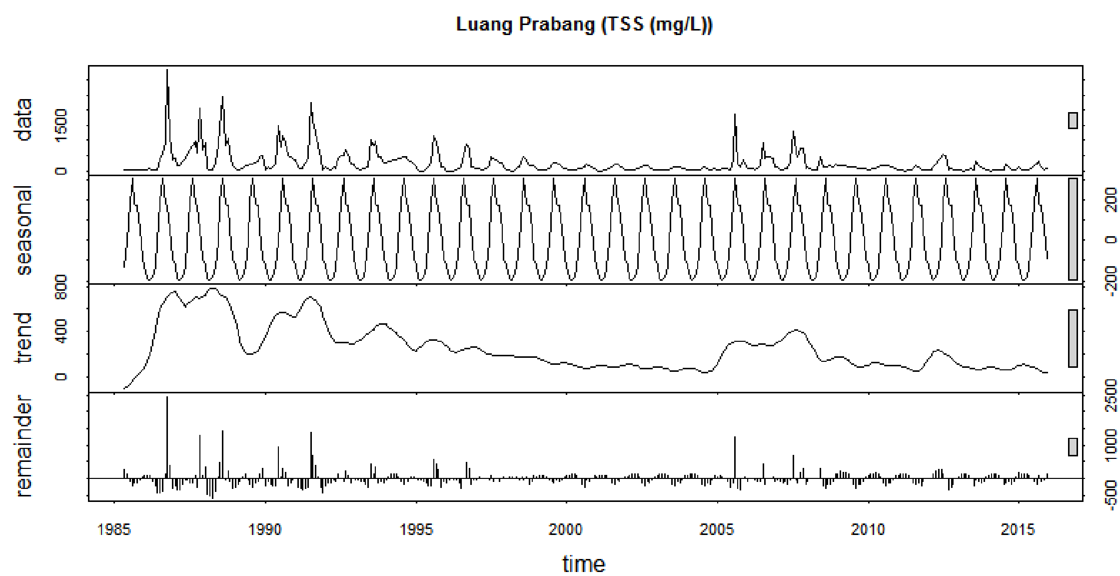


Figure A3 Decomposition of TSS time series at Luang Prabang Water Quality Monitoring Station (WLP).

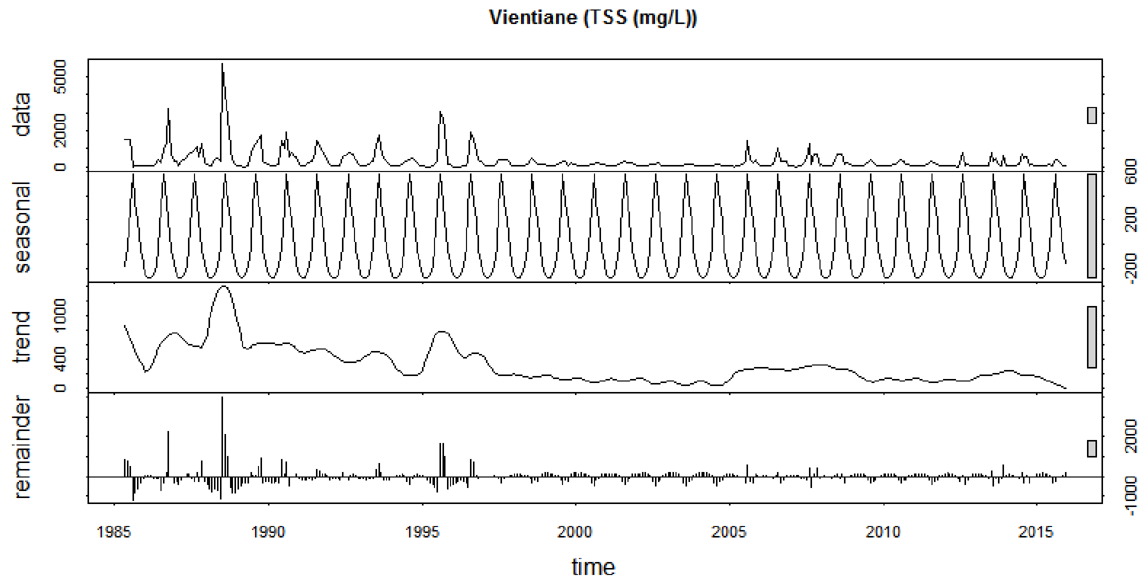


Figure A4. Decomposition of TSS time series at Vientiane Water Quality Monitoring Station (Station No. 4).

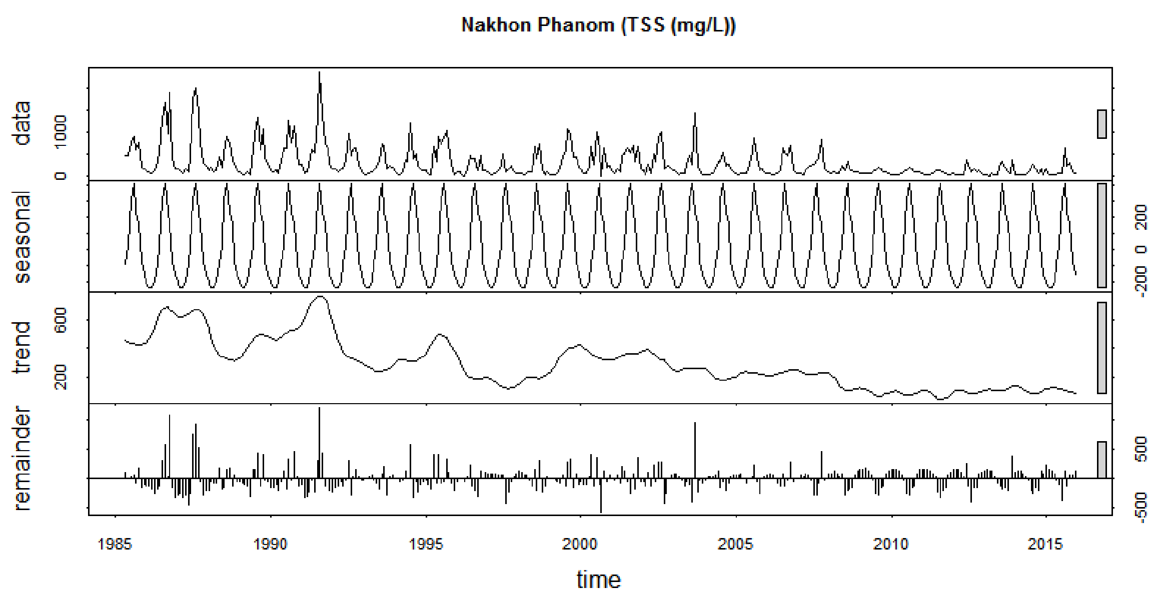


Figure A5. Decomposition of TSS time series at Nakhon Phanom Water Quality Monitoring Station (WNP).

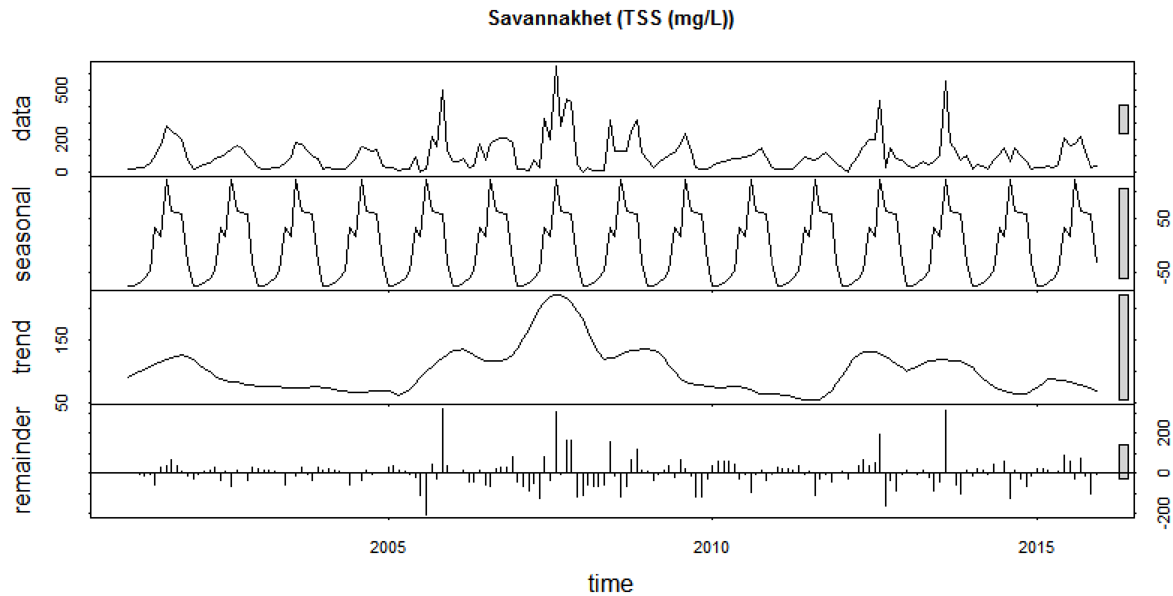


Figure A6. Decomposition of TSS time series at Savannakhet Water Quality Monitoring Station (WSK).

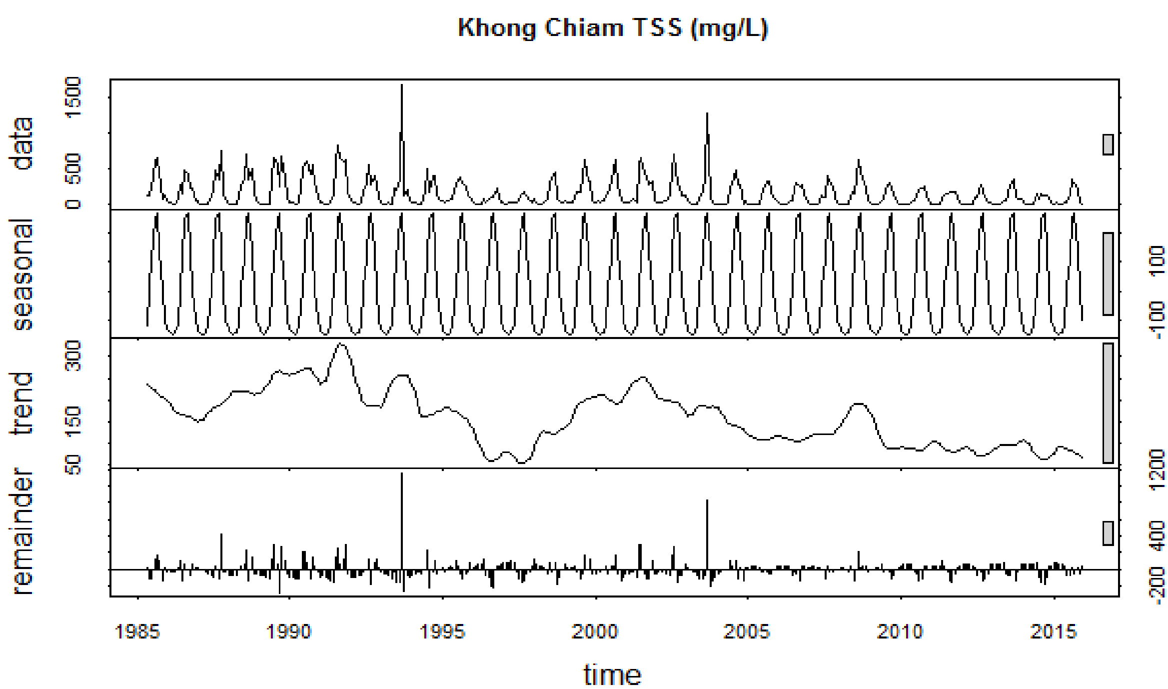


Figure A7. Decomposition of TSS time series at Khong Chiam Water Quality Monitoring Station (WKC).

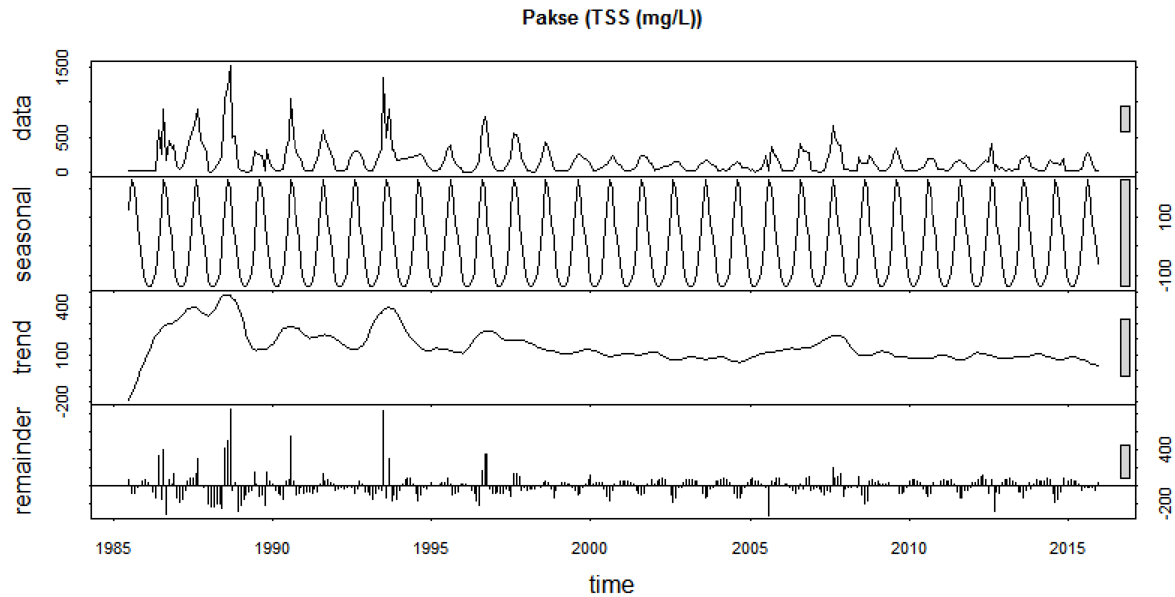


Figure A8. Decomposition of TSS time series at Pakse Water Quality Monitoring Station (WPS).

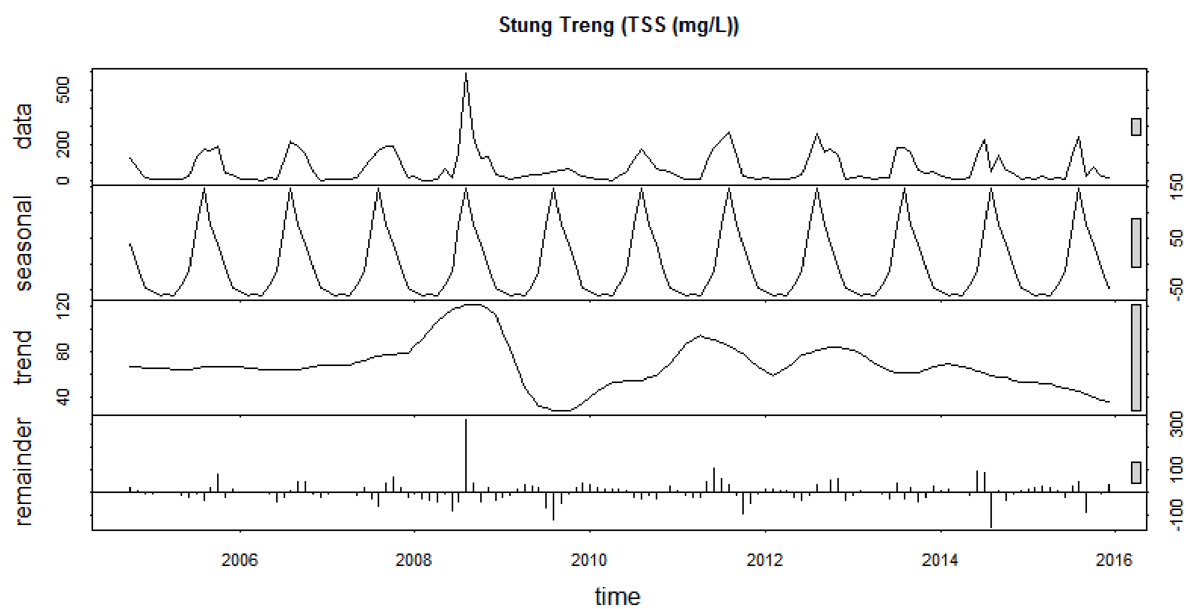


Figure A9. Decomposition of TSS time series at Khong Chiam Water Quality Monitoring Station (WST).

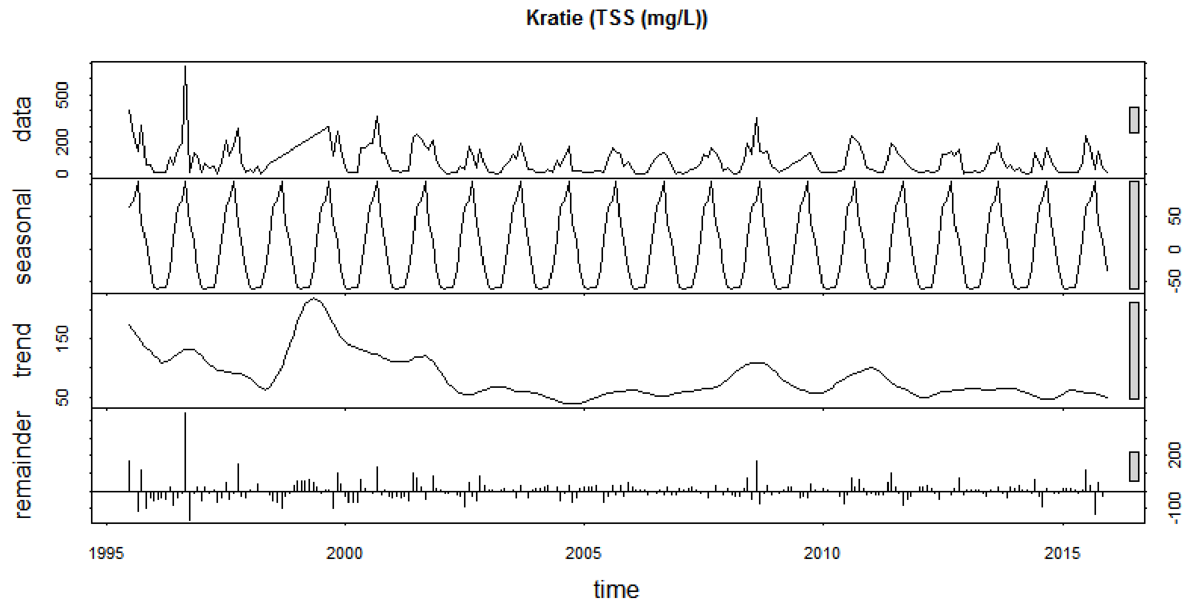


Figure A10. Decomposition of TSS time series at Kratie Water Quality Monitoring Station (WKT).

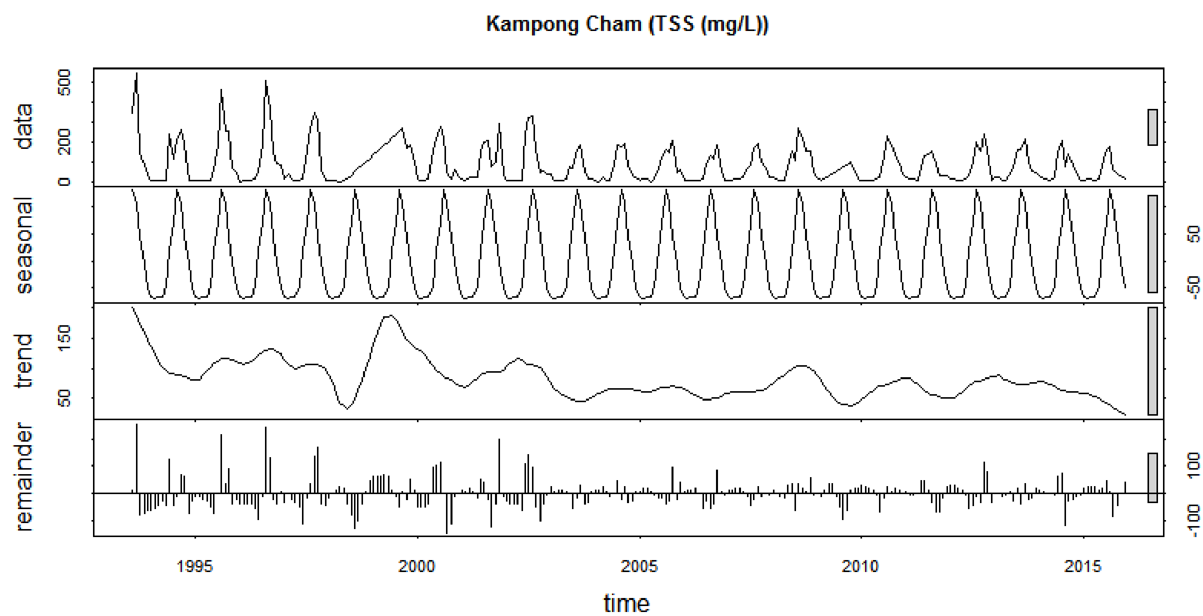


Figure A11. Decomposition of TSS time series at Kampong Cham Water Quality Monitoring Station (WKA).

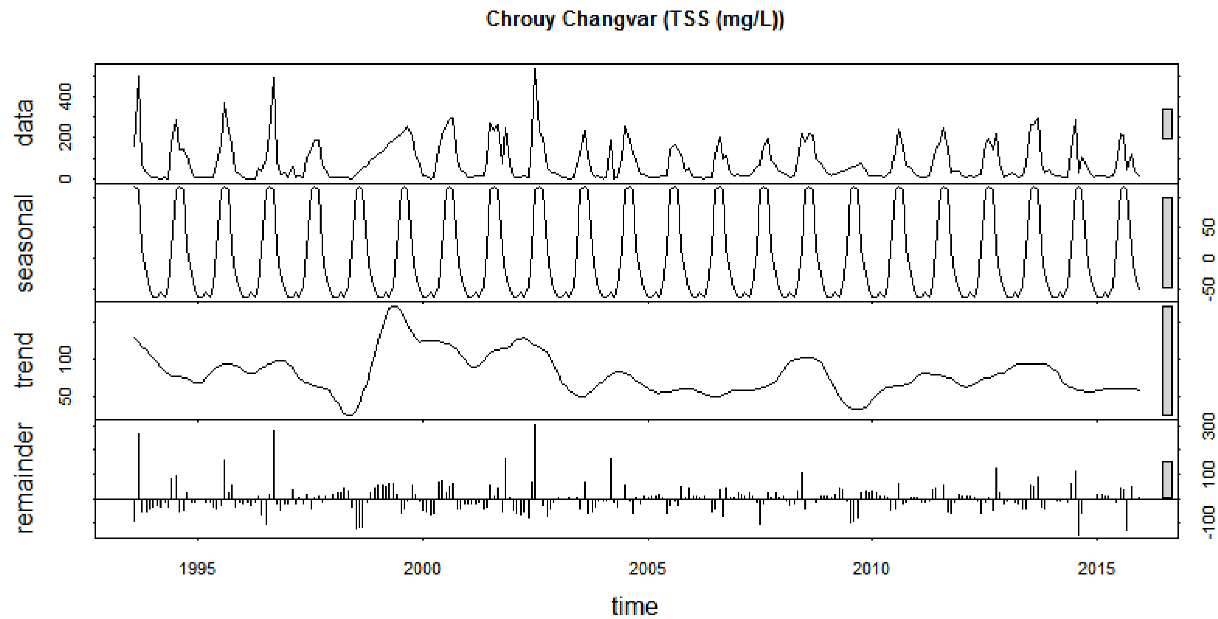


Figure A12. Decomposition of TSS time series at Chrouy Changvar Water Quality Monitoring Station (WCC).

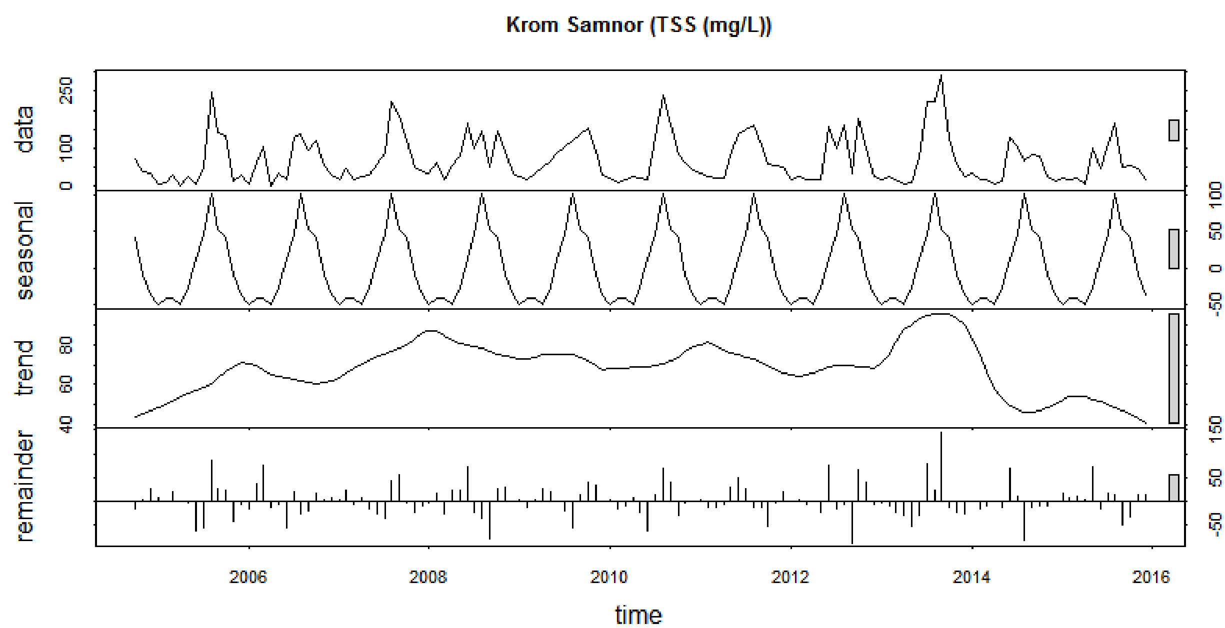


Figure A13. Decomposition of TSS time series at Krom Samnor Water Quality Monitoring Station (WKS).

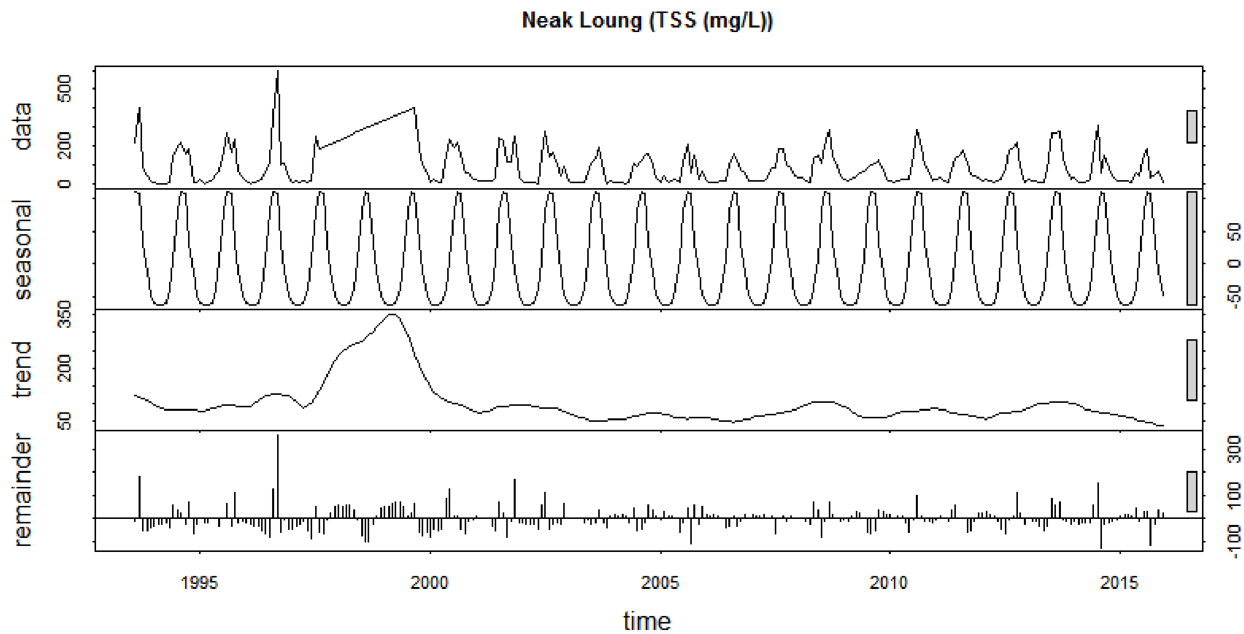


Figure A14. Decomposition of TSS time series at Neak Loung Water Quality Monitoring Station (WNL).

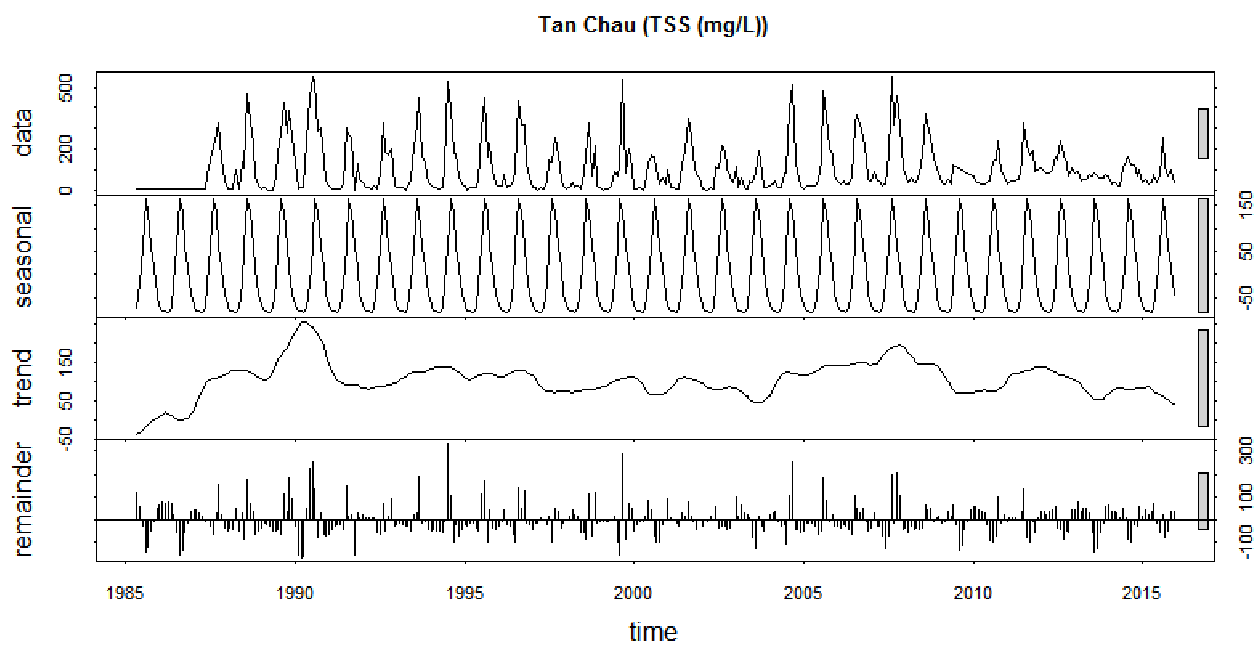


Figure A15. Decomposition of TSS time series at Tan Chau Water Quality Monitoring Station (WTC).

Appendix 2.D: Nitrate Time series Decomposition

The decompositions of nitrate time series at the 14 water quality monitoring stations in the Lower Mekong are shown in Figures A16–A29.

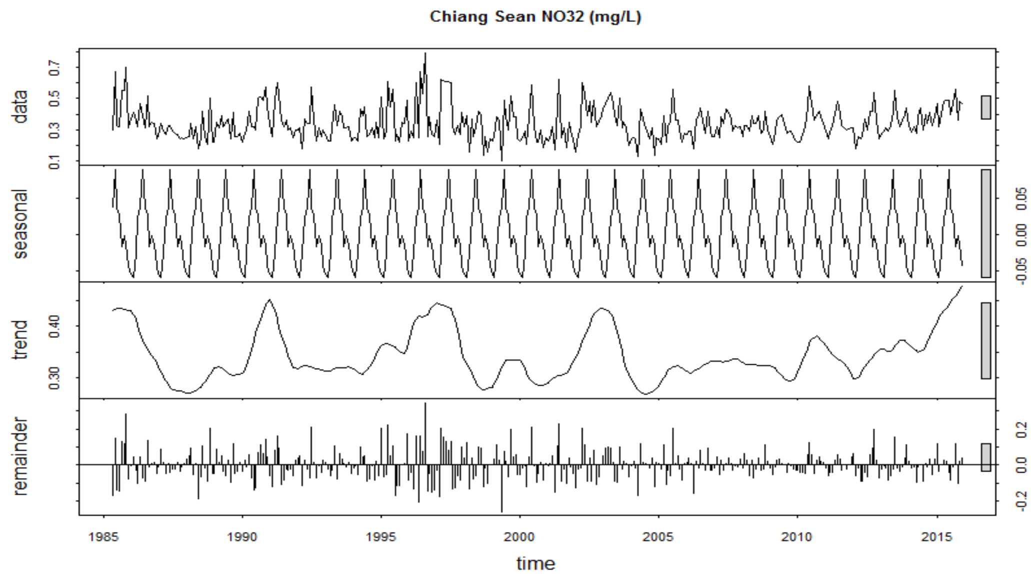


Figure A16. Decomposition of nitrate time series at Chiang Sean Water Quality Monitoring Station (WCS).

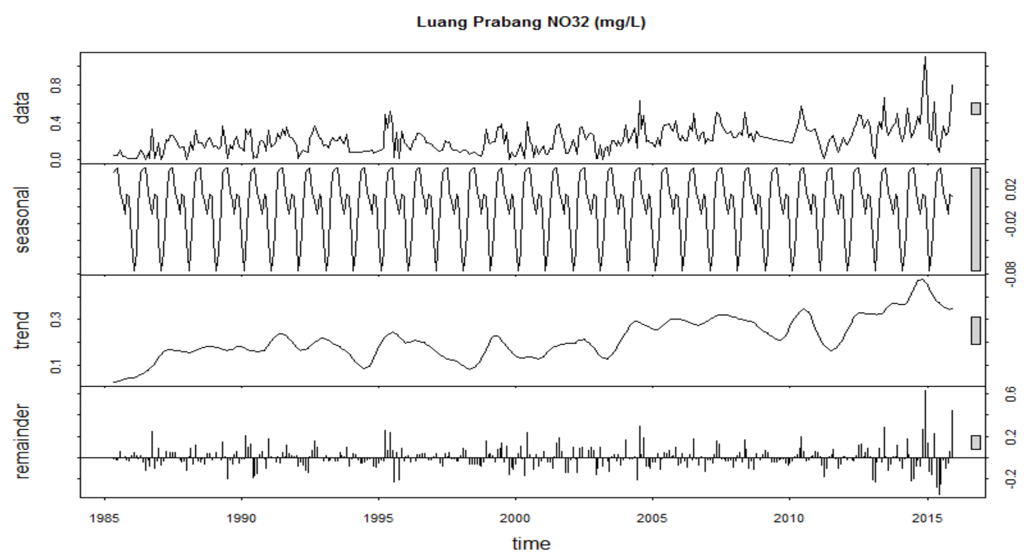


Figure A17. Decomposition of nitrate time series at Luang Prabang Water Quality Monitoring Station (WLP).

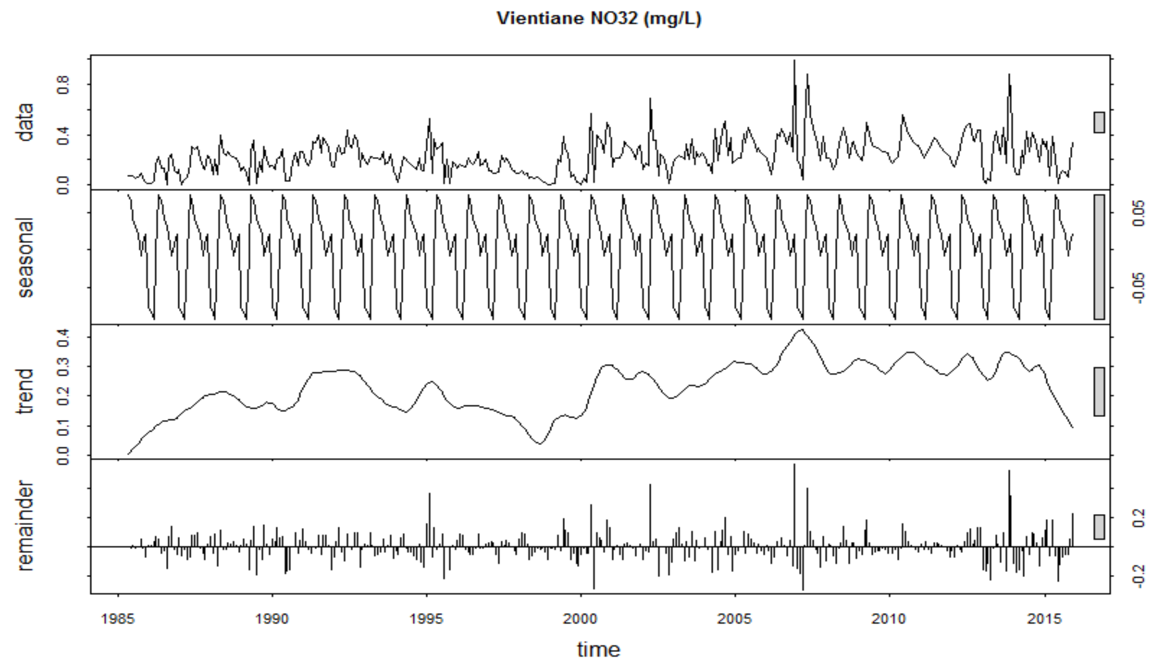


Figure A18. Decomposition of nitrate time series at Vientiane Water Quality Monitoring Station (WVT).

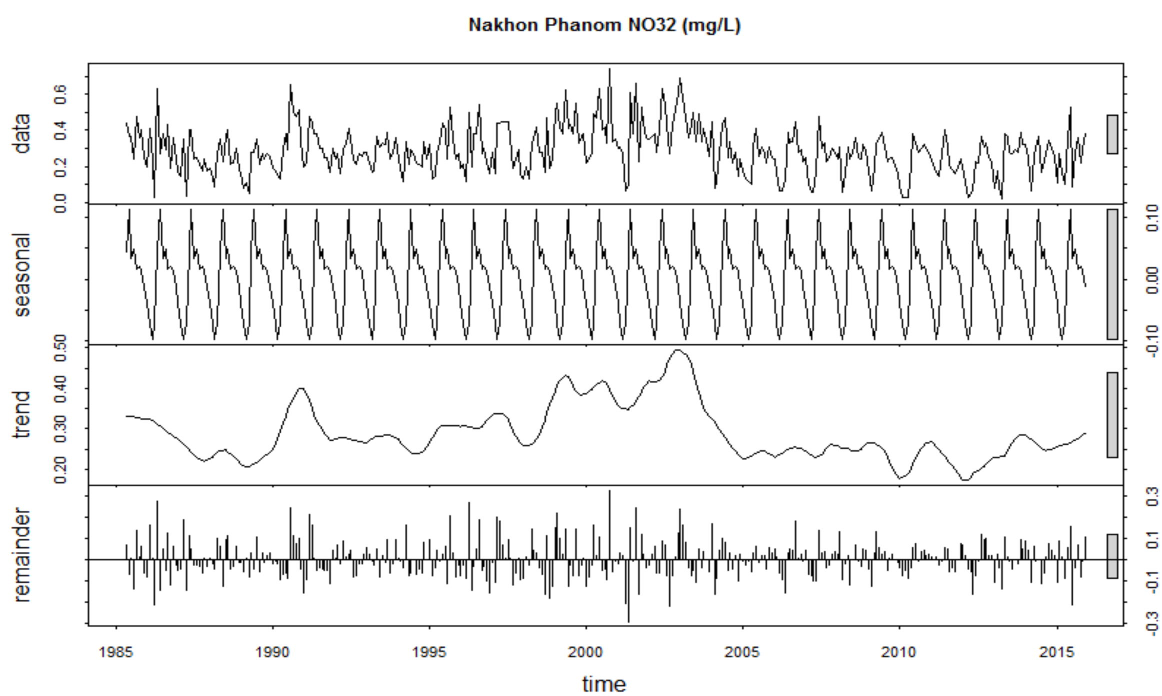


Figure A19. Decomposition of nitrate time series at Nakhon Phanom Water Quality Monitoring Station (WNP).

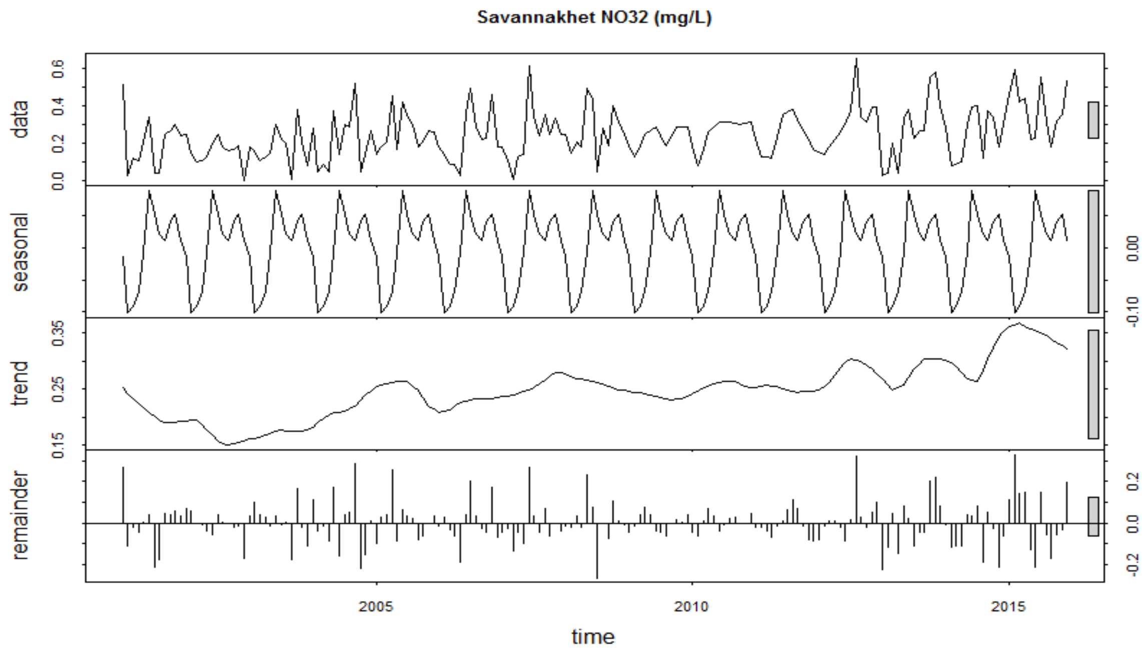


Figure A20. Decomposition of nitrate time series at Savannakhet Water Quality Monitoring Station (WSK).

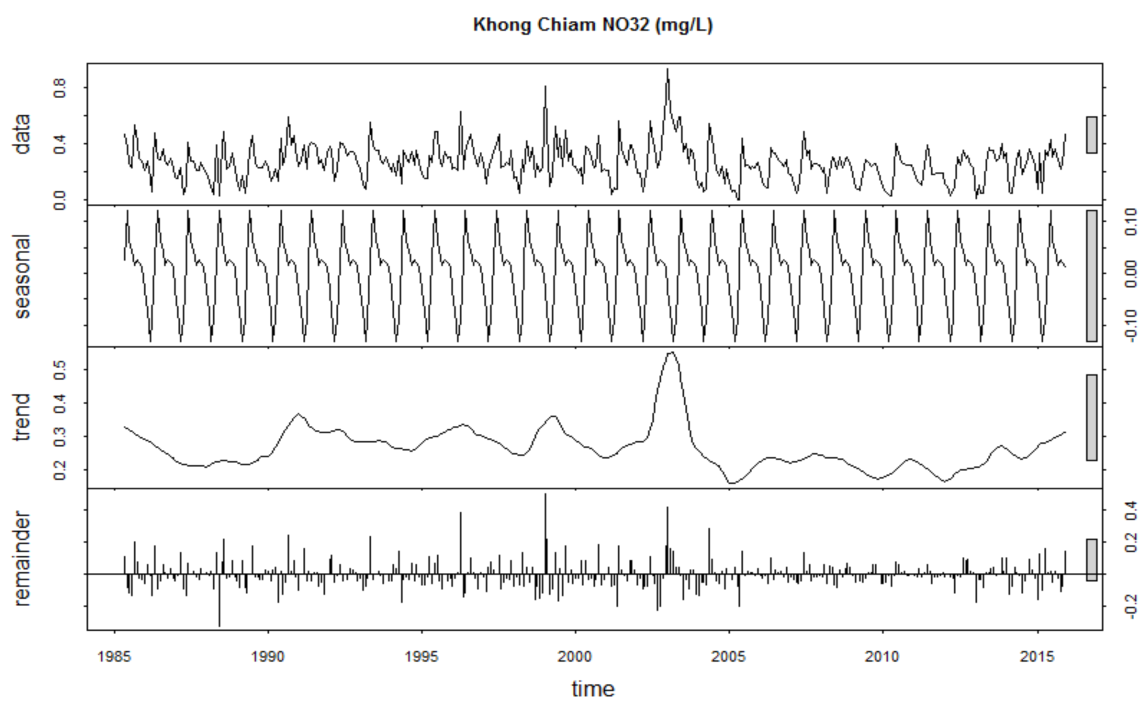


Figure A21. Decomposition of nitrate time series at Khong Chiam Water Quality Monitoring Station (WKC).

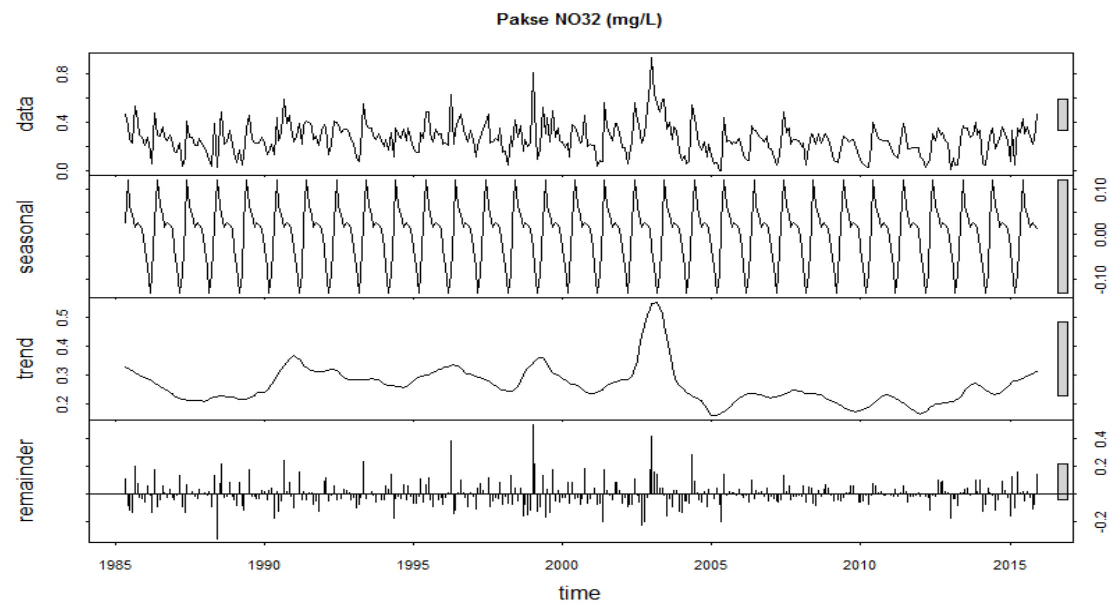


Figure A22. Decomposition of nitrate time series at Pakse Water Quality Monitoring Station (WPS).

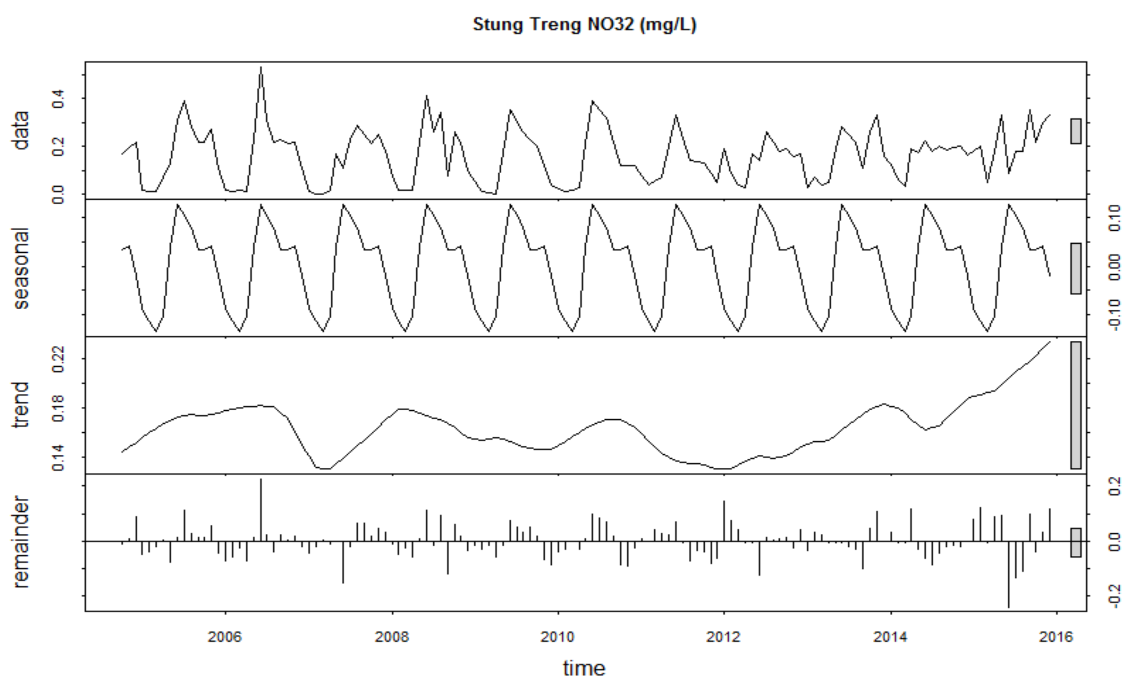


Figure A23. Decomposition of nitrate time series at Stung Treng Water Quality Monitoring Station (WST).

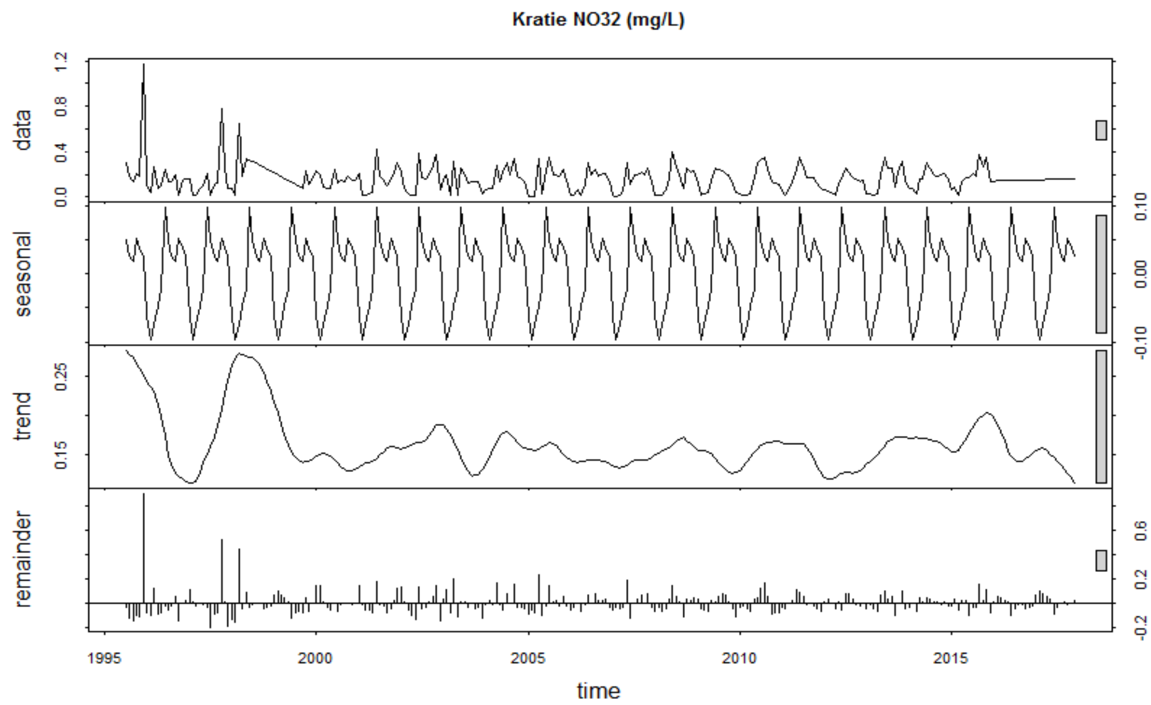


Figure A24. Decomposition of nitrate time series at Kratie Water Quality Monitoring Station (WKT).

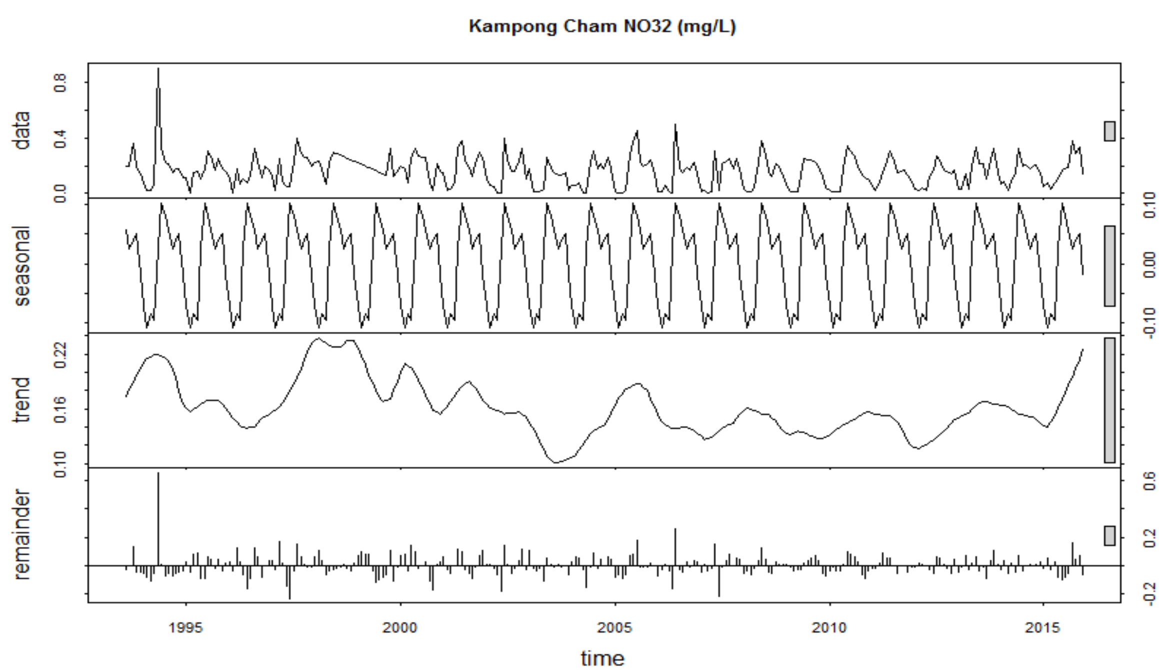


Figure A25. Decomposition of nitrate time series at Kampong Cham Water Quality Monitoring Station (WKA).

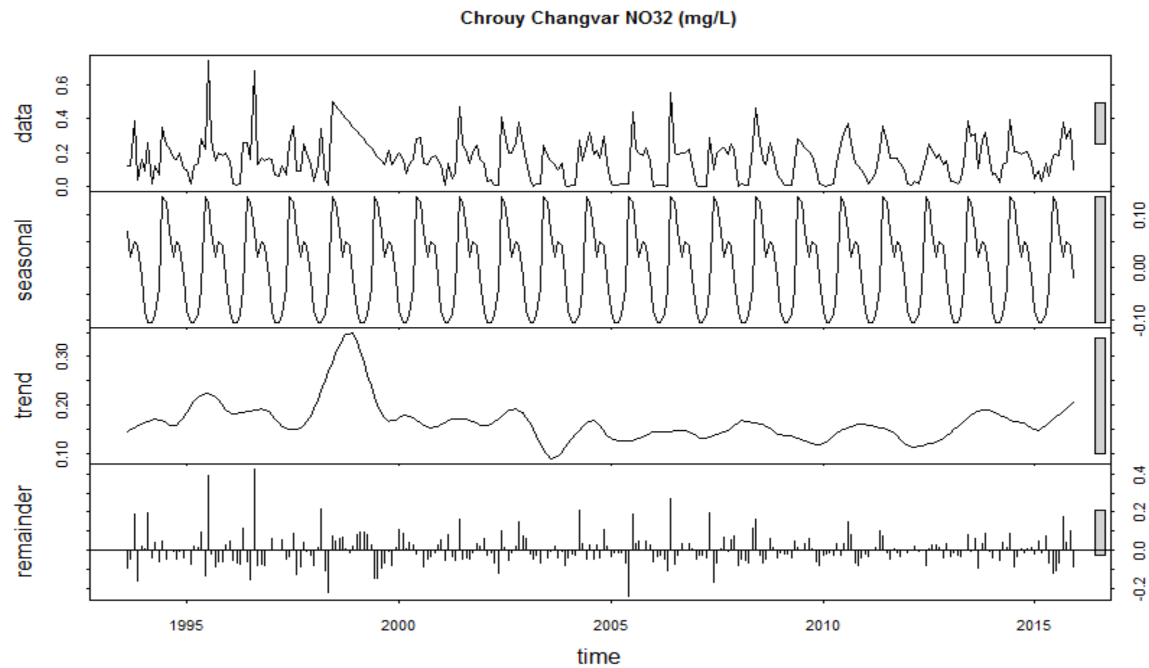


Figure A26. Decomposition of nitrate time series at Chrouy Changvar Water Quality Monitoring Station (WCC).

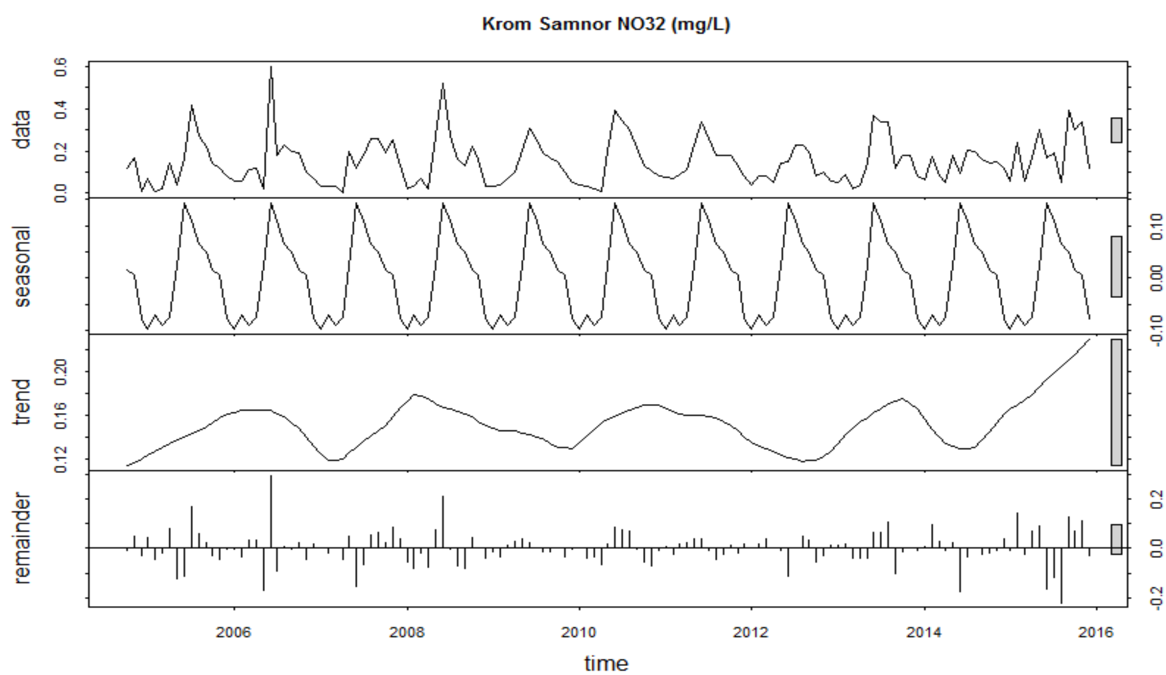


Figure A27. Decomposition of nitrate time series at Krom Samnor Water Quality Monitoring Station (WKS).

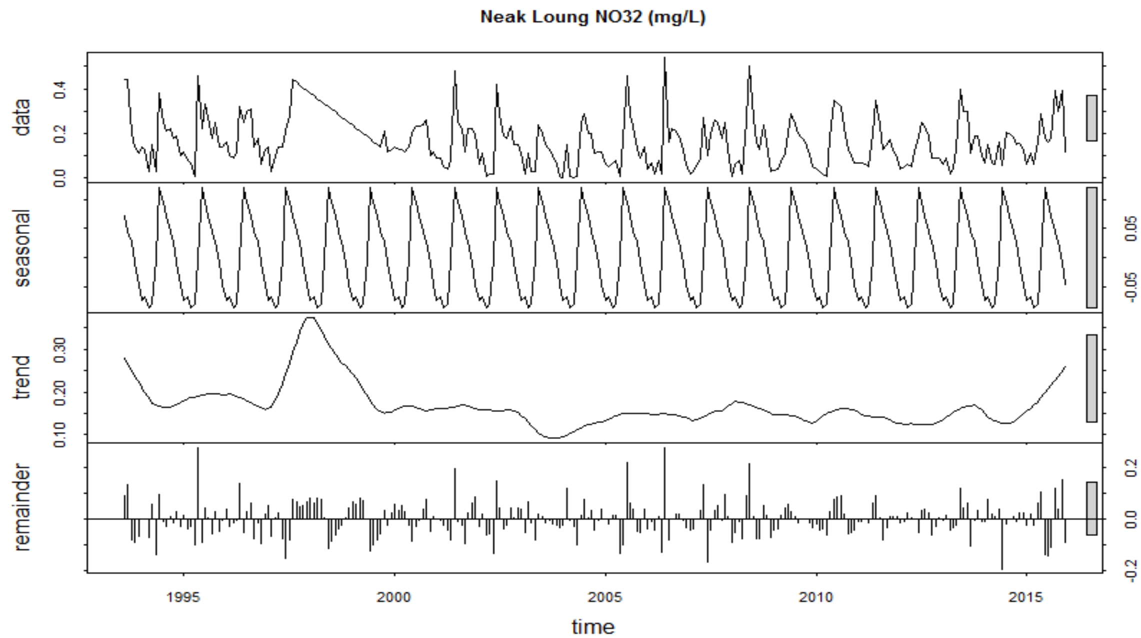


Figure A28. Decomposition of nitrate time series at Neak Loung Water Quality Monitoring Station (WNL).

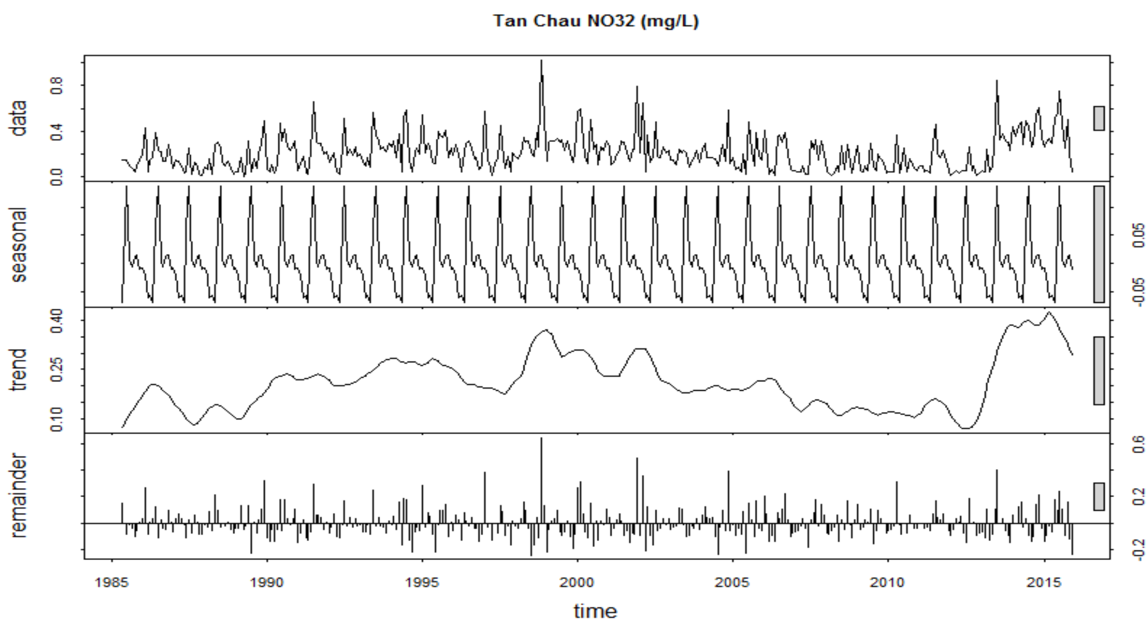


Figure A29. Decomposition of nitrate time series at Tan Chau Water Quality Monitoring Station.

Appendix 2.E – Factor analyses of relationships between LULC and instream nitrate and TSS concentrations at SVT

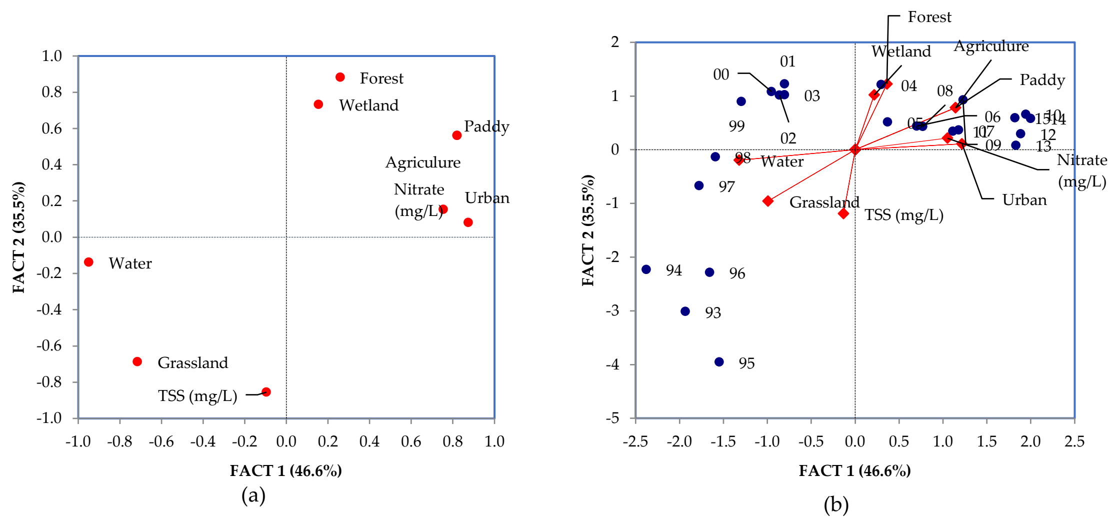


Figure A30. Analysis of mean annual instream nitrate and TSS concentration time series at Vientiane Water Quality Monitoring Station (1993–2005). Relationships between LULC parameters and water quality indicators at WVT showing (**a**) loading and (**b**) factor plots illustrating their overall correlations.

Appendix 2.F – Unpaved LULC in urban areas of SVT

Figure A31. Unpaved road and bare land in Vientiane sub-basin. Unpaved roads and bare land can be commonly seen in the urban area of SVT (Source: Kongmeng Ly, 2020).

Chapter 3. Transboundary river catchment areas of developing countries: Potential and limitations of watershed models for the simulation of sediment and nutrient loads. A review

Kongmeng Ly, Graciela Metternicht, Lucy Marshall

Published Journal: Ly, K., Metternicht, G. and Marshall, L., 2019. Transboundary river catchment areas of developing countries: Potential and limitations of watershed models for the simulation of sediment and nutrient loads. A review. Journal of Hydrology: Regional Studies, 24, p.100605. https://doi.org/10.1016/j.ejrh.2019.100605.

Keywords: Watershed models, transboundary river basin management, sustainable development, Lower Mekong Basin, water quality simulation, streamflow simulation.

Contribution: This study was conceptualised by Kongmeng Ly in close consultation with Professor Graciela Metternicht and Professor Lucy Marshall, both of whom provided guidance on the available methods that can be applied to achieve the study objectives. The identification and review of relevant publications were carried out by Kongmeng Ly, who also drafted and finalized the manuscript with the review and editing supports of Professors Metternicht and Marshall in their roles of academic supervisors.

Thesis relevancy: it provides results of my reviews of over 250 peer-reviewed journals on (i) the management challenges of transboundary river basin of developing countries and (ii) available watershed management tools to support the management of these basins. Based on the results of the reviews, I established a set of criteria that were divided into two groups. As well, 12 WMs were preliminary identified as to have potential to support the management of transboundary river basin of developing countries. However, one by one these MWs were assessed against the pre-determined criteria with eWater Source modelling framework being found to have comparative advantage to support the management of the transboundary river basin of developing countries.

Research highlights and innovations:

- Identified challenges associated with the management of transboundary river basin of developing countries.
- Reviewed over 250 peer-review journal papers to identify watershed models that have been previously used to assist the management of river basins including large-scale transboundary river basin.
- Piloting the LMB as a transboundary river basin of developing countries, developed criteria for assessing suitability of watershed models to support the management of instream nutrients and sediment concentration.
- Against the developed criteria, identified the never have been applied before Source modelling framework to have comparative advantage as management tools for large-scale transboundary river basin such as the LMB.

3.1 Abstract

Study region: The management of transboundary river basins is challenging given frequent divergences in political, cultural, developmental and conservation priorities of countries that make up the basin. In the Lower Mekong River Basin where multiple countries are beneficiaries of its water resources, ensuring good quality of the river waters is crucial for sustainable development, and for protecting the integrity of its ecosystems.

Study focus: The focus of this paper is on identifying an appropriate decision support tool for assisting the management of in-stream nutrients and sediment concentrations taking into account the abilities to (i) satisfactory simulate hydrological processes and pollutant loadings in a time continuous manner; (ii) simulate the effects

of various land use/land cover (LULC) change scenarios; (iii) handle issues of data scarcity and compatibility stemming from different development policies and priorities of each administrative jurisdiction; (iv) have a record of previous applications in a large transboundary river basin; and (v) have a track record of use by government agencies to support decision making. These criteria guide in-depth analysis of 250 peer-reviewed journal papers.

New hydrological insights for the region: Four models meet the pre-determined criteria, with eWater Source providing a comparative advantage of prior use in a transboundary catchment larger than the Lower Mekong River Basin

3.2 Introduction

The management of non-point source pollution arising from land use/land cover (LULC) practices has been a long standing and significant concern for water resource managers. While many options exist to deal with non-point source pollution (King, 2018; Lu and Xie, 2018), there are conflicting ideas of how watersheds and water resources should be managed (Lonergan, 2018; Neef et al., 2018). Consequently, water resource managers face difficult decisions on how to balance their options so that mitigation measures implemented to address non-point source pollution do not affect the catchment's livelihood and economic development.

In developing countries where the focus is placed on improving living standards and ensuring sustainable food supplies, environmental issues are often overlooked (Sachs, 2012). However, failure to pay attention to environmental issues can lead to unsustainable development and lower economic performance (Schaltegger and Synnestvedt, 2002). Without proper integrated planning and management, development at a watershed scale can lead to environmental problems, including loss of habitat, water contamination, diminishing freshwater supplies and ecosystem degradation (Bauer et al., 2015; Oeurng et al., 2016; Ribolzi et al., 2017; Liao et al., 2018; Zhou et al., 2019). Therefore, it is important that watersheds are properly managed if the goal of sustaining high water quality is to be achieved. This can mean implementing plans and strategies to maintain vegetation coverage to promote rainfall infiltration; minimizing soil loss through deforestation and unsustainable agricultural practice such as slash and burn agriculture; controlling erosion and sedimentation; and minimising cuts and fill activities on hilly slopes (Yan et al., 2015; Her et al., 2017; Blevins et al., 2018). Prior research has evidenced correlations between LULC and water quality (Mouri et al., 2011; Guédron et al., 2014; Chea et al., 2016; Oeurng et al., 2016; Yu et al., 2016). Studies have shown that forest, agriculture and urban LULC areas can influence sediment and nutrient levels in rivers and streams (Allan et al., 1997; Arheimer and Lidén, 2000; Schilling, 2002; Buck et al., 2004; Salvia-Castellví et al., 2005). Work of Howarth et al. (2002) demonstrated that stream nitrate concentration tends to correlate with the proportion of agricultural LULC in a catchment, and urbanization has been known to influence stream sediment, chemical oxygen demand and total nitrogen levels (Nelson and Booth, 2002; Chang, 2008). In addition, biological oxygen demand has been found to be high in urban areas with high population density and wastewater runoff (Mouri et al., 2011).

One way to improve or sustain water quality is through appropriate LULC management practices. A LULC management technique often suggested by researchers and water resource managers is an Integrated Water Resources Management approach (Mitchell, 2005; Liu et al., 2008; Cohen and Davidson, 2011; Sokolov, 2011; Tas, 2013), which provides a solid basis for assessing, identifying and managing water resource related-problems through integrated and holistic frameworks (Mitchell, 2005; Garcia, 2008). Integrating all aspects of a watershed (LULC, hydrological process, climate condition, existing forest and vegetation cover, and capacity of the receiving waterways) can help water resource managers improve their policies and implement appropriate management practices (Goharian and Burian, 2018).

3.2.1 Overview of integrated watershed models

With growing concerns about non-point sources of pollution, many researchers and government agencies have invested time and effort in the development of watershed models that can simulate relationships between LULC and the quality and/or quantity of water in a watershed. In the United States of America, for example, various government agencies have a long history of developing models to assist in the management of water resources; the US Environmental Research Laboratory developed the Hydrological Simulation Program – Fortran (HSPF) model (USEPA, 2015) and the USDA Agricultural Research Service who developed the Annualized Agricultural Non-Point Source Pollution (AnnAGNPS) model (Young et al., 1989). In Australia, the Federal Government funded the development of Source, an integrated hydrological modelling platform (Carr and Podger, 2012). Likewise, the development of MIKE-SHE was financially supported by the Commission of European Communities (Abbott et al., 1986). Since the development of the Stanford Watershed Model (Crawford and Linsley, 1966), many researchers have created and used watershed models to simulate the interaction between LULC and water quality, seeking to gain a better understanding of their interactions and their effects on one another (Saleh and Gallego, 2007; He et al., 2008; Mannik et al., 2012; Maranda and Anctil, 2015). Over the past few decades, watershed models have been widely used to simulate runoff behaviour in an urbanizing watershed (Brun and Band, 2000); simulate water quality parameters (Mannik et al., 2012); assess the relationship between LULC and water quality including total suspended solids and nutrients at the watershed level (Wang and Yin, 1997; Misigo and Suzuki, 2018); simulate hydrological process (Kite, 2001; He et al., 2008); and promote environmental democracy in water resource management (Parisi et al., 2003; Wheeler et al., 2018). The goal of many watershed models is to assist water resource managers in identifying crucial sources of non-point source pollution so that informed decisions and adequate management can be made to minimize runoff impacts (Singh et al., 2006).

These models have become important tools for Integrated Water Resource Management (IWRM), defined as a process that considers the balancing of ecological, economic and social welfare when developing and managing water and its resources (Xie, 2006). With the advancement of computing technology, models' capabilities for data processing and an interdisciplinary approach to watershed management have increased. In turn, this has enabled the integration of physical, socioeconomic and political aspects found in a watershed to be included in the assessment of the potential implications of water resources development and management, as illustrated in Figure 3.1 (Mirchi et al., 2009). Table B.1 (Appendix 3) presents some of the most common watershed models used for the simulation of non-point source pollution, along with their developers, regions of application and examples of application. Current watershed models can simulate hydrologic processes within a watershed, as well as the effects of different uses and management of land on a river ecosystem (Devia et al., 2015; Romero-Zaliz and Reinoso-Gordo, 2018).

3.2.2 Challenges of transboundary water resources modelling

Despite advances in watershed model development, challenges remain in their applications, especially in transboundary river catchments. Prior research, notably Singh and Woolhiser (2002); (Trambauer et al., 2013) and Moore (2006) critically reviewed and thoroughly described selected models (see Table B.1 in Appendix 3). Devia et al. (2015) complemented and extended these prior reviews, and further assessed models' performance against observed data (see Table B.1 in Appendix 3). Their study demonstrates that simulation results are not necessarily correlated with model complexity. In addition, researchers have also undertaken reviews of watershed models focusing on different criteria including low-flow conditions (Pushpalatha et al., 2012), catchments dominated by drought condition (Trambauer et al., 2013), in-stream water quality (Cox, 2003; Chinyama et al., 2014), integrated environmental assessment and management (Kelly et al., 2013).

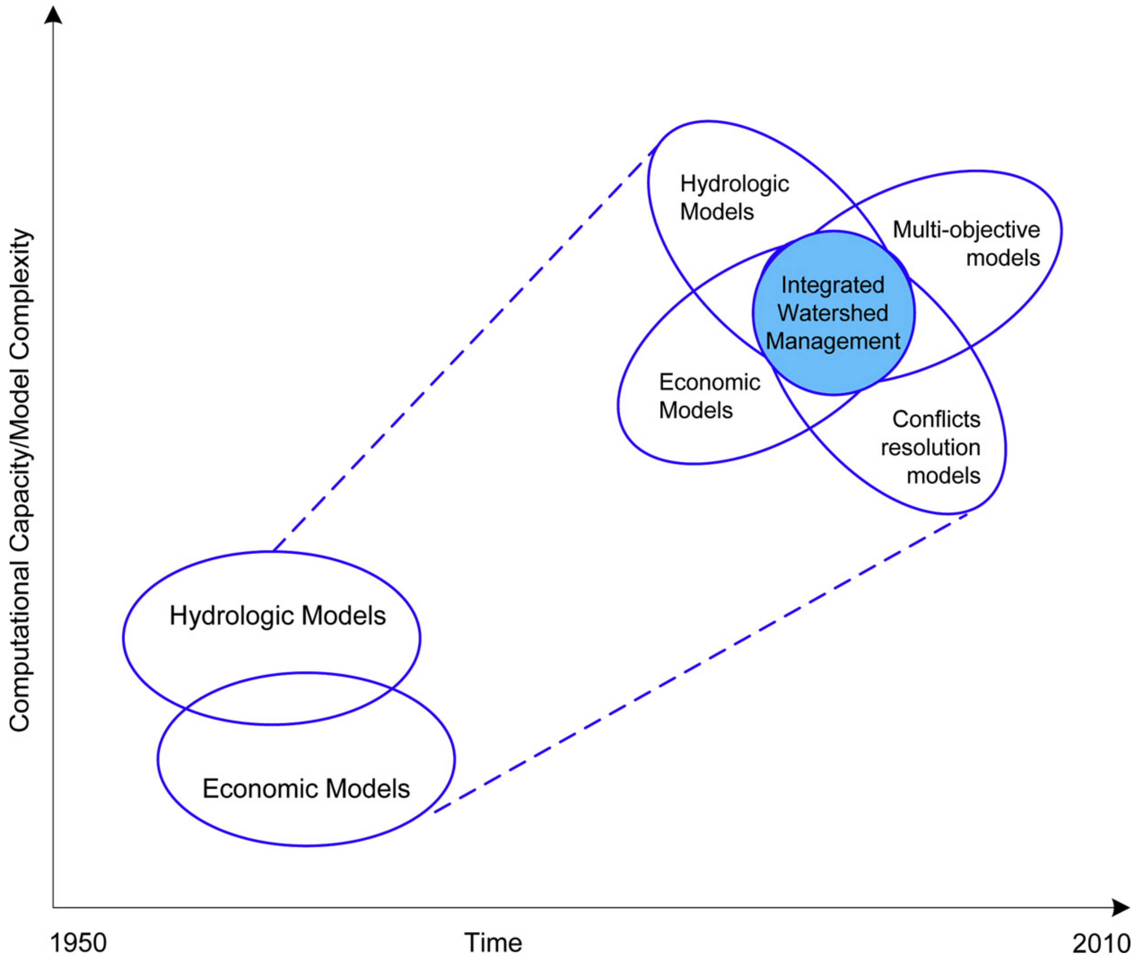


Figure 3.1: An evolution of watershed models (Mirchi et al., 2009).

However, review and analysis has so far been insufficient for assessing the suitability of watershed models to simulate the water condition (ie. quality and quantity) of transboundary river catchments large in area (i.e. greater than 100,000 square kilometres), dealing with challenges of diversity in topography and LULC. Also, divergent data governance arrangements and policies for data collection and collation (with data irregularly monitored, and/or monitored using different methods and techniques) causes data to be incompatible. The latter are the main characteristics of the Lower Mekong Basin, a transboundary river basin comprised of four countries

(Cambodia, Lao PDR, Thailand, and Viet Nam) and an area of about 571,000 square kilometres (Mekong River Commission, 2018). Due to its large area, the basin has diverse topography with elevations ranging from zero metre above sea level at the Mekong Delta, to about 2800m above sea level in the mountainous region of Lao PDR (Mekong River Commission, 2018). The countries that make up the Lower Mekong Basin have different development policies and priorities which have resulted in different types of monitoring data being recorded (Department of Foreign Affairs and Trade, 2016). While the establishment of the Mekong River Commission, an intergovernmental agency, has increased data compatibility and data harmonization efforts among the Lower Mekong River countries. Capacities within government agencies tasked for collecting data are still varied, and therefore, data uncertainty and/or incompleteness remains an issue. As such, watershed models selected for transboundary watersheds such as the Lower Mekong River Basin must be able to cope with these characteristics.

3.3 Review aim and method

This review aims to compile freely available watershed models and examine their suitability for transboundary watershed application (a river catchment covering two or more jurisdictions). A comprehensive literature search is conducted to this end, using three primary sources of scholarly information: Google Scholar, the Thomson Reuters Web of Science database, and Science Direct, focusing on water science and water resources management related academic journals. A number of unique characteristics associated with transboundary river basins are identified and subsequently used to identify, compare, and contrast the models' suitability against the set criteria. Recommendations follow on the models' capability to simulate nutrients and sediment loads, and to support decision making in transboundary river basins such the Lower Mekong River Basin. The next section introduces the methodology designed for data collection and analysis.

3.3.1 Criteria for selection of relevant literature

The United Nations Environment Programme defines transboundary river basins as river systems that cross national boundaries of countries linking them not only geographically but also politically, economically and environmentally (UNEP-DHI and UNEP, 2016). As such, the management of these river systems is challenging due to the different priorities in economic development and environmental conservation of each involved country. Further, countries making up the transboundary river basins generally possess different levels of human and infrastructure capacity for water resources management, as in the case of the Lower Mekong River Basin (Department of Foreign Affairs and Trade, 2016).

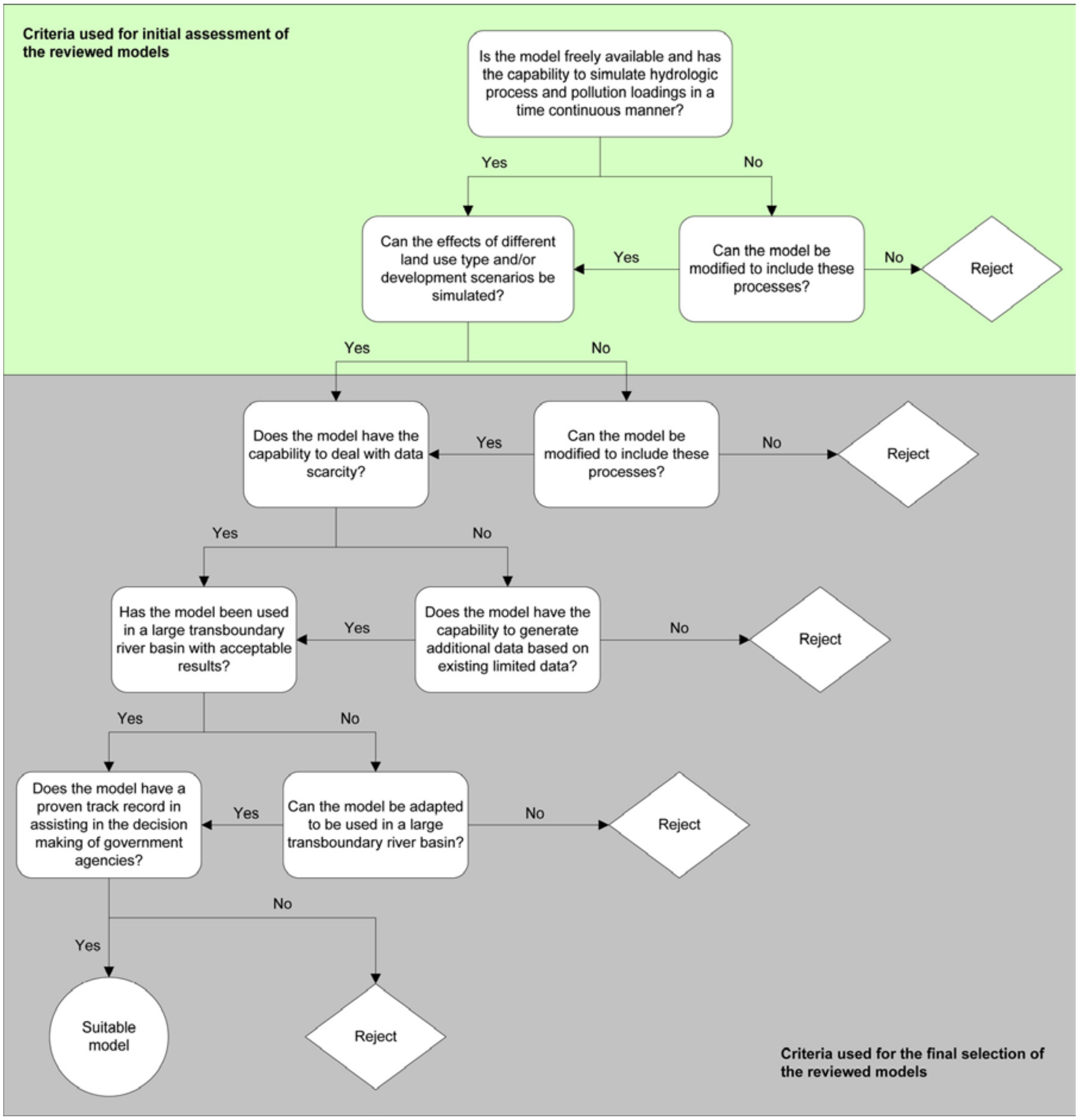


Figure 3.2: Decision making diagram for selecting a suitable watershed model for the simulation of LULC changes on water quality and quantity of a large transboundary river basin such as the Lower Mekong River Basin (adapted from Trambauer et al. (2013)).

Using expert opinion and local knowledge on the Lower Mekong Basin data gaps, a set of relevant criteria were established to categorise and examine models searched in the literature. These include (i) be a freely available model with the ability to satisfactory simulate hydrologic process and pollutant loadings in a time continuous manner; (ii) have the ability to simulate the effects of various LULC change scenarios; (iii) have the capability to handle issues of data scarcity (e.g. complex models with onerous data requirements, for example, may be prohibitively high resource and computational requirements) and compatibility stemming from different development policies and priorities of concerned administrative jurisdictions; (iv) have a record of previous applications in a large transboundary river basin; and (v) have track record of being used by government agencies to support their decision making. Using these criteria, a decision diagram (Figure 3.2) was developed illustrating the selection process to identify the most suitable watershed model for transboundary river basin for the management of nutrients and total suspended. The rationales for their developments are outlined in Table 3.1.

Table 3.1: Selection criteria and rationale for model selection.

Criteria No.	**Criteria**	**Rationale**
(i)	Freely available model with the ability to satisfactory simulate hydrologic processes and pollutant loadings in a time continuous manner	Transboundary river basins are usually large in area, and comprise countries with different levels of human and financial capacities. While developed countries may be able to direct financial resources to assist in the management of water resources, less developed countries may prioritise spending on other development activities, neglecting the importance of tools that can be used to help managing water resources, especially if those tools require financing. As such, a freely available model is an important aspect to ensure its sustainable implementation. Furthermore, given the rapid rate of development experienced in many transboundary river basins of developing countries, including the Lower Mekong Basin, the model must be able to simulate hydrologic processes and pollutant loadings in a time continuous manner. Such developments have the potential to affect the hydrological processes of the receiving waterbodies, and pollutant loads.
(ii)	Ability to simulate the effects of various LULC change scenarios	Increased socio-economic development of river basins causes changes in LULC patterns. To assist decision-makers in balancing economic benefits and social welfare while maintaining ecological integrity, a watershed model must be able to quantity how different LULC stemming from development policies, including hydropower and irrigation infrastructure development, may affect the integrity of water resources.
(iii)	Have the capability to handle issues of data scarcity and compatibility stemming from different	Large transboundary river basins of developing countries, such the Lower Mekong River Basin, present issues of data scarcity and compatibility that effect the performance of watershed models. Hence, a watershed model must possess the capability to produce satisfactory results despite

	development policies and priorities of concerned administrative jurisdictions	limited data input, or it must have the ability to derive inputs based on available data to produce satisfactory outputs, as defined in Moriasi et al. (2015).
(iv)	Have a record of previous applications in a large transboundary river basin	Reports of satisfactory application of the model in a large transboundary river basin are crucial for implementation in the Lower Mekong Basin, given the need to address issues associated with data scarcity and different priorities of development policies. If the model has not been used in a large transboundary river basin, it must at least have a track record of satisfactory implementation on a large river basin facing complex planning scenarios associated with different development priorities, and with evidence of delivering acceptable results with limited data.
(v)	Have a track record of being used by government agencies to support their decision making	Evidence that the model has been successfully used by government agencies to manage national or State-level water resources, so that outcomes can influence policy and decision-making beyond the research work.

3.3.2 Literature database and keywords

Three databases were used to identify relevant literature; Science Direct, Google Scholar, and Web of Science. To identify the most suitable watershed model that satisfies the set criteria (Section 3.3.1), the approach for a systematic review was adapted from Moher et al. (2009), and specific keywords were used to search the databases, including "watershed models", "hydrologic models", "LULC and water quality", "water quality models", "transboundary river basin management", "Mekong River Basin", and "integrated watershed management". Figure 3.3 illustrates the search process undertaken to identify relevant literature for this study.

The key words yielded over 1.5 million results combined, which were initially narrowed down to a period of publication from 2000 to 2018. Duplicated records were removed, and abstracts of the remaining records were initially reviewed. A total of 250 peer review journals were screened. Most peer review papers were published in Environmental Modelling and Software, Water Science and Technology, Agricultural Water Management, Journal of Hydrology, and Journal of Environmental Management. Their proportions are shown in Figure 3.4.

3.4 Results

As stated in Section 3.2, there has been a proliferation of watershed models since the development of Stanford Watershed Model. While this review begun including a broad set of watershed models, some were eliminated during the initial reviewing process due to a combination of their data requirement and user licenses (Figure 3.2). These include the MIKE-SHE and Water Evaluation and Planning (WEAP) models, which prior scientific reviews found to have demanding data requirements, be unsuitable for large river basins with data gap issues, and to be not freely available for public use (Jaber and Shukla, 2012; Devia et al., 2015; Sandu and Virsta, 2015). Consequently, a total of 14 watershed models were initially identified (Table 3.2). A two-stage selection process followed; firstly, models were assessed against the first two defined criteria (Section 3.3.1, Figure 3.2) to ensure that they were (i) freely available time continuous models that can be used to simulate hydrologic processes and pollution loadings, (ii) applied on catchments with a mix of LULC. The initial assessment (columns (i) and (ii) in Table 3.2) shows that while all models are freely available and have the capability to simulate hydrologic processes and nutrients and sediment transport loadings, not all can be applied in a time continuous manner.

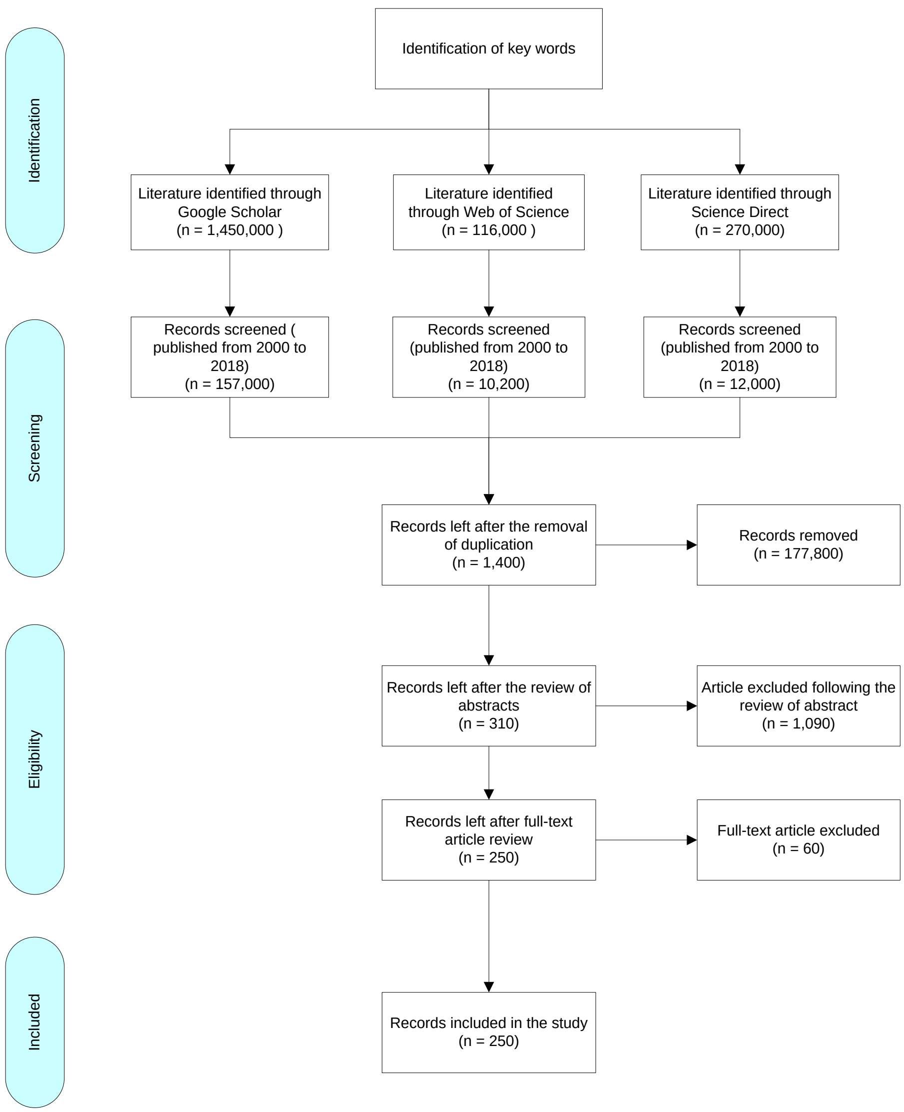


Figure 3.3: Flow diagram illustrating the process of identifying relevant literature for this study (Moher et al., 2009).

Agricultural Non-Point Source Pollution (AGNPS), for instance, is an event driven model that cannot be used to assess the transformation of nutrients and their process within the stream (Adu and Kumarasamy, 2018). Furthermore, not all models appear capable of simulating the effects of multiple LULC on total suspended solids and nutrients. For example, Chemicals, Runoff, and Erosion from Agricultural Management System (CREAMS) (Knisel, 1980) has been mainly used to assess the effects of agricultural management and practice, while Storm Water Management Model (Rossman, 2004) is mostly suitable for storm water runoff and wastewater management in urban watershed. Of the identified models, only four met all the initial assessment requirements. These models are Hydrologic Simulation Program – Fortran (HSPF), Soil Water Assessment Tool (SWAT), Annualized Agricultural Non-Point Source Pollution (AnnAGNPS), and SOURCE (Table 3.2, green coloured rows). Consequently, only four these models were reviewed in detail and further assessed against the remaining criteria. The results of the assessment follow in the next Section.

3.4.1 Model 1 –annualized agricultural non-point source pollution (AnnAGNPS)

The Annualized Agricultural Non-Point Source Pollution model (AnnAGNPS) is a continuous watershed model that can be used to simulate non-point source loading of sediment, nutrients and pesticides in large watershed systems (Bingner et al., 2009). It is a continued version of the Agricultural Non-Point Source Pollution model, a distributed parameter single event computer based model developed by the USDA Agricultural Research Service (Young et al., 1989), and enhanced in the mid-1990s to improve automation of data input for simulation of long-term transport of sediment, nutrients and pesticides in large watersheds (Bingner et al., 2009). As an integrated and holistic model it allows for the generation of flow, weather and pollutant loadings (He, 2003).

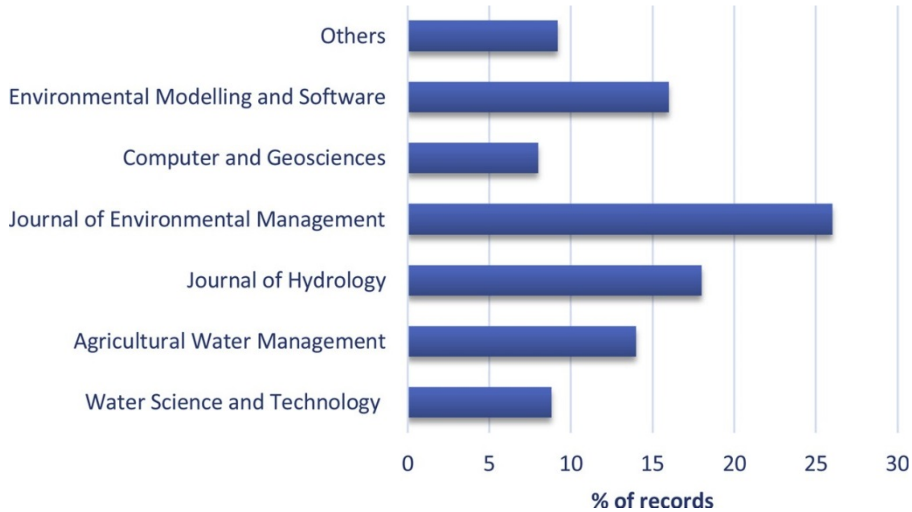


Figure 3.4: Proportion of records identified through various publications.

AnnAGNPS subdivides a watershed into small grids to allow the effects of various practices on water quality be simulated and assessed (Bhuyan et al., 2003). Daily runoff is determined by the SCS Curve Number techniques (USDA, 1972) while both the Revised Universal Soil Loss Equation (RUSLE) (Renard et al., 1996) and the Hydro-geomorphic Universal Soil Loss Equation (HUSLE) (Theurer and Clarke, 1991) are applied to determine sediment yield from sheet and rill erosion. The transport of chemicals including nutrients can be estimated for both soluble and sediment adsorbed phases, and is simulated based on the Chemicals, Runoff, and Erosion from Agricultural Management Systems (CREAMS) model (Young and Shepherd, 1995). Data requirements for AnnAGNPS are extensive. Prior research by Pease et al. (2010), who applied the model to estimate sediment and nutrient loads from Pipestem Creek watershed in North Dakota, USA, lists the inputs as including topography, soil, weather, observed stream flow, water quality, LULC and management data.

AnnAGNPS has been applied extensively worldwide to support watershed management. Applications have covered analysis of water quality and quantity in catchment areas of varying size, though none have been carried out in transboundary river catchments. For example, Baginska et al. (2003) applied the model in a small sub-catchment of the Hawkesbury-Nepean basin (Australia) to predict the exportation of nitrogen and phosphorus. They found that while the daily simulated nutrients data deviated from the measured data, model-derived trends aligned with the recorded trends. Similarly, Pease et al. (2010) used AnnAGNPS to estimate pollutant loads from an agriculture-dominated watershed, with an area of about 1700 square kilometres, and found the correlation between the observed and simulated pollutant data to be poor. Underestimation was attributed to the size of study area, and the high variability in LULC and management practices.

Additional applications of AnnAGNPS include simulation of runoff and sediment loads, with satisfactory results reported for runoff simulation at event, monthly and annual scales following calibration and validation (Licciardello et al., 2007; Sarangi et al., 2007; Chahor et al., 2014; Li et al., 2015). However, when simulating sediment loadings the model underestimated outputs (Suttles et al., 2003).

3.4.2 Model 2 – hydrological simulation program – fortran (HSPF)

Hydrological Simulation Program – Fortran (HSPF) is a continuous watershed model capable of simulating non-point source runoff and pollutant loadings. Developed by the US Environmental Research Laboratory, it is an updated version of the 1960s Stanford Watershed Model (USEPA, 2015). With three main application modules and five utilities modules, the model allows simulating water quality and quantity for impervious land, pervious land and stream reaches. The simulation of water quality and quantity over pervious land accounts for different flow types as well as chemicals transported by them. Simulations of water quality and quantity over impervious land segments are focused mainly on surface runoff (Crossette et al., 2015). HSPF is a time continuous model that requires extensive data input (Crossette et al., 2015). The set up includes spatial definition of the catchment to be modelled using terrain elevation, watershed boundaries, a river network and LULC information; thus enabling delineation of watershed and the establishment of the stream network and sub-catchments. Runoff simulation is driven by meteorological data including precipitation, temperature, dewpoint, solar radiation, wind speed, and evaporation. Al-Abed and Al-Sharif (2008) noted that for the simulation of sediments and pollutant loadings an input of a complete meteorological dataset is required. Observed water quality and flow data are also needed for calibration purposes.

Numerous applications of HSPF to simulate the impacts of LULC on hydrological processes and water quality of watersheds have been reported (Al-Abed and Al-Sharif, 2008; Lee et al., 2010b; Liu and Tong, 2011; Petersen et al., 2011; Rolle et al., 2012). Lee et al. (2010b) state the model was effective in describing the behaviour of pollutants and could be used in various types of LULC, particularly when using monitoring data acquired at hourly scale. Similarly, Rolle et al. (2012) found HSPF to be an effective tool for identifying the source of pollution and concluded that the model's performance was acceptable with a coefficient of determination equal to 0.64 when comparing observed and predicted pollutant concentrations.

In simulating nutrient runoff, Ribarova et al. (2008) and Bergman et al. (2002) found good agreement between the outputs of HSPF and recorded values, concluding that the model can be valuable in forecasting nutrient concentrations during storm events. Likewise, using the percent difference between observed and simulated values, the model was found to perform adequately for evaluating watershed processes and best management practices in the Han River Basin in South Korea, with a catchment area of about 20,000 square kilometres Jung et al. (2008).

Table 3.2: Initial assessment of the watershed models against defined criteria for this review

Models	Processes	i	ii	iii	iv	v
		Stage 1		Stage 2		
Areal Non-point Source Watershed Environment Response Simulation (Beasley et al., 1980)	An event based or continuous distributed parameter and event-oriented model for agricultural watersheds	x				
Agricultural Non-Point Source Pollution Model (Young et al., 1989)	Event based distribute model capable of simulating hydrologic process and sediment and nutrient transport in watersheds	x				
Dynamic Watershed Simulation Model (Borah, 2011)	Event based watershed model capable of simulating runoff and water quality in agricultural and rural watersheds	x				
Agricultural Transport Model (Frere et al., 1975)	Conceptual and event-based models capable of simulate runoff and water quality from agricultural land	x				
Simulator for Water Resources in Rural Basin (Williams et al., 1985)	A semi-distributed water resources model that was developed for the simulation of hydrologic and related process in rural basins	x				
Chemicals, Runoff, and Erosion from Agricultural Management System (Knisel, 1980)	Process based agricultural runoff simulation model capable of simulating hydrologic and sediment yield	x				
Distributed Hydrological Model (HYDROTEL) (Fortin et al., 2001)	Physical and distributed continuous hydrologic simulation model	x				
Water Evaluation and Planning (WEAP) (SEI, 2001)	Semi-distributed model that can be used to simulate hydrological processes in each individual sub-basin of the watershed	x				

Models	Processes	i	ii	iii	iv	v
		Stage 1		Stage 2		
Storm Water Management Model (SWMM) (Rossman, 2004)	A rainfall-runoff simulation model that can be used to simulate the quality and quantity of runoff for a single or continuous event.	√	x			
Hydrologic Simulation Program – Fortran (Bicknell et al., 2001)	A continuous, high level watershed model with capability to perform continuous simulation of hydrologic process and pollutant loading	√	√	√	x	
Soil Water Assessment Tool (Arnold et al., 2012a)	Distributed and physical based watershed model that capable of simulating the impacts of LULC practices on water and chemical yields in large and complex watersheds	√	√	√	√	√
Annualized Agricultural Non-Point Source Pollution model (Bingner et al., 2009)	A continuous watershed model that can be used to simulate non-point source loading of sediment, nutrients and pesticides in large watershed systems	√	√	√	x	
SOURCE (Carr and Podger, 2012)	An Australia's modelling platform developed by the eWater Cooperative Research Centre (CRC) as an integrated eco-hydrological modelling environment that consists algorithms that allows the model to simulate water quantity and quality of a catchment.	√	√	√	√	√

Assessment criteria: (i) freely available time continuous model capable of simulating nutrients and sediment transport, (ii) applicable to mix LULC types, (iii) able to handle data scarcity and compatibility issues, (iv) previously been applied in large transboundary river basin; (v) proven track record as a tool to support decision making in a large transboundary river basin.

3.4.3 Model 3 - the soil and water assessment tool (SWAT)

SWAT is a semi-distributed, time continuous and process-based model used to simulate the potential impact of LULC change and management on water quality and quantity (Arnold et al., 2012a). The model was first developed and applied in the early 1990s, being later on integrated with a geographic information system (GIS) to allow input of digital topographic, LULC, and soil data. Under SWAT, surface runoff is determined by a modified SCS Curve Number (CN) method (Hjelmfelt Allen, 1991) which estimates rainfall excess from a rainfall event. The model also allows for the simulation of evaporation and runoff losses from drainage channels.

As the model is based on the hydrologic cycle and centred on the water balance equation, each component of water balance can be determined at sub-catchment level (Abbaspour et al., 2015). The initial set up allows the modelled watershed to be divided into smaller sub-catchments and hydrologic response units (HRUs); the latter consist of units of homogeneous LULC and management, topographic and soil attributes (Arnold et al., 2012a). Watershed hydrology can be simulated in land phase and in stream phase, with the former allowing the determination of runoff loadings of water, sediment and chemicals from each sub catchment, while the latter allows the determination of the movement of these variables through the stream network of the watershed. For the simulation of water quality, SWAT integrates of the Groundwater Loading Effects of Agricultural Management System model (GLEAMS) and CREAMS (Knisel, 1980), and therefore, can be used to simulate not only the river hydrologic process but also pollutant transport (Arnold et al., 2012a). A single plant growth model enables simulating the removal of water and nutrients as function of landcover type, while the Modified Universal Soil Loss Equation (MUSLE) (Williams and Berndt, 1997) predicts sediment yielded from LULC.

The SWAT database is context-dependant (ie. needs to be modified when used in different study areas), and being a continuous and semi-distributed watershed model, it requires extensive data input for successful simulation (Adu and Kumarasamy, 2018). Data requirements include rainfall, air temperature, wind speed, relative humidity and solar radiation. For calibration and validation purpose observed flow and water quality data are also required.

SWAT is one of the most popular watershed models implemented to assess the impact of LULC change and management on water quality and quantity across a number of continents including America, Asia, Africa and Europe (Jayakrishnan et al., 2005; LÉVesque et al., 2008; Ndomba et al., 2008; Xu et al., 2009; Betrie et al., 2011). Reported performance on simulations vary; its application on a small agricultural watershed (49 square kilometres) in Canada yielded satisfactory performances on a daily level, but the model overestimated flow during the summer season, when the flow is low (LÉVesque et al., 2008). When used to estimate runoff and for understanding the effects of agricultural practices on pollution loadings over a data-poor catchment area in California, Saleh et al. (2009) found the model underperformed for continuous flow simulation. Applied on the 7280 square kilometres Kikuletwat River basin of Tanzania, where little data is available, Ndomba et al. (2008) found the model to be moderately satisfactory with a Nash-Sutchliffe Coefficient of Efficiency (NS) (Nash and Sutcliffe, 1970) of about 55% for calibration; this value improved when more data was used. When applied to estimate environmental benefits of water pollution abatement in the agriculture-dominated, transboundary Minho river basin (Portugal and Spain) of about 17,000 square kilometres, Roebeling et al. (2014) found SWAT's performance satisfactory to good with a NS value of 0.58.

Noteworthy is the use of SWAT in the Lower Mekong River Basin for establishing a hydrologic baseline. More to the point, Rossi (2009) used SWAT to evaluate the hydrology of the Lower Mekong River basin, concluding the model performed satisfactorily for simulating river hydrology (ie. NS values ranging from 0.8 to 1.0 on a monthly and daily time steps). The study, however, focused only on water quantity and not pollutant loadings. Likewise, Shrestha et al. (2013) confirmed the SWAT's accuracy for simulating streamflow of one of the Mekong River tributaries, the Nam Ou River, but pointed out it was unable to capture peak flows; and produced low accuracy sediment yield simulations (coefficient of determination and NS values of less than 0.6 out of maximum value of 1).

3.4.4 Model 4 – eWater source

Source is a modelling platform developed in Australia as an integrated eco-hydrological modelling tool that includes algorithms for the simulation of catchment water quality and quantity, and the impacts of resource management and development (Carr and Podger, 2012). Under Source, a watershed to be modelled can be configured spatially or schematically, over a set time frame, depending on the modelling requirements. The Source platform provides a range of tools for rainfall-runoff modelling, including tools for tools for catchment delineation, six rainfall runoff models, a calibration tool, regionalization methods for ungauged catchments and different LULC types (Carr and Podger, 2012). The model includes export and routing methods for water quality simulation, including models such as SEDNET (Prosser et al., 2001) which can be used to construct sediment and nutrient budgets for a river network.

Source can be used to simulate water resource processes of a catchment in support of enhanced governance and planning of a river basin, and it can accommodate a wide range of climatic, geographic, policy and governance settings (eWater Ltd., 2018). The model has been used successfully within Australia for: simulating how LULC change could affect sediment and nutrient concentration in the Hawkesbury-Nepean River basin (22,000 square kilometres) (Mannik et al., 2012); assessing the effectiveness of agricultural management practice in the Great Barrier Reef catchment for improving water quality (423,000 square kilometres) (Shaw et al., 2013; Waters et al., 2013); examining changes in sediment chemistry over space and time (Krull et al., 2008); simulating nutrients and TSS in a catchment area (Nattai River) comprised of eight different types including agriculture, urban and vegetated areas (Chong, 2010); supporting the management of water resources of the Oven River Basin (6295 square kilometres) in Northern Victoria (Barlow et al., 2011) and; examining impacts of LULC change on hydrological processes (Browne et al., 2008). In researching effects of water abstraction and dam release, the flexible nature of the Source model allowed Barlow et al. (2011) using it in conjunction with other models, including the Parameter Estimated Tool (PEST), thus increasing prediction accuracy of streamflow. Likewise, Waters et al. (2013) used Source for ex-ante assessment of LULC change scenarios on sediment, nutrient and herbicide loads entering the Great Barrier Reef. The modelling undertaken provided evidence to argue that levels of water pollutants could be reduced through improved land management practices. Applications outside Australia include investigating management of nutrients in a catchment area of 77 square kilometres in the Dongshan Peninsula, Suzhou (China) (Waters et al., 2012). The outputs of this study enabled identifying major sources of nutrient exported to the lake, and three potential nutrient management options, including the improvement of (i) point source management, (ii) diffuse source management, and (iii) the construction of wetlands.

A cited advantage of the Source model (Chong, 2010) is its in-built capacity for delineating sub-catchment boundaries when a digital elevation model is supplied, enabling to disaggregate very large study areas into smaller sub-catchments as needed. Like other hydrological simulation models, Source requires meteorological, catchment, LULC, streamflow, and in-stream water quality data for simulation, calibration and validation. Prior research (Barlow et al., 2011; Waters et al., 2013; Welsh et al., 2013) reports very good performance, as indicated by high NS (up to 97%) and coefficient of determination (up to 0.99), in Australian catchments ranging from 1748 square kilometres to 7985 square kilometres. In addition to the strong performance for hydrologic processes simulation, the model has also shown similarity between simulated and observed water quality constituents (Chong, 2010).

3.5 Discussion

A total of 14 watershed models were initially identified using the criteria set out in Section 3.3.1. The first two criteria were used as screening criteria to ensure that the models further examined in detail have the capability to simulate nutrients and sediment loading from catchment with mix LULC.

Several models failed to meet the first criterion (Column (i) in Table 3.2). For example, not all models reviewed are freely available, and hence those failing to meet that criterion were eliminated from further analysis. Of those freely available that can be used to simulate hydrologic processes and pollution loading, only five are time continuous and can be used to synthesize hydrologic processes and pollutant loadings over a long period of time. With the complexity of managing transboundary river basins, where consequences of long term development plans are uncertain, time continuous models are needed to assist water resource managers in solving complex water resources and environmental conflicts, such as water demand and total maximum daily pollutant loads, that may affect one or more countries. Chu and Steinman (2009) noted that while event-based models are useful for understanding the fundamental of hydrologic processes, time continuous models allow these processes to be synthesized, and the cumulative effects of land development simulated. Therefore, event-based models were eliminated from further consideration, and were not assessed against the subsequent criteria.

The five remaining models (Table 3.2, √ symbol) were then examined against the second criterion (column ii in Table 3.2) to ensure that they can and have been previously used in catchments with mixed LULC. The inclusion of mixed LULC is important in extensive transboundary river basins, which given this characteristic tend to include different types of LULC. Likewise, changes in any one LULC type, particularly involving rapid conversion of large tracks of land, can cause a great impact on the environment including hydrologic processes and water constituents loadings

(Karakus et al., 2015). Following the results of the initial screening only four models met the first two criteria, as models that can be used to simulate nutrients and TSS from catchments with mixed LULC in a time continuous basis.

Furthermore, while the interaction between LULC change and stream integrity has been well documented (Monaghan et al., 2007; Tu, 2013; Yu et al., 2013; Connolly et al., 2015; Lawniczak et al., 2016), different LULC types tend to generate different pollutants (see Section 3.2). In this regard, only AnnAGNPS, SWAT, HSPF and eWater Source have been applied to simulate hydrologic processes and nutrients and sediment loadings in various river basins, and evidenced prior use in catchments with mix LULC types. These four models can also anticipate (ie., ex-ante assessment) the effects of various development and LULC change scenarios on water quality and quantity (see Section 3.4 for examples).

While all models have been reported as successful in their prior applications (Sections 3.4.1 – 3.4.4), the degree of their success depends greatly on data availability. Prior reviews of AnnAGNPS, SWAT, HSPF and Source have revealed that these models demand a great number of input data (Chong, 2010; Crossette et al., 2015; Luo et al., 2015; Adu and Kumarasamy, 2018). This can be problematic in large transboundary river basins where long term monitoring data may not be available, may contain gaps and/or may have insufficient frequency, as discussed in Section Challenges of transboundary water resources modelling (Section 3.2.2). In many instances, the level of performance of watershed models has been related to the availability and quality of the input data (see Section 3.4.1 for AnnAGNPS and Section 3.4.2 for the HSPF model). Given that these are sophisticated models that required a large amount of data input, they may not be suitable for a large transboundary river basin where data scarcity and incompatibility are major issues (see Section 3.2.1).

While most models reviewed perform satisfactorily when simulating the effects of LULC change on water quality and quantity, only a few have been applied in a large transboundary river basin such the Lower Mekong River. More to the point, only SWAT and Source have been applied in transboundary river catchments. Of relevance is that SWAT was used in the Lower Mekong River, though pollutant loading simulation was excluded from this study (see Section 3.4.3). Unlike Source, that has been applied in transboundary river catchments to simulate hydrologic processes and nutrient and sediment transport, as summarised in Section 3.4.4. Being successfully applied in the Australian Murray-Darling River Basin (Dutta et al., 2012), a transboundary river basin that expands across five states and covers an area of more than one million square kilometres, almost twice the size of the Lower Mekong Basin, Source is a model that could cope with demands associated to watershed dimension. Both SWAT and Source have been used by government agencies to support decision making on water resources management. Francesconi et al. (2016) provided a comprehensive list of studies using SWAT to support decision making, including assessing the effects of conservation practices, identifying ecosystem services thresholds, and evaluating best management practices. Noteworthy is that SWAT applications have been largely on non-transboundary catchments (see Section 3.4.3). Source has been adopted as a watershed modelling platform to support decision making in Australia for water resource management (Welsh et al., 2013). Section 3.4.4 summarises satisfactory performances reported in applications related to simulation of flow, water quality loading and resource management by different actors, including in a large transboundary river basin (Mannik et al., 2012; Ellis and Searle, 2013; Shaw et al., 2013). Other comparative advantages of Source that make it a valuable integrated water management tool for large transboundary basins like the Lower Mekong River are: flexibility of design allowing it to be customized and updated when new information and policy become available; set of hydrological, water balance and water quality tools; in-built capacity for disaggregating very large study areas into smaller sub-catchments as needed.

3.6 Conclusions

This paper examined freely available watershed models against a set of criteria designed to establish their suitability for simulating the effects of LULC change on hydrological processes and pollutant loadings in transboundary basins characterised by diverse topography topography, data scarcity and compatibility issues, and complex development policies and priorities. In all 14 models were examined, with four models (AnnAGNPS, SWAT, HSPF, and Source) being reviewed in detail given their fulfillment of all pre-defined criteria, including proven capability to simulate hydrologic processes and/or pollutant loadings. The review shows that model performance depends on a number of factors including the size of the watershed, and availability of required data input. Previous applications of AnnAGNPS were found to be mainly in small river basins with agriculture as predominate LULC; hence it was concluded that there is insufficient evidence of the model's ability to deal with the complexity associated to modelling transboundary river basins of large catchment areas.

The Lower Mekong River Basin, encompassing four countries requires a model that works as a generic tool suitable for different jurisdictions. This review shows that all models require extensive data input, which could be difficult to obtain in a transboundary river basin where data scarcity and incompatibility are major issues. However, Source has evidenced satisfactory outcomes in large transboundary river basin even with limited data input. The Source model appears to provide a flexible modelling environment that allows the simulation of hydrological processes and pollutant loadings from large transboundary river basins, as proven in its application for the Murry Darling River Basin. Furthermore, Source has proven track record as a decision support tool and has been used successfully for water planning and management purposes, including the assessment of water quality and quantity due to LULC change, water demand and sharing, and changes in water regulatory.

Given the complexity associated to the management of the Lower Mekong River Basin, where four different countries have diverse development strategies and conservation priorities, this review shows that the Source model has a comparative advantage over the other models based on the defined criteria pertaining to the simulation of the potential effects of LULC change on water quality and quantity of a transboundary river basin.

3.7 References

Abbaspour, K.C., et al., 2015. A continental-scale hydrology and water quality model for Europe: calibration and uncertainty of a high-resolution large-scale SWAT model. J. Hydrol. 524, 733–752. https://doi.org/10.1016/j.jhydrol.2015.03.027.

Abbott, M.B., et al., 1986. An introduction to the European Hydrological System — Systeme Hydrologique Europeen, "SHE", 1: history and philosophy of a physically based, distributed modelling system. J. Hydrol. 87, 45–59. https://doi.org/10.1016/0022- 1694(86)90114-9.

Adu, J.T., Kumarasamy, M.V., 2018. Assessing non-point source pollution models: a review. Pol. J. Environ. Stud. 27, 1913–1922. https://doi.org/10.15244/pjoes/76497.

Al-Abed, N., Al-Sharif, M., 2008. Hydrological modeling of Zarqa River Basin – Jordan using the hydrological simulation program – FORTRAN (HSPF) model. Water Resour. Manag. 22, 1203–1220. https://doi.org/10.1007/s11269-007-9221-9.

Allan, D., et al., 1997. The Influence of Catchment Land Use on Stream Integrity Across Multiple Spatial Scales.

Arheimer, B., Lidén, R., 2000. Nitrogen and phosphorus concentrations from agricultural catchments—influence of spatial and temporal variables. J. Hydrol. 227, 140–159. https://doi.org/10.1016/S0022-1694(99)00177-8.

Arnold, J.G., et al., 2012. SWAT: model use, calibration, and validation. Trans. ASABE 55, 1491. https://doi.org/10.13031/2013.42256.

Beasley, D.G., Huggins, L.F., 1980. ANSWERS: a model for watershed planning. Trans. ASAE 23, 938. https://doi.org/10.13031/2013.34692.

Baginska, B., et al., 2003. Modelling nutrient transport in Currency Creek, NSW with AnnAGNPS and PEST. Environ. Model. Softw. 18, 801–808. https://doi.org/10.1016/S1364-8152(03)00079-3.

Barlow, K., et al., 2011. A Source Model of the Ovens River Catchment in Victoria - Northen Victoria project. eWater CRC Application Report: eWater.

Bauer, S., et al., 2015. Impacts of surface water diversions for marijuana cultivation on aquatic habitat in four northwestern California watersheds. PLoS One 10,e0120016. https://doi.org/10.1371/journal.pone.0120016.

Bergman, M.J., et al., 2002. Calibration of Storm Loads in the South Prong Watershed, Florida, using BASINS/HSPF1. JAWRA J. Am. Water Resour. Assoc. 38, 1423–1436. https://doi.org/10.1111/j.1752-1688.2002.tb04356.x.

Betrie, G.D., et al., 2011. Sediment management modelling in the Blue Nile Basin using SWAT model. Hydrol. Earth Syst. Sci. 15, 807.

Bhuyan, S.J., et al., 2003. An integrated approach for water quality assessment of a Kansas watershed. Environ. Model. Softw. 18, 473–484. https://doi.org/10.1016/S1364-8152(03)00021-5.

Bicknell, B., et al., 2001. HSPF, Version 12, User's Mannual. U.S. Environmental Protection Agency, Athens, GA.

Bingner, R.L., et al., 2009. AnnAGNPS Technical Processes: Documentation Version 5 [Online]. Available: ftp://199.133.90.201/pub/outgoing/AGNPS/AGNPS_Web_Files/pdf_files/AnnAGNPS_Technical_Documentation.pdf (Accessed 3 December 2009). .

Blevins, R., et al., 2018. Conservation Tillage for Erosion Control and Soil Quality. Advances in Soil and Water Conservation. Routledge.

Browne, D., et al., 2008. A new saturated/unsaturated model for stormwater infiltration systems. Hydrol. Process. 22, 12.

Brun, S.E., Band, L.E., 2000. Simulating runoff behavior in an urbanizing watershed. Comput. Environ. Urban Syst. 24, 5–22.

Buck, O., et al., 2004. Scale-dependence of land use effects on water quality of streams in agricultural catchments. Environ. Pollut. 130, 287–299. https://doi.org/10.1016/j.envpol.2003.10.018.

Carr, R., Podger, G., 2012. eWater source - Australia's next generation IWRM modelling platform. Water Resources Symposium,2012 742–749.

Chahor, Y., et al., 2014. Evaluation of the AnnAGNPS model for predicting runoff and sediment yield in a small Mediterranean agricultural watershed in Navarre (Spain). Agric. Water Manag. 134, 24–37. https://doi.org/10.1016/j.agwat.2013.11.014.

Chang, H., 2008. Spatial analysis of water quality trends in the Han River basin, South Korea. Water Res. 42, 3285–3304. https://doi.org/10.1016/j.watres.2008.04.006.

Chea, R., et al., 2016. Evidence of water quality degradation in Lower Mekong Basin revealed by self-organizing map. PLoS One 11. https://doi.org/10.1371/journal.pone.0145527.

Chinyama, A., et al., 2014. A simple framework for selection of water quality models. Rev. Environ. Sci. Biotechnol. 13, 109–119. https://doi.org/10.1007/s11157-013-9321-3.

Chong, L., 2010. Nattai River Catchment Source Catchments Application Project. eWater Technical Report.

Chu, X., Steinman, A., 2009. Event and Continuous Modeling with HEC_HMS.

Cohen, A., Davidson, S., 2011. The watershed approach: challenges, antecedents, and the transition from technical tool to governance unit. Water Altern. 4, 1.

Connolly, N.M., et al., 2015. Water quality variation along streams with similar agricultural development but contrasting riparian vegetation. Agric. Ecosyst. Environ. 213, 11–20. https://doi.org/10.1016/j.agee.2015.07.007.

Cox, B.A., 2003. A review of currently available in-stream water-quality models and their applicability for simulating dissolved oxygen in lowland rivers. Sci. Total Environ. 314–316, 335–377. https://doi.org/10.1016/S0048-9697(03)00063-9.

Crawford, N.H., Linsley, R.K., 1966. Digital Simulation in Hydrology: Standford Watershed Model IV. Department of Civil Engineering, Standford University, Palo Alto, California, USA.

Crossette, E., et al., 2015. In: Agency, U.S.E.P. (Ed.), Application of BASINS/HSPF to Data Scarce Watersheds, Agency Washington, DC. EPA/600/R-15/007. Department of Foreign Affairs and Trade, 2016. Final Evaluation of the MRC Integrated Capacity Building Programme (ICBP). DFAT, Canberra.

Devia, G.K., et al., 2015. A review on hydrological models. Aquat. Procedia 4, 1001–1007. https://doi.org/10.1016/j.aqpro.2015.02.126.

Dutta, D., et al., 2012. A daily river system model for the Murray-Darling basin: development, testing and implementation. Hydrology and Water Resources Symposium 2012 1057–1066.

Ellis, R., Searle, R., 2013. An integrated Water quality modelling framework for reporting on Great Barrier Reef catchments. 20th International Congress on Modelling and Simulation.

Fortin, J.-P., et al., 2001. Distributed watershed model compatible with remote sensing and GIS data. I: description of model. J. Hydrol. Eng. 6, 91–99. https://doi.org/10.1061/(ASCE)1084-0699(2001)6:2(91).

Francesconi, W., et al., 2016. Using the Soil and Water Assessment Tool (SWAT) to model ecosystem services: a systematic review. J. Hydrol. 535, 625–636. https://doi.org/10.1016/j.jhydrol.2016.01.034.

Frere, M.H., et al., 1975. ACTMO, An Agricultural Chemical Transport Model. USDA, Washington, DC.

Garcia, L.E., 2008. Integrated water resources management: a 'small' step for conceptualists, a giant step for practitioners. Int. J. Water Resour. Dev. 24, 23–36.

Goharian, E., Burian, S.J., 2018. Developing an integrated framework to build a decision support tool for urban water management. J. Hydroinform. 20, 708.

Guédron, S., et al., 2014. Baseline investigation of (methyl)mercury in waters, soils, sediments and key foodstuffs in the Lower Mekong Basin: the rapidly developing city of Vientiane (Lao PDR). J. Geochem. Explor. 143, 96–102. https://doi.org/10.1016/j.gexplo.2014.03.020.

He, C., 2003. Integration of geographic information systems and simulation model for watershed management. Environ. Model. Softw. 18, 809–813. https://doi.org/10.1016/S1364-8152(03)00080-X.

He, H., et al., 2008. Modelling the impacts of environmental changes on hydrological regimes in the Hei River Watershed, China. Glob. Planet. Change 61, 175–193. https://doi.org/10.1016/j.gloplacha.2007.08.012.

Her, Y., et al., 2017. Implications of spatial and temporal variations in effects of conservation practices on water management strategies. Agric. Water Manag. 180,252–266. https://doi.org/10.1016/j.agwat.2016.07.004.

Hjelmfelt Allen, T., 1991. Investigation of curve number procedure. J. Hydraul. Eng. 117, 725–737. https://doi.org/10.1061/(ASCE)0733-9429(1991)117:6(725).

Howarth, R.W., et al., 2002. Nitrogen use in the United States from 1961–2000 and potential future trends. Ambio 31, 88–96.

Jaber, F.H., Shukla, S., 2012. MIKE SHE: Model Use, Calibration, and Validation. Transactions of the ASABE 55, 1479–1489. https://doi.org/10.13031/2013.42255.

Jayakrishnan, R., et al., 2005. Advances in the application of the SWAT model for water resources management. Hydrol. Process. 19, 749–762. https://doi.org/10.1002/hyp.5624.

Jung, K.-W., et al., 2008. Estimation of pollutant loads considering dam operation in Han River Basin by BASINS/Hydrological Simulation Program-FORTRAN. Water Sci. Technol. 58, 2329.

Borah, D.K., et al., 2002. DWSM-A Dynamic Watershed Simulation Model.

Karakus, C.B., et al., 2015. Determination of land use/cover changes and land use potentials of Sivas City and its surroundings using geographical information systems GIS) and remote sensing (RS). Procedia Earth Planet. Sci. 15, 454–461. https://doi.org/10.1016/j.proeps.2015.08.040.

Kelly, R.A., et al., 2013. Selecting among five common modelling approaches for integrated environmental assessment and management. Environ. Model. Softw. 47, 159–181. https://doi.org/10.1016/j.envsoft.2013.05.005.

King, M.D., 2018. Nutrient trading credits: best management practices and policy hurdles for non-point source polluters in the Chesapeake Bay. Environmental Policy and the Pursuit of Sustainability. Routledge.

Kite, G., 2001. Modelling the Mekong: hydrological simulation for enviornmental impact studies. J. Hydrol. 253, 1–13.

Knisel, W.G., 1980. CREAMS: A Field-Scale Model for Chemicals, Runoff, and Erosion from Agricultural Management Systems. USDA National Resources Conservation Service, Washington, D.C.

Krull, E., et al., 2008. Changes in organic matter chemistry in the Coorong Lagoons over space and time. CSIRO Water for a Healthy Country National Research

Flagship report, CSIRO. Available from: http://www.clw.csiro.au/publications/waterforahealthycountry/cllamm/CLLAMM-CoorongOrganicMatterChemistry.pdf.

Lawniczak, A.E., et al., 2016. Impact of agriculture and land use on nitrate contamination in groundwater and running waters in central-west Poland. Environ. Monit. Assess. 188, 172. https://doi.org/10.1007/s10661-016-5167-9.

Lee, S.-B., et al., 2010. Comparative evaluation of runoff and water quality using HSPF and SWMM. Water Sci. Technol. 62, 1401.

LÉVesque, É., et al., 2008. Evaluation of streamflow simulation by SWAT model for two small watersheds under snowmelt and rainfall. Hydrol. Sci. J. 53, 961–976. https://doi.org/10.1623/hysj.53.5.961.

Li, Z., et al., 2015. Assessment of the AnnAGNPS model in simulating runoff and nutrients in a typical small watershed in the Taihu Lake basin, China. CATENA 133, 349–361. https://doi.org/10.1016/j.catena.2015.06.007.

Liao, H., et al., 2018. Interactive effects of water quality, physical habitat, and watershed anthropogenic activities on stream ecosystem health. Water Res. 130, 69–78. https://doi.org/10.1016/j.watres.2017.11.065.

Licciardello, F., et al., 2007. Runoff and soil Erosion evaluation by the AnnAGNPS model in a small mediterranean watershed. Trans. ASABE 50, 1585. https://doi.org/10.13031/2013.23972.

Liu, Y., et al., 2008. Linking science with environmental decision making: experiences from an integrated modeling approach to supporting sustainable water resources management. Environ. Model. Softw. 23, 846–858.

Liu, Z., Tong, S.T.Y., 2011. Using HSPF to model the hydrologic and water quality impacts of riparian land-use change in a small watershed. J. Environ. Inform. 17, 1–14. https://doi.org/10.3808/jei.201100182.

Lonergan, S.C., 2018. Water and Conflict: Rhetoric and Reality. Environmental Conflict. Routledge.

Lu, H., Xie, H., 2018. Impact of changes in labor resources and transfers of land use rights on agricultural non-point source pollution in Jiangsu Province, China. J. Environ. Manage. 207, 134–140. https://doi.org/10.1016/j.jenvman.2017.11.033.

Luo, C., et al., 2015. Evaluation of the AnnAGNPS model for predicting runoff and nutrient export in a typical small watershed in the hilly region of Taihu Lake. Int. J. Environ. Res. Public Health 12, 10955–10973.

Mannik, R., et al., 2012. Applying eWater source as the catchment model for the Hawkesbury-Nepean water quality model system. Hydrology and Water Resources Symposium 2012.

Maranda, B., Anctil, F., 2015. SWAT performance as influenced by potential evapotranspiration formulations in a Canadian watershed. Trans. ASABE 58, 1585. https://doi.org/10.13031/trans.58.11290.

Mekong River Commission, 2011. Planning Atlas of the Lower Mekong River Basin. Mekong River Commission, Vientiane, Lao PDR.

Mirchi, A., et al., 2009. Modeling for watershed planning, management, and decision making. In: Vaughn, J.C. (Ed.), Watersheds: Management, Restoration and Environmental Assessment. Nova Science Publishers, Inc..

Misigo, A.W., Suzuki, S., 2018. Spatial-temporal sediment hydrodynamics and nutrient loads in Nyanza Gulf, characterizing variation in water quality. World J. Eng. Technol. 6, 98.

Mitchell, B., 2005. Integrated water resource management, institutional arrangements, and land-use planning. Environ. Plan. A 37, 1335–1352. https://doi.org/10.1068/a37224.

Moher, D., et al., 2009. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. PLoS Med. 6, e1000097. https://doi.org/10.1371/journal.pmed.1000097.

Monaghan, R.M., et al., 2007. Linkages between land management activities and water quality in an intensively farmed catchment in southern New Zealand. Agric. Ecosyst. Environ. 118, 211–222. https://doi.org/10.1016/j.agee.2006.05.016.

Moriasi, D.N., et al., 2015. Hydrologic and water quality models: performance measures and evaluation criteria. Trans. ASABE 58, 1763. https://doi.org/10.13031/trans.58.10715.

Mouri, G., et al., 2011. Spatial and temporal variation in nutrient parameters in stream water in a rural-urban catchment, Shikoku, Japan: effects of land cover and human impact. J. Environ. Manage. 92, 1837–1848. https://doi.org/10.1016/j.jenvman.2011.03.005.

MRC, 2011. In: Programme, B.D.P. (Ed.), Planning atlas of the Lower Mekong River Basin, Vientiane, Lao PDR.

Nash, J.E., Sutcliffe, J.V., 1970. River flow forecasting through conceptual models part I—a discussion of principles. J. Hydrol. 10, 282–290. https://doi.org/10.1016/0022-1694(70)90255-6.

Ndomba, P., et al., 2008. SWAT model application in a data scarce tropical complex catchment in Tanzania. Phys. Chem. Earth Parts A/B/C 33, 626–632. https://doi.org/10.1016/j.pce.2008.06.013.

Neef, A., et al., 2018. Land tenure and water rights in Thailand and Vietnam: challenges for ethnic minorities in mountainous forest regions. Geogr. Helv. 61, 255–265.

Nelson, E.J., Booth, D.B., 2002. Sediment sources in an urbanizing, mixed land-use watershed. J. Hydrol. 264, 51–68. https://doi.org/10.1016/S0022-1694(02)00059-8.

Oeurng, C., et al., 2016. Assessment of changes in riverine nitrate in the Sesan, Srepok and Sekong tributaries of the Lower Mekong River Basin. J. Hydrol. Reg. Stud. 8, 95–111. https://doi.org/10.1016/j.ejrh.2016.07.004.

Parisi, D., et al., 2003. Promoting enviornmental democracy using GIS as a means to integrate community into the EPA-BASINS approach. Soc. Nat. Resour. 16, 205–219.

Pease, L.M., et al., 2010. Estimating sediment, nitrogen, and phosphorous loads from the Pipestem Creek watershed, North Dakota, using AnnAGNPS. Comput. Geosci. 36, 282–291. https://doi.org/10.1016/j.cageo.2009.07.004.

Petersen, C.M., et al., 2011. Modeling Escherichia coli and its sources in an urban bayou with hydrologic simulation program—FORTRAN. J. Environ. Eng. 137, 487–503. https://doi.org/10.1061/(ASCE)EE.1943-7870.0000351.

Prosser, P., et al., 2001. Constructing river basin sediment budgets for the National Land and Water Resources Audit. CSIRO Land and Water. Available at: http://www.clw.csiro.au/publications/waterforahealthycountry/2010/wfhc-Daly-River-sediment-nutrient-budget.pdf.

Pushpalatha, R., et al., 2012. A review of efficiency criteria suitable for evaluating low-flow simulations. J. Hydrol. 420–421, 171–182. https://doi.org/10.1016/j.jhydrol.2011.11.055.

Renard, K.G., et al., 1996. Predicting Soil Erosion by Water: A Guide to Conservation Planning with the Revised Universal Soil Loss Equation (RUSLE).

Ribarova, I., et al., 2008. Modeling nutrient pollution during a first flood event using HSPF software: Iskar River case study, Bulgaria. Ecol. Modell. 211, 241–246. https://doi.org/10.1016/j.ecolmodel.2007.09.022.

Ribolzi, O., et al., 2017. From shifting cultivation to teak plantation: effect on overland flow and sediment yield in a montane tropical catchment. Sci. Rep. 7, 3987. https://doi.org/10.1038/s41598-017-04385-2.

Roebeling, P., et al., 2014. Gains from trans-boundary water quality management in linked catchment and coastal socio-ecological systems: a case study for the Minho region. Water Resour. Econ. 8, 32–42. https://doi.org/10.1016/j.wre.2014.10.002.

Rolle, K., et al., 2012. Assessing fecal coliform fate and transport in a coastal watershed using HSPF. Water Sci. Technol. 66, 1096.

Romero-Zaliz, R., Reinoso-Gordo, J.F., 2018. An updated review on watershed algorithms. In: Cruz Corona, C. (Ed.), Soft Computing for Sustainability Science. Springer International Publishing, Cham.

Rossi, C.G., 2009. Hydrologic evaluation of the lower Mekong River basin with the soil and water assessment tool model. Int. Agric. Eng. J. 18 (1–2), 1–13.

Rossman, L.A., 2004. SWMM (Storm Water Management Model). User Mannual. Environmental Protection Agency, Washington, DC.

Sachs, J.D., 2012. From millennium development goals to sustainable development goals. Lancet 379, 2206–2211. https://doi.org/10.1016/S0140-6736(12)60685-0.

Saleh, A., Gallego, O., 2007. Application of SWAT and APEX using the SWAPP (SWAT-APEX) program for the Upper North Bosque River Watershed in Texas. Trans. ASABE 50, 1177. https://doi.org/10.13031/2013.23632.

Saleh, D.K., et al., 2009. In: Using the Soil and Water Assessment Tool (SWAT) to simulate runoff in Mustang Creek Basin, California. U.S. Geological Survey Scientific Investigations Report 2009-5031. . Available from: https://pubs.usgs.gov/sir/2009/5031/.

Salvia-Castellví, M., et al., 2005. Dissolved and particulate nutrient export from rural catchments: a case study from Luxembourg. Sci. Total Environ. 344, 51–65. https://doi.org/10.1016/j.scitotenv.2005.02.005.

Sarangi, A., et al., 2007. Evaluation of the AnnAGNPS Model for prediction of runoff and sediment yields in St Lucia watersheds. Biosyst. Eng. 97, 241–256. https://doi.org/10.1016/j.biosystemseng.2007.02.015.

Sandu, M.-A., Virsta, A., 2015. Applicability of MIKE SHE to Simulate Hydrology in Argesel River Catchment. Agriculture and Agricultural Science Procedia 6, 517–524. https://doi.org/10.1016/j.aaspro.2015.08.135.

Schaltegger, S., Synnestvedt, T., 2002. The link between ‘green’ and economic success: environmental management as the crucial trigger between environmental and economic performance. J. Environ. Manage. 65, 339–346. https://doi.org/10.1006/jema.2002.0555.

Schilling, K.E., 2002. Chemical transport from paired agricultural and restored prairie watersheds. J. Environ. Qual. 31, 1184–1193.

SEI, 2001. WEAP (Water Evaluation and Planning): User Guide for WEAP21. Stockholm Environment Institute, Boston USA. Available from: www.seib.org/weap/.

Shafique, N.A., et al., 2002. Hyperspectral Remote Sensing of Water Quality Parameters for Large Rivers in the Ohio River Basin.

Shaw, M., et al., 2013. Paddock scale modelling to assess effectiveness of agricultural management practice in improving water quality in the Great barrier Reef catchments. 10th International Congress on Modelling and Simulation 1–6 December 2013.

Shrestha, B., et al., 2013. Impact of climate change on sediment yield in the Mekong River basin: a case study of the Nam Ou basin, Lao PDR. Hydrol. Earth Syst. Sci. Discuss. 17, 1–20. https://doi.org/10.5194/hess-17-1-2013.

Singh, V.P., Frevert, D.K., 2006. Watershed Models. CRC Press.

Singh, V.P., Woolhiser, D.A., 2002. Mathematical modeling of watershed hydrology. J. Hydrol. Eng. 7, 270–292. https://doi.org/10.1061/(ASCE)1084-0699(2002)7:4(270).

Sokolov, V., 2011. Integrated Water Resources Management. Water and Food Security in Central Asia. Springer.

Suttles, B.J., et al., 2003. Watershed-scale simulation of sediment and nutrient loads in Georgia coastal plain streams using the annualized AGNPS model. Trans. ASAE46, 1325. https://doi.org/10.13031/2013.15443.

Tas, E., 2013. Integrated Water Resources Management. Aerul Si Apa. Componente Ale Mediului. pp. 217.

Theurer, F.D., Clarke, C.D., 1991. Wash load component for sediment yield modeling. The Fifth Federal Interagency Sedimentation Conference.

Trambauer, P., et al., 2013. A review of continental scale hydrological models and their suitability for drought forecasting in (sub-Saharan) Africa. Phys. Chem. Earth Parts A/B/C 66, 16–26. https://doi.org/10.1016/j.pce.2013.07.003.

Tu, J., 2013. Spatial variations in the relationships between land use and water quality across an urbanization gradient in the Watersheds of Northern Georgia, USA. Environ. Manage. 51, 1–17. https://doi.org/10.1007/s00267-011-9738-9.

UNEP-DHI, UNEP, 2016. Transboundary River Basins: Status and Trends. United Nations Environment Programme (UNEP), Nairobi.

USDA, 1972. National Engineering Handbook. Soil Conservation, Washington, DC.

USEPA, 2015. Application of BASINS/HSPF to Data-Scarce Watersheds. Office of Research and Development, Washington, DC.

Wang, X., Yin, Z.-Y., 1997. Using GIS to assess the relationship between land use and water quality at a watershed level. Environ. Int. 23, 103–114.

Wang, Y., et al., 2018. Analysis of the environmental behavior of farmers for non-point source pollution control and management in a water source protection area in China. Sci. Total Environ. 633, 1126–1135. https://doi.org/10.1016/j.scitotenv.2018.03.273.

Waters, D., et al., 2013. Catchment modelling scenarios to inform GBR water quality targets. 20th International Congress on Modelling and Simulation.

Waters, D.K., et al., 2012. Application of Source to Investigate Nutrient Management Options for the Dongshan Peninsula, Suzhou China. eWater Cooperative Research Centre.

Welsh, W.D., et al., 2013. An integrated modelling framework for regulated river systems. Environ. Model. Softw. 39, 81–102. https://doi.org/10.1016/j.envsoft.2012.02.022.

Wheeler, K.G., et al., 2018. Modelling to bridge many boundaries: the Colorado and Murray-Darling River basins. Reg. Environ. Change. 18, 1607–1619. https://doi.org/10.1007/s10113-018-1304-z.

Williams, J.R., Berndt, H.D., 1997. Sediment yield prediction based on watershed hydrology. Trans. ASAE 20, 1100–1104.

Williams, J.R., et al., 1985. Simulator for water resources in rural basins. J. Hydraul. Eng. 111, 970–986. https://doi.org/10.1061/(ASCE)0733-9429(1985)111:6(970).

Xie, M., 2006. Integrated water resources management (IWRM)—introduction to principles and practices. Africa Regional Workshop on IWRM, Nairobi. October.

Xu, Z.X., et al., 2009. Assessment of runoff and sediment yield in the Miyun Reservoir catchment by using SWAT model. Hydrol. Process. 23, 3619–3630. https://doi.org/10.1002/hyp.7475.

Yan, Q., et al., 2015. Effects of watershed management practices on the relationships among rainfall, runoff, and sediment delivery in the hilly-gully region of the Loess Plateau in China. Geomorphology 228, 735–745. https://doi.org/10.1016/j.geomorph.2014.10.015.

Young, R.A., et al., 1989. AGNPS: a nonpoint-source pollution model for evaluating agricultural watersheds. J. Soil Water Conserv. 44, 168–173.

Young, R.A., Shepherd, R.G., 1995. AGNPS - agricultural nonpoint source model. Workshop on Computer Applications in Water Management. Fort Collins, Colorado.

Yu, D., et al., 2013. Detecting land use-water quality relationships from the viewpoint of ecological restoration in an urban area. Ecol. Eng. 53, 205–216. https://doi.org/10.1016/j.ecoleng.2012.12.045.

Yu, S., et al., 2016. Effect of land use types on stream water quality under seasonal variation and topographic characteristics in the Wei River basin, China. Ecol. Indic. 60, 202–212. https://doi.org/10.1016/j.ecolind.2015.06.029.

Zhou, T., et al., 2019. Characterizing interactions of socioeconomic development and environmental impact at a watershed scale. Environ. Sci. Pollut. Res. Int. 26, 5680–5692. https://doi.org/10.1007/s11356-018-3875-0.

Appendix 3 – Chapter 3's Supplementary Information (SI)

Appendix 3.A: Watershed models and their selected applications

Table B.1 presents some of the most common watershed models used for the simulation of non-point source pollution, along with their developers, regions of application and examples of application.

Table B.1: Watershed models for simulating hydrologic processes and non-point source pollution, including examples of applications.

Models	**Acronym**	**Authors**	**Applied Regions**	**Example application**
Agricultural Non-Point Source Pollution	AGNPS	Young et al. (1989)	North America, Europe, Asia and Pacific, Africa, South America	*Validation of an agricultural non-point source (AGNPS) pollution model for a catchment in the Jiulong River watershed, China (Jianchang et al., 2008)*
Annualized Agricultural Non-Point Source Pollution	AnnAGNPS	Bingner et al. (2009)	North America, Asia and Pacific	*Application of AnnAGNPS to model an agricultural watershed in East-Central Mississippi for the evaluation of an on-farm water storage (OFWS) system (Karki et al., 2017)*

Models	Acronym	Authors	Applied Regions	Example application
Areal Non-Point Source Watershed Environment Response Simulation	ANSWERS	Beasley and Huggings (1982)	North America, Asia	*Simulating watershed outlet sediment concentration using the ANSWERS model by applying two sediment transport capacity equation (Ahmadi et al., 2006)*
Hydrological Simulation Program Fortran	HSPF	Bicknell et al. (1994)	North America, Europe, Asia and Pacific, Africa, South America	*HSPF - Paddy simulation of water flow and quality for the Saemangeum watershed in Korea (Jeon et al., 2007)*
Soil and Water Assessment Tool	SWAT	Arnold et al. (1998)	North America, Europe, Asia, Africa, South America	*Spatial-temporal sediment hydrodynamics and nutrient loads in Nyanza Gulf, characterizing variation in water quality (Misigo and Suzuki, 2018)*
Storm Water Management Model	SWMM	Metcalf and Eddy et al. (1971)	North America, Asia and Pacific	*Modeling of a lot scale rainwater tank system in XP-SWMM: A case study in Western Sydney, Australia (van der Sterren et al., 2014)*
Simulator for Water Resources in Rural Basins	SWRRB	Williams et al. (1985)	USA, Turkey	*Assessment of the effects of agricultural practices on non-point source pollution for a coastal watershed: A case study Nif Watershed, Turkey (Esen and Uslu, 2008)*

Models	Acronym	Authors	Applied Regions	Example application
Generalized River Modeling Package - Systeme Hydroloque European	MIKE-SHE	Refsgaard and Storm (1995)	North America, Asia and Pacific	*Assessing the impacts of land use changes on watershed hydrology using MIKE-SHE (Im et al., 2008)*

Chapter 4. Simulation of streamflow and instream loads of total suspended solids and nitrate in a large transboundary river basin using Source model and geospatial analysis

Kongmeng Ly, Graciela Metternicht, Lucy Marshall

Published Journal: Ly, K., Metternicht, G. and Marshall, L., 2020. Simulation of streamflow and instream loads of total suspended solids and nitrate in a large transboundary river basin using Source model and geospatial analysis. *Science of The Total Environment*, *744*, p.140656. https://doi.org/10.1016/j.scitotenv.2020.140656.

Keywords: transboundary river basin management, watershed models, Source model, Lower Mekong Basin, hydrological simulation, water quality simulation, hydrologic signatures, hydrological response characteristics, water quality overland generation and removal dynamics.

Contribution: This study was conceptualised by Kongmeng Ly in close consultation with Professor Graciela Metternicht and Professor Lucy Marshall, both of whom provided guidance on the available methods that can be applied to achieve the study objectives. Pre-experimental data collection and analyses were carried out by Kongmeng Ly. He also assembled and conducted the experiments and analysed the results of the experiment. Professional personnel of eWater's Limited provided supports during the experiment set up. Kongmeng Ly drafted and finalised the manuscript with the review and editing supports of Professors Metternicht and Marshall in their roles of academic supervisors.

Thesis relevancy: This chapter evaluates the capability of the eWater Source modelling framework in simulate watershed behaviours, hydrological processes and instream water quality dynamics of the LMB, a transboundary river basin made up of four developing countries. As part of this evaluation, I set up LMB-Source model based on the eWater Source modelling framework. Integral to the model set up are the generation of parameter values of previously unavailable hydrological response characteristics (HRCs) and TSS and nitrate overland generation and removal dynamics (GRDs). These are crucial for the model calibration and optimisation. To assess the capability of the LMB-Source model, I used a combination of widely used PPMs and novice application of hydrologic signatures to diagnose and improve model performance. With the simulation results, I confirmed that eWater Source modelling framework is suitable as a watershed management tools for large-scale transboundary river basin of developing countries.

Research highlights and innovations:

- First ever application of the Source modelling framework to simulate the hydrological behaviours and instream TSS and nitrate dynamics of the Lower Mekong Basin.
- Innovative utilisation of a combined predictive performance metrics and diagnostic by hydrologic signatures to assess model capabilities and improve model performance.
- Demonstrated the strength of the LMB basin-specific hydrologic signatures for WM calibration by targeting specific components of the model parameterisations to improve the model performance and reliability.
- Generated parameter values for the previously unavailable hydrological response characteristics (HRCs) and TSS and nitrate overland generation and removal dynamics (GRDs) specific to the LMB that can be regionalised for future studies.

4.1 Abstract

The management of LULC changes in transboundary river basins continues to challenge water resources managers due to the differences in development and conservation priorities of the countries sharing the basin. While various watershed models (WMs) exist to support decision making, basin-wide sustainable application of the instituted WM depends on the management priorities, resources, data availability, and knowledge gaps at national and sub-basin levels. Building on the results of our prior comparative analysis of WMs for a large transboundary river basin, we applied the 'Source' model to the Lower Mekong Basin (LMB). The constructed LMB-Source model was evaluated based on its streamflow and instream total suspended solids (TSS) and nitrate loads simulative performances. A combination of predictive performance metrics (PPMs) and sophisticated hydrologic signatures were used to calibrate model parameters and diagnose the model performance. Calibration results indicated strong similarity between the simulated and observed time series data and were further confirmed by the validation results. The successful model calibration generated parameters that represent hydrologic response characteristics (HRCs) and overland TSS and nitrate generation and removal dynamics (GRDs) previously not available for the LMB. The HRCs and GRDs can be regionalised with physical attributes of the LMB in future studies which can be used to support the management of ungauged sub-basins. This study confirms Source's capability as a decision support tool for the management of transboundary river basins, and provides basin-specific values of HRCs and GRDs that can be used for a better evaluation of the potential effects of LULC changes.

4.2 Introduction

In many parts of the world, land use/land cover (LULC) continues to be transformed either through the conversion of natural land cover for human use or changing management practices on existing land use (Fox et al., 2012; Ribolzi et al., 2017; Lacombe et al., 2018). The impact of these changes have been well documented and are linked to various environmental impacts including climate change (Searchinger et al., 2008; Heald and Spracklen, 2015), biodiversity degradation (Jantz et al., 2015; Solar et al., 2016), changes in hydrologic cycle (López-Moreno et al., 2014; Spera et al., 2016; Ang and Oeurng, 2018), and elevated pollutant loads (El-Khoury et al., 2015; Mehdi et al., 2015). Prior studies have established LULC changes as a major factor that affects hydrological processes and instream water quality (Le et al., 2018; Liu et al., 2018b; Mirzaei et al., 2019; Motew et al., 2019; Nobre et al., 2020). For example, increased agricultural activities can lead to excessive loads of nutrients and sediment run-off (Trambauer et al., 2013; Chea et al., 2016; Oeurng et al., 2016) and that increase urban land cover can increase runoff ratio and stream flashiness (Safeeq and Hunsaker, 2016), which facilitate the transported of non-point source pollutants to stream networks (Ly et al., 2020a).

Despite the knowledge provided by these studies, LULC management continues to challenge water resources managers due to the complex relationships of LULC and instream discharge and water quality. For example, factors influencing hydrological processes and instream water quality dynamics in one basin may not have similar effects in another. This is because the overwhelming investigations of these relationships have been undertaken in developed regions and temperate climate where LULC are different from those found in developing regions with tropical climate (Baker, 2003).

In developing regions, investment on research and development to acquire basin-specific information has been limited due to priorities given to increase and sustain economic growth (Das, 2015). In the Lower Mekong Basin (LMB), for example, large-scale LULC changes are occurring at an unprecedent pace stemming from rapid economic growth and increased population (Yadav et al., 2019; Liu et al., 2020; Ly et al., 2020a). Yet, only limited studies are available linking the effects of LULC changes on water quality and quantity, although the few available have revealed the effects to be significant. For example, changes of the Mekong River's total suspended solids concentrations have been linked to the development and operation of mainstream hydropower (Kummu and Varis, 2007; Arias et al., 2014; Manh et al., 2015; Ly et al., 2020a) and the conversion of areas previously used for traditional agricultural activities to commercial tree plantation and intensive agricultural activities (Ribolzi et al., 2017; Ly et al., 2020a). Likewise, the expansion of urban and agricultural areas at the expense of grassland in many parts of the basin have reduced the basin's natural filtering capacity for trapping non-point source pollution leading to increased instream concentrations of nutrients (Chea et al., 2016; Ly et al., 2020a) and heavy metals (Guédron et al., 2014; Chea et al., 2016).

The management of LULC changes and their consequential impacts can be challenging in any river basin given the growing demands and conflicts stemming from increasing globalisation, population, and climate change. These challenges are exacerbated in transboundary river basins by governance and policy complexities. In the LMB these complexities are driven by differences in topography, LULC compositions, economic and human resources capacities, human–environmental interactions, and priorities for development and conservation of the countries sharing the basin (Ly et al., 2019). While many management options are available to minimise localised impacts of LULC changes (Al Bakri et al., 2008; Tian et al., 2010; Panagopoulos et al., 2012; Wesström et al., 2014), differing views exist on how development with transboundary implications should be managed in order to balance economic development and protection of shared resources (Garrick et al., 2014; Kauffman, 2015). With the advancement of communication technologies, increasing pressures are placed on countries to ensure that development undertaken within their national territories does not affect shared water resources. As such, in many transboundary river basins including the LMB, regional river basin organisations have been established as an integral part of water diplomacy efforts. Central to this type of cooperative management paradigm is the integrated water resources management (IWRM) framework (Agarwal et al., 2000) where sustainable management of shared water resources is carried out considering social and economic development interests of all countries (Kauffman, 2015). The framework also promotes regional decision-making to be done through the improvement of dialogue and coordination among stakeholders of the concerned countries, and the utilisation of scientifically credible tools to simulate potential transboundary impacts of development projects (Wheeler et al., 2018). One such tool is watershed models (WMs) which have been commonly used by water resources managers to simulate the interaction between LULC and instream water quality and hydrological dynamics (Ly et al., 2019). Since the development of the Stanford Watershed Model (Crawford and Linsley, 1966), WMs have not only been used to foster the understanding of how anthropogenic activities effect water resources, but they have also been used to identify likely impacts of alternative development scenarios, so that least damaging scenarios can be selected. For example, WMs have been used for water resource planning and management (Afzal et al., 2016; Vasiliades et al., 2017); to assess the cumulative impacts of hydropower development (Trung et al., 2018); the uncertainty in hydrologic and sediment regimes due to combined changes in land use/land cover and climate (Morán-Tejeda et al., 2015; Shrestha et al., 2016a); and effects of land use management practices on water quality (El-Khoury et al., 2015; Taylor et al., 2016; Nguyen et al., 2017).

A number of WMs are available to support decision making on water resources, and have been comparatively analysed and reviewed for their applicability by prior researches (Francesconi et al., 2016; Ma et al., 2016; Ly et al., 2019; Nguyen et al., 2019). These researchers have concluded that models proven effective in small watersheds may perform unsatisfactorily in larger ones where topographic and land cover features are diverse. Additionally, physically based models that require large volume of data may not be suitable for international transboundary river basins where data scarcity and compatibility are the main issues. These are further complicated by the uncertainty associated with the abilities of the models to produce reliable and meaningful performance that captures hydrological behaviours of the modelled watersheds. While a variety of performance evaluation strategies are available (Moriasi et al., 1015), many do not address the inadequacies of the model performances, and therefore, do not identify the deficiency components of the models that require correction for improved performance (Euser et al., 2013, Gupta et al., 2008). The use of predictive performance metrics (PPMs) such as the Nash Sutcliffe Efficiency (NSE) or the mean square error (MSE) alone have found to be insufficient as they do not take into account the varied influences of different model parameters on the simulated output (Yilmaz et al., 2008, Gupta et al., 2008). In recent years, a more diagnostic approach has been explored linking hydrologic signatures to the underlying processes of WMs (Euser et al. 2013, McMillan, 2019, Gupta et al., 2008). The approach not only allows the inadequacy of the model performance to be quantified, but it also allows the different aspects of the model components to be scrutinised, and therefore, specific calibration parameters to be modified to improve the overall model performance (Yilmaz et al., 2008).

Guided by the results of our prior comparative analysis of WMs for the management of large transboundary river basins (Ly et al., 2019), the main objective of this paper is to evaluate the performance of Source in the simulating hydrological processes and water quality of a large transboundary river basin using the LMB as a case study (*LMB-Source* model). To simplify the modelling processes, TSS and nitrate were selected as proxies to water quality due to available historical data and their roles in the Mekong River environment. The performance of the *LMB-Source* model was evaluated by a combination of predictive performance measures (PPMs) using key statistical metrics and a more novel process-based diagnostic approach that estimates hydrologic signatures of the LMB.

4.3 Study area and Method

Figure 4.1 illustrates the methodological framework for this study. Key components of the research are (i) characterisation of the selected study area; (ii) setting up the model for the LMB which includes the estimation of the basin specific input values for calibration parameters and (iii) model performance evaluation (validation and calibration). Each of these components is described in detail in the following sections.

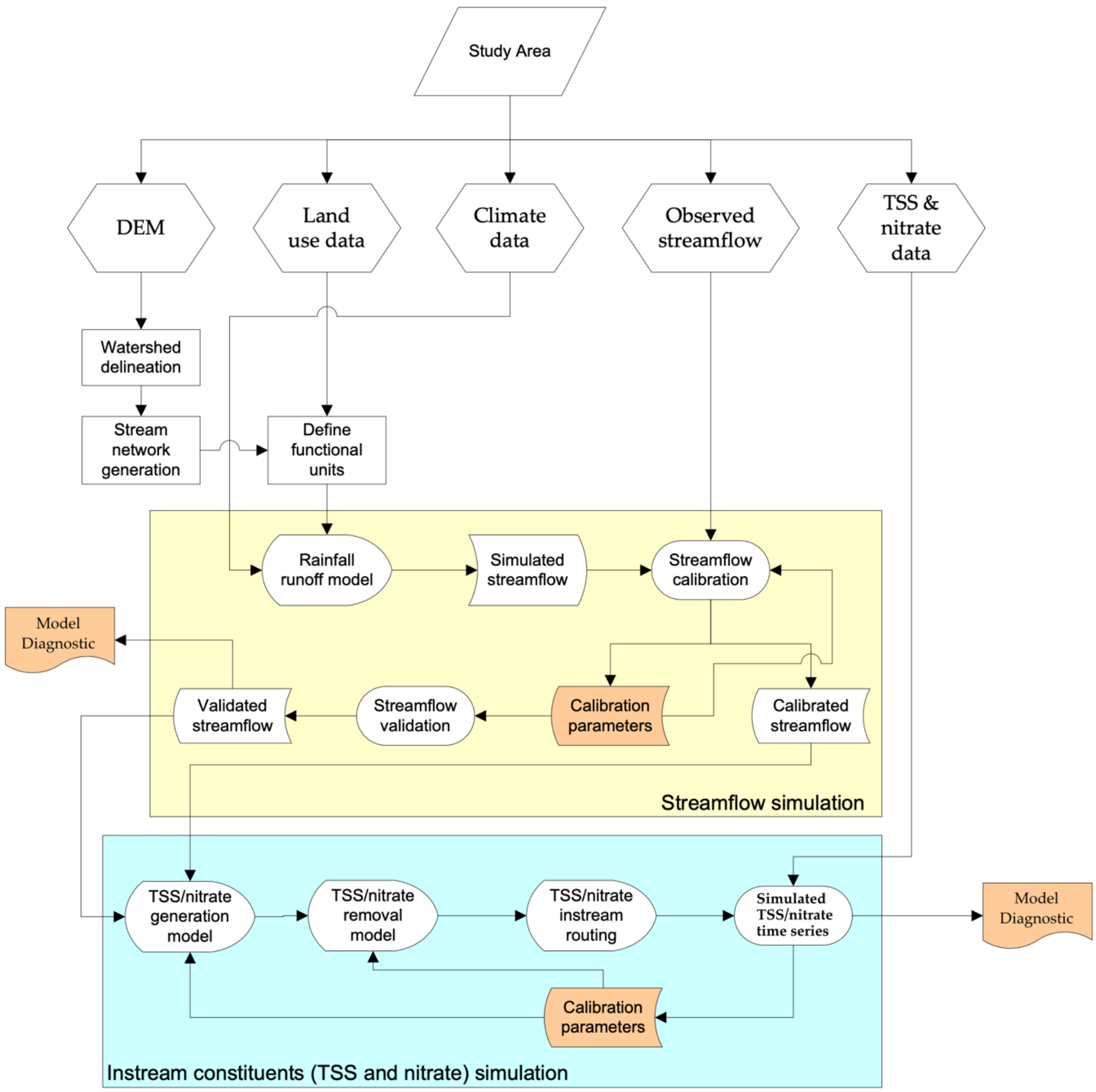


Figure 4.1: Methodological framework for simulating streamflow and water quality of the LMB using the Source Model.

4.3.1 Study Area

The study area is the LMB located in Southeast Asia, covering part of Cambodia, Lao PDR, Thailand and Vietnam. The basin has a total land area of 571,000 km^2 and is home to about 61 million people (Mekong River Commission, 2011). Across the basin, population density varies greatly with the largest density found in Phnom Penh City and the Delta (about 440 persons per km^2); in contrast, the Northern Highland is sparsely populated with the average population density of less than 20 persons per km^2. With elevation ranging from zero metre above sea level at the Delta area to about 2800 metre above sea level in the central part of Lao PDR, the LMB is characterised by four distinct physiographic regions, known as the Northern Highlands, Khorat Plateau, Tonle Sap Basin, and the Mekong Delta (Figure 4.2a). Topography influences landcover and land use type and spatial distribution in each region; forests cover the Northern Highlands while the Khorate Plateau is heavily dominated by agriculture (Figure 4.2b). Further south in the Tonle Sap Basin, the largest freshwater lake in Southeast Asia (Tonle Sap Lake) provides highly productive freshwater fisheries. In the Delta region, where soil is fertile, agricultural areas are the dominant land use type. Ly et al. (2020a), however, pointed out that LULC patterns are changing in the LMB due to increase development and population. For example, land previously used for shifting cultivation in the Northern Highlands has been converted to forest plantation areas resulting in increased soil erosion and sediment runoff (Sithong and Yayoi, 2006). The Delta region has experienced increased urbanization and a reduction of agricultural and forest land cover due to pressures from a growing and affluent population. Furthermore, the development of hydropower projects in the upper basin has affected both water quality and quantity of the Lower Mekong River (Arias et al., 2014; Cochrane et al., 2014; Manh et al., 2015; Hecht et al., 2019). These drivers of land use/land cover change are expected to increase and can pose a serious threat to the river biodiversity and food security (Manh et al., 2015; Dang et al., 2018).

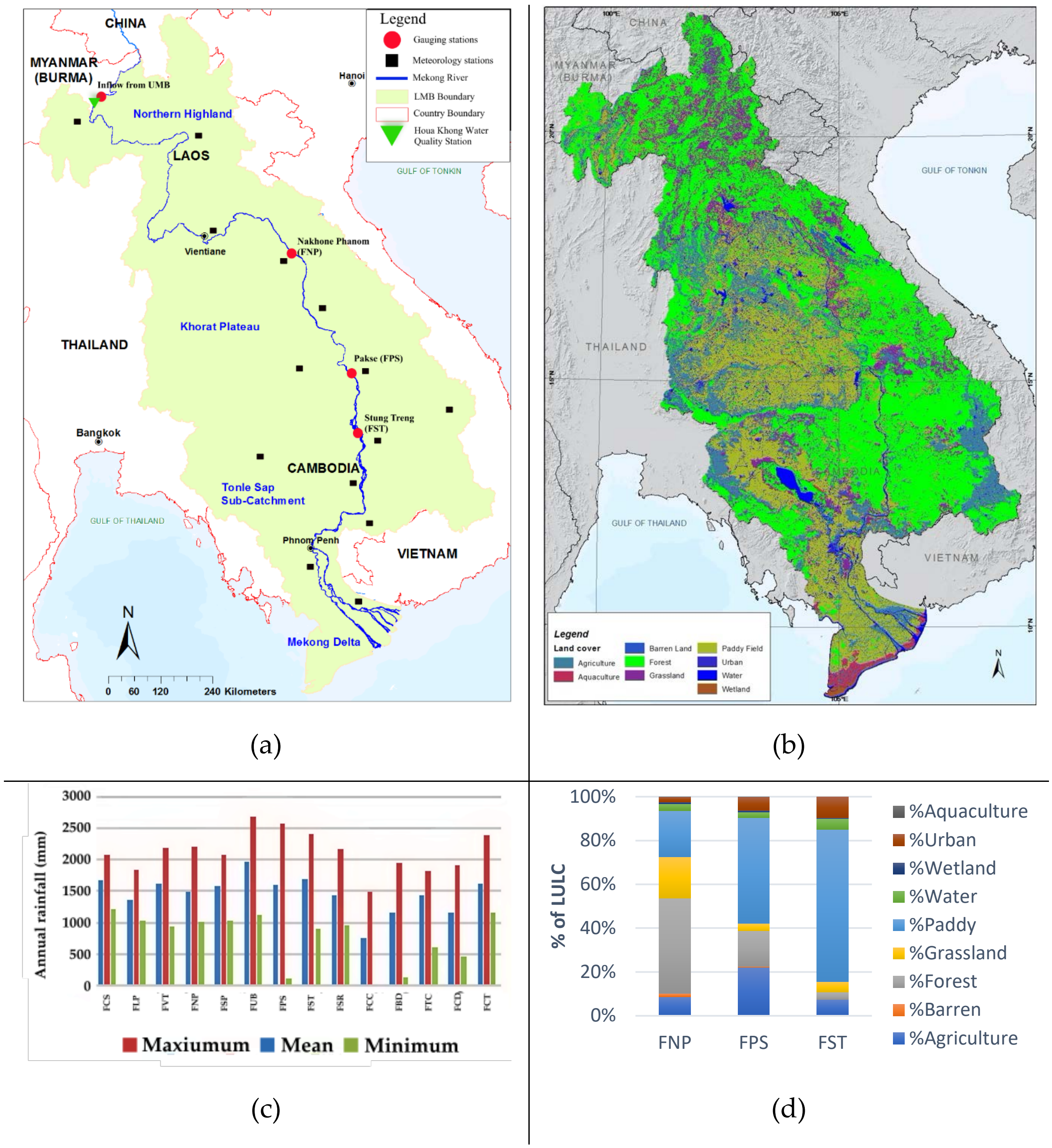


Figure 4.2: Study area of the LMB illustrating (a) location of the gauging stations and meteorology stations used in the study, (b) 2010 LULC, (c) variation of rainfall patterns (Table a.1 in Appendix 4.A of the Supplementary Information (SI) provides full name of

the abbreviated meteorological stations) , and (d) proportion of LULC of sub-catchment draining to the 3 gauging stations.

Due to the size of the basin, it is subject to highly variable distribution of mean annual rainfall. Daily meteorological data from 1985 to 2015 sourced from the Mekong River Commission reveals the highest mean annual rainfall was recorded at Pakse (MPS) (Figure 4.2c), with approximately 1970 mm per annum, while the Chouy Changvar (MCC) station recorded the lowest annual mean (approximately 750 mm per year). Overall, the highest rainfall levels correspond to the upper and middle parts of the Lower Mekong Basin with majority of the stations recording mean annual rainfall above 1600 mm. The lowest recorded levels are in the lower parts of the basin and delta areas.

4.3.2 Data acquisition and pre-processing

4.3.2.1 Meteorological, hydrological and water quality data

40 years (1985-2015) of daily and monthly environmental monitoring data in form of meteorological, hydrological and water quality data were sourced from the Mekong River Commission (MRC). The data were pre-processed for quality control using MATLAB (MathWorks, R2010a). The process involved the removal of stations where the measurement period was too short and those with extensive duration of measurement gaps. For all remaining stations, missing data points were interpolated using spline interpolation techniques in R, as described in Moritz and Bartz-Beielstein (2017). Following data pre-processing, time series for the period of 2003 to 2011 were used for the model simulation and evaluation. Time series data for the period of 1/1/2003 to 31/12/2007 were used for calibration while datasets from 1/1/2008 to 31/12/2011 were used for model validation.

Following the data pre-processing, meteorological data in the form of daily precipitation and temperature time series at 14 stations (Figure 4.2a and c) were used as the main climate input data for the model for rainfall runoff simulation. Similarly, records of daily streamflow at 3 stations (FNP, FPS and FST in Figure 4.2a) were used for calibration and validation. Key hydrologic signatures (streamflow magnitudes, runoff ratio R_C, and flashiness index *FI*) and drainage properties of these gauging stations during the study period (2003 – 2011) are summarised in Table a.2 of Appendix 4.B.

While water quality data were found to be suitable at 17 stations along the Lower Mekong River (LMR) for the period 1985 to 2015 (with exception of stations located in Cambodia where recording began when Cambodia joined the MRC in 1995), only records at 4 stations were used in this study. Houa Khong water quality monitoring station (Figure 4.2a) was used to represent instream TSS and nitrate levels coming from the Upper Mekong Basin (UMB) (see Section 4.3.3). The remaining three stations (FNP, FPS and FST in Figure 4.2a) were used for calibration and validation purposes. These stations are the same as those with suitable daily discharge data.

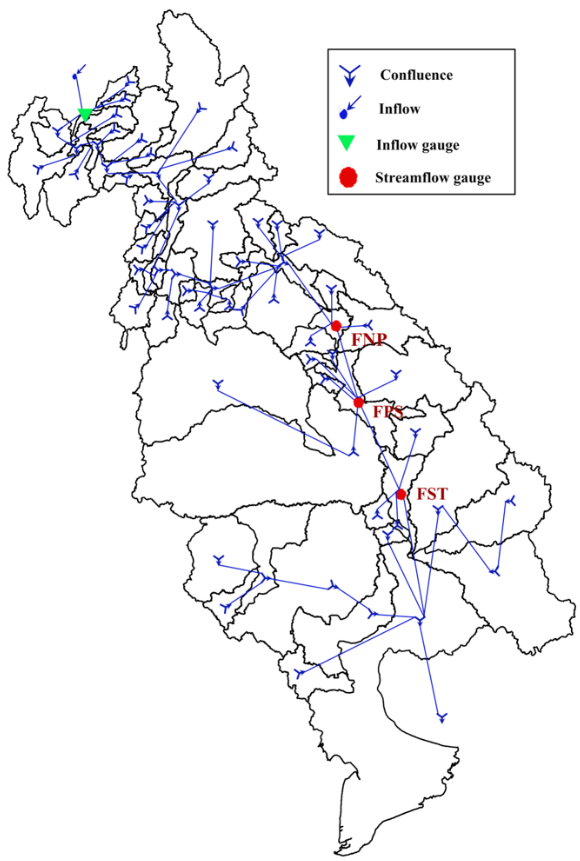
4.3.2.2 Land use/land cover and topographic data

This research uses the 2010 LULC map generated by the MRC (Mekong River Commission, 2010) from classification of Landsat-5 Thematic Mapper images at 30 meters spatial resolution, complemented with field surveys. The 2010 LULC map was selected due to the availability of the input climate data (Section 4.3.2.1). The map adopts the Land Cover Classification System (LCCS) of the United Nations Food and Agricultural Organization (FAO), differentiating 19 land cover types including various forest types, agricultural types and urban area (Ly et al., 2020). In this study, we reclassified these land cover types into 9 LULC types to facilitate model set up and modelling. The reclassified LULC types include forest, agriculture, paddy field, barren land, urban, wetland, grassland, water, and aquaculture (Figure 4.2b and d).

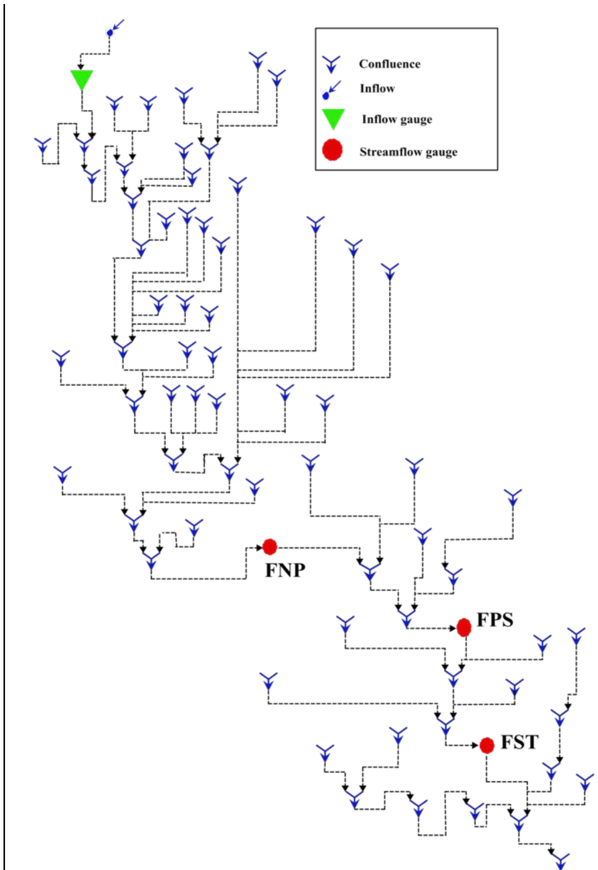
A digital terrain model (DTM) generated for the whole basin, at a spatial resolution of 50 meters obtained from the MRC, was used to define surface stream network and delineate sub-basins to be fed into the model when constructing the *LMB-Source* model. Using the watershed delineation method described in Ly et al., (2020), an optimal total of 65 sub-basins were generated for this study (Figure 4.3a), which enable the balancing of model computational efficiency and the spatial resolution of the model simulations.

4.3.3 Model description and set up

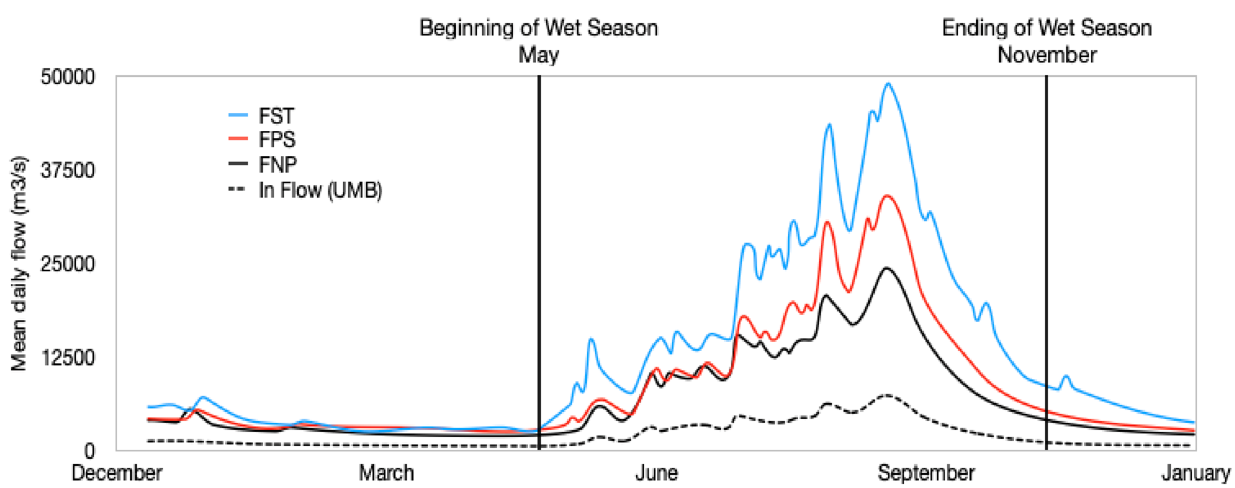
A public version of Source (version 4.7) (eWater Ltd., 2018) integrated model was used as it can be operated at daily and monthly time steps, and can produce simulations at various temporal (daily to annual) and spatial (from sub-catchment to the entire basin) scales (Barlow et al., 2011). This modelling framework has been used extensively to support decision makings at local and interstate levels (Ly et al., 2019), though applications on a large transboundary river basin involving multiple countries are yet to be undertaken. To assess its capability at transboundary river basin level, the framework was applied to the LMB where the *LMB-Source* Model was built schematically by loading the sub-basins map generated in ArcGIS (Section 4.3.2.2). Stream network was then manually drawn connecting each sub-catchment. With 65 sub-basins, 65 nodes were generated, presenting a joining of tributaries or branches in the river network (Figure 4.3a and b). In addition, an outlet node was generated to represent the point where the Mekong River to enter the South China Sea. Similarly, an inlet node was also generated to represent inflow from the UMB (Figure 4.3a and b). Daily precipitation and temperature time series at 14 stations (Section 4.3.2.1) were manually added to the *LMB-Source* model as input data. Hydrological stations (FNP, FPS, FST) with daily discharge and monthly TSS and nitrate time series were established as gauging nodes where the simulation of streamflow and instream nitrate and TSS loads were carried out by the model. Therefore, observed time series for streamflow, TSS, and nitrate at these stations were loaded into the model for calibration and validation purposes (see Section 4.3.5 for model calibration and validation processes). At the inlet node, streamflow, TSS and nitrate time series were also loaded to represent the incoming flow and loads from the UMB. This enables the model to accommodate for the unaccounted differences in water balances and instream loads of TSS and nitrate between the LMB and UMB. It should be noted, however, that since the study area only covers the LMB, inflow time series from the UMB was estimated by applying its percent contribution to the flow of the LMB. The Mekong River Commission (2009) estimated that the inflow from the UMB contributes 16% of the total outflow of the LMB, and represents 30% of flow at FNP. Using this figure, inflow time series was derived (Figure 4.3c). Instream TSS and nitrate time series at Houa Khong water quality monitoring station, located downstream of the national boundary of China and Lao PDR (Figure 4.2a and Figure 4.3a) were used to represent the inflow time series. This station was established by the MRC to capture the condition of water quality coming from the UMB (Mekong River Commission, 2011).


Confluence
Inflow
Inflow gauge
Streamflow gauge
FNP
FPS
FST

(a)


Confluence
Inflow
Inflow gauge
Streamflow gauge
FNP
FPS
FST

(b)


Beginning of Wet Season
May
Ending of Wet Season
November
Mean daily flow (m3/s)
50000
37500
25000
12500
0
December
March
June
September
January
FST
FPS
FNP
In Flow (UMB)

©

Figure 4.3: a) Geographical and (b) schematic representations of the *LMB-Source* model along with the (c) mean annual hydrographs of the 3 gauging stations and the estimated inflow from the UMB

Once the stream network was generated for the LMB-Source, functional units (FUs) representing different land use types were defined for each sub-basin. For this study, 9 FUs were defined based on the reclassified 2010 LMB LULC map (see section 4.3.2.2). The area for each FU was automatically computed within each sub-basin. In Source, FUs have significant roles as they provide different hydrological responses rainfall and temperature influencing the model simulation of both streamflow and water quality constituents.

4.3.3.1 Streamflow modelling

The Source modelling framework has a number of built-in rainfall runoff models. For this study, streamflow simulation was carried out using the built-in IHACRES – CMD rainfall runoff model (Identification of unit Hydrographs and Component flows from Rainfall, Evaporation and Streamflow data based on Catchment Moisture Deficit) (Croke et al., 2005). A modified version of the original IHACRES model proposed by Evans and Jakeman (1998), it that considers moisture deficit of the catchment (storage index) when estimating excessive rainfall and streamflow (Croke and Jakeman, 2004). Figure C.1 (Appendix 2.C) provides the conceptual layout of the IHACRES-CMD rainfall runoff model, where streamflow is produced through non-linear and linear modules. This figure and Equations a.1 to a.7 (Appendix 4.C) highlight the efficiency of the model requiring only 6 calibration parameters. The simplicity and low data demand required by the model has been found to have advantage in addressing regionalised issues (Kokkonen et al., 2003; Borzì et al., 2018) where data scarcity and basins sizes are often observed. These are all important factors that were considering when choosing rainfall runoff model for the *LMB-Source*. Additional detailed processes of the IHACRES-CMD rainfall runoff model are provided in Croke and Jakeman (2004).

4.3.3.2 TSS and nitrate modelling

The LMB-Source TSS and nitrate simulations were undertaken using Source (i) catchment water quality model and (ii) storage and link water quality model (eWater Ltd., 2018). The first model simulates generation and runoff processes of water quality constituents (TSS and nitrate) enabling loads of TSS and nitrate to be simulated through generation and transportation processes (eWater Ltd., 2018). The second model simulates instream dynamics of water quality constituent enabling instream modification processes to be captured (eWater Ltd., 2018).

Under the LMB-Source catchment water quality model, TSS and nitrate loads were generated by the Event Mean Concentration (EMC) and Dry Weather Concentration (DWC) module, where TSS and nitrate generation rate under event mean and dry weather conditions for each FU is required for optimisation. With this module, loads of a constituent (e.g. TSS or nitrate) are estimated for each FU or land use type, as different FUs have different influences on constituents' generation rates. Furthermore, prior studies have shown the LULC-water quality to be site or region specific (Baker, 2003; Hobbie et al., 2017; Ly et al., 2020a). Therefore, the total generation load of a constituent C_L is the sum of loads generated for all *I*, where *I* representing a FU (Equation 1).

$$C_L = \sum_{i=j}^{n} C_{Li} \qquad \text{Equation 1}$$

C_{Li} is the constituent load of the j^{th} FU and is calculated as a sum of the loads generated during the dry weather and storm events (Equation 2).

$$C_{Li} = Q_s D_i + Q_q E_i \qquad \text{Equation 2}$$

In this equation Q_s and Q_q are the slow and quick flows respectively (Equation a.6 and a.7 in Appendix 4.C) and D_i and E_i are calibration parameters representing the generation rates for the i^{th} FU during the dry weather and storm event, respectively. Once generated, C_L is transported as non-point source pollutant and modified by filtering module. LMB-Source uses a percent removal technique to modify constitute loads from their generated locations to stream network. With this technique, trapping efficiency of each FU is calibration parameter, and its initial value was estimated using a combination literature reviewed and suggestions from experts.

Instream processes of TSS and nitrate were simulated at FNP, FPS, and FST (represented by gauging nodes) as shown in Figure D.1 (Appendix 4.D). The constituent fully mixed approach was adopted due to its suitability for modelling water quality parameters at monthly time steps, consistent with the observed time series. In this way, constituents are assumed to be fully mixed at all sections of the stream network, and mass balance of simulated constituents is maintained in all nodes and links in the river network, as described by Equations a.8 to a.15 in Appendix 4.D.

4.3.4 Optimisation of the LMB-Source Model

The simulated streamflow of the *LMB-Source* model was calibrated using a combination of (i) automatic calibration by a built-in optimiser function and (ii) manually adjusted the calibration parameters based on the model performances (see Section 4.3.5). Calibrations were carried for all gauging stations in a nested fashion from the uppermost station (FNP) to the lowest station (FST).

Automatic calibration utilised four-step process including (i) establishing calibration targets; (ii) defining calibration period; (iii) calibration parameterisation of the rainfall-runoff model; and (iv) identifying optimisation function. The Nash-Sutcliffe efficiency (*NSE*) was defined as the calibration target as the objective was to minimise deviance between the simulated and observed streamflow time series. The calibration period was set for 2003 to 2007 (see Section 4.4.1). Six parameters (Table 4.1) were set for modification during the calibration run with an aim of improving the model fit to the observed data series. The Shuffled Complex Evolution method (SCE-UA) (Duan et al., 1992) was used as a calibration optimisation function to automatically optimise the calibration parameters. With this method, calibration optimisation is carried using a strategy that combines the strength of the simplex procedure for function minimisation (Nelder and Mead, 1965), with controlled random search (Price, 1987), competitive evolution (Holland, 1975), and complex shuffling. The strategy allows SCE-UA to be efficient and yet effective, and therefore, is commonly used as an optimiser function for modelling, including rainfall runoff (Gan and Biftu, 1996; Kannan et al., 2008). Detailed information on the algorithm of the SCE-UA is provided in Duan et al. (1992). Given the use of the SCE-UA automated optimisation function is applied within the IHACRES-CMD rainfall runoff model when calibrating streamflow, this study adopted the approach of Nguyen et al. (2019) and did not undertake sensitivity analysis of streamflow modelling. All optimisation parameters were assumed to influence the results of the simulation.

Following target calibration, hydrologic signatures were used to diagnose any observed poor performance (see Section 4.3.5). Calibration parameters were additionally modified to achieve the optimal calibration target while minimising the differences between the simulated and observed hydrological signatures. The optimised parameters were validated for the period 2008 to 2011.

For instream TSS and nitrate loads, calibration processes involved mainly the optimisation of parameters associated with catchment water quality modelling. Specifically, (i) EMC and DWC generation rates and (ii) trapping capacities for each FU or LULC type. These values are basin-specific and can be obtained from either prior studies, or can be estimated using basin monitoring data. As the first study to apply Source in the LMB, values EMC and DWC generation rate for TSS and nitrate had to be estimated for each FU using the method described in Chiew et al. (2002). A combination of basin-specific LULC data and time series data for precipitation, streamflow, TSS, and nitrate were used. Similarly, trapping capacity for each FU was estimated using existing literature and suggestions of local experts as references. These parameters were optimised during constituent loads calibration using NSE and %PBIAS as a target. The optimised parameters and the model ability to simulate instream TSS and nitrate loads were validated for the period of 2008 to 2011 (see Section 4.4.2).

4.3.5 Model performance evaluation

The LMB-Source performance was evaluated for both streamflow and instream constituents (TSS and nitrate) simulations. Varieties of performance metrics with different properties and objective functions are available for assessing the performance of watershed models during calibration and validation processes (Moriasi et al., 2015). The use of these metrics alone have been found to be inadequate as they do not differentiate the different factors influencing the model functioning (Gupta et al., 2008; Yilmaz et al., 2008). Therefore, to evaluate the performance of LMB-Source in simulating streamflow, we used a combination of (i) predictive performance metrics (PPMs) where the model performance was evaluated against a set of criteria (Moriasi et al., 2015; Ammann et al., 2019), and (ii) process based diagnostics linking hydrologic signatures with processes and behaviours of the basin (Yilmaz et al., 2008; McMillan, 2020).

4.3.5.1 Predictive performance metrics

The model predictive performance was evaluated using metrics (Table 4.2) that fulfil the three criteria recommended by Ammann et al. (2019) where the model is judged based on its ability to (a) minimise deviance between the simulated and observed time series, (b) reproduce the fluctuation dynamics of the observed time series, and (c) produce overall good predictive margin distribution.

The model ability to minimise deviance between the simulated and observed streamflow time series (criteria (a)) was evaluated using the Nash-Sutcliffe efficiency (*NSE*) (Nash and Sutcliffe, 1970) and coefficient of determination (R^2). Both metrics provide indicators of the model performance in relation to the observed time series, where the desired optimal values are 1.0 (Gupta et al., 1999). For this study, the NSE was set at a daily and monthly time steps; at a daily time step, it can assess the model's ability to capture the timing of flow peak and recession rates while the fit pattern of simulated to the observed time series is evaluated at a monthly time step (eWater Ltd., 2018). Performance levels for these metrics are as recommended by Moriasi et al. (2015) (Table a.4 in Appendix 4.E).

The model ability to reproduce the fluctuation dynamics of the observed streamflow time series (criteria (b)) was assessed using the Pearson's correlation coefficient (c). This metric describes the frequency and rapidity of changes in streamflow during runoff events, a key hydrologic signature that characterises the influences of both anthropogenic (e.g. urbanization, hydropower development) and naturogenic characteristics of the basin (e.g. LULC, topography catchment size) (Baker et al., 2004; Ulén et al., 2016; Li et al., 2020). For this study, Pearson's r was calculated and compared for both the observed and simulated time series.

For the third criteria (c), performance metrics that provide indication of the model reliability, precision, and bias were used. The model predictive reliability and precision were assessed using the reliability index (*RI*) and relative spread (*RSI*) index, respectively, as described in , while percent bias (%PBIAS), as outlined in Table a.4 of Appendix 4.E was used to evaluate the model bias. *RI* enables the consistency degree of the observed streamflow for being a sample of the simulated distribution to be quantified. The quantification and interpretation of *RI* follow those used by Ammann et al., (2019), where a value of 1 equates perfect reliability. *RSI* provides an indication of the preciseness of the simulation or uncertainty of the simulation, and therefore, the smallest value is desired. The model tendency to over and under simulate streamflow, compared to the observed time series, was assessed using %PBIAS where optimal value 0 is desired. However, the value can be either negative or positive depending on whether the streamflow was under or over predicted by the model.

4.3.5.2 Diagnostic of the model prediction

To complement the results of the PPMs, key process-based hydrologic signatures were applied to the simulated streamflow and its counterpart. With hydrologic signatures, our aim was to diagnose the model performance by differentiating the various aspects of the models functions in representing hydrologic processes and behaviour of LMR. For example, assessment of baseflow performance can be carried out using hydrologic signatures governing baseflow behaviours enabling quantification of differences between the simulated and observed baseflow. Thus, calibration parameters relating the model simulation of baseflow can be manually adjusted to prove model performance.

A number of signatures are available to describe various aspects of streamflow behaviours (McMillan, 2020), and have been used for the diagnostic of the model poor performance, and to facilitate model calibration (Gupta et al., 2008; Yilmaz et al., 2008). Signatures used in this study were those that can capture the functioning of the IHECRES-CMD rainfall runoff model, where stream flow simulation influenced by factors that govern the generation of effective rainfall (non-linear process) and streamflow (linear process) (Figure C.1 in Appendix 4.C). Therefore, signatures used include those that can evaluate vertical distribution of soil (e.g. midsegment slope of the flow duration curve (FDC) (Sawicz et al., 2011)); behaviours of base (e.g. low segment slope of the FDC baseflow index (McMillan, 2020)); and peak flows (e.g. low segment slope of the FDC (Sawicz et al., 2011)); and timing of the rise and fall of streamflow (e.g. Richards-Baker Flashiness Index *(FI)* (Baker et al., 2004))

The adjustment of calibration parameters based on the diagnostic of the model simulated streamflow was carried out following the initial automatic calibration run. Using the mentioned hydrologic signatures, different segments of the simulated streamflow were assessed against its counterparts. Calibration parameters responsible for poor simulation of streamflow segments compared to their counterparts were adjusted one at a time to produce a better segment fit while not compromising the model overall predictive performance.

4.3.5.3 Performance of instream TSS and nitrate loads

Calibration of instream TSS and nitrate loads were carried out simultaneously, and after streamflow calibration (Section 4.3.5.2). Calibration parameters relating to TSS and nitrate generation and overland removal processes were manually adjusted based on the model performances with initial input values being those estimated using techniques described in Section 4.3.4. The optimised model parameters were obtained by fitting the observed TSS and nitrate loads to those simulated by the model. PPMs including the NSE and %PBIAS were used to assess the model performance, where the simulation TSS was deemed satisfactory with %PBIAS < ± 20% and NSE > 0.45 while nitrate simulation is consider successful with %PBIAS < ± 30% and NSE > 0.35 (Table a.5 in Appendix 4.E) (Moriasi et al., 2015).

4.4 Results

4.4.1 Streamflow calibration and validation

Six parameters (Table 4.1) were used and optimised by the LMB-Source calibration and validation processes of streamflow (Sections 4.3.5.1 and 4.3.5.2). The model performance was assessed through a combination of PPMs and diagnostic approach, revealing that all parameters affected the results of streamflow simulation. Parameters *e, f,* and *d* (Table 4.1) represent non-linear behaviours of basin hydrologic systems where the process of converting precipitation to effective rainfall is controlled by soil moisture deficit (Equations a.1 to a.4 in Appendix 4.C); the linear process for converting effective rainfall into streamflow is characterised by parameters τ_q, τ_s, and v_s. Basin-specific optimisation of these parameters revealed that their values vary from station to station, with the exception of parameters *e* and *f* where their values were found to be similar for all 3 sub-basins ranging from 1.2 to 1.5 and 1.1 to 1.5, respectively. This is likely due to the similarity of vegetation cover and temperature levels of the three sub-basins. On the other hand, the catchment flow thresholds were revealed to be highly variable, with the highest value obtained for FNP's sub-basin — likely related to its hilly and mountainous dominated topographic characteristic.

The linear module delivered τ_q and τ_s parameters which describe the recession times for quick and slow flows of the basins drained to the 3 gauging stations. The model's optimised quick flow recession time ranged from 8.6 to 10 days, while the optimised slow flow recession time fluctuated from 150 to 450 days. The ratio of the slow flow to the total flow ranged from 0.21 to 0.30 and appears to be consistent with the observed hydrograph of the river where its annual discharge is dominated by wet season flow (Figure 4.3c).

Table 4.1: Optimised calibration parameters for IHACRES-CMD rainfall runoff model for the *LMB-Source* model.

Parameters	**Descriptions**	**Units**	**Optimised Calibration Parameters**		
			FNP	**FPS**	**FST**
τ_q	Time constant governing the rate of recession of direct runoff	Day	8.6	10	10
τ_s	Time constant governing rate of recession of baseflow	Day	32.9	26.2	19.5

e	Conversion factor for Temperature to PET	-	1.5	1.2	1.2
f	Plant stress threshold factor (expressed as a multiplicative factor of *d*)	-	1.3	1.1	1.5
d	Catchment flow threshold	mm	450	178.5	150
v_s	The proportion of slow flow to total flow	%	0.30	0.23	0.21

4.4.1.1 Predictive performance metrics

With the NSE selected as the target function of automatic streamflow calibration (Section 4.3.4), the model produced NSE values that ranged from 0.64 to 0.82. While this range is satisfactory when compared to the recommended criteria in Table a.4 (Appendix 4.E), closer examination of the simulated and observed streamflow patterns revealed that the model under-simulated both high and low flow. Therefore, the model performance was further diagnosed using key hydrologic signatures (Section 4.3.5.2), where relevant calibration parameters were manually adjusted. The results of the process produced optimal calibration parameters (Table 4.1) that improved the model performance during calibration (2003-2007) and validation (2008-2011) of streamflow simulation that closely match pattern of observed streamflow in both timing and magnitude (Figure 4.4), as can be seen in the values of PPMs (Table 4.2) and hydrologic signatures (Table 4.3).

Table 4.2 summarises values of the PPMs during both calibration and validation periods using the optimal calibration values; it shows the model had “very good” abilities to minimise deviance between the simulated and observed streamflow time series at all 3 gauging stations. NSE values ranged from 0.89 to 0.93 when evaluating daily streamflow, and from 0.92 to 0.95 for monthly time steps. Further, R^2 values ranged from 0.9 to 0.93 indicating high correlation between the observed and simulated time series (Figure 4.4). These values are above the values classified as “very good” model performance by Moriasi et al. (2015) (Table a.4 Appendix 4.E), and confirm the model’s ability to capture the timing of flow peak, recession rate and fit pattern (eWater Ltd., 2018). These figures were further corroborated by the validation results (Table 4.2), with NSE values for the daily time series varying from 0.89 to 0.92, and R^2 values ranging 0.91 to 0.93. This indicates “very good” model performance compared to the recommended criteria (Table a.4 Appendix 4.E)

In terms of the model ability to capture streamflow fluctuation timings and magnitudes, the most optimal calibration run produced r values greater than 0.95 for all 3 stations. During the validation period, the model produces similar level of performances with $r > 0.95$ (Table 4.2) confirming its ability to capture the fluctuation observed in the recorded streamflow, and therefore, correlated well with the input rainfall.

Regarding the model ability to produce overall good predictive margin of distribution, the RI values ranged from 0.85 to 0.89 indicates high degree of consistency of the observed flows being a sample of the simulated one. This is consistent with the high levels of precision obtained between the simulated and observed streamflow time series, as illustrated by the very low RSI values (0.0002 to 0.0004). In addition, the overall error between simulated and observed streamflow volumes were low, with values of %PBIAS varying from -1.6 to 6.8%. These figures are within “very good” and “good” performance criteria recommended by Moriasi et al. (2015) (Table a.4 Appendix 4.E). Large errors were detected at FST where the model under-simulated both high (%PBIAS of -11.3%) and low (%PBIAS of -13.5%) flow condition, compared to those of the observed time series despite the adjustment of calibration parameters following the model diagnostic. When compared to the recommended criteria (Table a.4 Appendix 4.E), the model performance on simulating high and low flow condition can still be considered as satisfactory. Similar levels of reliability, relative spread and errors were obtained during the validation period which confirm that the model has a good ability overall to predict the margin of distribution of the streamflow (Table 4.2).

Table 4.2: Performance of LMB-Source based on the PPMs of observed and simulated streamflow during the calibration (2003-2007) and validation (2008-2011) periods.

PPM Metrics		Indication of the metrics	Calibration			Validation		
			FNP	FPS	FST	FNP	FPS	FST
NSE	Q_{daily}	Measuring of how well hydrographs of the simulated and observed time series correspond to one another (timing of flow peak and recession rate)	0.89	0.93	0.90	0.92	0.91	0.89
	$Q_{monthly}$	Measuring the fit pattern of the simulated and observed time series	0.93	0.95	0.92	0.93	0.92	0.89
	Q_{FD}	Measuring the fit of the magnitudes regardless of timing	0.92	0.95	0.89	0.93	0.93	0.87
R^2		Measuring of how well hydrographs of the simulated and observed time series correspond to one another	0.9	0.93	0.92	0.93	0.91	0.93
Pearson's r		Correlate the magnitude of simulated and observed time series	0.95	0.96	0.96	0.96	0.95	0.96

		reflecting the model performance of the model in simulating the fluctuation time of the observed time series						
△FI		Different in the flashiness index of the observed and simulated time series	0.01	0.03	0.02	0.02	0.02	0.03
RI		Consistency degree of the observed flows being a sample of the simulated streamflow distribution	0.89	0.91	0.85	0.87	0.89	0.85
RSI		Preciseness of the simulated time series compared to its counterpart	0.0004	0.0002	0.0004	0.0004	0.0002	0.0002
%PBIAS	Q_{daily}	Overall error of total flow volume between the simulated and observed streamflow time series	-1.6	0.5	6.8	1.8	3.5	7.2
	Q_{10}	Overall error in high flow between the simulated and observed streamflow time series	3.8	-7.2	-11.3	3.4	-8.6	-10.6
	Q_{90}	Overall error in low flow between the	-5.4	-6.7	-13.5	-2.3	-7.3	-12.1

	simulated and observed streamflow time series	

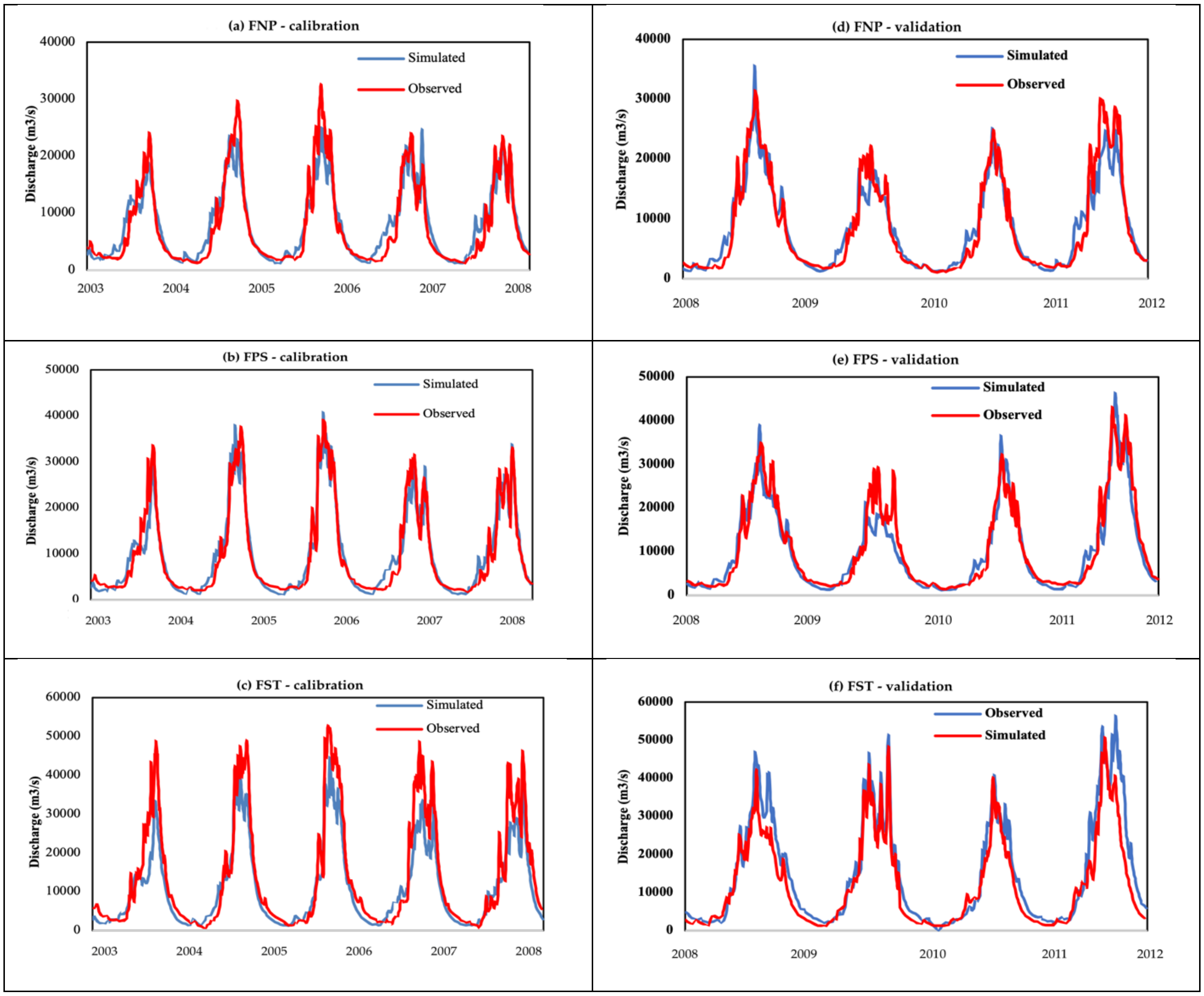


Figure 4.4: Comparison of simulated and observed streamflow time series for the calibration (2003 to 2007) and validation (2008-2011) periods at FNP (a and d), PPS (b and e), and FST (c and f)

4.4.1.2 Diagnostic with hydrologic signatures

Various components of the simulated and observed streamflow were evaluated to diagnose the model performance in relation to the values of the calibration parameters. Figure 4.5 shows a comparison of the FDCs between the observed and simulated streamflow under optimal and baseline conditions. Here, the baseline condition refers the streamflow that was produced by the SCE-UA automatic optimisation function and the optimal condition refers to the streamflow produced by the optimal calibration parameters obtained following the model diagnostic. As can be seen in the Figure 4.5 streamflow simulations by automatic optimisation function (hereafter "baseline streamflow") produced overall satisfactory results with NSE daily values ranged from 0.69 to 0.74 for the 3 stations, compared to the criteria recommended by Moriasi et al. (2015). However, a closer examination revealed differences between the observed and baseline FDC at various segments (Figure 4.5), underlying the problem associated with the NSE in providing a meaningful model performance.

Process-based hydrologic signatures have gained increasing traction as a diagnostic approach to model performance evaluation (McMillan et al., 2014; Gupta et al., 2008; Yilmaz et al., 2008). Using the baseline streamflow and the mathematical relationships of IHECRES – CMD (Equations a.1 – a.7 in Appendix 4.C) as references, calibration parameters influencing the target flow segment were adjusted one by one. The process enabled the model to produce optimal fits between observed and simulated streamflow (Figure 4.4) resulting in the improvement of PPMs (Table 4.2) and minimal deviation between hydrologic signatures estimated from the observed and simulated streamflow (Table 4.3).

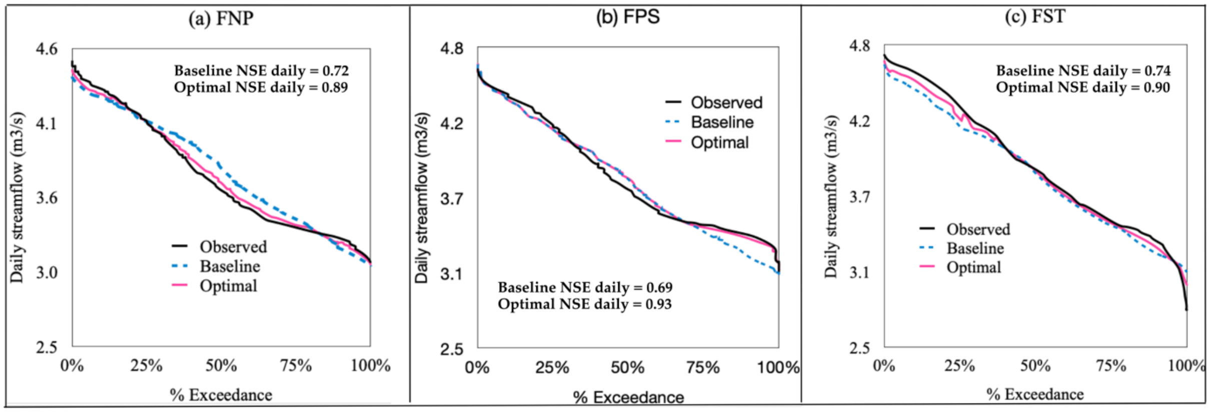


Figure 4.5: Flow duration curves of the observed and simulated streamflow at FNP, FPS AND FST.

Table 4.3 compares values of the selected hydrologic signatures computed for both the observed and simulated streamflow at FNP, FPS, and FST from 2003 to 2011 under the most optimal condition. Under this condition, calibration parameters (Table 4.1) appear to produce optimal streamflow at the 3 gauging stations that closely resemblance patterns of the observed ones. In particular, the magnitudes (Q_{max}, Q_{mean} and Q_{min}) of the simulated and observed flow appear to be similar for all 3 gauging stations, where the differences in Q_{mean} were merely 1.2 ± 14, 3.3 ± 10, and 8.7 ± 17 m^3/s for FNP, FPS, and FST, respectively at 95% confidence interval. These values represent an improvement of 33%, 12%, and 5% from those of baseline streamflow at FNP, FPS and FST, respectively.

Despite improvement made, differences in low flow segments remain. With the LS_{fdc} values being relatively close to zero and trending toward horizontal, flows in the low segment at these stations appear to be sustained by groundwater storage (Cheremisinoff, 1997), and the differences appear to be due to a combination of factors including the inability of the model to truly capture the complex relationships between the watershed system and its hydrologic processes (e.g. groundwater and streamflow relationships, spatial distribution of rainfall and flow level at the gauging station).

Further, uncertainty in the corrected data may have also contributed to the deviation. Shrestha et al. (2013) and Rossi et al. (2009) encountered similar problems using SWAT in the same region, and speculated that errors in the observed high and low flow data may have caused the mismatch in the FDCs respective segment. In contrast, the model performance for mid-segment flow simulation were found to be very good with relative similar magnitudes of MS_{fdc} and HS_{fdc} at all stations (Table 4.3), indicating that the model was able to duplicate both middle and high segment flows.

With two clear distinct seasons (wet and dry), the rise and fall of the river discharges and levels mainly occur during the wet season where 80 to 90% of the annual river discharge accumulates (Mekong River Commission, 2009). Figure 4.3c evidences that changes in flow occur at the onset of the wet season (May) where the river hydrograph begins to show the fluctuation pattern in correspondence to the storm event. This pattern lasts until the onset of the dry season. With the annual rise and fall pattern confined from May to October, the *FI* of the observed time series were well reproduced by *FI* of the simulated time series, with small magnitude of the differences —from 0.01 to 0.03. These figures confirm the results of the PPMs using Pearson's correlation (Table 4.2).

Table 4.3: Comparison of hydrologic signatures for the observed and simulated streamflow of the LMB by LMB-Source model

Hydrologic Signatures		Description	Observed			Simulated			References
			FNP	FPS	FST	FNP	FPS	FST	
Q (100 m3/s)	Max	Daily maximum discharge	326.1	431.4	528.1	315.5	463.5	449.7	
	Mean	Mean daily discharge	77.5	101.9	117.9	78.7	98.6	109.2	
	Min	Minimum discharge	12.2	12.4	16.1	11.5	11.6	11.8	

	90%	90 percentile discharge	203.4	267.8	388.2	178.6	249.7	333.6	
	10%	10 percentile discharge	18.1	22.9	20.2	15.4	15.7	16.8	
	SD	Standard deviation	74.2	99.1	141.4	62.3	93.7	103.1	
HS_{fdc}		High-segment slope of the FDC	-2.1	-2.10	-1.53	-2.42	-2.60	-1.76	
MS_{fdc}		Mid-segment slope of the FDC	-1.67	-1.63	-1.97	-1.76	-1.67	-1.64	(Sawicz et al., 2011)
LS_{fdc}		Low-segment slope of the FDC	-1.71	-2.7	-5.20	-1.52	-2.30	-2.89	
FI		Flashiness index	0.035	0.036	0.039	0.036	0.036	0.041	(Baker et al., 2004)

4.4.2 Calibration and validation of TSS and Nitrate simulation

4.4.2.1 Parameterisation of LMB-Source TSS and nitrate modelling

The simulation of TSS and nitrate by LMB-Source encompassed overland generation and runoff processes, as well as instream routing processes (Section 4.3.3.2). The overland components utilise EMC/DWC generation model and percent removal filtering model while the instream processes utilise the storage and link model. The overland processes take into consideration the influences of individual FUs or land use types on the generation rates of TSS and nitrate during storm and dry weather events. Furthermore, the model also recognised that different FUs also have different capacities for trapping TSS and nitrate during overland runoff. With in-stream water quality known to be generally influenced by its watershed system (Baker, 2003), baseline values for these parameters were obtained from prior studies in the LMB. In the absence of the existing values, long-term time series data of the LMB were used to estimate baseline values of the unavailable parameters (Section 4.3.4). These parameters were optimised through calibration processes (Section 4.3.5.3).

Table 4.4 shows the optimised calibration parameters for both the EMC/DWC generation model and the percent removal filtering model. Among the FU included in this study, barren land, agricultural and urban areas were the major contributors of instream TSS. Under the model optimal condition, these 3 LULC types generate about 83, 44.2 and 15 mg/L of TSS during the storm event, respectively. Similarly, agriculture (19.7 mg/L) and urban areas (12.1 mg/L) were the main contributing FUs of instream nitrate during the storm event. These outcomes are consistent with finding by Yoshimura et al. (2009) and Ly et al., (2020) who links instream nutrients including nitrate and TSS of the LMR to agricultural and urban areas.

In comparison, the TSS and nitrate generation rates for the same LULC were much lower during the dry weather condition. Table 4.4 shows that values generated by these FUs were about 7 to 26 time lower than values generated during the storm event. Of the 9 FUs defined for the *LMB-Source* model, wetlands, grasslands and forest areas appear to have the best sediment trapping capacity, with grassland removing approximately 61% of the TSS load during overland runoff. In addition, wetland was found to have the highest nitrate trapping capacity removing approximately 57% of overland nitrate runoff. Many studies have evidenced decreasing patterns of both grassland and wetlands areas in the LMB due to expansion of urban and agricultural areas (Okamoto et al., 2014; Liu et al., 2020; Ly et al., 2020a). With documented effects on instream TSS and nitrate levels (Okamoto et al., 2014; Phung et al., 2015; Chea et al., 2016), future development will need to take into consideration the impacts of further reducing spatial cover of LULC types with natural buffer capacities of pollutants removal.

Table 4.4: Calibration parameters for nitrate and TSS under LMB-Source (* sourced from Boonsong et al. (2003), ** sourced from Daniels and Gilliam (1996), *** sourced from Cooper et al. (2019), **** sourced from Martínez-Mena et al. (2019), and ***** sourced from (Hey et al., 1994)

Constituents	Functional Units	EMC/DWC Generation Model		% Removal Routing Model (total flow)	
		EMC (mg/L)	DWC (mg/L)	Initial Default Values	Optimised Values
TSS load	Agriculture	44.2	6.8	5	15.3
	Aquaculture	0.8	0.4	0	0.0
	Barren Land	83.0	3.2	0	0.5
	Forest* (Boonsong et al., 2003)	9.0	1	17.1*	31.0
	Grassland** (Daniels and Gilliam, 1996)	7.5	1	80**	61.1
	Urban	15	2.3	0	0.5
	Water	0.1	0	0	0.0
	Wetland*** (Cooper et al., 2019)	0.1	0	80***	57.3
Nitrate load	Agriculture**** (Martínez-Mena et al., 2019)	19.7	2.4	45****	21.2
	Aquaculture	11.3	4.8	0	0.0
	Barren Land	0.1	0.0	0	0.1
	Forest* (Boonsong et al., 2003)	3.0	0.2	44.0*	23.0

Grassland** (Daniels and Gilliam, 1996)	0.2	0.0	50**	48.0
Urban	12.1	4.4	0	0.5
Water	0.0	0.0	0	0.0
Wetland***** (Hey et al., 1994)	0.0	0.0	39*****	56.5

4.4.2.2 LMB-Source performance on TSS and nitrate simulation

The model performance on simulating instream TSS and nitrate are presented in Table 4.5 and Figure 4.6 and Figure 4.7. Compared to the criteria recommended by Moriasi et al. (2015) (Section 4.3.5.3), it can be concluded that the *LMB-Source* model is reliable and suitable for instream TSS and nitrate simulations in the LMB. At sub-basin levels, the optimal calibration parameters (Table 4.4) produced good fit between the simulated and observed time series of both instream TSS and nitrate (Figure 4.6). % PBIAS and NSE values were found to be well within and above the performance criteria, respectively (Table a.5 in Appedix D of SI). During calibration period (2003 – 2007), %PBIAS for nitrate simulations were found to range from -2.2 to 8.9% while the values for TSS ranged from -0.5 to 12%. These values corresponded to the NSE monthly values of 0.74 to 0.8 and 0.76 to 0.83 for instream nitrate and TSS, respectively.

The performance of the model was further confirmed by the results of the model validation (2008 – 2011) (Figure 4.7). Similar levels of %PBIAS and NSE were obtained at all 3 stations indicating that the optimised calibration parameters are basin-specific to the LMB and can be used to reliably replicate the observed instream loads of TSS and nitrate regardless of time period. With the values of these parameters presenting generation and removal rates of individual FUs or LULC types, the model performance is not expected to be affected by the changes in spatial coverage of each LULC types.

Table 4.5: Performance statistics of water quality simulation using the *LMB-Source* model, for the calibration period (2003-2007) and validation (2008-2011)

Performance metrics	**Stations**	**Performance Criteria (Moriasi et al., 2015)**		**Calibration**		**Validation**	
		Nitrate	**TSS**	**Nitrate**	**TSS**	**Nitrate**	**TSS**
%PBIAS	**FNP**	< ± 20%	< ± 30	-2.2	-0.4	0.3	1.1
	FPS			-1.3	-0.6	4.6	2.4
	FST			8.9	12	13.6	15.9
NSE monthly	**FNP**	> 0.35	> 0.45	0.78	0.81	0.80	0.82
	FPS			0.80	0.83	0.77	0.78
	FST			0.74	0.76	0.75	0.74

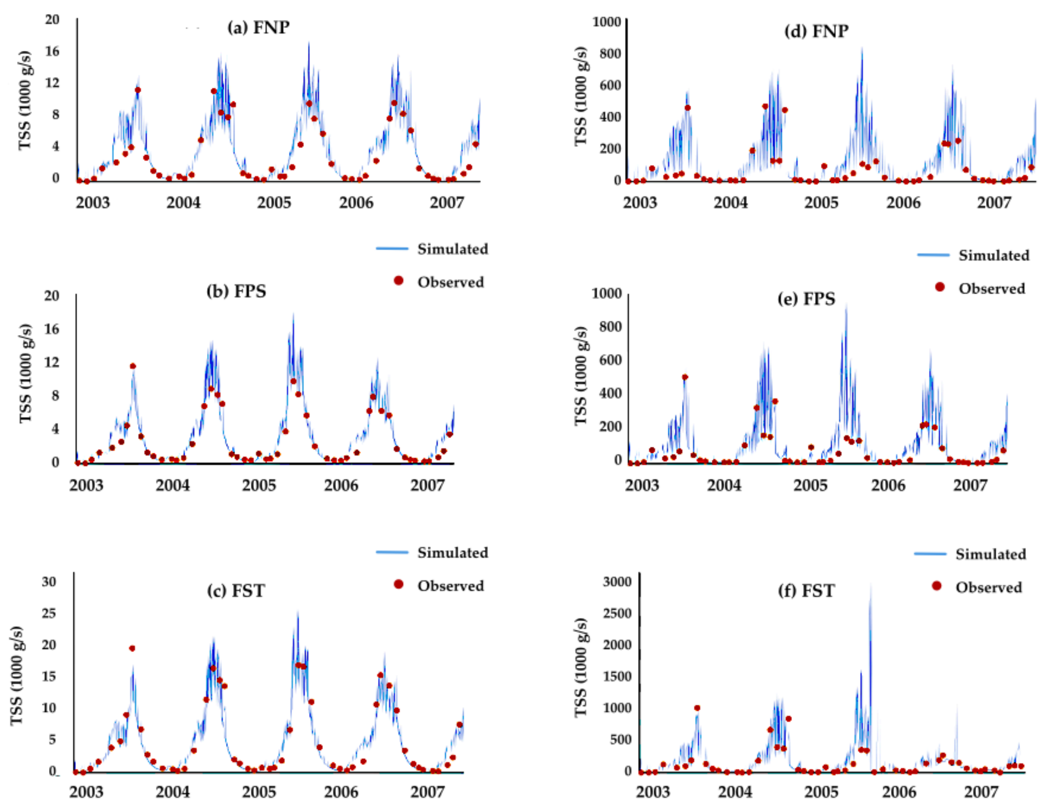


Figure 4.6: Simulated and observed instream nitrate and TSS loads at FNP (a and d), FPS (b and e), and FST (c and d) during the calibration period 2003–2007, under optimal condition.

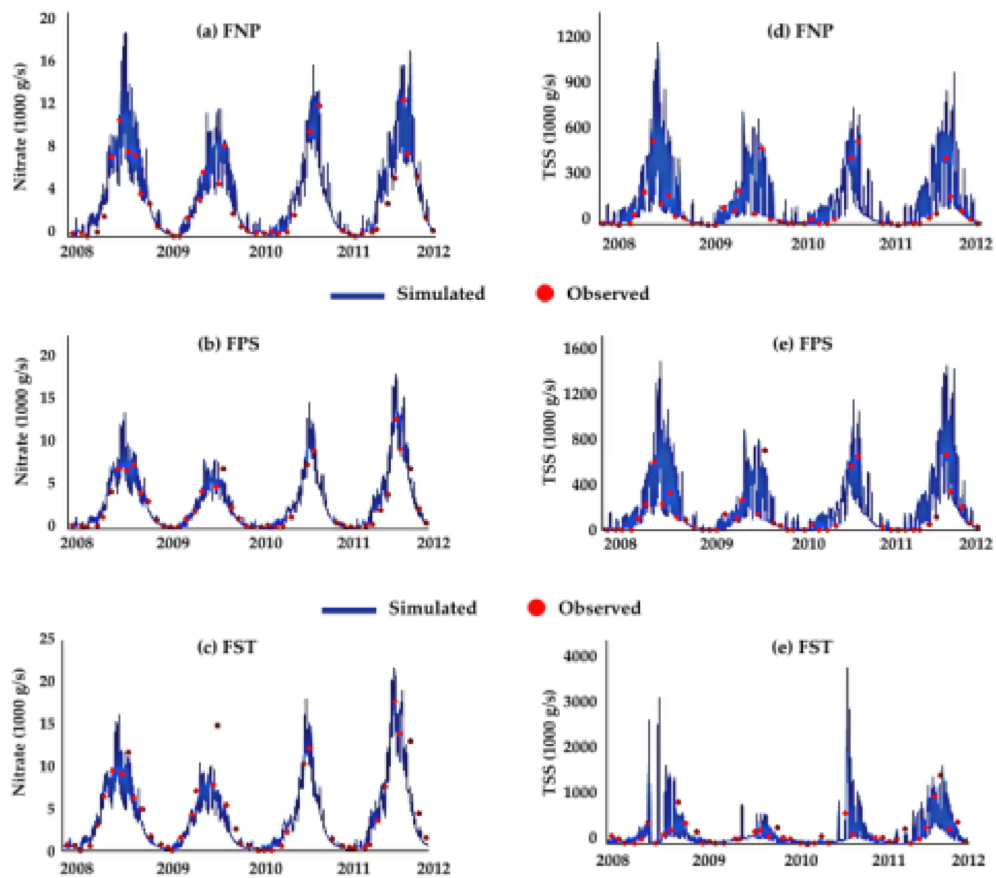


Figure 4.7: Simulated and observed nitrate loads at FNP (a and d), FPS (b and e), and FST (c and d) during the calibration period 2008–2011, under optimal conditions.

4.5 Discussion

4.5.1 Model performance

The advancement of computing technologies has increased WMs capabilities for data processing allowing the complexity of watershed behaviours to be characterised and quantified for a better management of water resources. However, ensuring the abilities of these models to produce reliable and meaningful performances continues to be one of the key focus of many water resources researchers and managers. While a variety of approaches are available, many do not address the inadequacies of the model performances, and therefore, do not identify the deficiency components of the models that require correction for improved performance (Gupta et al., 2008; Yilmaz et al., 2008). In this study, LMB-Source performance evaluation for streamflow and constituents (TSS and nitrate) modellings were carried out separately. A combination of PPMs and diagnostic approaches for evaluating the model performance on streamflow simulation allowed improvement of the LMB-Source by identifying specific deviations and modifying relevant model calibration parameters.

As a new model to the LMB, a number of calibration parameters describing watershed characteristics were estimated and validated (Table 4.1 and Table 4.4). Despite usual challenges associated to simulating hydrologic and instream water quality processes of large transboundary river basins (Ly et al., 2019), model streamflow calibration utilising diagnostic and PPMs approaches were found to be successful in improving the model performance. The diagnostic approach to model calibration, enabled linking key hydrologic signatures of the LMB to optimise model calibration parameters. This resulted in simulated time series that were closely match with the observed ones at all calibration sites, as captured by the PPMs. Using the optimised calibration parameters (Table 4.1), the model was able to firstly minimise deviance between the simulated and observed time series, as illustrated by the high values of NSE and R^2 which were greater than 0.89 and 0.90, respectively. Second, the model was able reproduce the fluctuation dynamics of the observed time series, as illustrated by the results of the Pearson' r calculation (> 0.9 for all 3 stations), where the simulated and observed time series were correlated temporally, point by point. Finally, the model was able to produce overall good predictive margin of distribution compared to the observed one which resulted in relatively small %PBIAS values and high levels of reliability (RI > 0.85) and preciseness (RSI < 0.004).

Furthermore, the model was able to replicate its performance during validation processes with similar range of values obtained for each PPM. Validation of the model was also confirmed by the small differences between the hydrologic signatures of the simulated and observed streamflow (Table 4.3). In spite of these figures showing overall good performance levels of LMB-Source, the model functioning for characterising the relationship between baseflow and groundwater has room for improvement. Of note is that other WMs have had problems in capturing the dynamics of surface and groundwater interactions (Xu and Valocchi, 2015; Lee et al., 2018; Gharari et al., 2019), including those applied in the LMB; this has been attributed to not only the model functioning but also to the quality and adequacy of the input data and the data used for calibration (Lacombe et al., 2014; Shrestha et al., 2018).

In relation to the simulation of instream TSS and nitrate loads, the model was found to perform at good levels at all stations. Specifically, the overall load errors represented by values of %PBIAS varied from -2.2 to 8.9% for nitrate simulation and -0.6 to 12% for TSS simulation. These %PBIAS values indicate that the total loads produced by the model were similar to those derived from the observed data. In addition, NSE values ranged from 0.74 to 0.78 and 0.76 to 0.83, respectively for nitrate and TSS, revealing minimal deviance between the simulated and observed time series for both constituents. Based on the results of the calibration, the largest deviations were detected at FST for both instream TSS and nitrate loads and appeared to have been affected by the simulated streamflow quality. Prior researches on sediment modelling have pointed to the low frequency of monitoring data as a contributing factor for large %PBIAS values (Potter and Hiatt, 2009; Shrestha et al., 2018). However, for this study the monitoring frequency does not appear to affect the overall load error, as monitoring time series with the same frequency are used for calibration at the 3 stations. Instead, studies have linked topographic characteristics and human disturbance through LULC practices to changes in instream levels of TSS and nitrate (Chaplot et al., 2007; Lacombe et al., 2016; Suif et al., 2016; Ly et al., 2020a). While LMB-Source constituent modelling considers the influences of LULC, inclusion of other basin-specific factors such as LULC management practices and topography characteristics can help reduce the deficiencies of the model performances.

4.5.2 Comparing the performance of LMB-Source with other hydrological models and other Source-based applications

In our previous studies, we linked changes of the Mekong River instream TSS and nitrate levels to LULC changes (Ly et al., 2020) and explore potential tools that can be used to assist in the management of these changes (Ly et al., 2019). One such tools identified was the use of WMs to help support the management of LMB, where a comparative analysis was carried out to identify a model that produce satisfactory performance while fulfilling challenging criteria associated with the management of developing transboundary river basin. The results of the analysis identified Source to have that potential given its simplicity interface, low data demand, and previous application as a decision supporting tool at local and interstate transboundary levels (Ly et al., 2019).

The application of Source for the LMB has produced good performances for both streamflow and instream TSS and nitrate simulations (Sections 4.4 and 4.5.1). Comparing the performance of *LMB-Source* for modelling streamflow on the basis of ‘basin size’, the results are better than those reported by McCloskey et al. (2011) who applied the Source modelling framework in the Great Barrier Reef Basin (GBR) (450,000

km^2, about 80% of the total area of the LMB). The NSE daily values for this study were reported to range from 0.24 to 0.81 and they attributed the results to the simplicity of the selected runoff generation process (SIMHYD rainfall runoff model (Porter and McMahon, 1975)) which did not account for the losses of groundwater in the area of the study. However, when compared to research carried out in smaller catchment areas, the *LMB-Source* performs slightly poorer than that of Welsh et al. (2013) but better than that of Nguyen et al. (2019). More to the point, Welsh et al. (2013) reports strong agreement between observed and simulated discharge (NSE value of 0.97, and R^2 value of 0.99) of the Upper Murray Basin, though its size is about 3% of the LMB. On the other hand, Nguyen et al. (2019) record NSE values between 0.74-0.82 in a river basin of 43 km^2 (<0.01% of the LMB). Nguyen et al. (2019) also assess the performance of the modelling framework for simulating TSS and nutrients loads, with %PBIAS values ranging from 2.5 to 38.8%. Likewise, a study in the Cape York region of the GBR (about 8% of the LMB) by McCloskey et al. (2014), exhibited %PBIAS values between -27.69 and 20.93% for nutrients and TSS simulations. These values are slightly higher than the values reported in this study, and illustrate the better performance of the *LMB-Source* model.

It is also important to compare the *LMB-Source* model outputs with similar research conducted in the LMB using different watershed models. Vilaysane et al. (2015) used the SWAT model (Arnold et al., 2012) to simulate stream hydrology of a tributary of the Mekong River, the Xedon River, with an area of about 7,200 km^2 (about 1.3% of the area covered in this research). Results of the performance evaluation of streamflow simulation using R^2 and NSE daily values were reported to be 0.82 and 0.82, respectively; while the NSE monthly value was greater than 0.80. In comparison, *LMB-Source* produced the R^2 values of 0.90 to 0.93 and NSE daily values of 0.89 to 0.93 over the entire LMB. On a monthly time-step, *LMB-Source* produced NSE values greater than 0.92.

At a whole river basin scale, Whitehead et al. (2019) used the Integrated Catchment Model (Whitehead et al., 1998) to simulate streamflow and water quality of the entire Mekong Basin and reported NSE values between 0.57-0.85, with R^2 values of 0.69 to 0.86. These values are slightly lower than the values produced from this study and hence indicative of lower performance for streamflow simulation. Their simulations of nitrogen flux were found to be reasonable with R^2 of 0.63 and 0.67 at the two stations selected for their study (no %PBIAS was computed in their study for nitrogen flux simulation). Lastly, Shrestha et al. (2018) conducted SWAT-based streamflow modelling in the Nam Ou River Basin, a tributary of the Mekong River with an area of 26,181 km^2 (about 5% of the LMB area), reporting daily values greater than 0.6. Simulation of TSS produced %PBIAS value of 4.18% which is similar to the results generated by this study.

It should be noted, however, that none of the case studies used in this comparison utilised a diagnostic approach for model performance evaluation. With all case studies, NSE was the main metric used for assessing models' performances. Our results suggest that modelling performances of the aforementioned studies could have been drastically improved if the models' deficiencies were appropriately identified and corrected. More importantly, the results indicate that Source, a low data demand model is capable performing at level comparable, if not better, than those required by models demoing large volume of data – cited an compared in this section.

4.5.3 Basin-specific parameterisation and implications for transboundary river basin management

In many river basins — and particularly transboundary river basins— environmental effects of LULC continues to be undervalued. The natural capacities of LULC for removing non-point sources pollutants during overland runoff processes, for example, have rarely been included in decision making processes. In developing regions, such as the LMB, the inclusion of LULC environmental values depend on variety of factors, including priority for economic development and the lack of research that provide useful basin-specific information to support decision making (Section 4.2). While many WMs can and have been used as an essential component of IWRM, their usefulness as decision supporting tools rest not only on ensuring their satisfactory abilities in capturing interactions within a watershed system, but also ensuring that they provide reliable information specific to the watershed.

In this paper, the application Source on the LMB confirmed its capabilities and potentials in simulating hydrologic processes and instream dynamics of TSS and nitrate of large transboundary river basins. Through the successful calibration and validation processes where model performances were assessed using a combined PPMs and diagnostic approaches, useful and reliable information pertaining to the behaviours of the watershed systems were quantified for future use. For example, the successful calibration and validation of streamflow modelling produced parameter values that represent the hydrological response characteristics (HRCs) specific to FNP, FPS, and FST (Table 4.1). Similarly, successful calibration and validation of instream TSS and nitrate simulation provided parameter values that represent TSS and nitrate overland generation and runoff dynamics (GRDs) (Table 4.4).

In transboundary river basins of developing countries — such as the LMB— limited information pertaining watershed functions is available; therefore, the parameter values derived by this study provide valuable information that can be applied in further research and management for long-term sustainability of the basin water resources use. In other river basins where abundant information on the hydrological response characteristics are available, these information have been used for tracking sources of riverine pollutants (Huang et al., 2020); similarity between watersheds (Yaeger et al., 2013); catchment scale interactions between landscape characteristics and climate properties (Troch et al., 2013); assessing the effects of hydrologic alteration on aquatic ecosystems (Richter et al., 1996); and hydrologic regionalisation to assess the effects of LULC changes (Peterson et al., 2011).

Specific to the management of the LMB, differences in capacities and priorities for collecting and analysing long-term streamflow and water quality data among countries sharing the basin have resulted in data scarcity and uncertainty at many sub-basins (Ang and Oeurng, 2018; Ly et al., 2019). This has challenged strategies aimed at *management for development*, as long-term hydrological and environmental monitoring data are required for a wide range of reasons, including civil infrastructure development (e.g. siting of hydropower dams, environmental impact assessment), flood and drought forecasting, instream ecological habitat assessment, and assessment of LULC best management practices (Post, 2009; McMillan, 2020). For example, the lack of quantitative values specific to the biophysical context of the LMB for all calibration parameters was a challenge that this research had to overcome. Through the successful implementation of *LMB-Source*, information derived from this study can be used to predict streamflow, TSS and nitrate data of the ungauged sub-basins using a top-down technique of parameters regionalisation as suggested by Kokkonet et al., (2003) and Post (2009). Specifically, relationships can be established between physical attributes (e.g. slope, drainage area, LULC, soil, etc.) of LMB and the HRCs and GRDs derived from this study. The relationships established can then be transferred to un-monitored tributaries sub-basins where streamflow and instream TSS and nitrate data can be estimated based on the similarity of the physical attributes (Kokkonen et al., 2003). Consequently, the improved insights and understanding on the functions and behaviours of the basin will help better evaluate the effects of development and their management practices.

4.6 Conclusion

Understanding how development and LULC changes affect hydrological processes and water quality of a river basin is crucial for appropriate river basin management. While watershed models are available to support decision making, identifying an appropriate model that can achieve the management goals continues to be a challenge. The management of transboundary river basins presents additional issues, considering the different development and conservation priorities of the countries making up a basin.

Building on our previous research where the Source modelling framework was identified as a potential tool for large transboundary river basin management, we constructed the *LMB-Source* aiming at evaluating its capabilities where the LMB was selected as a case study. The results of the study confirmed the capabilities and suitability of the Source modelling framework for simulating hydrological process and instream dynamics of TSS and nitrate in the LMR. With the use of a combined PPMs and diagnostic approaches for the model performance evaluation, we were able to improve the model performance by linking hydrologic signatures to individual calibration parameters. With two combined approached showing the model to perform at a good level, we are confident that the calibration parameters of the LMB-Source can be used to present the HRCS and overland TSS and nitrate GRDs of FNP, FPS and FST drainage basins.

As the first research to apply the Source modelling framework in the LMB, the model generated values for HRCs and overland TSS and nitrate GRDs that are specific to the basins draining to the FNP, FPS and FST gauging stations. The HRCs and GRDs values are important for the development and management of the LMB, and can inform decision making and research relating to the hydrologic, TSS and nitrate behaviours of the LMB.

4.7 Acronyms

Acronym	Definition
LMB	Lower Mekong Basin

FNP	Nakhone Phanom Gauging Station
FST	Stung Treng Gauging Station
FPS	Pakse Gauging Station
WMs	Watershed models
TSS	Total suspended solids
HRCs	Hydrological response characteristics
GRDs	Generation and removal dynamics
LULC	Land use/land cover
UMB	Upper Mekong Basin
GIS	Geographic Information Systems
MRC	The Mekong River Commission
LMR	Lower Mekong River
FI	Flashiness Index
Rc	Runoff ratio
DTM	Digital terrain model
IHACRES – CMD	Identification of unit Hydrographs and Component flows from Rainfall, Evaporation and Streamflow data based on Catchment Moisture Deficit
EMC	Event Mean Concentration
DWC	Dry Weather Concentration
FU	Functional Unit
PPMs	Predictive Performance Metrics
RSI	Relative spread index
RI	Reliability index
NSE	Nash-Sutcliffe Efficiency

SI	Supplementary Information
FDC	Flow duration curve
MSE	Mean square error

4.8 References

Afzal, M., Battilani, A., Solimando, D., & Ragab, R. (2016). Improving water resources management using different irrigation strategies and water qualities: Field and modelling study. *Agricultural Water Management, 176*, 40-54. doi:https://doi.org/10.1016/j.agwat.2016.05.005

Agarwal, A., delos Angeles, M. S., Bhatia, R., Chéret, I., Davila-Poblete, S., Falkenmark, M., . . . Kindler, J. (2000). *Integrated water resources management*: Global water partnership.

Al Bakri, D., Rahman, S., & Bowling, L. (2008). Sources and management of urban stormwater pollution in rural catchments, Australia. *Journal of Hydrology, 356*(3), 299-311. doi:https://doi.org/10.1016/j.jhydrol.2008.04.017

Ammann, L., Fenicia, F., & Reichert, P. (2019). A likelihood framework for deterministic hydrological models and the importance of non-stationary autocorrelation. *Hydrology and Earth System Sciences, 23*(4), 2147-2172. doi:10.5194/hess-23-2147-2019

Ang, R., & Oeurng, C. (2018). Simulating streamflow in an ungauged catchment of Tonlesap Lake Basin in Cambodia using Soil and Water Assessment Tool (SWAT) model. *Water Science, 32*(1), 89-101. doi:https://doi.org/10.1016/j.wsj.2017.12.002

Arias, M. E., Cochrane, T. A., Kummu, M., Lauri, H., Holtgrieve, G. W., Koponen, J., & Piman, T. (2014). Impacts of hydropower and climate change on drivers of ecological productivity of Southeast Asia's most important wetland. *Ecological Modelling, 272*, 252-263. doi:https://doi.org/10.1016/j.ecolmodel.2013.10.015

Baker, A. (2003). Land use and water quality. *Hydrological Processes, 17*(12), 2499-2501. doi:10.1002/hyp.5140

Baker, D. B., Richards, R. P., Loftus, T. T., & Kramer, J. W. (2004). A NEW FLASHINESS INDEX: CHARACTERISTICS AND APPLICATIONS TO MIDWESTERN RIVERS AND STREAMS. *Journal of the American Water Resources Association, 40*(2), 503-522. doi:10.1111/j.1752-1688.2004.tb01046.x

Barlow, K., Weeks, A., F., G., Christy, B., & Cheng, X. (2011). *A Source model of the Ovens River Catchment in Victoria - Northen Victoria Project*. Retrieved from eWater CRC Application Report:

Boonsong, K., Piyatiratitivorakul, S., & Patanaponpaiboon, P. (2003). Potential use of mangrove plantation as constructed wetland for municipal wastewater treatment. *Water Sci Technol, 48*(5), 257-266.

Borzì, I., Bonaccorso, B., & Fiori, A. (2018). A Modified IHACRES Rainfall–Runoff Model for Predicting Hydrologic Response of a River Basin System with a Relevant Groundwater Component. *Proceedings, 7*(1), 24. doi:10.3390/ecws-3-05830

Chaplot, V., Khampaseuth, X., Valentin, C., & Bissonnais, Y. L. (2007). Interrill erosion in the sloping lands of northern Laos subjected to shifting cultivation. *Earth Surface Processes and Landforms, 32*(3), 415-428. doi:http://dx.doi.org/10.1002/esp.1411

Chea, R., Grenouillet, G., & Lek, S. (2016). Evidence of Water Quality Degradation in Lower Mekong Basin Revealed by Self-Organizing Map. *PLoS One, 11*(1). doi:http://dx.doi.org/10.1371/journal.pone.0145527

Cheremisinoff, N. P. (1997). 2 - Relationship Between Groundwater and Surface Water. In N. P. Cheremisinoff (Ed.), *Groundwater Remediation and Treatment Technologies* (pp. 39-83). Westwood, NJ: William Andrew Publishing.

Chiew, F., Scanlon, P., Vertessy, R., & Watson, F. (2002). Estimation of pollutant concentrations for EMSS modelling of the South-East Queensland region. *Technical Report, Report 02/1*. Retrieved from https://ewater.org.au/archive/crcch/archive/pubs/pdfs/technical200201.pdf

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*(11), 4529-4541. doi:10.5194/hess-18-4529-2014

Cooper, R. J., Battams, Z. M., Pearl, S. H., & Hiscock, K. M. (2019). Mitigating river sediment enrichment through the construction of roadside wetlands. *Journal of Environmental Management, 231*, 146-154. doi:https://doi.org/10.1016/j.jenvman.2018.10.035

Crawford, N. H., & Linsley, R. K. (1966). Digital Simulation in Hydrology'Stanford Watershed Model 4.

Croke, B. F., Andrews, F., Jakeman, A., Cuddy, S., & Luddy, A. (2005). *Redesign of the IHACRES rainfall-runoff model.* Paper presented at the 29th Hydrology and Water Resources Symposium: Water Capital, 20-23 February 2005, Rydges Lakeside, Canberra.

Croke, B. F. W., & Jakeman, A. J. (2004). A catchment moisture deficit module for the IHACRES rainfall-runoff model. *Environmental Modelling & Software, 19*(1), 1-5. doi:https://doi.org/10.1016/j.envsoft.2003.09.001

Dang, T. D., Cochrane, T. A., Arias, M. E., & Tri, V. P. D. (2018). Future hydrological alterations in the Mekong Delta under the impact of water resources development, land subsidence and sea level rise. *Journal of Hydrology: Regional Studies, 15*, 119-133. doi:https://doi.org/10.1016/j.ejrh.2017.12.002

Daniels, R. B., & Gilliam, J. W. (1996). Sediment and Chemical Load Reduction by Grass and Riparian Filters. *60*(1), 246-251. doi:10.2136/sssaj1996.03615995006000010037x

Das, G. G. (2015). Why some countries are slow in acquiring new technologies? A model of trade-led diffusion and absorption. *Journal of Policy Modeling, 37*(1), 65-91. doi:10.1016/j.jpolmod.2015.01.001

Duan, Q., Sorooshian, S., & Gupta, V. (1992). Effective and efficient global optimization for conceptual rainfall-runoff models. *Water Resources Research, 28*(4), 1015-1031. doi:10.1029/91wr02985

El-Khoury, A., Seidou, O., Lapen, D. R., Que, Z., Mohammadian, M., Sunohara, M., & Bahram, D. (2015). Combined impacts of future climate and land use changes on discharge, nitrogen and phosphorus loads for a Canadian river basin. *Journal of Environmental Management, 151*, 76-86. doi:https://doi.org/10.1016/j.jenvman.2014.12.012

Evans, J. P., & Jakeman, A. J. (1998). Development of a simple, catchment-scale, rainfall-evapotranspiration-runoff model. *Environmental Modelling & Software, 13*(3), 385-393. doi:https://doi.org/10.1016/S1364-8152(98)00043-7

eWater Ltd. (2018). Source User Guide 4.7. Retrieved from https://wiki.ewater.org.au/display/SD47/Source+User+Guide+4.7

Fox, J., Vogler, J. B., Sen, O. L., Giambelluca, T. W., & Ziegler, A. D. (2012). Simulating Land-Cover Change in Montane Mainland Southeast Asia. *Environmental Management, 49*(5), 968-979. doi:https://doi.org/10.1007/s00267-012-9828-3

Francesconi, W., Srinivasan, R., Pérez-Miñana, E., Willcock, S. P., & Quintero, M. (2016). Using the Soil and Water Assessment Tool (SWAT) to model ecosystem services: A systematic review. *Journal of Hydrology, 535*(Supplement C), 625-636. doi:https://doi.org/10.1016/j.jhydrol.2016.01.034

Gan, T. Y., & Biftu, G. F. (1996). Automatic Calibration of Conceptual Rainfall-Runoff Models: Optimization Algorithms, Catchment Conditions, and Model Structure. *Water Resources Research, 32*(12), 3513-3524. doi:10.1029/95wr02195

Garrick, D., Anderson, G., Connell, D., & Pittock, J. (2014). Federal rivers: Managing water in multi-layered political systems.

Gharari, S., Clark, M., Mizukami, N., Wong, J. S., Pietroniro, A., & Wheater, H. (2019). Improving the representation of subsurface water movement in land models. *Journal of Hydrometeorology*(2019).

Guédron, S., Tisserand, D., Garambois, S., Spadini, L., Molton, F., Bounvilay, B., . . . Polya, D. A. (2014). Baseline investigation of (methyl)mercury in waters, soils, sediments and key foodstuffs in the Lower Mekong Basin: The rapidly developing city of Vientiane (Lao PDR). *Journal of Geochemical Exploration, 143*, 96-102. doi:http://dx.doi.org/10.1016/j.gexplo.2014.03.020

Gupta, H. V., Sorooshian, S., & Yapo, P. O. (1999). Status of Automatic Calibration for Hydrologic Models: Comparison with Multilevel Expert Calibration. *Journal of Hydrologic Engineering, 4*(2), 135-143. doi:10.1061/(asce)1084-0699(1999)4:2(135)

Gupta, H. V., Wagener, T., & Liu, Y. (2008). Reconciling theory with observations: elements of a diagnostic approach to model evaluation. *Hydrological Processes, 22*(18), 3802-3813. doi:10.1002/hyp.6989

Heald, C. L., & Spracklen, D. V. (2015). Land Use Change Impacts on Air Quality and Climate. *Chemical Reviews, 115*(10), 4476-4496. doi:10.1021/cr500446g

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. *Journal of Hydrology, 568*, 285-300. doi:https://doi.org/10.1016/j.jhydrol.2018.10.045

Hey, D. L., Kenimer, A. L., & Barrett, K. R. (1994). Water quality improvement by four experimental wetlands. *Ecological Engineering, 3*(4), 381-397. doi:https://doi.org/10.1016/0925-8574(94)00008-5

Hobbie, S. E., Finlay, J. C., Janke, B. D., Nidzgorski, D. A., Millet, D. B., & Baker, L. A. (2017). Contrasting nitrogen and phosphorus budgets in urban watersheds and implications for managing urban water pollution. *Proceedings of the National Academy of Sciences*. doi:10.1073/pnas.1618536114

Holland, J. H. (1975). Adaptation in natural and artificial systems. An introductory analysis with applications to biology, control, and artificial intelligence. [Press release]

Huang, Y., Huang, J., Ervinia, A., & Duan, S. (2020). Tracking riverine nitrate sources under changing land use pattern and hydrologic regime. *Marine Pollution Bulletin, 152*, 110884. doi:https://doi.org/10.1016/j.marpolbul.2020.110884

Jantz, S. M., Barker, B., Brooks, T. M., Chini, L. P., Huang, Q., Moore, R. M., . . . Hurtt, G. C. (2015). Future habitat loss and extinctions driven by land-use change in biodiversity hotspots under four scenarios of climate-change mitigation. *Conservation Biology, 29*(4), 1122-1131. doi:doi:10.1111/cobi.12549

Kannan, N., Santhi, C., & Arnold, J. G. (2008). Development of an automated procedure for estimation of the spatial variation of runoff in large river basins. *Journal of Hydrology, 359*(1), 1-15. doi:https://doi.org/10.1016/j.jhydrol.2008.06.001

Kauffman, G. J. (2015). Governance, Policy, and Economics of Intergovernmental River Basin Management. *Water Resources Management, 29*(15), 5689-5712. doi:10.1007/s11269-015-1141-5

Kokkonen, T. S., Jakeman, A. J., Young, P. C., & Koivusalo, H. J. (2003). Predicting daily flows in ungauged catchments: model regionalization from catchment descriptors at the Coweeta Hydrologic Laboratory, North Carolina. *Hydrological Processes, 17*(11), 2219-2238. doi:10.1002/hyp.1329

Kummu, M., & Varis, O. (2007). Sediment-related impacts due to upstream reservoir trapping, the Lower Mekong River. *Geomorphology, 85*(3), 275-293. doi:https://doi.org/10.1016/j.geomorph.2006.03.024

Lacombe, G., Douangsavanh, S., Vogel, R. M., McCartney, M., Chemin, Y., Rebelo, L.-M., & Sotoukee, T. (2014). Multivariate power-law models for streamflow prediction in the Mekong Basin. *2*, 35-48. doi:10.1016/j.ejrh.2014.08.002

Lacombe, G., Ribolzi, O., de Rouw, A., Pierret, A., Latsachak, K., Silvera, N., . . . Valentin, C. (2016). Contradictory hydrological impacts of afforestation in the humid tropics evidenced by long-term field monitoring and simulation modelling. *Hydrol. Earth Syst. Sci., 20*(7), 2691-2704. doi:https://doi.org/10.5194/hess-20-2691-2016

Lacombe, G., Valentin, C., Sounyafong, P., de Rouw, A., Soulileuth, B., Silvera, N., . . . Ribolzi, O. (2018). Linking crop structure, throughfall, soil surface conditions, runoff and soil detachment: 10 land uses analyzed in Northern Laos. *Science of The Total Environment, 616-617*, 1330-1338. doi:https://doi.org/10.1016/j.scitotenv.2017.10.185

Le, T. N., Bregt, A. K., van Halsema, G. E., Hellegers, P. J. G. J., & Nguyen, L.-D. (2018). Interplay between land-use dynamics and changes in hydrological regime in the Vietnamese Mekong Delta. *Land Use Policy, 73*, 269-280. doi:https://doi.org/10.1016/j.landusepol.2018.01.030

Lee, J., Kim, J., Jang, W. S., Lim, K. J., & Engel, B. A. (2018). Assessment of Baseflow Estimates Considering Recession Characteristics in SWAT. *Water, 10*(4), 371. Retrieved from https://www.mdpi.com/2073-4441/10/4/371

Li, Y., Zhang, Q., Liu, X., & Yao, J. (2020). Water balance and flashiness for a large floodplain system: A case study of Poyang Lake, China. *Science of The Total Environment, 710*, 135499. doi:10.1016/j.scitotenv.2019.135499

Liu, J., Shen, Z., & Chen, L. (2018). Assessing how spatial variations of land use pattern affect water quality across a typical urbanized watershed in Beijing, China. *Landscape and Urban Planning, 176*, 51-63. doi:https://doi.org/10.1016/j.landurbplan.2018.04.006

Liu, S. A., Li, X., Chen, D., Duan, Y., Ji, H., Zhang, L., . . . Hu, X. (2020). Understanding Land use/Land cover dynamics and impacts of human activities in the Mekong

Delta over the last 40 years. *Global Ecology and Conservation, 22*, e00991. doi:10.1016/j.gecco.2020.e00991

López-Moreno, J. I., Zabalza, J., Vicente-Serrano, S. M., Revuelto, J., Gilaberte, M., Azorin-Molina, C., . . . Tague, C. (2014). Impact of climate and land use change on water availability and reservoir management: Scenarios in the Upper Aragón River, Spanish Pyrenees. *Science of The Total Environment, 493*, 1222-1231. doi:https://doi.org/10.1016/j.scitotenv.2013.09.031

Ly, K., Metternicht, G., & Marshall, L. (2019). Transboundary river catchment areas of developing countries: Potential and limitations of watershed models for the simulation of sediment and nutrient loads. A review. *Journal of Hydrology: Regional Studies, 24*, 100605. doi:https://doi.org/10.1016/j.ejrh.2019.100605

Ly, K., Metternicht, G., & Marshall, L. (2020). Linking Changes in Land Cover and Land Use of the Lower Mekong Basin to Instream Nitrate and Total Suspended Solids Variations. *Sustainability, 12*(7), 2992. Retrieved from https://www.mdpi.com/2071-1050/12/7/2992

Ma, L., He, C., Bian, H., & Sheng, L. (2016). MIKE SHE modeling of ecohydrological processes: Merits, applications, and challenges. *Ecological Engineering, 96*, 137-149. doi:https://doi.org/10.1016/j.ecoleng.2016.01.008

Manh, N. V., Dung, N. V., Hung, N. N., Kummu, M., Merz, B., & Apel, H. (2015). Future sediment dynamics in the Mekong Delta floodplains: Impacts of hydropower development, climate change and sea level rise. *Global and Planetary Change, 127*, 22-33. doi:https://doi.org/10.1016/j.gloplacha.2015.01.001

Martínez-Mena, M., Carrillo-López, E., Boix-Fayos, C., Almagro, M., García Franco, N., Díaz-Pereira, E., . . . de Vente, J. (2019). Long-term effectiveness of sustainable land management practices to control runoff, soil erosion, and nutrient loss and the role of rainfall intensity in Mediterranean rainfed agroecosystems. *CATENA*, 104352. doi:https://doi.org/10.1016/j.catena.2019.104352

MathWorks. (R2010a). M. The MathWorks: Natick, USA, 2010.

McMillan, H. (2020). Linking hydrologic signatures to hydrologic processes: A review. *Hydrological Processes, 34*(6), 1393-1409. doi:10.1002/hyp.13632

Mehdi, B., Ludwig, R., & Lehner, B. (2015). Evaluating the impacts of climate change and crop land use change on streamflow, nitrates and phosphorus: A modeling study in Bavaria. *Journal of Hydrology: Regional Studies, 4*, 60-90. doi:https://doi.org/10.1016/j.ejrh.2015.04.009

Mekong River Commission. (2009). The flow of the Mekong. In T. Burnhill (Ed.), *MRC management informantion booklet series* (Vol. 2).

Mekong River Commission. (2010). Land use and land cover lower Mekong Basin parts in Laos, Thailand, Cambodia and Vietnam.

Mekong River Commission. (2011). *Planning Atlas of the Lower Mekong River Basin*. Retrieved from Vientiane, Lao PDR: http://www.mrcmekong.org/assets/Publications/basin-reports/MRC-SOB-report-2010full-report.pdf

Mirzaei, M., Jafari, A., Gholamalifard, M., Azadi, H., Shooshtari, S. J., Moghaddam, S. M., . . . Witlox, F. (2019). Mitigating environmental risks: Modeling the interaction of water quality parameters and land use cover. *Land Use Policy*, 103766. doi:https://doi.org/10.1016/j.landusepol.2018.12.014

Morán-Tejeda, E., Zabalza, J., Rahman, K., Gago-Silva, A., López-Moreno, J. I., Vicente-Serrano, S., . . . Beniston, M. (2015). Hydrological impacts of climate and land-use changes in a mountain watershed: uncertainty estimation based on model comparison. *Ecohydrology, 8*(8), 1396-1416. doi:doi:10.1002/eco.1590

Moriasi, D. N., Gitau, M. W., Pai, N., & Daggupati, P. (2015). Hydrologic and Water Quality Models: Performance Measures and Evaluation Criteria. *Transactions of the ASABE, 58*(6), 1763. doi:https://doi.org/10.13031/trans.58.10715

Moritz, S., & Bartz-Beielstein, T. (2017). imputeTS: Time Series Missing Value Imputation in R. *R Jounal 9.1*.

Motew, M., Chen, X., Carpenter, S. R., Booth, E. G., Seifert, J., Qiu, J., . . . Kucharik, C. J. (2019). Comparing the effects of climate and land use on surface water quality using future watershed scenarios. *Science of The Total Environment, 693*, 133484. doi:https://doi.org/10.1016/j.scitotenv.2019.07.290

Nash, J. E., & Sutcliffe, J. V. (1970). River flow forecasting through conceptual models part I — A discussion of principles. *Journal of Hydrology, 10*(3), 282-290. doi:https://doi.org/10.1016/0022-1694(70)90255-6

Nelder, J. A., & Mead, R. (1965). A Simplex Method for Function Minimization. *The Computer Journal, 7*(4), 308-313. doi:10.1093/comjnl/7.4.308

Nguyen, H. H., Recknagel, F., Meyer, W., Frizenschaf, J., & Shrestha, M. K. (2017). Modelling the impacts of altered management practices, land use and climate changes on the water quality of the Millbrook catchment-reservoir system in South Australia. *Journal of Environmental Management, 202*, 1-11. doi:https://doi.org/10.1016/j.jenvman.2017.07.014

Nguyen, H. H., Recknagel, F., Meyer, W., Frizenschaf, J., Ying, H., & Gibbs, M. S. (2019). Comparison of the alternative models SOURCE and SWAT for predicting catchment streamflow, sediment and nutrient loads under the effect of land use changes. *Science of The Total Environment, 662*, 254-265. doi:https://doi.org/10.1016/j.scitotenv.2019.01.286

Nobre, R. L. G., Caliman, A., Cabral, C. R., Araújo, F. D. C., Guérin, J., Dantas, F. D. C. C., . . . Carneiro, L. S. (2020). Precipitation, landscape properties and land use interactively affect water quality of tropical freshwaters. *Science of The Total Environment, 716*. doi:10.1016/j.scitotenv.2020.137044

Oeurng, C., Cochrane, T. A., Arias, M. E., Shrestha, B., & Piman, T. (2016). Assessment of changes in riverine nitrate in the Sesan, Srepok and Sekong tributaries of the

Lower Mekong River Basin. *Journal of Hydrology: Regional Studies, 8*, 95-111. doi:https://doi.org/10.1016/j.ejrh.2016.07.004

Okamoto, K., Sharifi, A., & Chiba, Y. (2014). The Impact of Urbanization on Land Use and the Changing Role of Forests in Vientiane. In S. Yokoyama, K. Okamoto, C. Takenaka, & I. Hirota (Eds.), *Integrated Studies of Social and Natural Environmental Transition in Laos* (pp. 29-38). Tokyo: Springer Japan.

Panagopoulos, Y., Makropoulos, C., & Mimikou, M. (2012). Decision support for diffuse pollution management. *Environmental Modelling & Software, 30*, 57-70. doi:https://doi.org/10.1016/j.envsoft.2011.11.006

Peterson, H. M., Nieber, J. L., & Kanivetsky, R. (2011). Hydrologic regionalization to assess anthropogenic changes. *Journal of Hydrology, 408*(3-4), 212-225. doi:10.1016/j.jhydrol.2011.07.042

Phung, D., Huang, C., Rutherford, S., Dwirahmadi, F., Chu, C., Wang, X., . . . Dinh, T. A. D. (2015). Temporal and spatial assessment of river surface water quality using multivariate statistical techniques: a study in Can Tho City, a Mekong Delta area, Vietnam. *Environmental Monitoring and Assessment, 187*(5), 229. doi:10.1007/s10661-015-4474-x

Post, D. A. (2009). Regionalizing rainfall–runoff model parameters to predict the daily streamflow of ungauged catchments in the dry tropics. *40*(5), 433. doi:10.2166/nh.2009.036

Potter, C., & Hiatt, S. (2009). Modeling river flows and sediment dynamics for the Laguna de Santa Rosa watershed in Northern California. *Journal of Soil and Water Conservation, 64*(6), 383. doi:10.2489/jswc.64.6.383

Price, W. L. (1987). Global optimization algorithms for a CAD workstation. *Journal of Optimization Theory and Applications, 55*(1), 133-146. doi:10.1007/BF00939049

Ribolzi, O., Evrard, O., Huon, S., de Rouw, A., Silvera, N., Latsachack, K. O., . . . Valentin, C. (2017). From shifting cultivation to teak plantation: effect on overland flow and sediment yield in a montane tropical catchment. *Scientific Reports, 7*(1), 3987. doi:10.1038/s41598-017-04385-2

Richter, B. D., Baumgartner, J. V., Powell, J., & Braun, D. P. (1996). A Method for Assessing Hydrologic Alteration within Ecosystems. *Conservation Biology, 10*(4), 1163-1174. doi:10.1046/j.1523-1739.1996.10041163.x

Safeeq, M., & Hunsaker, C. T. (2016). Characterizing Runoff and Water Yield for Headwater Catchments in the Southern Sierra Nevada. *JAWRA Journal of the American Water Resources Association, 52*(6), 1327-1346. doi:10.1111/1752-1688.12457

Sawicz, K., Wagener, T., Sivapalan, M., Troch, P. A., & Carrillo, G. (2011). Catchment classification: empirical analysis of hydrologic similarity based on catchment function in the eastern USA. *Hydrology and Earth System Sciences, 15*(9), 2895-2911. doi:10.5194/hess-15-2895-2011

Searchinger, T., Heimlich, R., Houghton, R. A., Dong, F., Elobeid, A., Fabiosa, J., . . . Yu, T.-H. (2008). Use of U.S. Croplands for Biofuels Increases Greenhouse Gases Through Emissions from Land-Use Change. *Science, 319*(5867), 1238. Retrieved from http://science.sciencemag.org/content/319/5867/1238.abstract

Shrestha, B., Cochrane, T. A., Caruso, B. S., Arias, M. E., & Piman, T. (2016). Uncertainty in flow and sediment projections due to future climate scenarios for the 3S Rivers in the Mekong Basin. *Journal of Hydrology, 540*, 1088-1104. doi:https://doi.org/10.1016/j.jhydrol.2016.07.019

Shrestha, B., Maskey, S., Babel, M. S., van Griensven, A., & Uhlenbrook, S. (2018). Sediment related impacts of climate change and reservoir development in the Lower Mekong River Basin: a case study of the Nam Ou Basin, Lao PDR. *Climatic Change, 149*(1), 13-27. doi:10.1007/s10584-016-1874-z

Sithong, T., & Yayoi, F. (2006). Recent Land Use and Livelihoods Transitions in Northern Laos. *Mountain Research and Development, 26*(3), 237-244. Retrieved from http://www.jstor.org/stable/4096458

Solar, R. R. d. C., Barlow, J., Andersen, A. N., Schoereder, J. H., Berenguer, E., Ferreira, J. N., & Gardner, T. A. (2016). Biodiversity consequences of land-use change and forest disturbance in the Amazon: A multi-scale assessment using ant communities. *Biological Conservation, 197*, 98-107. doi:https://doi.org/10.1016/j.biocon.2016.03.005

Spera, S. A., Galford, G. L., Coe, M. T., Macedo, M. N., & Mustard, J. F. (2016). Land-use change affects water recycling in Brazil's last agricultural frontier. *Global Change Biology, 22*(10), 3405-3413. doi:doi:10.1111/gcb.13298

Suif, Z., Fleifle, A., Yoshimura, C., & Saavedra, O. (2016). Spatio-temporal patterns of soil erosion and suspended sediment dynamics in the Mekong River Basin. *Science of The Total Environment, 568*, 933-945. doi:https://doi.org/10.1016/j.scitotenv.2015.12.134

Taylor, S. D., He, Y., & Hiscock, K. M. (2016). Modelling the impacts of agricultural management practices on river water quality in Eastern England. *Journal of Environmental Management, 180*, 147-163. doi:https://doi.org/10.1016/j.jenvman.2016.05.002

Tian, Y., Huang, Z., & Xiao, W. (2010). Reductions in non-point source pollution through different management practices for an agricultural watershed in the Three Gorges Reservoir Area. *Journal of Environmental Sciences, 22*(2), 184-191. doi:https://doi.org/10.1016/S1001-0742(09)60091-7

Trambauer, P., Maskey, S., Winsemius, H., Werner, M., & Uhlenbrook, S. (2013). A review of continental scale hydrological models and their suitability for drought forecasting in (sub-Saharan) Africa. *Physics and Chemistry of the Earth, Parts A/B/C, 66*(Supplement C), 16-26. doi:https://doi.org/10.1016/j.pce.2013.07.003

Troch, P. A., Carrillo, G., Sivapalan, M., Wagener, T., & Sawicz, K. (2013). Climate-vegetation-soil interactions and long-term hydrologic partitioning: signatures of catchment co-evolution. *17*(6), 2209-2217. doi:10.5194/hess-17-2209-2013

Trung, L. D., Duc, N. A., Nguyen, L. T., Thai, T. H., Khan, A., Rautenstrauch, K., & Schmidt, C. (2018). Assessing cumulative impacts of the proposed Lower Mekong Basin hydropower cascade on the Mekong River floodplains and Delta – Overview of integrated modeling methods and results. *Journal of Hydrology*. doi:https://doi.org/10.1016/j.jhydrol.2018.01.029

Ulén, B., Stenberg, M., & Wesström, I. (2016). Use of a flashiness index to predict phosphorus losses from subsurface drains on a Swedish farm with clay soils. *Journal of Hydrology, 533*, 581-590. doi:10.1016/j.jhydrol.2015.12.044

Vasiliades, L., Sarailidis, G., & Loukas, A. (2017). Hydrological modelling of low flows for operational water resources management.

Wesström, I., Joel, A., & Messing, I. (2014). Controlled drainage and subirrigation – A water management option to reduce non-point source pollution from agricultural land. *Agriculture, Ecosystems & Environment, 198*, 74-82. doi:https://doi.org/10.1016/j.agee.2014.03.017

Wheeler, K. G., Robinson, C. J., & Bark, R. H. (2018). Modelling to bridge many boundaries: the Colorado and Murray-Darling River basins. *Regional Environmental Change, 18*(6), 1607-1619. doi:10.1007/s10113-018-1304-z

Xu, T., & Valocchi, A. J. (2015). Data-driven methods to improve baseflow prediction of a regional groundwater model. *Computers & Geosciences, 85*, 124-136. doi:https://doi.org/10.1016/j.cageo.2015.05.016

Yadav, S., Babel, M. S., Shrestha, S., & Deb, P. (2019). Land use impact on the water quality of large tropical river: Mun River Basin, Thailand. *Environmental Monitoring and Assessment, 191*(10). doi:10.1007/s10661-019-7779-3

Yaeger, M. A., Sivapalan, M., McIsaac, G. F., & Cai, X. (2013). Comparative analysis of hydrologic signatures in two agricultural watersheds in east-central Illinois: legacies of the past to inform the future. *17*(11), 4607-4623. doi:10.5194/hess-17-4607-2013

Yilmaz, K. K., Gupta, H. V., & Wagener, T. (2008). A process-based diagnostic approach to model evaluation: Application to the NWS distributed hydrologic model. *Water Resources Research, 44*(9), n/a-n/a. doi:10.1029/2007wr006716

Appendix 4 – Chapter 4's Supplementary Information (SI)

Appendix 4.A – Abbreviation for meteorological stations

Table a.1: Abbreviation for meteorological stations

Abbreviation	Full Name	Countries
FCS	Chiang Sean	Thailand
FLP	Luang Prabang	Laos
FVT	Vientiane	Laos
FNP	Nakhone Phanoim	Thailand
FSP	Savannakhet	Laos
FUB	Ubon	Thailand
FPS	Pakse	Laos
FST	Stung Treng	Cambodia
FSR	Siem Reap	Cambodia
FCC	Chrouy Changvar	Cambodia
FBD	Ban Don	Viet Nam
FTC	Tan Chau	Viet Nam
FCD	Chau Doc	Viet Nam
FCT	Can Tho	Viet Nam

Appendix 4.B – Key hydrological signatures of the gauging stations

Table a.2: Hydrologic and drainage properties of 3 gauging stations during the study period from 2003 to 2012 (*A* is the drainage area, *r* is the mean annual rainfall, R_C is the runoff coefficient, *Q* is daily streamflow, S_{fdc} is the slope of the flow duration curve, and *FI* is the flashiness index of the observed streamflow)

Stations	A (100 km2)	r (mm)	Q (100 m3/s)			S_{fdc}	R_C	*FI*
			Max	Mean	Min			
FNP	373	1494	326.1	77.5	12.2	-3.7	0.45	0.035
FPS	545	1875.5	431.4	101.9	12.4	-3.79	0.3	0.036
FST	635	1696.5	528.1	117.9	16.1	-4.14	0.38	0.039

Appendix 4.C – IHECRES – CMD Rainfall Runoff Theoretical Information

Figure C.1 provides a conceptual layout of the IHACRES-CMD rainfall runoff model, where streamflow is produced through non-linear and linear modules.

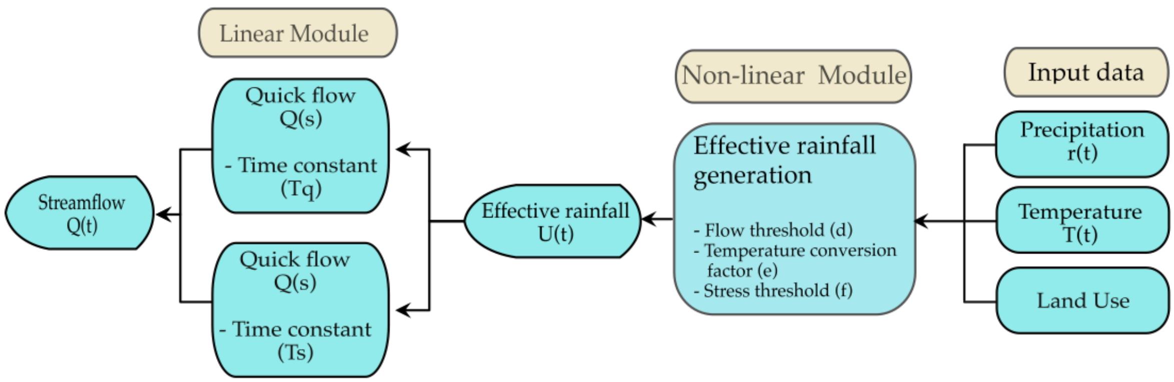


Figure C.1: Conceptual layout of the IHACRES-CMD rainfall runoff model (eWater Ltd., 2018)

Under non-linear module, effective rainfall U is assumed to be an instantaneous linear function of catchment moisture deficit s and given by:

$$\frac{dU}{dr} = 1 - \min\left(1, \frac{s}{d}\right) \qquad \text{Equation a.1}$$

Where, r is the rainfall at time step t and d is catchment flow threshold that can be adjusted during calibration. At time step t, $s(t)$ is calculated by:

$$s(t) = s(t-1) - r(t) + E(t) + U(t) \qquad \text{Equation a.2}$$

Where E is the actual evapotranspiration and is given at time step t by:

$$E(t) = e \times T(t)exp\left(2\left(1 - \frac{s(t)_f}{g}\right)\right) \qquad \text{Equation a.3}$$

In Equation 3, *T(t)* represent the temperature at time step *t*, while s_f represents the catchment moisture deficit value before taking into account evapotranspiration loss. *e* is the temperature to *PET* conversion factor, and *g* represents *s(t)* value above which the evapotranspiration rate will begin to decline due to insufficient water availability for plant transpiration and is given as a product of catchment flow threshold *d* and plant stress threshold factor *f* (calibration parameter) (Equation a.4).

$$g = f \times d \qquad \text{Equation a.4}$$

Under the linear routing module, effective rainfall is converted into total streamflow *Q* through direct runoff (quick flow Q_q) and baseflow (slow flow Q_s) and is calculated at each time step *t* as:

$$Q_t = Q_{s(t)} + Q_{q(t)} \qquad \text{Equation a.5}$$

Where, Q_q and Q_s are given by Equations a.6 and a.7, respectively.

$$Q_{q(t)} = -\tau_q Q_{q(t-1)} + (1 - \tau_q)v_q U(t) \qquad \text{Equation a.6}$$

$$Q_{s(t)} = -\tau_s Q_{s(t-1)} + (1 - \tau_s)v_s U(t) \qquad \text{Equation a.7}$$

In Equations a.6 and a.7, τ_q and τ_s are calibration parameters representing the time constant governing the rate of recession of Q_q and Q_s, respectively. v_q and v_s are the proportions of excessive rainfall diverted to Q_q and Q_s, respectively. Under quick flow module, 100% of excessive rainfall is assumed to be converted to Q_q, Therefore, only v_s is used as calibration parameters.

Appendix 4.D: Instream routing processes of TSS and nitrate

Figure D.1 illustrates the instream routing processes of TSS and nitrate for this study where at any gauging node, the overall concentration of a given constituent $C_{(t)}$ at a time step t is the ratio of the total mass balance $M_{(t)}$ to the total flow volume $V_{(t)}$ at the node (Equation a.8).

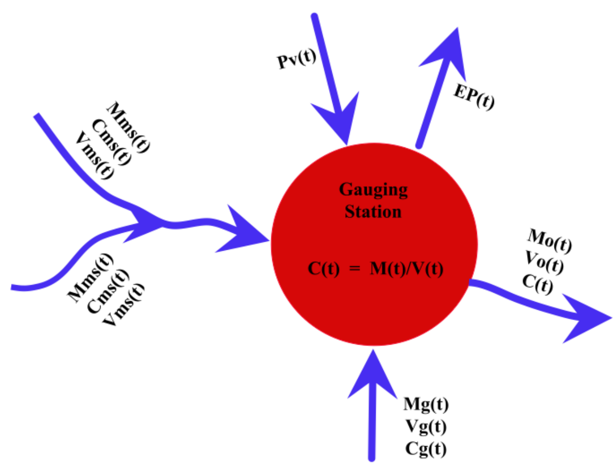


Figure D.1: Schematic of LMB-Source water quality constituent simulation at a gauging station

$$C_{(t)} = \frac{M_{(t)}}{V_{(t)}} \qquad \text{Equation a.8}$$

The overall mass balance $M_{(t)}$ is the sum of the mass balance from the previous time step $M_{(t-1)}$, the inflow mass balance $Mi_{(t)}$, and ground water mass balance $M_{g(t)}$ (Equation a.9). Similarly, $V_{(t)}$ is the sum of the flow volume from the previous time step $V_{(t-1)}$, volume of the inflow $V_{i(t)}$, ground flow volume $V_{g(t)}$, rainfall volume $Pv_{(t)}$, and evaporation volume $EP_{(t)}$ at the modelled node (Equation a.10).

$$M_{(t)} = M_{(t-1)} + M_{i(t)} + M_{g(t)} \qquad \text{Equation a.9}$$

$$V_{(t)} = V_{(t-1)} + V_{i(t)} + V_{g(t)} + P_{v(t)} - EP_{(t)} \qquad \text{Equation a.10}$$

In Equation a.9, $M_{i(t)}$ is calculated as the sum of the inflow mass balances from tributaries $M_{tr(t)}$ and mainstream $\mathrm{M_{ms(t)}}$ (Equation a.11). The inflow mass balance of tributaries $M_{tr(t)}$, mainstream $\mathrm{M_{ms(t)}}$, and groundwater $M_{g(t)}$ are the product of their respective inflow volumes and constituent concentrations, respectively (Equations a.12 to a.14).

$$M_{i(t)} = M_{tr(t)} + M_{ms(t)} \qquad \text{Equation a.11}$$

$$M_{tr(t)} = V_{tr(t)} \times C_{tr(t)} \qquad \text{Equation a.12}$$

$$M_{ms(t)} = V_{ms(t)} \times C_{ms(t)} \qquad \text{Equation a.13}$$

$$M_{g(t)} = V_{g(t)} \times C_{g(t)} \qquad \text{Equation a.14}$$

The outflow mass $M_{o(t)}$ from node is then given by Equation a.15, where $Vo(t)$ is the outflow volume.

$$M_{o(t)} = V_{o(t)} \times C_{(t)} \qquad \text{Equation a.15}$$

Appendix 4.E: Predictive performance metrics and hydrologic signatures

Table a.3: Equations for PPMs and hydrologic signatures

Metrics	Equations	Definition
Nash-Sutchliffe Efficiency (NSE)	$NSE = 1 - \frac{\sum_{t=1}^{T}(Q_s^t - Q_o^t)^2}{\sum_{t=1}^{T}(Q_o^t - \overline{Q}_o)^2}$	Q_s^t – simulated discharge at time t Q_o^t – Observed discharge at time t $\overline{Q}_o$- Mean of the observed discharge
Coefficient of determination (R^2)	$R^2 = \left[\frac{\sum_{i=1}^{n}(x_i - \overline{x})(y_i - \overline{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \overline{x})^2}\sqrt{\sum_{i=1}^{n}(y_i - \overline{y})^2}}\right]^2$	x_i is the value of time series x at time step i
Pearson's correlation coefficient (r)	$r_{xy} = \frac{\sum_{i=1}^{n}(x_i - \overline{x})(y_i - \overline{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \overline{x})^2}\sqrt{\sum_{i=1}^{n}(y_i - \overline{y})^2}}$	y_i is the value of time series y at time step i
% PBIAS	$\%PBIAS = 100 \times \frac{\sum_{t=1}^{T}(Q_s^t - Q_o^t)}{\sum_{t=1}^{T}Q_o^t}$	Q_s^t – simulated discharge at time t Q_o^t – Observed discharge at time t
Reliability Index *(RI)*	$RI = 1 - \frac{2}{n+1}\sum_{i=0}^{n}\left|\left(F_{Q(t_i)}(Q_o(t_i)\right) - F_\zeta(F_{Q(t_i)}(Q_o(t_i)))\right|$ Where, $\zeta = \{F_{Q(t_i)}(Q_o(t_i))\mid i\epsilon N, 0 \le i \le n\}$	F_ζ- the empirical cumulative distribution function of ζ $F_{Q(t_i)}$- the empirical cumulative distribution

		function of the simulated streamflow at time t_i
Relative spread index (RSI)	$RSI = \frac{\sum_{i=0}^{T} \sigma Q(t_i)}{\sum_{i=0}^{N} Q_o\,(t_i)}$	$\sigma Q(t_i)$ – Standard deviation of the distribution at time point t_i $Q_o(t_i)$ – Observed discharge at time point t_i
Flashiness index	$FI = \frac{\sum_{t=1}^{T} (Q_t - Q_{t-1})}{\sum_{t=1}^{T} Q_t}$	Q_t – Discharge at time t Q_{t-1} – Discharge at time $t-1$

Table a.4: Performance levels of selected metrics used for LMB-Source model streamflow simulation (Moriasi et al., 2015)

Performance levels	NSE	R^2	%PBIAS
Not satisfactory	≤ 0.5	≤ 0.6	≥ ± 15
Satisfactory	0.5 < NSE ≤ 0.7	0.6 < R^2 ≤ 0.75	± 10 ≤ %PBIAS ≤ ± 15
Good	0.7 < NSE ≤ 0.8	0.75 < R^2 ≤ 0.85	± 5 ≤ %PBIAS ≤ ± 10
Very good	> 0.8	> 0.85	< ± 5

Table a.5: Performance levels of selected metrics used for LMB-Source model instream TSS and nitrate simulation (Moriasi et al., 2015)

	Performance Criteria (Moriasi et al., 2015)	
Performance metrics	Nitrate	TSS
%PBIAS	< ± 20%	< ± 30
NSE monthly	> 0.35	> 0.45

Chapter 5. Evaluating the effects of transboundary river basin hydropower development and operation under extreme climate conditions

Kongmeng Ly, Graciela Metternicht, Lucy Marshall

Publication: Manuscript submitted to Science of the Total Environment.

Keyword: Transboundary river basin, eWater Source model, Mekong River, Lower Mekong Basin, Streamflow, Total Suspended Solids, Nitrate.

Contribution: This study was conceptualised by Kongmeng Ly in close consultation with Professor Graciela Metternicht and Professor Lucy Marshall, both of whom provided guidance on the available methods that can be applied to achieve the study objectives. Pre-experimental data and information collection, reviews and analyses were carried out by Kongmeng Ly. He formulated plausible future development narratives, conducted experiments, analysed experimental results, and drafted and finalised the manuscript with the review and editing supports of Professors Metternicht and Marshall in their roles of academic supervisors.

Thesis relevancy: it explores and evaluates the potential effects of future development on streamflow and instream TSS and nitrate of the LMB. In this chapter, I reviewed existing national and regional development plans in the LMB and identified hydropower development to be the region's development priority to sustain economic growth and expand electricity coverage. Based on this finding, I constructed four plausible future hydropower development scenarios exploring likely impacts of each scenario using the LMB-Source model previously set up. In addition, the effects of each scenario under extreme climate conditions were investigated to illustrate their potential severity. As hydropower development is inevitable, I examined whether alternative hydropower operational practices can help alleviate potential effects of each development scenario. The results of this study are valuable for the sustainable development and operation of the hydropower in the region.

Research highlights and innovations:

- Explored and evaluated the different effects of four plausible future hydropower operation scenarios on streamflow and instream total suspended solids (TSS) and nitrate loads, under extreme climatic conditions and operational alternatives.
- Hydropower operations on either tributary or mainstream could result in annual and wet season flow reduction while increase dry season comparing to a business-as-usual scenario.
- Both instream TSS and nitrate loads are projected to decrease under all hydropower operational scenarios.
- Impacts on streamflow and instream TSS and nitrate loads are projected to magnify under extreme climatic wet and dry conditions but less severe under improved operational alternatives.
- In a region where the development of hydropower is inevitable, cooperative frameworks and concerted decisions on operational alternatives represent effective integrated water resources management pathways.

5.1 Abstract

The management of transboundary river basins across developing countries, such as the Lower Mekong River Basin (LMB), is challenging given frequent divergences on development and conservation priorities. Driven by needs to sustain economic performance and reduce poverty, the LMB countries are embarking on significant land use changes in the form of more hydropower dams, to satisfy growing energy demands. This pathway could lead to irreversible changes to the ecosystem of the Mekong River, if not properly managed. Given the uncertain environmental externalities and trade-offs associated with further hydropower development and

operation in the LMB, we developed four plausible scenarios of future hydropower operation, and assessed their likely impact on streamflow and instream total suspended solids and nitrate loads of the Mekong River. Our findings suggest that further hydropower operations on either tributary or mainstream could result in annual and wet season flow reduction between 11 to 25% while increase dry season flows by 1 to 15%, when compared to a business-as-usual scenario. Conversely, hydropower operation on both tributary and mainstream could result in dry season flow reduction between 10 to 15%. Both instream TSS and nitrate loads were predicted to reduce under all three scenarios by as much as 78 and 20%, respectively, compared to the business-as-usual one. These effects are predicted to magnify under extreme climate conditions with dry season flow, TSS, and nitrate levels reduced as much as 44, 81 and 35%, respectively, during the extreme dry climate condition, but less severe under improved operational alternatives. With further hydropower development in the LMB being highly unavoidable, findings from this chapter provide an enhanced understanding on the importance of cooperative frameworks and concerted decisions on operational alternatives, as effective transboundary management pathways for balancing electricity generation and protection of riverine ecology, water and food security, and people livelihoods.

5.2 Introduction

Land use/land cover (LULC) changes driven by rapid economic development and urbanization not only continue to transform the landscape features of many river basins, but also threaten their aquatic ecosystems. As an example, results of prior studies have shown that streamflow and water quality of the Mekong River are strongly correlated to LULC patterns and human activities (Oeurng et al., 2016; Li et al., 2017; Ribolzi et al., 2017; Lacombe et al., 2018; Ly et al., 2020a). In developing regions where sustainable development and poverty reduction are the main policy priorities (Christiaensen and Martin, 2018; Ivanic and Martin, 2018; Nguyen and Pham, 2018), the impacts of LULC on the receiving stream networks and their supporting ecosystem services are often ignored (Cowie et al., 2018; Hecht et al., 2019; Intralawan et al., 2019; Yoshida et al., 2020). Yet, access to good quality and sufficient quantity of water have been cited as essential for poverty reduction and sustainable socio-economic development (Metternicht, 2018; Cetrulo et al., 2020). The role of freshwater for sustainable development has been well documented in past research where mismanagement of water bodies and their resources have been demonstrated to lead to changes in streamflow regimes and ecosystem degradation leading to transboundary water conflict and scarcity (Gupta, 2011; Morán-Tejeda et al., 2015; Intralawan et al., 2018; Oyebode et al., 2019; Cetrulo et al., 2020; Silva et al., 2020).

The importance of freshwater for sustainable development can be quantified by its usage. For the Lower Mekong River (LMR), its water is used to irrigate over 5.7 million ha of agriculture land, generate over 10,000 MW of electricity, and transport over 23 million tonnes of goods to approximately 70 million people through inland navigation (Figure 5.1a) (Mekong River Commission, 2018). Owing to rapid economic growth and increasing population, the LMR water usage is expected to increase. As demand increases, pressures on water resources, as well as tension around water use by stakeholders from local (Badiger et al., 2018; Kondolf and Lopez-Llompart, 2018; Sukhwani et al., 2020; Páez and Vallejo Piedrahíta, 2021) to regional scales (De Stefano et al., 2017; Kittikhoun and Staubli, 2018; Gorgoglione et al., 2019) will likely intensify.

With the introduction of the United Nation's Sustainable Development Goals (SDGs) (United Nations, 2018), ensuring universal access to affordable, reliable, sustainable and modern energy, renewable energy generation has been widely promoted to replace fossil and natural gas power plants (Foley and Olabi, 2017). Chief among them is energy generated by hydropower which accounts for approximately 16% of the world's electricity production (Sovacool and Walter, 2017; IHA, 2020).

As sustainability becomes the focal point of development in the Lower Mekong Basin the MRC Countries have integrated the SDGs into their national development plans and actions. These plans outline strategies to help the LMCs achieve the 169 targets of the 17 SDGs of the United Nations. While the SDGs are not binding, countries are expected to utilise their available resources to help achieve these goals (Gulseven, 2020), and while the SDGs are presented as separate goals, they are interrelated and can affect each other positively or negatively (Pradhan, 2019; Gulseven, 2020; Harris et al., 2020). As such, countries face many interlinked environmental and social challenges that require multi-sectoral, concerted efforts when addressing them (Allen et al., 2019).

In a developing region such as the Lower Mekong Basin where focus is placed on sustaining economic development, priority is often placed on ensuring access to affordable, reliable and modern energy to all (SDG goal # 7). Hydropower development is rapidly becoming the main source of energy in the Lower Mekong Basing (LMB), supplying not only energy for the expanding urban population but also boosting the growing economies of the basin countries (Suhardiman et al., 2014). Hydropower is frequently seen as an avenue for poverty reduction where electricity generated is not only exported for revenue, but also to increase electricity coverage to villages and households without electricity (Chattranond, 2018; Tran and Suhardiman, 2020; Atkinson, 2021). For example, in the Lao People's Democratic Republic (Lao PDR) where topography is largely mountainous with large drops in elevation and intensive rainfall dominated climate, considerable hydropower potential exists to not only meet the growing domestic electricity demand but also the demands of the neighbouring countries (Mekong River Commission, 2018). With an installed capacity of about 26.5 GW, the country is one of the richest in terms of hydropower resources (International Hydropower Association, 2020). Only about 6.5 GW have been realised, and the country is aiming to increase its hydropower capacity to 16.5 GW by 2030 (ADB, 2019).

Once realised, installed hydropower of the Lao PDR would make up about 88% of the total installed capacity of the LMB (Mekong River Commission, 2018).

The development of water resources of the LMB for energy production is highly controversial, and it has been contested by different stakeholders with concerns as diverse as economic interests, livelihoods, food security, and ecosystem conservation (Molle et al., 2009; Yeophantong, 2014). Exploitation of water resources for hydropower generation can produce benefits for developers while also causing permanent and wide ranging negative environmental and social impacts. For example, it has already been shown that hydropower development and operation affects the Mekong River streamflow and instream total suspended solids (TSS) regimes, with significant reduction of TSS levels recorded at many water quality monitoring stations across the LMB (Le et al., 2020; Ly et al., 2020a; Trung et al., 2020; Bussi et al., 2021). While these impacts have long been recognised and generally explored during environmental and social impact assessment processes (Tilt et al., 2009; Zhang et al., 2016; Botelho et al., 2017; Lange et al., 2018; Sun et al., 2020), the scope of these assessments was largely limited to the national boundaries of the countries developing hydropower plants, ignoring or insufficiently accounting for downstream cumulative impacts.

To address these concerns, regional river basin organizations have been established in many river basins including that of the LMB, to foster cooperation through integrated water resources management (IWRM) approaches (Mekong River Commission, 1995; Agarwal et al., 2000; Campbell, 2016; Ly et al., 2020b). One such approach is the use of watershed models (WMs) to assess potential impacts of various development scenarios (Wheeler et al., 2018; Ly et al., 2020b), so that both economic development and environmental protection of all countries making up the basin are considered. While WMs have been widely used to support decision making, their application in transboundary river basins has been found challenging due to the extensive area usually covered by these basins, data gaps, and divergence in development policies and environmental conservation priorities (De Stefano et al., 2017; Wheeler et al., 2018; Gorgoglione et al., 2019; Ly et al., 2019).

In the LMB where policies and strategies on energy development exist, exploratory approaches can be used for deriving alternative future scenarios (Marthaler et al., 2020), enabling potential impacts to be evaluated through watershed management tools such as WMs (Rounsevell and Metzger, 2010; Straton et al., 2011; Swetnam et al., 2011). For example, Trung et al. (2020) developed scenarios to forecast changes to water quality and quantity of the Lower Mekong River due to projected upstream hydropower developments.

Considering the challenges associated with the management of transboundary river basins, our previous work (Ly et al., 2019), identified the advantages of eWater's Source watershed modelling framework over other models, for integrated management of the LMB. Using this modelling framework, the *LMB-Source model* was developed — and successfully validated— to simulate streamflow regime and instream dynamics of nitrate and total suspended solids (TSS) of the LMB (Ly et al., 2020b). Building on the results of these previous studies, this paper uses the *LMB-Source* model to simulate four scenarios of plausible hydropower development pathways in the LMB, and it explores the potential impacts of such development pathways. Given uncertain future climate variability which could exacerbate projected impacts, the effects of each development pathway are appraised under alternatives of extreme climatic conditions. Furthermore, the paper explores whether hydropower operational alternatives may be used as cooperative transboundary management measures for mitigating cross-border impacts of hydropower operations.

5.3 Study area and method

The exploration and evaluation of potential effects hydropower development under climate extremes requires collation of data to inform model inputs, including existing national socioeconomic development policies (to formulate plausible future hydropower development pathways) and existing historical environmental monitoring data (to inform model inputs, and to identify precipitation conditions for simulated climatic extremes). Figure 5.1 illustrates the overall approach adopted, and the methodology for each step is described in subsequent sections.

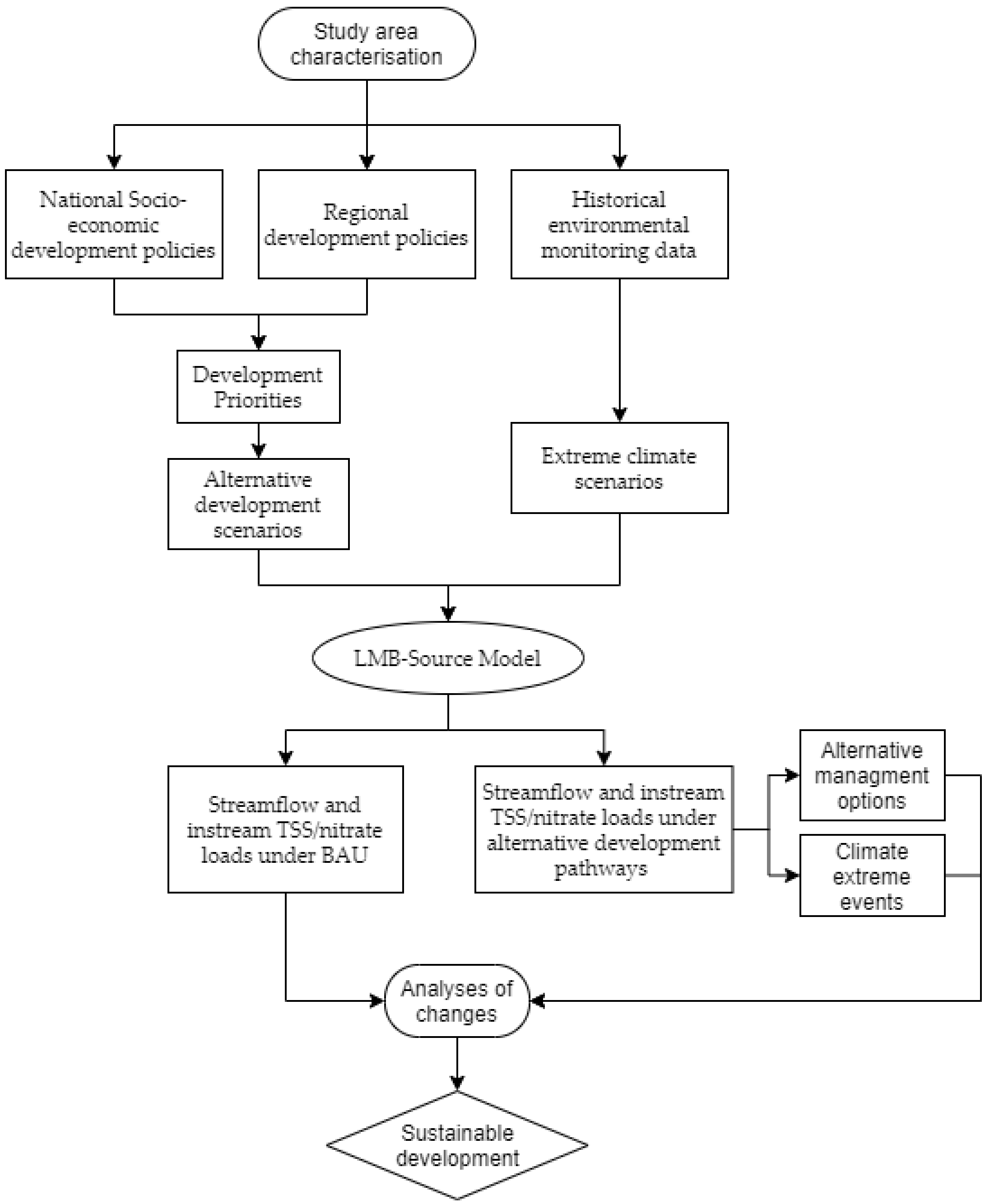


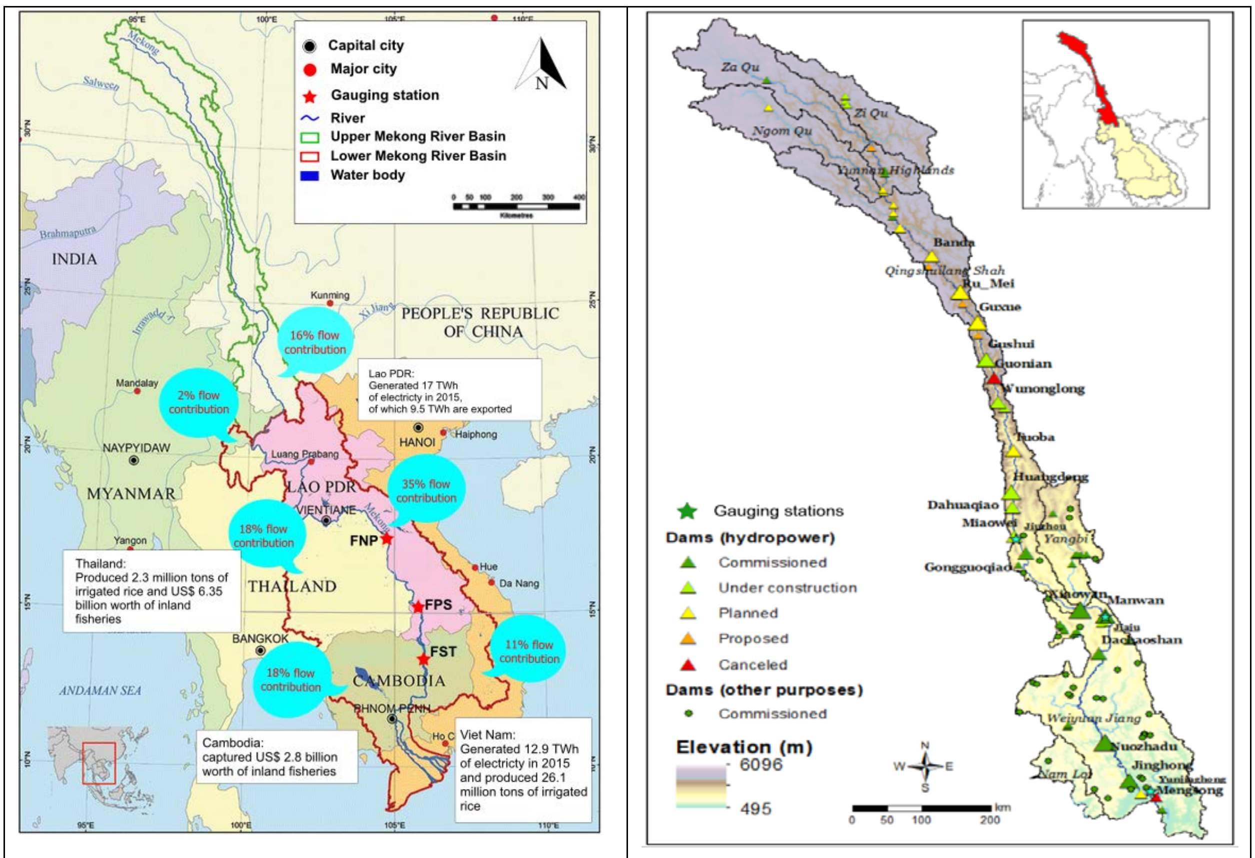
Figure 5.1: Flow diagram illustrating the process used for assessing the effects of different hydropower development scenarios, including alternatives for extreme climate conditions

5.3.1 Study area characterisation and data sets

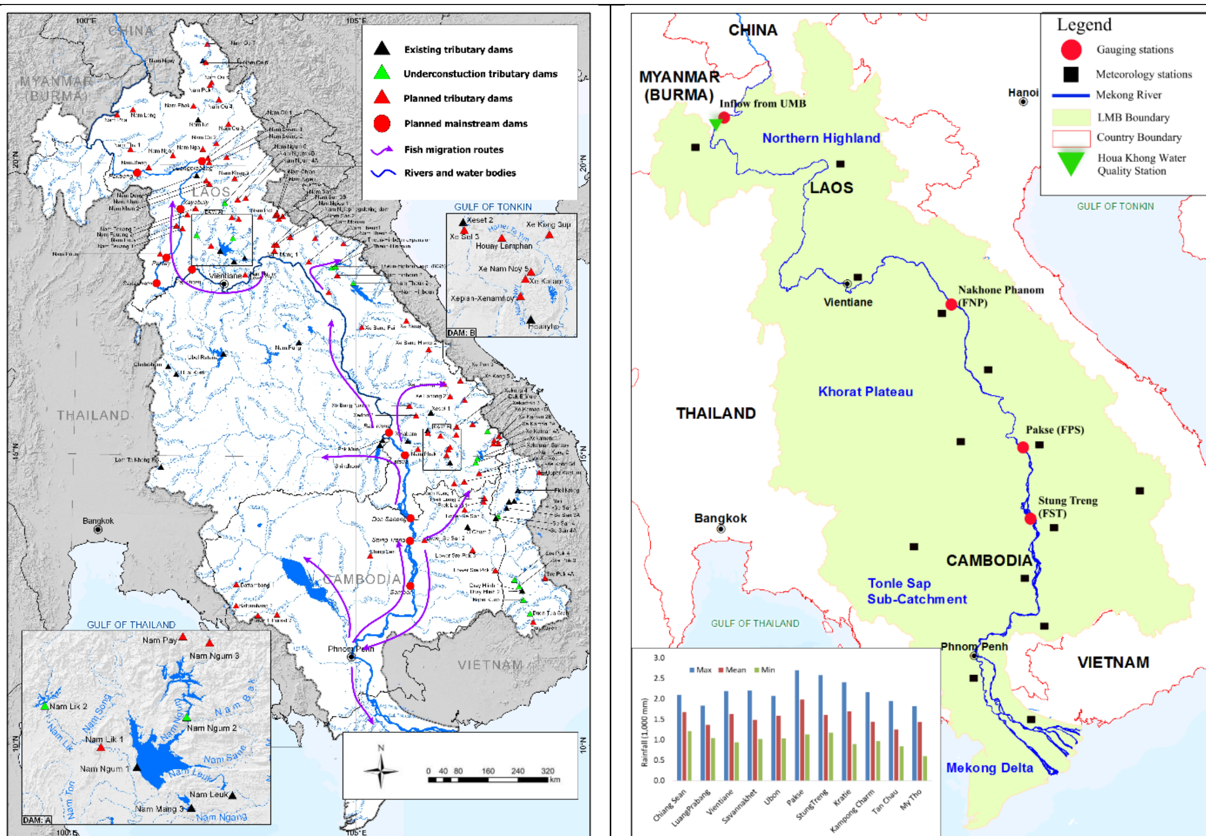
The Mekong River —ranked as the 8th largest globally in terms of its mean annual flow— originates from the mountain ranges of the Himalaya, this transboundary river runs through the Peoples Republic of China (PRC) and Myanmar forming the Upper Mekong River Basin (UMB) before flowing through the Lower Mekong River Basin (LMB) (Figure 5.2a), discharging approximately 457 km^3 of water annually into the South China Seas, also known as the East Sea (Chen et al., 2020). Its geographic coverage of 795,000 sq km is made up of diverse topography and landforms, with the UMB dominated by mountainous areas with steep valleys, narrow river channel, and high elevation drops giving it over 40,000 MW of theoretical hydropower potential (Geheb and Suhardiman, 2019). As such, this section of the Mekong River has been recognized as an important water resource for hydropower development (Cosslett and Cosslett, 2018) and it has been rapidly exploited since 1993 —when the Manwan Hydropower became operational on the mainstream of the River (Fan et al., 2015) (Figure 5.2b).

The LMB (with a total land area of 624,000 km^2) is more topographically diverse, with complex draining patterns and elevations ranging from 0 m above sea level at the Mekong Delta, to 2800 m above sea level in the upper part of the LMB (Mekong River Commission, 2009). The mountainous topography of the northern and eastern part of the LMB, along with annual rainfall reaching as high as 3,000 mm, has made this part of the basin also highly suitable for hydropower development with an estimation of theoretical installed capacity of up to 30,000 MW (Mekong River Commission, 2016) (Figure 5.2c).

The LMB is endowed with a wide variety of terrestrial and aquatic natural resources. The Mekong River Commission (2018) estimated that the river network system is home to 1,148 fish species, many of which undertake long-distance migration from the flood plains of the Tonle Sap Lake or the Mekong Delta, to major tributaries of the upper part of the basin during the annual flood pulse caused by the monsoon rain of the wet season (Figure 5.2c) (Baran, 2006; Ziv et al., 2012; Intralawan et al., 2018). This phenomenon has led to productive inland wild capture fisheries (Kummu and Sarkkula, 2008; Cosslett and Cosslett, 2018; Halls and Hortle, 2021), an important source of dietary protein of the basin population of over 60 million people (Mekong River Commission, 2018; Chan et al., 2020).



(a)	(b)



(c)	(d)

Figure 5.2: Study area of the LMB illustrating (a) ecological and economical values of the Mekong River, (b) planned and developed hydropower in the UMB, (c) planned and developed hydropower in the LMB, and (d) meteorological locations of the LMB (Mekong River Commission, 2018).

5.3.1.1 Hydropower development in the LMB

The MRC manages a database of existing and planned hydropower projects in the LMB, compiled from national databases of the MRC Member Countries (Cambodia, Lao PDR, Thailand and Viet Nam) (Table 5.1).

Table 5.1: Tributary and mainstream hydropower projects proposed to be operated from 2016, and their combined specifications grouped by gauging watersheds (Mekong River Commission, 2016).

Specifications	Unit	FNP	FPS	FST	Downstream

		TB	MS	TB	MS	TB	MS	TB	MS
No. of Project	No.	26	6	9	2	15	2	7	1
Average design discharge	m^3/s	100.6	5,268.7	124.3	10,850.0	295.1	10,446.5	44.4	19,163.0
Average full supply level (FSL)	mamsl	605.5	262.8	491.9	106.3	449.0	64.8	263.0	40.0
Average minimum supply level (MSL)	mamsl	585.8	257.3	475.6	99.1	430.8	61.0	249.7	38.0
Total Installed capacity	MW	1,671.5	7,499.0	431.0	2,558.0	1,992.4	1,340.0	216.0	3,300.0
Total mean annual energy generation	GWh	7,430.5	32,494.4	2,163.5	11,185.0	10,230.9	7,245.0	1,097.9	14,870.0
Total live reservoir storage	1000 m^3	17,104.6	2,107.9	3,869.4	932.9	16,744.7	185.0	2,425.0	2,000.0
Total reservoir area at live storage level	km^2	798.7	377.2	257.3	181.0	2,924.4	60.0	160.7	1,000.0
Total reservoir area at full supply level	km^2	1,203.9	416.9	398.0	230.1	3,231.8	78.8	223.2	1,061.5
No. with installed capacity of ≥ 100 MW	No.	6	6	1	2	6	2	0	1
Average designed discharged of projects with installed capacity ≥ 100 MW	m^3/s	99.8	5,268.7	756.8	10,850.0	498.1	10,446.5	-	19,163.0
Total live reservoir storage of projects with installed capacity ≥ 100 MW	1000 m^3	8,054.0	2,107.9	154.0	932.9	13,018.9	185.0	-	2,000.0

The MRC's hydropower development database shows that 68 projects have been constructed as of 2015 generating over 20,000 GWh annually (Appendix 5.A). However, this represents only 50% of the total planned projects. By 2040, a total of 136 projects are expected to be in operation, providing the basin with another 87,000 GWh annually (Figure 5.3). These 136 mainstream and tributaries projects include the 14 in Cambodia, 100 in Lao PDR, 7 in Thailand, and 15 in Viet Nam.

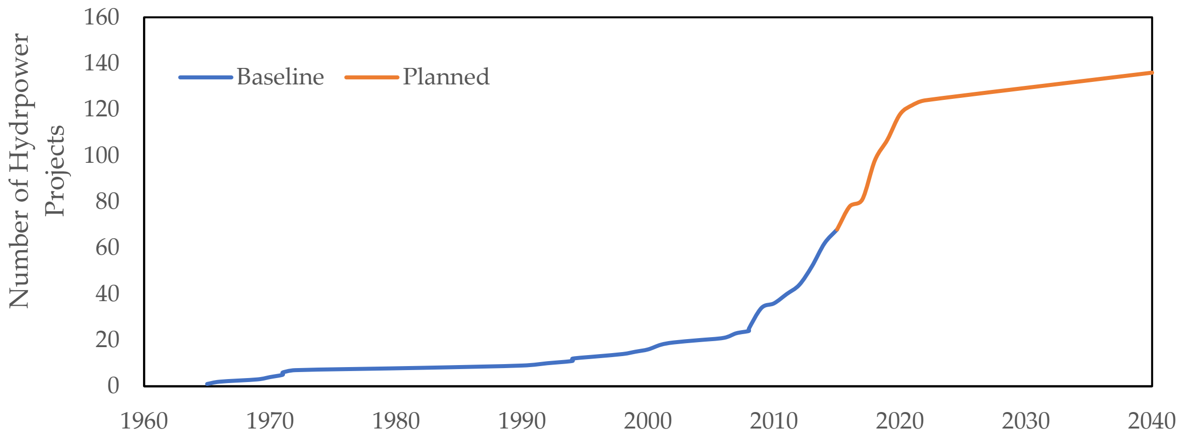


Figure 5.3: Planned timeframe for hydropower development in the LMB (Mekong River Commission, 2016)

While hydropower has been known to produce renewable, low cost, and clean energy, it is also well known that damming a river for hydropower purposes causes various environmental and social issues, including permanently altering LULC and the river ecosystems (Pokhrel et al., 2018; Hecht et al., 2019; Ly et al., 2020a; Trung et al., 2020). These impacts can be even more profound during extreme climate conditions (e.g. drought).

5.3.1.2 Environmental Data

Key environmental data (consist of historical climate, hydrological and water quality monitoring data) were sourced from the MRC. Climate datasets consist of daily rainfall (mm) and air temperature (◦C) observations from 17 stations across the LMB (Figure 5.2d) from 1985 to 2015. Similarly, hydrological data in the form of daily water levels was obtained for the same time period at 3 gauging stations Nakhone Phnome (FNP), Pakse (FPS), and Stung Treng (FST) (Figure 5.2d). The MRC has developed rating curves at these stations allowing relationships to be established between water levels and the river discharge. At these same stations, the MRC also monitors and records instream nitrate and total suspended solids on a monthly basis. The monitoring is carried out as part of the MRC Water Quality Monitoring Network (WQMN) with records dating from 1985.

5.3.2 Methodological framework for hydropower development scenarios

Given future uncertainty (including that of climate variability), thorough analyses of potential impacts associated with development scenarios are needed to assist water managers in making informed decisions and management strategies (Lekavičius et al., 2019; Marthaler et al., 2020; Mitic et al., 2020). Scenarios of alternative future development are commonplace for ex-ante evaluation of the potential impacts of land use planning and decisions (Straton et al., 2011). A number of qualitative and quantitative methods exist to develop scenario storylines exploring alternative pathways that can potentially maximise development benefits while at the same minimise any adverse impacts (Rounsevell and Metzger, 2010).

While both qualitative and quantitative methods for scenario development are available (Gausemeier et al., 1998), the former has been proven effective in documenting future scenarios that integrate social, economic and biophysical attributes (Ligmann-Zielinska and Jankowski, 2010; Metz and Hartley, 2020), and therefore was selected to guide the framework (Figure 5.4) for exploring the impacts of projected hydropower development on the sustainable development of the LMB. The framework adopts a five stage scenario management approach as described in Rounsevell and Metzger (2010) and Gausemeier et al. (1998).

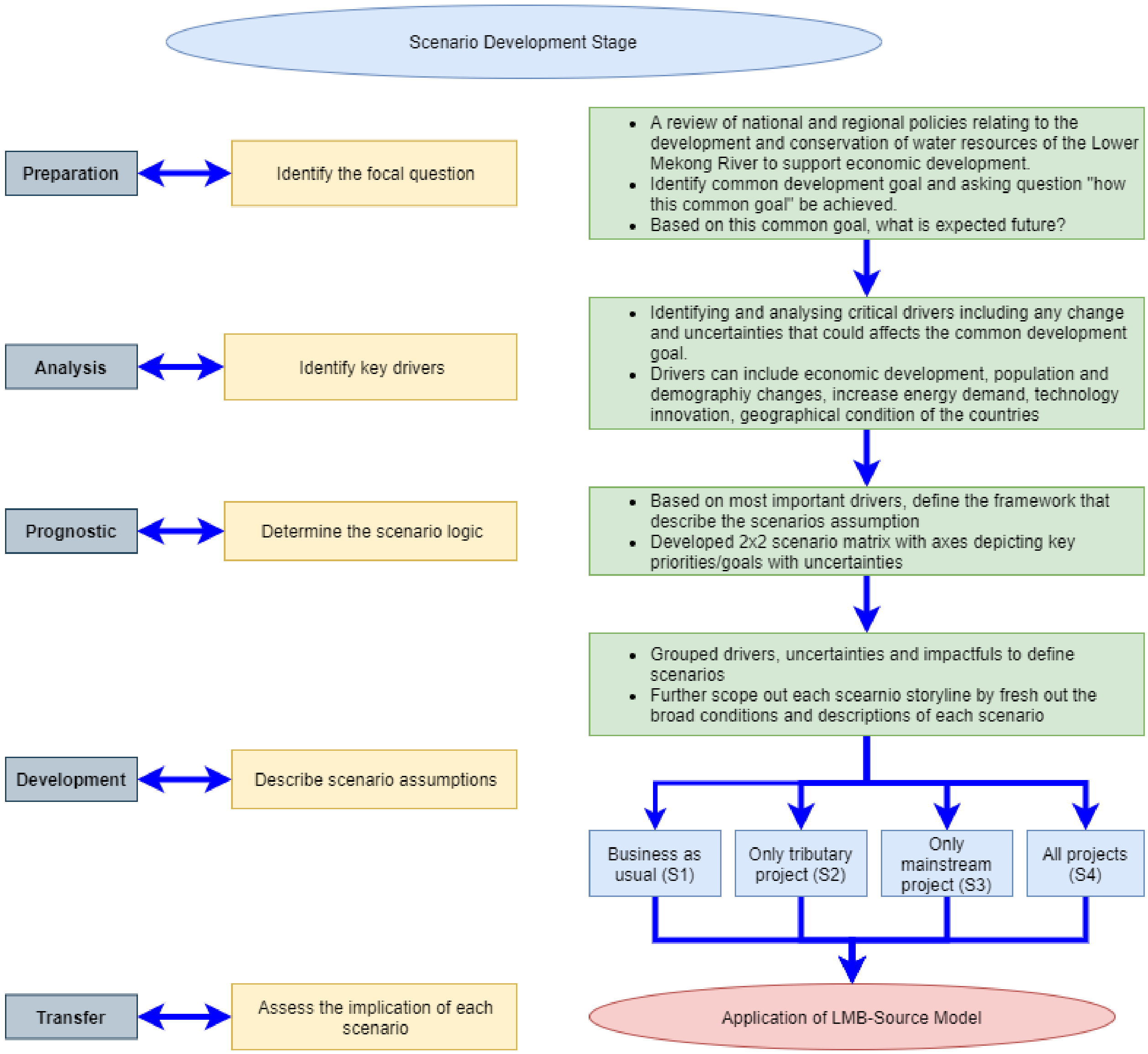


Figure 5.4: Steps used for generating plausible future hydropower development scenarios (Rounsevell and Metzger, 2010)

5.3.2.1 Identification of key question and major drivers:

Like most scenario development processes for the energy sector (McPherson and Karney, 2014; Mirjat et al., 2018; Moallemi and Malekpour, 2018), scenario development for this study commenced with the identification of drivers that help shape the formulation of development strategies and decision-making. As illustrated in Figure 5.5, driven by rapid economic growth and increase population, demand for electricity has increased across the basin (Nguyen and Pham, 2018; Nguyen et al., 2020). The average per capita electricity consumptions for the four LMB countries in 2015 was estimated at 1,310 kWh, representing an increase of over 138% since 2002 (World Bank Group, 2015). Despite this increase, it is estimated that approximately 10% of the basin population have yet to access electricity (UNESCAP, 2021). Findings from the review of existing national and regional socioeconomic development policies in LMB revealed that affordable and reliable energy supplies are integral for eradicating poverty, extending electricity coverage, and sustaining, if not increasing, the levels of economic growth observed in the basin during the past decades. Tables A.2 to A.5 (Appendix 5.B of the Supplementary Information (SI)) provide a summary of policies targets and outputs of the LMB Countries, where development of water resources for food production and electricity generation are considered as priorities at both national (Government of the Lao PDR, 2016; Government of Viet Nam, 2016; Government of Thailand, 2017; Government of Cambodia, 2019) and regional levels (Mekong River Commission, 2016; Mekong River Commission, 2018).

While fossil fuel and natural gas continue to be the main energy sources, supplying the basin with close to 60% of its total energy (World Bank Group, 2015), several factors at national, regional and global scales have driven the integration of renewable energy sources into national and regional development strategies. For example, commitments to combat global climate change and its impacts (SDG 13) have influenced LMB countries to establish their individual target of reducing national annual CO_2 emission by 20-25%, whilst concurrently increasing the share of domestic energy consumption from renewable energy to 20-30% by 2030 (Government of the Lao PDR, 2011; Government of Viet Nam, 2015; IRENA, 2017; ADB, 2018; ADB, 2019).

With its diverse topography, hydropower has become the main renewable energy source of the basin. Other major reports of the region also cite hydropower infrastructure as the main development opportunity that can help the LMB Countries achieving their goal of ensuring affordable and clean electricity (Mekong River Commission, 2016; Intralawan et al., 2019; International Hydropower Association, 2020; Atkinson, 2021). While hydropower has been highlighted as a renewable and sustainable resource for countries to meet SDG7 and their energy needs, it has also been known to cause negative effects on the ecosystems (Section 5.2). As more and more rivers are dammed, uncertainties associated with costs and benefits of hydropower development and operation have become the focal point of debate and water politics in the LMB (Geheb and Suhardiman, 2019; Intralawan et al., 2019; Trung et al., 2020; Yoshida et al., 2020; Atkinson, 2021).

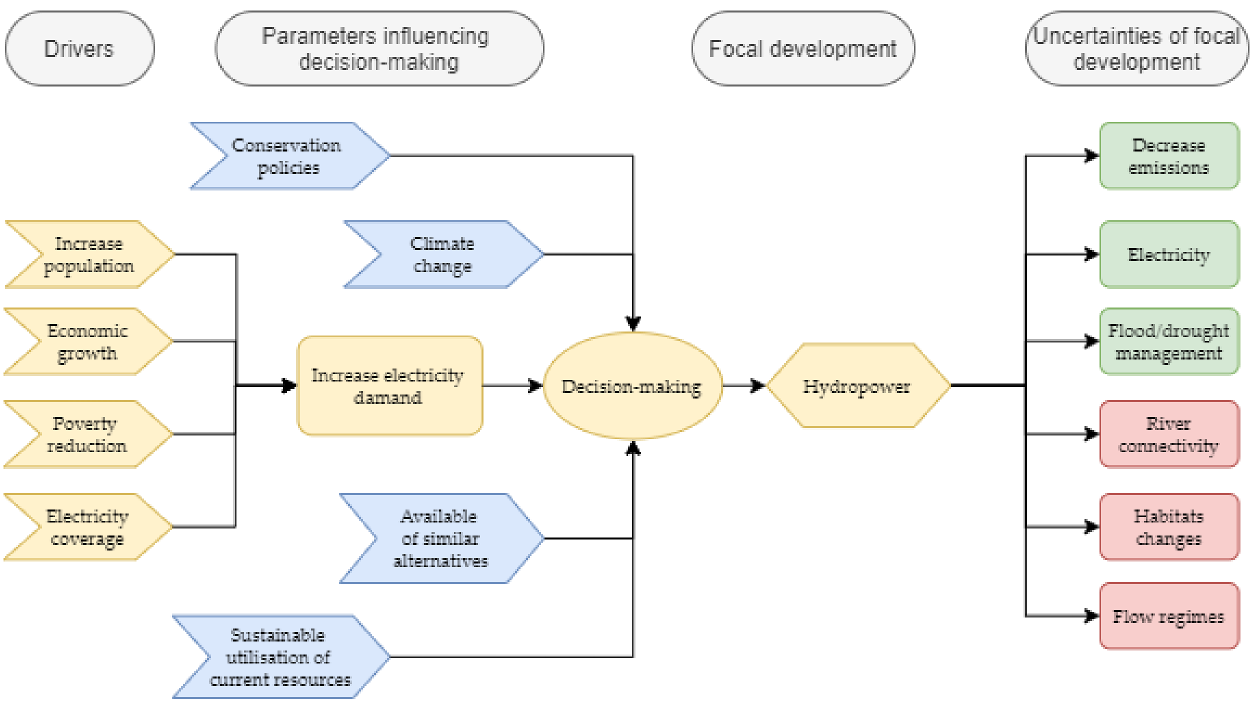


Figure 5.5: Drivers and parameters influencing decisions on the needs for hydropower development (Government of the Lao PDR, 2016; Government of Viet Nam, 2016; Government of Thailand, 2017; Government of Cambodia, 2019).

5.3.2.2 Determining the Scenario logic and assumptions

Applying an exploratory scenario storyline approach, narratives associated with the driving forces and critical uncertainties of hydropower development in the LMB were identified and evaluated (Figure 5.5 and Appendix 5.D of SI). These drivers and uncertainties were identified based on prior studies where both negative and positive impacts of hydropower development of different types and sizes have well been explored and discussed (Fan et al., 2015; Zhang et al., 2016; Intralawan et al., 2018; Williams, 2019; Laborde et al., 2020; Trung et al., 2020; Atkinson, 2021), with many concluded that developing hydropower on the river mainstream could lead to severe and irreversible environmental and social impacts (Le et al., 2020; Trung et al., 2020; Yoshida et al., 2020). Drivers allow the establishment of various assumptions used for deriving distinct future alternative narratives that can be implemented to help the LMB Countries achieving their goals of ensuring access to affordable and clean energy, while pursuing ecologically sustainable development.

Analyses of these drivers led to the construction of storyline assumptions that were framed around two axes describing two key uncertainties when prioritising regional policies that favour (i) the development of hydropower for achieving SDG-7 and (ii) maintenance the integrity of the Mekong River mainstream —measured by the proxies of streamflow and instream TSS and nitrate dynamics. Using a matrix as described by Rounsevell and Metzger (2010), these two key uncertainties allow for the construction of four plausible future hydropower operation scenarios (Figure 5.6).

The scenarios consider that a total of 68 hydropower projects have been in operation across the LMB as of 2015 (Section 5.3.1.1 and Appendix 5.A of SI). By 2040, the number of hydropower projects across the basin is expected to reach 136, of which 11 projects will be built on the mainstream of the LMR (Table 5.1 and Section 5.3.1.1). The scenarios consider the cumulative impacts of their development in terms of providing clean and affordable energy, while maintaining the integrity of the mainstream. These scenarios are intended to compare and contrast the likely cumulative effects of hydropower development on mainstream, tributaries, and a combination thereof. These four plausible scenarios are briefly introduced hereafter, and in Figure 5.6, with a more detailed description presented in Appendix 5.C of SI.

Scenario 1 (S1): A business-as-usual or baseline (BS) scenario that favours the protection of the integrity of the Mekong River to maintain its ecological function. The scenario operates on the assumption that no more hydropower will be developed in the basin beyond 2015. With no additional hydropower development, the river streamflow regime and instream TSS and nitrate loads are assumed to remain at the same levels as in 2015. The LMB countries would be required to find alternative energy sources, both renewable and non-renewable, to meet its electricity demand.

Scenario 2 (S2): A tributary-only hydropower operation (TB) scenario. This scenario assumes that the LMB countries reach an agreement to allow hydropower development only on tributaries, to preserve mainstream connectivity. Under S2, an additional 57 hydropower projects would be developed (from the baseline of S1), holding back an estimated combined 40 million m^3 of water to generate additional 21,000 GWh of electricity annually (Table 5.1). The LMB countries would be required to find alternative energy sources, both renewable and non-renewable to meet their growing electricity demands.

Scenario 3 (S3): A mainstream-only hydropower operation (MS) scenario. This scenario assumes that the LMB countries reach an agreement to allow only the development of mainstream hydropower to maintain the connectivity of the tributaries, and reduce impacts on streamflow regimes ensuring capacities of the river network in transporting TSS and nitrate from tributary sub-basins to the mainstream. Under S3, an additional 11 hydropower projects would be developed from S1, holding back an estimated combined 3.2 million m^3 of water to generate additional 66,000 GWh of electricity annually (Table 5.1). The LMB countries would be required to meet their energy requirements with other energy sources, both renewable and non-renewable.

Scenario 4 (S4): mainstream and tributary hydropower operation (MS+TB) scenario. This scenario favours harvesting electricity from hydropower operations at its full potential; maintaining ecological integrity and functions of the river system is secondary. Under this scenario additional 68 tributary and mainstream hydropower would be developed from the mainstream, holding back an estimated combined 43.2 million m^3 of water to generate additional 87,000 GWh of electricity annually (Table 5.1).

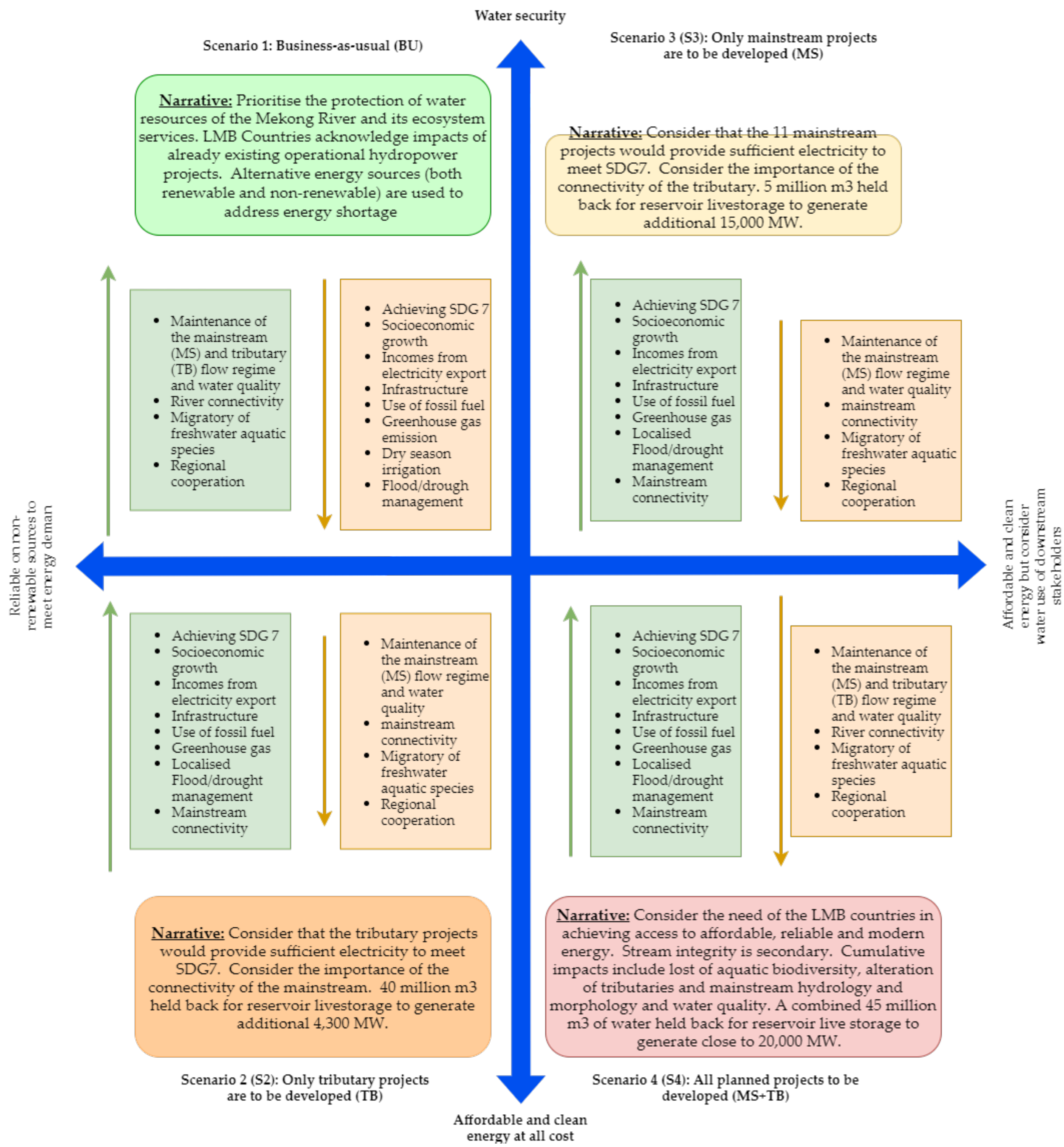


Figure 5.6: Scenario matrix of the four plausible hydropower development scenarios describing their narratives and uncertainties with green arrows indicating potential positive uncertainties and orange arrows indicating potential negative uncertainties (adapted from Nieto-Romero et al. (2016)).

5.3.3 Scenario alternatives

5.3.3.1 Future hydropower development scenarios under extreme climatic conditions

To help better understand the potential effects of various hydropower development under future climate extremes, historic climatic records of 30 years at 11 stations across the LMB (Section 5.3.1.1) were analysed to identify the wettest and driest years recorded at each station. Evidence suggests that extreme climate conditions have profound effects on hydrologic cycles (Stott, 2016), also affecting species composition, diversity, and functional attributes of terrestrial and aquatic ecosystems (Parmesan et al., 2000; Ummenhofer and Meehl, 2017). While existing global climate model (GCM) for the LMB have been downscaled (Appendix 5.E), the outputs cannot capture well characteristics of climatic extremes (Lanzante et al., 2018; Kaini et al., 2020). Therefore, this research analysed daily precipitation data recorded from 1985 to 2015, and it identified the wettest and driest records. These data were input to the *LMB-Source* model to simulate the likely effects of the 4 hydropower development scenarios (Section 5.3.2.2) under extreme wet and dry conditions.

5.3.3.2 Operational alternatives of future hydropower development scenarios

Studies have revealed that optimization of hydropower operation can lead to increased electricity generation (Sorachampa et al., 2020) and improved downstream flow and ecological condition (Barros et al., 2003; Liu et al., 2018a; Yu et al., 2019), and operational alternatives of hydropower plants such as hydropeaking mitigation and increased turbine efficiency are a way to reach such optimisation. Therefore, in addition to the four scenarios described in Figure 4.2, operational alternatives of large-scale hydropower projects under each scenario were also examined to determine whether these changes could help ease projected impacts on the Mekong mainstream.

Singh (2009) and Gaius-obaseki (2010) classified large-scale hydropower as those having installed capacity of 100 MW or greater. The development of these types of hydropower has long been contested; it has been argued they cause a range of negative environmental and social impacts, including changes to stream hydrology as well as instream dynamics of ecologically important water quality indicators (O'Connor et al., 2015; Van Cleef, 2016; Koirala et al., 2017; Moran et al., 2018; Aung et al., 2020). Of the planned 68 tributary and mainstream projects in the LMB, 24 (13 tributary and all mainstream projects) will have an installed capacity greater than 100 MW (Table 5.1), and therefore, can be considered large-scale projects.

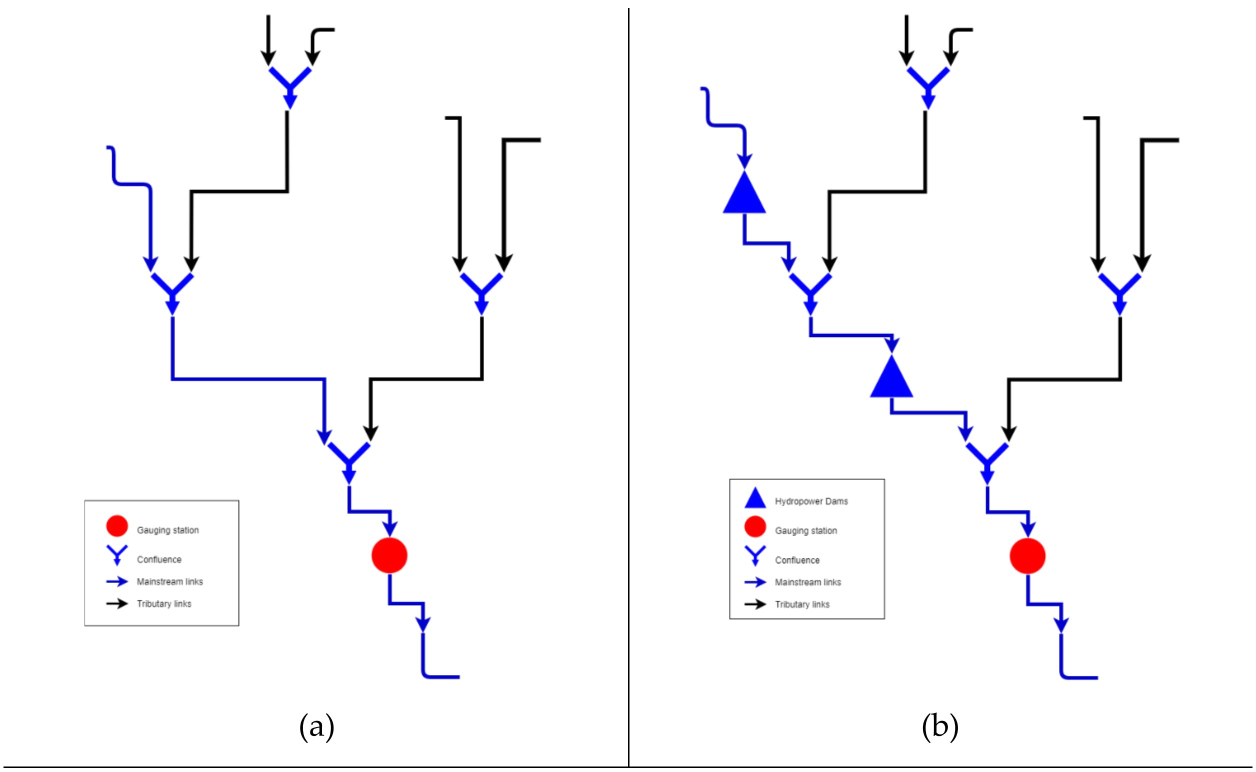
5.3.4 Assessing the implication of each scenario: Model setup and scenario forecasting

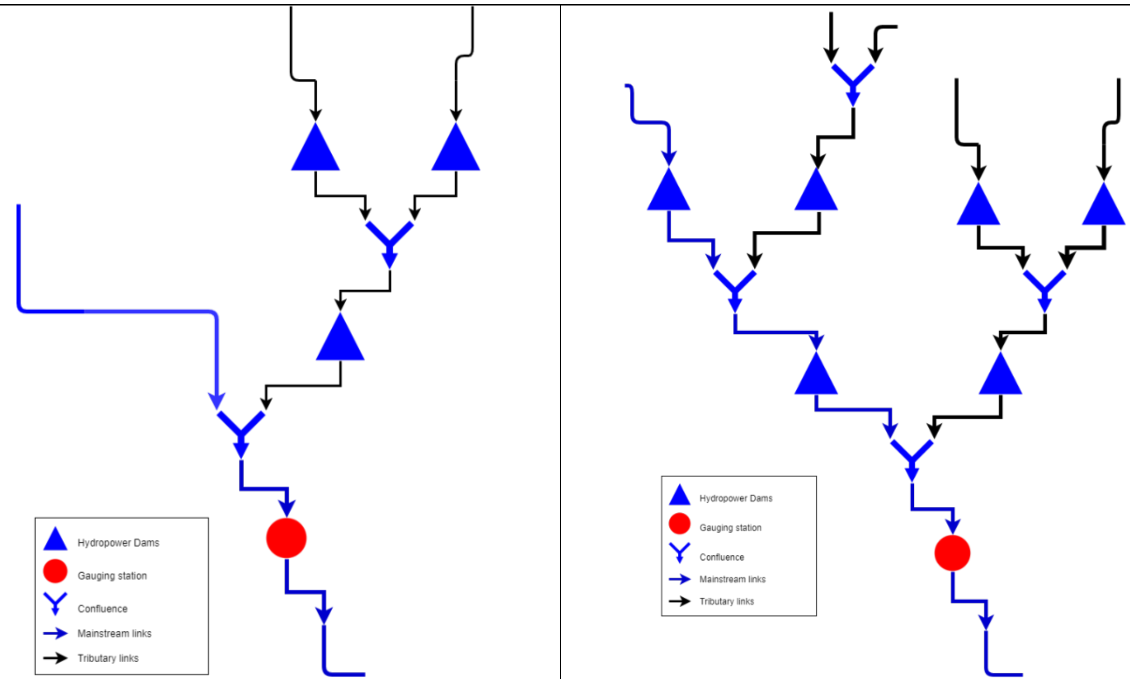
The *LMB-Source* (Ly et al., 2020b) was utilized to simulate potential impacts of four plausible hydropower development scenarios (Figure 5.6 and Section 5.3.2.2) on streamflow and instream TSS and nitrate levels of the Mekong River. Using Source's river operation forecasting built-in feature, the four hydropower operational scenarios were set up (Figure 5.7). 57, 11 and 68 storage nodes representing the number of hydropower projects under development pathways of S2, S3 and S4, respectively, were added to the LMB-Sources model. Figure 5.7 provides snapshot illustrations of the LMB-Source schematic diagram of four hydropower development scenarios examined. Each added node was configured with its specific storage dimension and capacity, inflow link representing incoming streamflow and/or runoff from upstream catchments, outflow conditions that meet the operational requirements, and planned operational commencement date. In addition, instream nitrate and TSS processes at each storage node were configured using the constituent fully mixed approach as described in Ly et al. (2020b).

Under each scenario, streamflow and instream TSS and nitrate forecasting were carried out at 3 locations, namely at Nakhone Phanom (FNP), Pakse (FPS), and Stung Treng (FST) gauging stations where historical time series for streamflow, TSS and nitrate were available (Figure 5.2a and Section 5.3.1.2). These stations were also used in a previous study when assessing the performance of LMB-Sources (Ly et al., 2020b) and were used as control points for assessing cumulative changes of the modelled scenarios.

Source's operational forecasting allows predictions of streamflow and constituents in two phases; the historic warm-up phase is designed to warm-up the network's physical models using known available historical data, while the forecast phase extend historical data into the future and it provides an estimate of the effects on the scenario being examined (eWater Ltd., 2018).

For this study, historical timeseries data from 2003 to 2015 were used for the model warm-up phase, with the model forecast length defined from 2016 to 2040 when the last planned hydropower will be fully operated. Storage nodes, each with different release timing to represent the different commission timing for each hydropower project, were added to the LMB-Source model.





(c) (d)

Figure 5.7: Snapshot illustrations of LMB-Source schematic diagrams set up for four plausible hydropower development scenarios: (a) scenario 1 – business-as-usual, (b) scenario 2 – development of tributary hydropower only, (c) scenario 3 – development of mainstream hydropower only, and (d) scenario 4 – development of all planned tributary and mainstream hydropower

5.3.5 Analyses of changes

Against the baseline scenario, 9 indicators of change were used to examine the effects of alternative future hydropower development scenarios (Table 5.2). These indicators allow evaluating changes to streamflow and instream loads of TSS and nitrate in the Mekong River mainstream, at 3 gauging stations (FNP, FPS, and FST) (Figure 5.2a). These 3 gauging stations were used in our previous study (Ly et al., 2020b) as calibration and validation locations to evaluate the performance of *LMB-Source* model. In addition, selected indicators (ΔQ_{mean}, ΔQ_{dry}, ΔQ_{95}, ΔL_{TSS}, and $\Delta L_{NO3,}$, Table 5.2) were used to examine the effects operational alternatives (Section 5.3.3) on streamflow and instream TSS and nitrate loads at FNP, FPS and FST. To ascertain whether optimization of hydropower operation help improve flow, TSS and nitrate levels, non-parametric Wilcoxon signed-rank test (Woolson, 2007) was applied to streamflow time series of each scenario (S) and its corresponding operational alternative (A).

Table 5.2: Indicators of change assessed at FNP, FPS, and FST gauging stations.

No.	Indicators of Change	Symbols	Unit of Indicators	Gauging Stations
1	Mean annual discharge	ΔQ_{mean}	%	
2	Mean wet season discharge	ΔQ_{wet}	%	
3	Mean dry discharge	ΔQ_{dry}	%	
4	5 % exceedance probability flow (High flow condition)	ΔQ_{5}	%	FNP,
5	95 % exceedance probability flow (Low flow condition)	ΔQ_{95}	%	FPS,
6	Mean annual TSS load	ΔL_{TSS}	%	FST
7	Mean wet season TSS load	ΔWL_{TSS}	%	
8	Mean annual nitrate load	ΔL_{NO3}	%	
9	Mean wet season nitrate load	ΔWL_{NO3}	%	

5.4 Results

5.4.1 Climate extreme variability

The analysis of 1985 – 2015 precipitation (P) time series at 11 monitoring stations across the LMB reveals highly variable rainfall distribution (Section 5.3.1.2). As such, the occurrence of extreme wettest and driest climate conditions varied from location to location (Figure 5.8). While these extreme wettest and driest rainfall conditions only occurred once for each station during the period from 1985 to 2015, these conditions deviated greatly from the mean annual rainfall at each respective station (Table 5.3). For example, under the driest condition, rainfall volume could be reduced between 24%

and up to 60% in some parts of the basin. In contrast, under the wettest projected conditions, the volume of rainfall could increase by as much as 60% (Table 5.3).

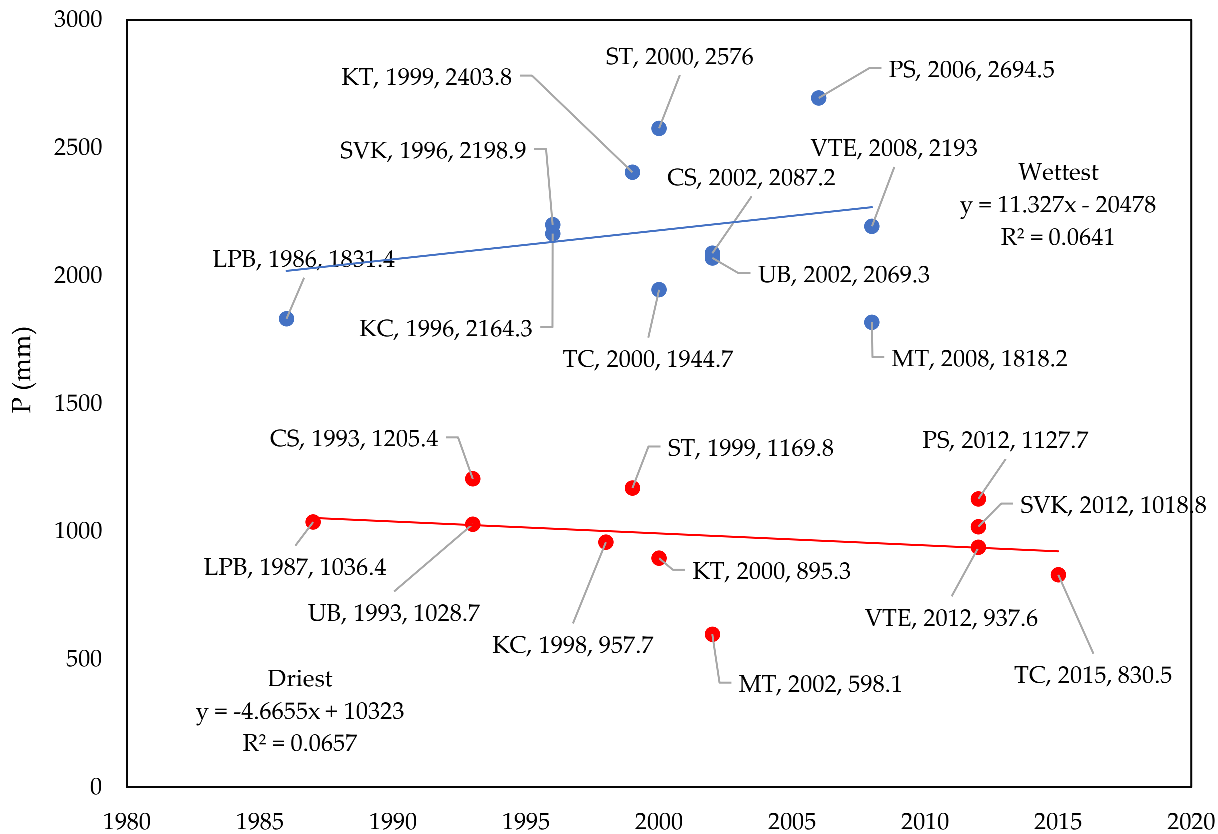


Figure 5.8: Annual precipitation (P) distribution of the wettest (blue dots) and driest (red dots) extremes at 11 rainfall monitoring stations cross the LMB based on the analysis of rainfall time series from 1985 to 2015 (Table 5.3 provides a full list of the station names)

Table 5.3: Changes in precipitation across the LMB under projected wettest and driest extremes

Rainfall Stations	Acronym	P (mm)	Wettest		Driest	
			P (mm)	% Deviation	P (mm)	% Deviation
Chiang Sean (CS)	CS	1,669.0	2,087.2	+25.1	1,205.4	-27.8

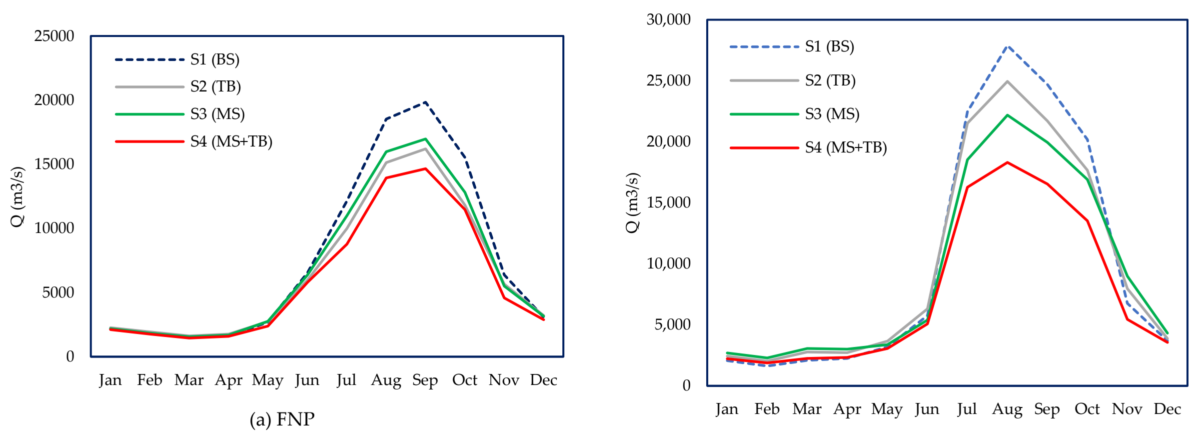
Luang Prabang (LPB)	LPB	1,363.0	1,831.4	+34.4	1,036.4	-24.0
Vientiane (VTE)	VTE	1,622.0	2,193.0	+35.2	937.6	-42.2
Savannakhet (SVK)	SVK	1,487.0	2,198.9	+47.9	1,018.8	-31.5
Ubon (UB)	UB	1,578.0	2,069.3	+31.1	1,028.7	-34.8
Pakse (PS)	PS	1,976.0	2,694.5	+36.4	1,127.7	-42.9
Stung Treng (ST)	ST	1,608.0	2,576.0	+60.2	1,169.8	-27.3
Kratie (KT)	KT	1,693.0	2,403.8	+42.0	895.3	-47.1
Kampong Charm	KC	1,439.0	2,164.3	+50.4	957.7	-33.4
Tan Chau	TC	1,250.0	1,944.7	+55.6	8,30.5	-33.6
My Tho	MT	1,428.0	1,818.2	+27.3	598.1	-58.1

5.4.2 Changes in streamflow regime

Using the *LMB-Source* model —previously evaluated to have high capability in simulating watershed behaviours of the LMB (Ly et al., 2020b)— each plausible hydropower development scenario was modelled, and forecasted streamflow time series were obtained at FNP, FPS, and FST (Figure 5.2a and Section 5.3.1.2). A visual inspection of mean monthly streamflow regimes at FNP, FPS, and FST (Figure 5.9) revealed that S4 (MS+TB, see Figure 5.6), with the operation of 11 mainstream and 57 tributary hydropower projects, exerts the greatest effect on flow regime of the Mekong River.

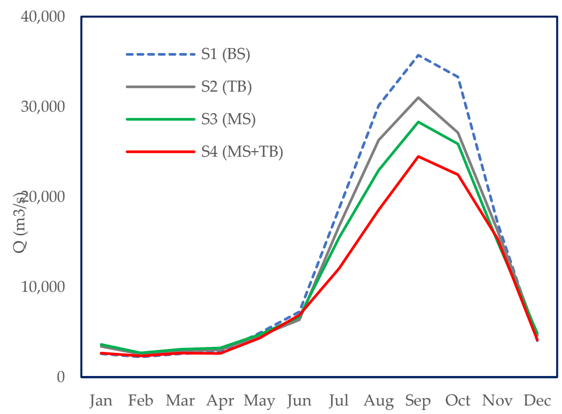
Flow regimes of the Mekong River at FNP, FPS, and FST gauging stations under S1, S2, S3 and S4 are shown in Figure 5.9, where mean monthly flow reductions were predicted from -2.3 to -28.0%, -0.5 to -34.3%, and -0.4 to -38.5%, respectively (Figure 5.10). Comparing S2 (TB) and S3 (MS), the results of the model simulation evidenced that, at FNP, the operation of tributary hydropower projects (S2) influences more the flow regime of the Mekong River; whereas at FPS and FST the river flow regimes appear more influenced by the operation of mainstream projects(S3) (Figure 5.9).

The results highlight the significant flow contribution of tributaries upstream of FNP, where major tributaries —including the likes of Nam Ou River, Nam Ngum River, and Nam Hinboun River— are located. Together they contribute approximately 35% of the total mean annual flow of the Mekong River (Mekong River Commission, 2009). At FNP, the S2 (tributaries only) holds back approximately 17,100 thousand m^3 of water to maintain reservoir live storages of the 26 tributary hydropower projects (Table 5.1) majority of which have been proposed as cascade dams on major tributaries of the Mekong River. By comparison, only 2,100 thousand m^3 are held back to maintain reservoir live storages of the 6 mainstream cascade projects located upstream of FNP under S3 (Table 5.1).



(a) FNP

(b) FPS



(c) FST

Figure 5.9: Forecasted mean annual flow hydrographs of the Mekong River from 2016 to 2040 at (a) FNP, (b) FPS and (c) FST, under S1, S2, S3 and S4.

When comparing against the baseline scenario (S1), the largest reduction in the Mekong River flow regime is predicted during the wet season —June to October— for all three scenarios (S2, S3 and S4), at all three gauging stations; whereas increased flow levels are predicted during the dry season —November to April— for S2 and S3 (Figure 5.10). Of the three alternative scenarios, it is predicted that S3 will impact the most on the dry season flow of the Mekong River, with changes ranging from 1 to 2.3 % at FNP, 4 to 11.6% at FPS, and 12.1 to 19.6% at FST. With no tributary flow being held back under S3, it is likely that FST will benefit from the input flow of the Sesan-Sre Prok-Sekong (3S) River system which drains an area of approximately 78,650 km^2 and it contributes an average of 2,800 m^3/s annually to the Mekong River total flow (Oeurng et al., 2016).

While not at the same levels of contribution, S2 (tributary only scenario) was also predicted to help increase flow during dry seasons with levels at FNP, PPS, and PST increasing from 1.7 to 6.4%, 2.2 to 7.8%, 5.3 to 11.5%, respectively. The increased dry season flow could be considered an added benefit and consistent with known benefits associated with hydropower operation which include increased water availability for irrigation of dry season crops and drought management (Rossel and de la Fuente, 2015; Branche, 2017; Hecht et al., 2019; Intralawan et al., 2019).

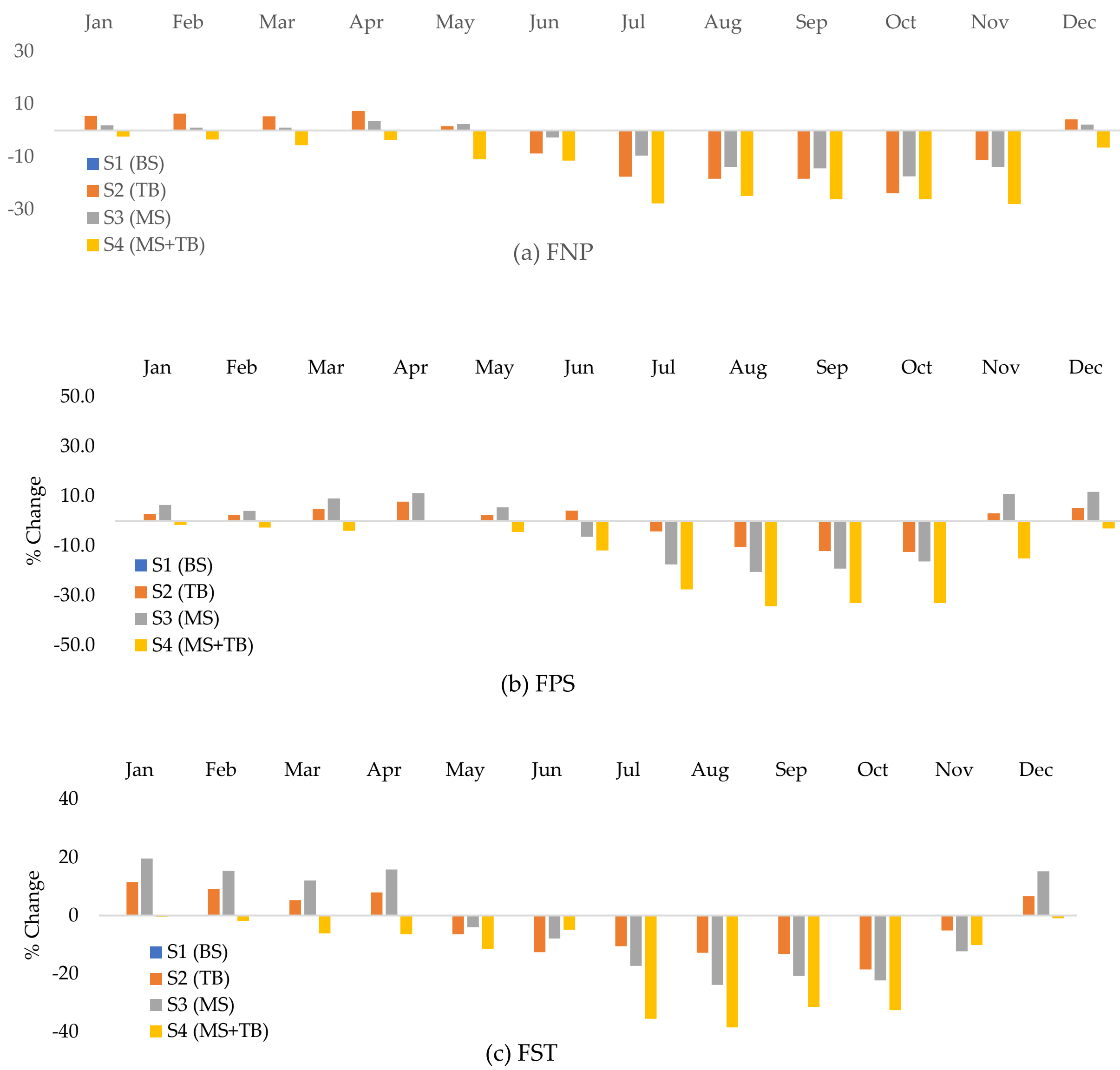


Figure 5.10: Change in average instream monthly flows of the Mekong River at (a) FNP, (b) FPS and (c) FST under alternative hydropower development scenarios.

Table 5.4 provides a summary of changes in the Mekong River flow as predicted by *LMB-Source* at FNP, FPS, and FST stations. Of the three plausible future development scenarios, changes in river flow were predicted to be greatest under S4, with indicators of changes such as ΔQ_{mean} estimated to reduce by -27.4, -23.5, and -31.5%, respectively at FNP, FPS, and FST during the like-current climate conditions. Under the driest projected climate condition (where the amount of rainfall across the basin could decrease between -24 to -58%), changes in ΔQ_{mean} at these same three stations could be as much as 49%.

Conversely, under the wettest projected climatic extreme (where some parts of the basin receive would increase rainfall by up to 55.6% more than normal years), ΔQ_{mean} was found to be less impacted by S4 with change in ΔQ_{mean} of -3.9, -3.1, and -9.3%, respectively at FNP, FPS and FST —in comparison with the baseline flow condition of S1. These projections also reveal that increased flows —considering the alternative scenario of the wettest extreme condition— would not be able to offset the effect of hydropower operations under S4.

The results of simulating S4 also reveal severe reduction in dry season flow (relative to the baseline), with ΔQ_{dry} ranging from -10.8 to -15.5%. Under projected extreme dry condition, the reductions are predicted to be even greater —with ΔQ_{dry} ranging from -34.7 to -43.8%. These levels of flow reduction during dry season could severely affect the river's capacity to adequately dilute pollutants of anthropogenic origin, maintain instream habitat, support aquatic biodiversity, and supply water for irrigation, domestic and industrial consumption purposes (Rossel and de la Fuente, 2015; Chen et al., 2016; Greimel et al., 2018; Vericat et al., 2020). Under S4, the costs associated with these negative impacts could outweigh the electricity generation benefits provided by hydropower operation if no appropriate operational or management measures are put in places to maintain ecological functioning of dry season flow levels.

Comparing S2 and S3, changes in river flows at FPS and FST were greater under S3, whereas at FNP, S2 appears to affect river flow more than S3. This further confirms the importance contribution of tributaries to the Mekong River flow at FNP. While there are 6 mainstream dams upstream of FNP under S3, the nearest one is located more 400 km away. In comparison, the nearest upstream mainstream dam to FPS is approximately 50 km away, and therefore FST is more effected by S3. The same patterns remains under projected extreme dry conditions, with the overall change in river flow at FNP being more impacted by S2; whereas at FPS and FST the opposite is predicted. Simulation of S2 and S3 under projected wettest extreme condition, predicts that river flows at FNP, FPS, and FST will be greater than the baseline scenario (S1).

Table 5.4: Percent of changes in mean annual, wet and dry season flow under alternative hydropower scenarios and extreme rainfall conditions at (a) FNP, (b) FPS, and (c) FST

			Normal condition			Wettest Extreme			Driest Extreme		
Gauging locations	**Indicators of Change**	**Unit**	**S2 (TB)**	**S3 (MS)**	**S4 (MS+TB)**	**S2 (TB)**	**S3 (MS)**	**S4 (MS+TB)**	**S2 (TB)**	**S3 (MS)**	**S4 (MS+TB)**
	ΔQ_{mean}	%	-15.2	-10.9	-27.4	6.0	5.6	-3.9	-26.2	-19.9	-48.8
	ΔQ_{wet}	%	-19.5	-15.0	-34.8	12.8	9.4	-9.3	-38.8	-31.6	-41.9
	ΔQ_{dry}	%	3.4	1.1	-10.8	17.6	12.5	-5.4	-16.5	-12.2	-34.7
	ΔQ_{5}	%	-16.3	-18.8	-23.2	22.2	24.2	-5.9	-15.4	-12.1	-27.1
FNP	ΔQ_{95}	%	6.2	3.0	-6.4	19.5	26.9	8.1	52.0	53.9	10.0
	ΔL_{TSS}	%	-59.1	-48.5	-64.6	-39.42	-46.0	-44.7	-63.5	-54.8	-67.0
	ΔWL_{TSS}	%	-60.5	-54.2	-69.3	-39.31	-44.9	-46.9	-64.7	-54.4	-71.5
	ΔL_{NO3}	%	-4.5	-10.1	-12.2	-3.7	-7.6	-10.7	-8.0	-14.8	-13.5
	ΔWL_{NO3}	%	-4.3	-16.0	-14.0	-4.56	-9.4	-11.6	-10.7	-12.9	-13.6
	ΔQ_{mean}	%	-10.8	-17.4	-23.5	5.7	6.7	-3.1	-23.6	-30.0	-44.4
	ΔQ_{wet}	%	-11.1	-25.5	-29.8	3.2	9.0	-5.3	-30.6	-37.9	-45.8
	ΔQ_{dry}	%	6.9	2.4	-11.1	9.9	14.0	-2.8	-10.6	-9.1	-37.0
FPS	ΔQ_{5}	%	-19.4	-14.6	-30.2	13.9	17.3	-2.9	-34.8	-29.0	-38.4
	ΔQ_{95}	%	9.1	13.2	-7.2	23.7	27.1	7.8	-14.5	-14.7	-25.1
	ΔL_{TSS}	%	-50.1	-64.8	-63.9	-30.1	-46.4	-51.1	-68.7	-63.3	-71.1
	ΔWL_{TSS}	%	-49.9	-64.8	-65.6	-29.8	-45.7	-53.3	-68.6	-63.2	-71.8

Gauging locations	Indicators of Change	Unit	Normal condition S2 (TB)	Normal condition S3 (MS)	Normal condition S4 (MS+TB)	Wettest Extreme S2 (TB)	Wettest Extreme S3 (MS)	Wettest Extreme S4 (MS+TB)	Driest Extreme S2 (TB)	Driest Extreme S3 (MS)	Driest Extreme S4 (MS+TB)
	ΔL_{NO3}	%	-16.5	-20.7	-19.9	-13.5	-16.0	-12.9	-20.2	-29.5	-34.8
	ΔWL_{NO3}	%	-17.1	-31.2	-36.4	-23.0	-19.0	-12.3	-25.6	-28.0	-38.3
FST	ΔQ_{mean}	%	-18.3	-17.0	-31.5	2.7	6.7	-9.3	-23.7	-28.5	-43.2
	ΔQ_{wet}	%	-24.2	-22.3	-35.0	2.7	6.7	-11.5	-27.6	-36.5	-43.0
	ΔQ_{dry}	%	14.6	9.4	-15.5	2.5	6.5	0.8	-9.2	-19.4	-43.8
	ΔQ_{5}	%	-20.2	-17.7	-26.6	9.5	5.6	-11.8	-26.9	-34.0	-47.5
	ΔQ_{95}	%	10.3	7.1	-5.7	13.7	9.4	2.7	-10.0	-14.1	-19.9
	ΔL_{TSS}	%	-48.9	-65.0	-78.1	-33.4	-45.1	-56.9	-59.6	-69.6	-81.1
	ΔWL_{TSS}	%	-49.9	-62.1	-78.6	-35.0	-46.3	-58.2	-61.1	-70.2	-81.3
	ΔL_{NO3}	%	-10.5	-11.3	-12.3	-10.7	-14.1	-13.2	-9.5	-10.3	-15.7
	ΔWL_{NO3}	%	-11.1	-12.5	-12.9	-13.4	-13.1	-15.1	-10.7	-9.5	-18.1

5.4.3 Changes in instream TSS loads

At all three gauging stations, TSS levels —relative to the baseline levels (S1)— are predicted to decrease. The greatest decreases are projected under the scenario where hydropower stations are constructed in mainstream and tributaries (S4) (Table 5.4). Under this scenario, about 64% of instream suspended solids at FNP and FPS are expected to be diminished due to reservoir deposition, while levels at FST could diminish by as much as 80%.

Simulation of extreme climatic events predicts TSS levels to decrease under the driest climate condition, but increase slightly under the wettest condition. Under a driest than current condition, there would be less rainfall to generate overland runoff that would carry detached topsoils (from bare land and cultivated areas with scarce vegetation cover) to the Mekong and its tributaries; whereas under the wettest conditions localised overland sediment runoff could occur in those land uses.
When comparing the effects of S2 and S3 on instream TSS levels of the Mekong River (Figure 5.11), instream TSS appears more affected by S2. With overland sediment runoff being identified as one of the main sources of instream TSS concentration (Ly et

al., 2020a), tributary hydropower operations under S2 could prevent suspended solids from reaching the mainstream, regardless of climatic conditions.

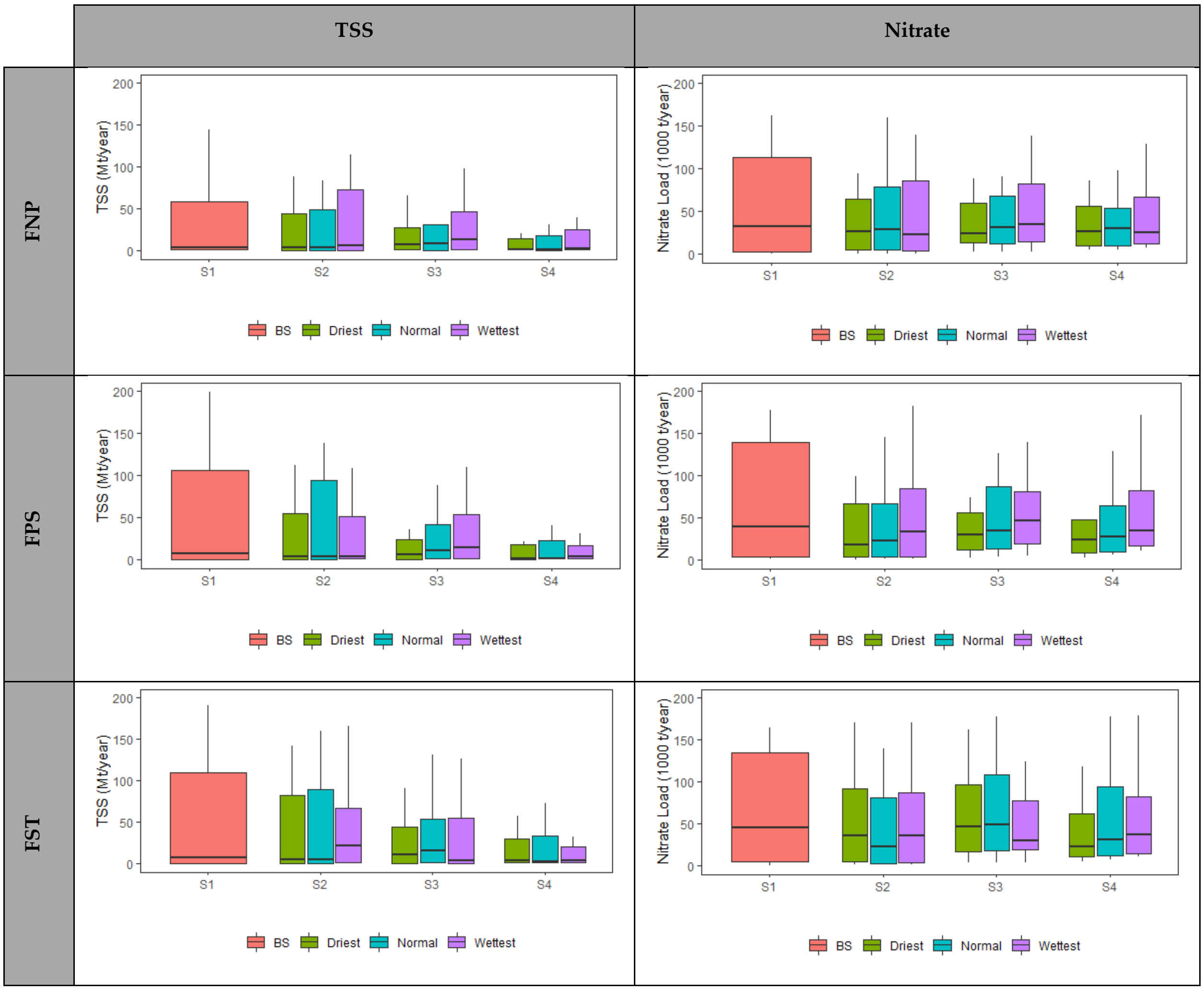


Figure 5.11: Instream loads of TSS (million tonnes per year) and nitrate (thousand tonnes per year) at FNP, FPS, and FST under four scenarios and different climatic conditions (i.e., normal meaning as at present, driest or wettest). BS means business as usual.

5.4.4 Changes in instream nitrate loads

Consistent with results of Trung et al. (2020), decreases in instream nitrate loads are projected for three hydropower development scenarios of this study due to the reduction of streamflow and instream TSS loads (Table 5.4). This is to be expected as the results from Ly et al. (2020a) for streamflow and instream TSS and nitrate levels of the Mekong River found these three parameters to have statistically significant positive correlation. Under climatic conditions that resemble the presence, the largest reductions of instream nitrate loads are predicted to occur under S4 and S3 (Table 5.4 and Figure 5.11), indicating potential instream transport process of nitrate and other nutrients along the mainstream. For all three scenarios, instream levels of nitrate are projected to decrease further during driest years (Figure 5.11), causing a slight increase relative to the baseline (S1) (Table 5.4). Conversely, slight increase in levels are predicted during wet years, causing a slight decrease relative to the baseline (S1). These patterns forecasted for extreme wettest and driest years confirm the contribution of nutrient laden overland runoff discussed by Ly et al. (2020a).

5.4.5 Operational alternatives

Hydropeaking operational alternatives for large-scale hydropower projects (installed capacity ≥ 100 MW) (Table 5.1) were simulated for S2, S3 and S4. Table 5.5 provides a comparison of changes in streamflow and instream TSS and nitrate loads at FNP, FPS, and PST for S2, S3, and S4 under climatic condition resemble the presence, and modified operational conditions (alternative scenario) for large-scale hydropower projects. The modelling results reveal that at FNP (with six tributary and six mainstream large-scale hydropower projects), modification of hydropeaking operation of these projects could increase flow in the mainstream significantly, with ΔQ_{mean} increasing from -27.4% (S4) to 20.2% (A4).

Similarly, projected changes to hydropeaking operation could also increase streamflow levels at FPS (S4 ΔQ_{mean} = -23.5%, A4 ΔQ_{mean} = -14.0%) and FST (S4 ΔQ_{mean} = -31.5%, A4 ΔQ_{mean} = -19.1%). The differences between S4 and A4 streamflow time series at FNP, FPS and FST were found to be statistically significant (p-value < 0.05) with Wilcoxon signed-rank tests (Table 5.5).

More importantly, modifications of hydropeaking operation improved dry season flows of the Mekong River at all three stations, with the largest improvement projected at FST (S4 ΔQ_{dry} = -15.5%, A4 ΔQ_{dry} = -4%). While changes in streamflow of the Mekong River under S4 remain lower than the baseline (S1), the results of this study illustrate the importance of best management and operational practices to minimize impacts from hydroelectricity generation.

Table 5.5: Comparison of changes in streamflow and instream TSS and nitrate loads of the Mekong River under different scenarios and operational conditions (* denotes that the change resulting from operational modification is statistically significant at 0.05 level with a Wilcoxon signed-rank test)

Gauging Locations	Indicators of Change	Normal operation			Alternative operation			Wilcoxon signed-rank test		
		S2 (TB)	S3 (MS)	S4 (MS+TB)	A2 (TB)	A3 (MS)	A4 (MS+TB)	Z-score (S2:A2)	Z-score (S3:A3)	Z-score (S4:A4)
FNP	ΔQ_{mean}	-15.2	-10.9	-27.4	-9.9	-8.1	-18.2	1.311*	0.262	1.530*
	ΔQ_{dry}	3.4	1.1	-10.8	6.8	1.9	-4.2	-	-	-
	ΔQ_{95}	6.2	3.0	-6.4	10.1	3.9	-1.1	-	-	-
	ΔL_{TSS}	-59.1	-48.5	-64.6	-56.8	-45.1	-62.1	-	-	-
	ΔL_{NO3}	-4.5	-10.1	-12.2	-4.1	-9.7	-11.8	-	-	-
FPS	ΔQ_{mean}	-10.8	-17.4	-23.5	-7.7	-5.2	-14.0	0.822	1.720*	1.908*
	ΔQ_{dry}	6.9	2.4	-11.1	8.1	11.7	-2.1	-	-	-
	ΔQ_{95}	9.1	13.2	-7.2	9.6	15.1	-3.0	-	-	-
	ΔL_{TSS}	-50.1	-64.8	-63.9	-51.9	-60.8	-60.1	-	-	-
	ΔL_{NO3}	-16.5	-20.7	-19.9	-16.1	-20.0	-17.2	-	-	-
FST	ΔQ_{mean}	-18.3	-17.0	-31.5	-8.2	-6.7	-19.1	2.39*	2.77*	3.05*
	ΔQ_{dry}	14.6	7.4	-15.5	17.1	14.2	-4.7	-	-	-
	ΔQ_{95}	10.3	7.1	-5.7	14.9	12.0	-1.4	-	-	-
	ΔL_{TSS}	-48.9	-65.0	-78.1	-47.1	-66.1	-72.2	-	-	-
	ΔL_{NO3}	-10.5	-11.3	-12.3	-9.8	-10.7	-11.9	-	-	-

5.5 Discussion

With the adoption of the UN SDG7 (ensure affordable and clean energy) in early 2016, electricity generation using renewable resources has increased popularity (Foley and Olabi, 2017; Sharvini et al., 2018). Chief among the renewable energy sources is hydropower owning to its reliability, efficiency and low maintenance cost (de Oliveira Serrão et al., 2021). In developing regions such as the LMB where countries are committed to sustainable economic growth and reduction in poverty, hydropower development has increasingly become an integral part of energy security (Section 5.3.1.1). However, development of hydropower in transboundary river basins such as the LMB is controversial due to its known adverse environmental and social impacts, and competing water users (Section 5.2). Under this context, there has been increased attention on the sustainability of hydropower development and operation in the LMB, particularly under uncertain future climate variability (Intralawan et al., 2019; Trung et al., 2020; Yoshida et al., 2020; Atkinson, 2021).

Four plausible future hydropower operational scenarios —that includes a total of 68 planned projects— and their projected impact on streamflow and instream TSS and nitrate loads of the Mekong River were examined and contrasted in the previous section. To further explore additional impacts that may arise from increased climatic extremes, each scenario was subjected to a simulation of extreme wettest and driest conditions, derived from historical records across the basin from 1985 to 2015. The effects of modifying hydropeaking operation on the Mekong River flow and instream TSS and nitrate loads were also assessed to illustrate the importance of management practices for sustainable hydropower operation.

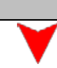
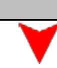
Hereafter we compare our findings with prior research in the area and discuss the implications of these four scenarios in the context of sustainable development of the LMB.

5.5.1 Impact of hydropower operations: comparison to other studies

5.5.1.1 Impacts on streamflow of the Mekong River

Compared to past studies with similar approaches (Table 5.6), the results of our study show similar consequences from hydropower operation. Specifically, our study predicted reduction in mean annual flow at all three Mekong mainstream gauging stations (FNP, FPS, and FST), with the scenario that involves the operation of all 57 tributary and 11 mainstream projects (S4) showing the greatest reduction. This is consistent with results from Trung et al. (2020) who also predicted reduction in mean annual flows at all six locations along the Mekong River under a scenario narrative of combined tributary and mainstream hydropower operation. However, unlike Trung et al. (2020)'s results —where largest changes in streamflow are predicted during dry season for both mainstream hydropower scenario and mainstream plus tributary hydropower scenario—our study reveals the largest changes in streamflow levels are likely to occur during the wet season, when water from the Mekong and its tributaries is held back for reservoir filling. At these full supply levels, approximately 45 million m^3 of water would be retained by the 68 mainstream and tributaries projects (Table 5.1). In contrast, the results of our S2 (tributary hydropower only) and S3 (mainstream hydropower only) modelling shows mean dry season flows to increase slightly during average years. For example, changes in streamflow under S3 are predicted to range from 1.1 to 7.4% with hydropower operational release during the dry season (Section 5.4.2).

Table 5.6: Comparison of changes between this study and other studies in the LMB. Flow decrease (red arrow); Increase (green arrow).

Study	**Scenarios**	**Change from baseline**	
		Dry season flow	**Wet season flow**
	Mainstream projects		

Trung et al. (2020)	Mainstream and tributary projects	▼	▼
	Mainstream project and inter-basin diversion of up to 450 m3/s	▼	▼
Hoang et al. (2019)	Future climate scenario (2036-2065)	▲	▲
	Mainstream and tributary hydropower operational scenario	▲	▼
	Irrigation scenario	▼	▼
Piman et al. (2013)	2010-2030 tributary and mainstream hydropower operation scenario	▲	▼
	2010-2030 tributary hydropower operation scenario	▲	▼
Hoanh et al. (2010)	81 LMB hydropower projects including 11 mainstream ones.	▲	▼
This study	S2: 2016-2050 tributaries scenario	▲	▼
	S3: 2016-2050 mainstream scenario	▲	▼
	S4: 2016-2050 tributary and mainstream scenario	▼	▼

Table 5.6 synthesises the findings from a number of studies involving the modelling of various combinations of hydropower operation in the LMB. These include the study carried out by Hoanh et al. (2010) who investigated cumulative impacts of 81 LMB hydropower projects including 11 mainstream ones. Their modelling results revealed that wet season flows would decrease 8-17% while dry season flows would increase 30-60% from tributary hydropower operation compared to the baseline.

In another basin-wide modelling study, Piman et al. (2013) predicted dry season flows increase by 28% with wet season flow decrease by 9%. Similarly, Hoang et al. (2019) investigated future flows of the Mekong River under multiple drivers and found seasonal flows could be strongly affected by hydropower operation. Specifically, the results of their study revealed an increase of future dry season flow of up to 70%, while future wet season flow is predicted to decrease by as much as -15%.

In summary, changes in wet and dry season streamflow patterns of the Mekong River predicted by these three studies are consistent with the projections of our study, and further confirm the added benefits of hydropower operation as flood and drought management option.

5.5.1.2 Impacts on instream TSS and nitrate loads of the Mekong River

In relation to impacts on TSS, the results show patterns and magnitude of reduction similar to those reported by prior studies. For example, Trung et al. (2020) predicted that the operations of 11 mainstream hydropower could reduce instream sediment and nitrogen levels of the Mekong Delta by more than 55%. Likewise, Kummu et al. (2010) predicted sediment loads reduction in the Mekong Delta from 51-60% if all 11 planned mainstream hydropower projects are developed. In comparison, our study using eWater's Source Model predicts that about 48-65% of instream TSS loads could be lost in a scenario that considers 11 mainstream hydropower dams (S3), due to the increased number of reservoirs trapping sediments.

Our study further predicts that the reduction level could amount up to 78% under a S4 (11 mainstream and 57 tributary projects). The reduction level predicted by our study is slightly greater than those predicted by Bussi et al., 2021, under a similar S4 scenario of 47-53%. Already the existing hydropower projects including the mainstream Chinese projects have been cited as the main reason for the observed reduction in TSS levels recorded between 1985 to 2015 (Kummu and Varis, 2007; Binh et al., 2020; Ly et al., 2020a; Bussi et al., 2021). Future development of hydropower projects under S3 and S4 scenarios could seriously affect instream transportation of sediment to the Mekong Delta.

With nitrate having been determined to have strong positive correlation with TSS and streamflow (Ly et al., 2020a), reductions in streamflow and TSS levels inevitably would result in the reduction of nitrate levels. While our study predicts reduction patterns of nitrate similar to those forecasted by Trung et al. (2020), the magnitudes of reduction we predict (from -4.5 to -20.7%) are lower than those of Trung et al. (2020) (about -55%). Similar to TSS, hydropower reservoirs are expected to hinder instream transport of nitrate across the river network and therefore reduce instream nitrate loads of the Mekong River. For example, the operation of hydropower in the 3-S sub-basin, a key tributary of the Mekong River, could annually prevent close to 79,000 tonnes of nitrate generated within the basin —or about 30% of the total Mekong nitrate load at FPS (Oeurng et al., 2016)— from reaching the mainstream.

5.5.1.3 Alternative scenarios: climatic extremes

Piman et al. (2013) also examined the add-on consequences of climate variability when investigating basin-wide impacts of hydropower operation. Specifically, they predicted a decrease of annually river flooded area by 5% during dry years due to additional reduced streamflow caused by less rainfall, whereas in the wet years annual river flooded area was predicted to decreased by only 0.4% due smaller reduction of streamflow caused by more rainfall.

When examining the effects of climate change on flow of the Mekong River, Hoang et al. (2019) concluded that increase in mean annual rainfall could increase dry season flows from 15 to 20%. These results are similar to the results of our scenarios under extreme wettest and driest climatic conditions, where decreased rainfall under extreme driest condition (Table 5.4) is predicted to further reduce flows of the Mekong River while increase rainfall under extreme wettest condition could improve dry season flows. However, our study shows that these improvements may not be able to offset induced decreases derived from the larger hydropower (Section 5.4.2).

Prior studies have concluded that changes in river flow induced by climate change are comparatively lower than changes induced by hydropower operation (Ngo et al., 2018; Hoang et al., 2019; Yun et al., 2020).

This study is the first to examine whether increased dry season streamflow induced by climate change could help offset the much larger and cumulative hydropower induced streamflow decreases in the LMB.

5.5.1.4 Alternative scenario: operational alternatives

Operational alternative of the planned hydropower projects with installed capacity of 100 MW or greater were examined through the modification of their hydropeaking periods. The latter is a common hydropower operation practice for meeting energy demands.

Of the 68 planned future hydropower projects, 28 have installed capacity of 100 MW or greater including all 11 mainstream projects (Table 5.1). Once realised, these projects could withhold a combined 26.5 million m^3 for reservoir live storage, with the average designed discharge of about 7,000 m^3/s that would affect downstream flow regimes as well as instream water quality dynamics. Our modelling results suggest that modification of hydropeaking operation could help increase dry season flows of the Mekong River significantly, for all three plausible future hydropower development scenarios (Table 5.5 and Section 5.4.5). These results are consistent with findings from Trung et al. (2020) which revealed lower impacts from hydropower operation on both the mainstream and tributaries.

Although documented effects of hydropeaking include disruption to natural river flows and health of the river (Bejarano et al., 2018; Mihalicz et al., 2019; Boavida et al., 2020; Elgueta et al., 2021), measures such as modifying hydropower operations have been found to successfully mitigate hydropeaking impacts (Premstaller et al., 2017; Tonolla et al., 2017; Moreira et al., 2019). In scenarios where hydropower development appears to be unavoidable (Section 5.2 and Section 5.3.3), well-designed operational options such as hydropeaking modification could offer pathways for management alternatives that accounts for future climate variability, electricity demands and downstream water requirements.

5.5.2 Ecological and food security implications

Studies of socio-ecological impacts of existing hydropower operations in the LMB have been summarised in detailed by Hecht et al. (2019) including evidences which suggest that changes in natural flood pulse dynamics have altered the river fish assemblage and diminished its wild freshwater fisheries (Pittock, 2019). These effects are expected to exacerbate with the add-on effects of operating the planned hydropower projects included in the scenarios developed for this study. Our results suggest that while approximately 90,000 GWh of additional electricity could be generated annually, on average, from the operation of the 68 planned hydropower project (Table 5.1), collectively these projects could reduce mean annual flows of the Mekong River by -23.5 to -31.5%, and dry season flows by -10.8 to -15.5%, relative to the baseline condition (Table 5.4 and Section 5.4.2).

Our findings are of concern in light of Intralawan et al. (2018) study that analysed trade-offs between electricity generation and ecosystem services, postulating that planned hydropower projects will not only change further the river's flow regime , but they will also alter fish habitat and migration passage (Figure 5.2c) resulting in an annual loss of 725,000 tons of capture fisheries(Figure 5.2a). Further, the loss of river connectivity from these hydropower operations is projected to have great ecological implication to migratory freshwater fish of the Mekong River, with Ziv et al. (2012) forecasting a net change of -51.3% of migratory fish biomass.

Additional evidence of potential impacts to fish populations are contained on Ngor et al. (2018) study of 7-year daily fish monitoring, that correlates decreasing trends in local fish species diversity and abundance to flow alteration caused by hydropower operation. Surveys of local people also evidence that flow alteration from existing hydropower operation have changed the river ecosystem resulting in resource shortages and livelihood changes (Uthai, 2018).

While extreme climatic events are not annual occurrence, studies have projected increasing frequencies due to climate change (Thilakarathne and Sridhar, 2017; Zhang and Liu, 2020). Under uncertain climate variability, the effects of hydropower operation on dry season flow could be exacerbated during periods with lesser rainfall. In this study, we illustrate the likely severity of hydropower operation under extreme driest conditions, where dry season flows of the Mekong River are predicted to change by -34.7 to -43.8% due to rainfall decrease (-24.0 to -58.1%). The reduction projected for dry season flows can be detrimental for downstream riverine ecosystems and water use for human consumption, as the flow quantity available during this period may insufficient to balance downstream competing interests of maintaining ecosystem integrity (Intralawan et al., 2018; Wild et al., 2019) and food security (Sabo et al., 2017; Chen et al., 2020; Soukhaphon et al., 2021).

5.5.3 Toward sustainable hydropower development

Hydropower is rapidly becoming part of core energy security strategies of the LMB countries to support continuous economic development, poverty reduction, and electricity coverage (Section 3.3). With more than 70 projects already in operation, environmental externalities and social impacts of these plants have been well-documented (Kummu and Varis, 2007; Arias et al., 2012; Räsänen et al., 2017); and the development of new hydropower poses great challenges for sustainable development of the LMB, with intense debates and growing concerns over the long-term and irreversible environmental and social impacts (Fan et al., 2015; Pokhrel et al., 2018; Hecht et al., 2019).

Despite these growing concerns, for most of the LMB countries hydropower development remains fixture as an obvious and only solution to the region energy requirements (Olson and Gareau, 2018). Therefore, development of all planned hydropower projects in the basin is likely unavoidable. As the narrative on hydropower development in the LMB becomes more centred on costs and benefits, and trade-offs (Ziv et al., 2012; Intralawan et al., 2019; Wild et al., 2019), focus should be shifted to sustainable hydropower development that promotes economic development and protects the environment and social values (Tang et al., 2018). While the concept of sustainable hydropower development has been applied with certain degree of success (Sparkes, 2014; Bhagabati et al., 2017), common attributes of failures have been the lack of institutional enforcement and policies that recognize environmental values and social rights beyond national boundaries (Moran et al., 2018; Williams, 2019).

As LMB countries continue to embark on the development of both mainstream and tributary hydropower, basin-wide integrated management and cooperative approaches for sustainable hydropower development are needed to provide transparency on transboundary socio-ecological impacts of individual hydropower development, regardless of location. Past experiences of early engagement and high levels of basin-wide cooperation have evidenced greater basin-wide net benefits, in addition to the benefits realized by individual countries (Bhagabati et al., 2017; Xu et al., 2020). This is because countries can jointly identify cross-boundary impacts of development on the ecological, food and water security, and livelihood interests of the downstream countries (Bao et al., 2017).

With early impact identification, appropriate optimization measures can be explored and incorporated into project operational rules to balance electricity generation and downstream environmental and social interests (Yüksel, 2010; Liu et al., 2013; Singh et al., 2020). Depending on the downstream conservation objectives, one such optimization measure can include modification of hydropeaking operations as illustrated by this study, where changes in mean annual flow and dry season flow in relative to baseline condition were reduced (Section 4.6).

5.6 Conclusions

The LMB countries have increasingly embarked on development paths of freshwater systems exploitation for electricity generation. While hydropower operation for electricity generation is considered as clean energy, their operations have also evidenced irreversible environmental and social impacts. In a transboundary river basin such as the Mekong River Basin, where 68 hydropower are planned across the basin, their individual and cumulative cross-border impacts could outweigh the benefits provided, resulting in water resource degradation and water diplomacy conflicts.

Using exploratory scenarios, we developed four future hydropower development scenarios for the LMB. Among them, the business-as-usual scenario represents a baseline scenario (S1) where no additional hydropower development would be allowed. The other three plausible future scenarios represent pathways for the development of either projects located on the tributary (S2), mainstream (S3), or both (S4).

The cumulative effects of each development scenario on streamflow and instream TSS and nitrate loads of the Mekong River were predicted using an integrated watershed model (*LMB-Sources*). The results of the modelling suggest that exclusive development of either tributary (S2) or mainstream (S3) could result in the reduction of mean annual and wet season flow, but increase dry season flow which is beneficial for flood/drought management and dry season irrigation. However, electricity generation pathway of developing both tributary and mainstream projects (S4) could result in a reduction of dry season streamflow in relation to the baseline scenario (S1). The results further revealed that increased rainfall (under an alternative scenario of wettest conditions) could improve dry season flow project for S4. However, it was predicted that the improvement would not offset the cumulative impacts of S4 development pathway. Both instream TSS and nitrate loads were also predicted to decrease with all three scenarios in relation to the baseline (S1).

Modelling undertaken suggests that improvement of dry season flow could be realised by modifying hydropeaking operations of large-scale tributary and mainstream projects. The positive outcomes on dry season flow improvement from modifying operational period of electricity generation illustrate the importance of operational alternatives as management and mitigation options for sustainable hydropower development. However, the modifications of hydropeaking operations modelled showed to have little impact on instream TSS and nitrate loads, indicating different operational optimization may be required for enhanced downstream sediment and nitrate management strategies.

Overall, the results of hydropower operational modification from this study provide an insight into the importance of basin-wide integrated management and cooperation approaches for sustainable hydropower development. For the LMB where hydropower development and operation appear to be unavoidable, concerted decisions on operational alternatives facilitate effective transboundary cooperation and management pathways for balancing electricity generation and downstream protection of riverine ecology, water and food security, and people livelihoods.

5.7 References

ADB 2018. Cambodia: Energy sector assessment, strategy, and road map. Mandaluyong City, Philippines: Asian Development Bank.

ADB 2019. Lao People's Democratic Republic Engergy Sector Assessment, Strategy, and Road Map. *Country Sector and Thematic Assessments.* The Asian Development Bank.

AGARWAL, A., DELOS ANGELES, M. S., BHATIA, R., CHÉRET, I., DAVILA-POBLETE, S., FALKENMARK, M., VILLARREAL, F. G., JØNCH-CLAUSEN, T., KADI, M. A. & KINDLER, J. 2000. *Integrated water resources management*, Global water partnership.

ALLEN, C., METTERNICHT, G. & WIEDMANN, T. 2019. Prioritising SDG targets: assessing baselines, gaps and interlinkages. *Sustainability Science,* 14**,** 421-438.

ARIAS, M. E., COCHRANE, T. A., PIMAN, T., KUMMU, M., CARUSO, B. S. & KILLEEN, T. J. 2012. Quantifying changes in flooding and habitats in the Tonle Sap Lake (Cambodia) caused by water infrastructure development and climate change in the Mekong Basin. *Journal of Environmental Management,* 112**,** 53-66.

ATKINSON, C. L. 2021. Hydropower, development, and poverty reduction in Laos: promises realized or broken? *Asian Journal of Political Science,* 29**,** 67-87.

AUNG, T. S., FISCHER, T. B. & AZMI, A. S. 2020. Are large-scale dams environmentally detrimental? Life-cycle environmental consequences of mega-hydropower plants in Myanmar. *The International Journal of Life Cycle Assessment,* 25**,** 1749-1766.

BADIGER, S., GOPALAKRISHNAN, S. & PATIL, I. 2018. Contextualizing Rural–Urban Water Conflicts: Bio-Physical and Socio-Institutional Issues of Domestic Water Scarcity. *Globalization of Water Governance in South Asia.* Routledge India.

BAO, P. N., MITRA, B. K. & KUYAMA, T. 2017. Integrated approach for sustainable hydropower development in the Mekong River basin. *Environment and Natural Resources Research.,* 7**,** 60-75.

BARAN, E. 2006. *Fish migration triggers in the Lower Mekong Basin and other freshwater tropical systems. Technical paper # 14. Mekong River Commission. 2006*.

BARROS, M. T. L., TSAI, F. T.-C., YANG, S.-L., LOPES, J. E. G. & YEH, W. W.-G. 2003. Optimization of Large-Scale Hydropower System Operations. *Journal of Water Resources Planning and Management,* 129**,** 178-188.

BEJARANO, M. D., JANSSON, R. & NILSSON, C. 2018. The effects of hydropeaking on riverine plants: a review. *Biological Reviews,* 93**,** 658-673.

BHAGABATI, S. S., KAWASAKI, A. & BABEL, M. S. 2017. A cooperative framework for optimizing transboundary hydropower development. *Water International,* 42**,** 945-966.

BINH, D. V., KANTOUSH, S. & SUMI, T. 2020. Changes to long-term discharge and sediment loads in the Vietnamese Mekong Delta caused by upstream dams. *Geomorphology,* 353**,** 107011.

BOAVIDA, I., CAETANO, L. & PINHEIRO, A. N. 2020. E-flows to reduce the hydropeaking impacts on the Iberian barbel (Luciobarbus bocagei) habitat. An effectiveness assessment based on the COSH Tool application. *Science of The Total Environment,* 699**,** 134209.

BOTELHO, A., FERREIRA, P., LIMA, F., PINTO, L. M. C. & SOUSA, S. 2017. Assessment of the environmental impacts associated with hydropower. *Renewable and Sustainable Energy Reviews,* 70**,** 896-904.

BRANCHE, E. 2017. The multipurpose water uses of hydropower reservoir: The SHARE concept. *Comptes Rendus Physique,* 18**,** 469-478.

BUSSI, G., DARBY, S. E., WHITEHEAD, P. G., JIN, L., DADSON, S. J., VOEPEL, H. E., VASILOPOULOS, G., HACKNEY, C. R., HUTTON, C., BERCHOUX, T., PARSONS, D. R. & NICHOLAS, A. 2021. Impact of dams and climate change on suspended sediment flux to the Mekong delta. *Science of The Total Environment,* 755**,** 142468.

CAMPBELL, I. C. 2016. Integrated management in the Mekong River Basin. *Ecohydrology & Hydrobiology,* 16**,** 255-262.

CETRULO, T. B., MARQUES, R. C., MALHEIROS, T. F. & CETRULO, N. M. 2020. Monitoring inequality in water access: Challenges for the 2030 Agenda for Sustainable Development. *Science of The Total Environment,* 727**,** 138746.

CHAN, B., BROSSE, S., HOGAN, Z. S., NGOR, P. B. & LEK, S. 2020. Influence of Local Habitat and Climatic Factors on the Distribution of Fish Species in the Tonle Sap Lake. *Water,* 12**,** 786.

CHATTRANOND, O. Battery of Asia? The Rise of Regulatory Regionalism and Transboundary Hydropower Development in Laos. 2018.

CHEN, G., FANG, X. & DEVKOTA, J. 2016. Understanding flow dynamics and density currents in a river-reservoir system under upstream reservoir releases. *Hydrological Sciences Journal,* 61**,** 2411-2426.

CHEN, X., ZHENG, Y., XU, B., WANG, L., HAN, F. & ZHANG, C. 2020. Balancing competing interests in the Mekong River Basin via the operation of cascade hydropower reservoirs in China: Insights from system modeling. *Journal of Cleaner Production,* 254**,** 119967.

CHRISTIAENSEN, L. & MARTIN, W. 2018. Agriculture, structural transformation and poverty reduction: Eight new insights. *World Development,* 109**,** 413-416.

COSSLETT, T. L. & COSSLETT, P. D. 2018. The Lower Mekong Basin: Rice Production, Climate Change, ENSO, and Mekong Dams. *In:* COSSLETT, T. L. & COSSLETT, P. D. (eds.) *Sustainable Development of Rice and Water Resources in Mainland Southeast Asia and Mekong River Basin.* Singapore: Springer Singapore.

COWIE, A. L., ORR, B. J., CASTILLO SANCHEZ, V. M., CHASEK, P., CROSSMAN, N. D., ERLEWEIN, A., LOUWAGIE, G., MARON, M., METTERNICHT, G. I., MINELLI, S., TENGBERG, A. E., WALTER, S. & WELTON, S. 2018. Land in balance: The scientific conceptual framework for Land Degradation Neutrality. *Environmental Science & Policy,* 79**,** 25-35.

DE OLIVEIRA SERRÃO, E. A., SILVA, M. T., FERREIRA, T. R., DE ATAIDE, L. C. P., WANZELER, R. T. S., DA SILVA, V. D. P. R., DE LIMA, A. M. M. & DE SOUSA, F. D. A. S. 2021. Large-Scale hydrological modelling of flow and hydropower production, in a Brazilian watershed. *Ecohydrology & Hydrobiology,* 21**,** 23-35.

DE STEFANO, L., PETERSEN-PERLMAN, J. D., SPROLES, E. A., EYNARD, J. & WOLF, A. T. 2017. Assessment of transboundary river basins for potential hydro-political tensions. *Global Environmental Change,* 45**,** 35-46.

ELGUETA, A., GÓRSKI, K., THOMS, M., FIERRO, P., TOLEDO, B., MANOSALVA, A. & HABIT, E. 2021. Interplay of geomorphology and hydrology drives macroinvertebrate assemblage responses to hydropeaking. *Science of The Total Environment,* 768**,** 144262.

EWATER LTD. 2018. Source User Guide 4.7. Available: https://wiki.ewater.org.au/display/SD47/Source+User+Guide+4.7 [Accessed 03 November 2018].

FAN, H., HE, D. & WANG, H. 2015. Environmental consequences of damming the mainstream Lancang-Mekong River: A review. *Earth-Science Reviews,* 146**,** 77-91.

FOLEY, A. & OLABI, A. G. 2017. Renewable energy technology developments, trends and policy implications that can underpin the drive for global climate change. *Renewable and Sustainable Energy Reviews,* 68**,** 1112-1114.

GAIUS-OBASEKI, T. 2010. Hydropower opportunities in the water industry. *International Journal of Environmental Sciences,* 1**,** 392.

GAUSEMEIER, J., FINK, A. & SCHLAKE, O. 1998. Scenario Management: An Approach to Develop Future Potentials. *Technological Forecasting and Social Change,* 59**,** 111-130.

GEHEB, K. & SUHARDIMAN, D. 2019. The political ecology of hydropower in the Mekong River Basin. *Current Opinion in Environmental Sustainability,* 37**,** 8-13.

GORGOGLIONE, A., CRISCI, M., KAYSER, R. H., CHRETIES, C. & COLLISCHONN, W. 2019. A New Scenario-Based Framework for Conflict Resolution in Water Allocation in Transboundary Watersheds. *Water,* 11**,** 1174.

GOVERNMENT OF CAMBODIA 2019. National Strategic Development Plan (2019-2023). Phnom Penh, Cambodia: Ministry of Planning, The Royal Government of Cambodia.

GOVERNMENT OF THAILAND 2017. The 12th National Economic and Social Development Plan (2017 - 2021). *In:* OFFICE OF NATIONAL ECONOMIC AND SOCIAL DEVELOPMENT BOARD, O. O. T. P. M. (ed.). Bangkok, Thailand.

GOVERNMENT OF THE LAO PDR 2011. Renewable energy development strategy in the Lao PDR. Vientiane, Lao PDR.

GOVERNMENT OF THE LAO PDR 2016. 8th Five-Year National Socio-Economic Development Plan (2016-2020). Vientiane, Lao PDR: Ministry of Planning and Investiment.

GOVERNMENT OF VIET NAM 2015. Decision No. 2068/QD-TTg dated 02 November 2015 of the Prime Minister Approving the Viet Nam Renewable Energy Development Strategy to 2030, Outlook Up to 2050. . Ha Noi, Viet Nam.

GOVERNMENT OF VIET NAM 2016. The Five Year Socio-Economic Development Plan (2016-2020). Hanoi, Viet Nam.

GREIMEL, F., SCHÜLTING, L., GRAF, W., BONDAR-KUNZE, E., AUER, S., ZEIRINGER, B. & HAUER, C. 2018. Hydropeaking Impacts and Mitigation. *In:* SCHMUTZ, S. & SENDZIMIR, J. (eds.) *Riverine Ecosystem Management: Science for Governing Towards a Sustainable Future.* Cham: Springer International Publishing.

GULSEVEN, O. 2020. Measuring achievements towards SDG 14, life below water, in the United Arab Emirates. *Marine Policy,* 117**,** 103972.

GUPTA, J. 2011. An essay on global water governance and research challenges. *Principles of good governance at different water governance levels,* 5.

HALLS, A. S. & HORTLE, K. G. 2021. Flooding is a key driver of the Tonle Sap dai fishery in Cambodia. *Scientific Reports,* 11**,** 1-4.

HARRIS, P., RILEY, E., DAWSON, A., FRIEL, S. & LAWSON, K. 2020. "Stop talking around projects and talk about solutions": Positioning health within infrastructure policy to achieve the sustainable development goals. *Health Policy,* 124**,** 591-598.

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. *Journal of Hydrology,* 568**,** 285-300.

HOANG, L. P., VAN VLIET, M. T. H., KUMMU, M., LAURI, H., KOPONEN, J., SUPIT, I., LEEMANS, R., KABAT, P. & LUDWIG, F. 2019. The Mekong's future flows under multiple drivers: How climate change, hydropower developments and irrigation expansions drive hydrological changes. *Science of The Total Environment,* 649**,** 601-609.

HOANH, C. T., JIRAYOOT, K., LACOMBE, G. & SRINETR, V. 2010. Impacts of climate change and development on Mekong flow regimes. First assessment-2009. International Water Management Institute.

IHA 2020. Hydropower status report 2020: Sector trends and insights. Romford, United Kingdom: International Hydropower Association.

INTERNATIONAL HYDROPOWER ASSOCIATION 2020. Laos - the 2016 Hydropower Status Report.

INTRALAWAN, A., SMAJGL, A., MCCONNELL, W., AHLQUIST, D. B., WARD, J. & KRAMER, D. B. 2019. Reviewing benefits and costs of hydropower development evidence from the Lower Mekong River Basin. *WIREs Water,* 6**,** e1347.

INTRALAWAN, A., WOOD, D., FRANKEL, R., COSTANZA, R. & KUBISZEWSKI, I. 2018. Tradeoff analysis between electricity generation and ecosystem services in the Lower Mekong Basin. *Ecosystem Services,* 30**,** 27-35.

IRENA 2017. Renewable energy outlook: Thailand. *In:* AGENCY, I. R. E. (ed.) *Renewable Readiness Assessment and REmap analysis.* Abu Dhabi, United Arab Emirates: Thailand's Ministry of Energy.

IVANIC, M. & MARTIN, W. 2018. Sectoral Productivity Growth and Poverty Reduction: National and Global Impacts. *World Development,* 109**,** 429-439.

KAINI, S., NEPAL, S., PRADHANANGA, S., GARDNER, T. & SHARMA, A. K. 2020. Representative general circulation models selection and downscaling of climate data for the transboundary Koshi river basin in China and Nepal. *International Journal of Climatology,* 40**,** 4131-4149.

KITTIKHOUN, A. & STAUBLI, D. M. 2018. Water diplomacy and conflict management in the Mekong: From rivalries to cooperation. *Journal of Hydrology,* 567**,** 654-667.

KOIRALA, S., HILL, D. & MORGAN, R. 2017. Impacts of the delay in construction of a large scale hydropower project on potential displacees. *Impact Assessment and Project Appraisal,* 35**,** 106-116.

KONDOLF, G. M. & LOPEZ-LLOMPART, P. 2018. National-local land-use conflicts in floodways of the Mississippi River system. *AIMS Environmental Science,* 5**,** 47-63.

KUMMU, M., LU, X. X., WANG, J. J. & VARIS, O. 2010. Basin-wide sediment trapping efficiency of emerging reservoirs along the Mekong. *Geomorphology,* 119**,** 181-197.

KUMMU, M. & SARKKULA, J. 2008. Impact of the Mekong River Flow Alteration on the Tonle Sap Flood Pulse. *AMBIO - A Journal of the Human Environment,* 37**,** 185-192.

KUMMU, M. & VARIS, O. 2007. Sediment-related impacts due to upstream reservoir trapping, the Lower Mekong River. *Geomorphology,* 85**,** 275-293.

LABORDE, A., HABIT, E., LINK, O. & KEMP, P. 2020. Strategic methodology to set priorities for sustainable hydropower development in a biodiversity hotspot. *Science of The Total Environment,* 714**,** 136735.

LACOMBE, G., VALENTIN, C., SOUNYAFONG, P., DE ROUW, A., SOULILEUTH, B., SILVERA, N., PIERRET, A., SENGTAHEUANGHOUNG, O. & RIBOLZI, O. 2018. Linking crop structure, throughfall, soil surface conditions, runoff and soil detachment: 10 land uses analyzed in Northern Laos. *Science of The Total Environment,* 616-617**,** 1330-1338.

LANGE, K., MEIER, P., TRAUTWEIN, C., SCHMID, M., ROBINSON, C. T., WEBER, C. & BRODERSEN, J. 2018. Basin-scale effects of small hydropower on biodiversity dynamics. *Frontiers in Ecology and the Environment,* 16**,** 397-404.

LANZANTE, J. R., DIXON, K. W., NATH, M. J., WHITLOCK, C. E. & ADAMS-SMITH, D. 2018. Some Pitfalls in Statistical Downscaling of Future Climate. *Bulletin of the American Meteorological Society,* 99**,** 791-803.

LE, N. D., LE, T. P. Q., PHUNG, T. X. B., DUONG, T. T. & DIDIER, O. 2020. Impact of hydropower dam on total suspended sediment and total organic nitrogen fluxes of the Red River (Vietnam). *Proc. IAHS,* 383**,** 367-374.

LEKAVIČIUS, V., GALINIS, A. & MIŠKINIS, V. 2019. Long-term economic impacts of energy development scenarios: The role of domestic electricity generation. *Applied Energy,* 253**,** 113527.

LI, D., LONG, D., ZHAO, J., LU, H. & HONG, Y. 2017. Observed changes in flow regimes in the Mekong River basin. *Journal of Hydrology,* 551**,** 217-232.

LIGMANN-ZIELINSKA, A. & JANKOWSKI, P. 2010. Exploring normative scenarios of land use development decisions with an agent-based simulation laboratory. *Computers, Environment and Urban Systems,* 34**,** 409-423.

LIU, B., CHENG, C., WANG, S., LIAO, S., CHAU, K.-W., WU, X. & LI, W. 2018. Parallel chance-constrained dynamic programming for cascade hydropower system operation. *Energy,* 165**,** 752-767.

LIU, J., ZUO, J., SUN, Z., ZILLANTE, G. & CHEN, X. 2013. Sustainability in hydropower development—A case study. *Renewable and Sustainable Energy Reviews,* 19**,** 230-237.

LY, K., METTERNICHT, G. & MARSHALL, L. 2019. Transboundary river catchment areas of developing countries: Potential and limitations of watershed models for the simulation of sediment and nutrient loads. A review. *Journal of Hydrology: Regional Studies,* 24**,** 100605.

LY, K., METTERNICHT, G. & MARSHALL, L. 2020a. Linking Changes in Land Cover and Land Use of the Lower Mekong Basin to Instream Nitrate and Total Suspended Solids Variations. *Sustainability,* 12**,** 2992.

LY, K., METTERNICHT, G. & MARSHALL, L. 2020b. Simulation of streamflow and instream loads of total suspended solids and nitrate in a large transboundary river basin using Source model and geospatial analysis. *Science of The Total Environment*, 140656.

MARTHALER, F., GESK, J. W., SIEBE, A. & ALBERS, A. 2020. An explorative approach to deriving future scenarios: A first comparison of the consistency matrix-based and the catalog-based approach to generating future scenarios. *Procedia CIRP,* 91, 883-892.

MCPHERSON, M. & KARNEY, B. 2014. Long-term scenario alternatives and their implications: LEAP model application of Panama's electricity sector. *Energy Policy,* 68, 146-157.

MEKONG RIVER COMMISSION 1995. Agreement on the Cooperation for the Sustainable Development of the Mekong River Basin. *In:* COMMISSION, T. M. R. (ed.). Vientiane, Lao PDR.

MEKONG RIVER COMMISSION 2009. The flow of the Mekong. *In:* BURNHILL, T. (ed.) *MRC management informantion booklet series.* Vientiane, Lao PDR: MRC Secretariat.

MEKONG RIVER COMMISSION 2016. Basin Development Strategy. Vientiane, Lao PDR: The Mekong River Commission.

MEKONG RIVER COMMISSION 2018. State of the Basin Report 2018. Vientiane, Lao PDR: The Mekong River Commission Secretariat.

METTERNICHT, G. 2018. *Land use and spatial planning: Enabling sustainable management of land resources*, Springer.

METZ, A. & HARTLEY, P. 2020. Scenario development as valuation: Opportunities for reflexivity. *Technological Forecasting and Social Change,* 155, 120027.

MIHALICZ, J. E., JARDINE, T. D., BAULCH, H. M. & PHILLIPS, I. D. 2019. Seasonal effects of a hydropeaking dam on a downstream benthic macroinvertebrate community. *River Research and Applications,* 35**,** 714-724.

MIRJAT, N. H., UQAILI, M. A., HARIJAN, K., WALASAI, G. D., MONDAL, M. A. H. & SAHIN, H. 2018. Long-term electricity demand forecast and supply side scenarios for Pakistan (2015–2050): A LEAP model application for policy analysis. *Energy,* 165**,** 512-526.

MITIC, V., KANKARAS, M., NIKOLIC, D., DIMIC, S. & KOVAC, M. 2020. Rationalization of the scenario development process under conditions involving extensive dynamics. *Futures*.

MOALLEMI, E. A. & MALEKPOUR, S. 2018. A participatory exploratory modelling approach for long-term planning in energy transitions. *Energy Research & Social Science,* 35**,** 205-216.

MOLLE, F., FORAN, T. & KÄKÖNEN, M. 2009. *Contested Waterscapes in the Mekong Region: Hydropower, Livelihoods and Governance*.

MORÁN-TEJEDA, E., ZABALZA, J., RAHMAN, K., GAGO-SILVA, A., LÓPEZ-MORENO, J. I., VICENTE-SERRANO, S., LEHMANN, A., TAGUE, C. L. & BENISTON, M. 2015. Hydrological impacts of climate and land-use changes in a mountain watershed: uncertainty estimation based on model comparison. *Ecohydrology,* 8**,** 1396-1416.

MORAN, E. F., LOPEZ, M. C., MOORE, N., MÜLLER, N. & HYNDMAN, D. W. 2018. Sustainable hydropower in the 21st century. *Proceedings of the National Academy of Sciences,* 115**,** 11891.

MOREIRA, M., HAYES, D. S., BOAVIDA, I., SCHLETTERER, M., SCHMUTZ, S. & PINHEIRO, A. 2019. Ecologically-based criteria for hydropeaking mitigation: A review. *Science of The Total Environment,* 657**,** 1508-1522.

NGO, L. A., MASIH, I., JIANG, Y. & DOUVEN, W. 2018. Impact of reservoir operation and climate change on the hydrological regime of the Sesan and Srepok Rivers in the Lower Mekong Basin. *Climatic Change,* 149**,** 107-119.

NGOR, P. B., LEGENDRE, P., OBERDORFF, T. & LEK, S. 2018. Flow alterations by dams shaped fish assemblage dynamics in the complex Mekong-3S river system. *Ecological Indicators,* 88**,** 103-114.

NGUYEN, C. V. & PHAM, N. M. 2018. Economic growth, inequality, and poverty in Vietnam. *Asian-Pacific Economic Literature,* 32**,** 45-58.

NGUYEN, Q. H., TRAN, D. D., DANG, K. K., KORBEE, D., PHAM, L. D., VU, L. T., LUU, T. T., HO, L. H., NGUYEN, P. T. & T. NGO, T. T. 2020. Land-use dynamics in the Mekong delta: From national policy to livelihood sustainability. *Sustainable Development,* 28**,** 448-467.

NIETO-ROMERO, M., MILCU, A., LEVENTON, J., MIKULCAK, F. & FISCHER, J. 2016. The role of scenarios in fostering collective action for sustainable development: Lessons from central Romania. *Land Use Policy,* 50**,** 156-168.

O'CONNOR, J. E., DUDA, J. J. & GRANT, G. E. 2015. 1000 dams down and counting. *Science,* 348**,** 496-497.

OEURNG, C., COCHRANE, T. A., ARIAS, M. E., SHRESTHA, B. & PIMAN, T. 2016. Assessment of changes in riverine nitrate in the Sesan, Srepok and Sekong tributaries of the Lower Mekong River Basin. *Journal of Hydrology: Regional Studies,* 8**,** 95-111.

OLSON, K. A. & GAREAU, B. J. 2018. Hydro/power? Politics, discourse and neoliberalization in Laos's hydroelectric development. *Sociology of Development,* 4**,** 94-118.

OYEBODE, O., BABATUNDE, D. E., MONYEI, C. G. & BABATUNDE, O. M. 2019. Water demand modelling using evolutionary computation techniques:

integrating water equity and justice for realization of the sustainable development goals. *Heliyon,* 5**,** e02796.

PÁEZ, A. M. & VALLEJO PIEDRAHÍTA, C. 2021. Channeling Water Conflicts through the Legislative Branch in Colombia. *Water,* 13**,** 1214.

PARMESAN, C., ROOT, T. L. & WILLIG, M. R. 2000. Impacts of Extreme Weather and Climate on Terrestrial Biota. *Bulletin of the American Meteorological Society,* 81**,** 443-450.

PIMAN, T., COCHRANE, T. A., ARIAS, M. E., DAT, N. D. & VONNARART, O. 2015. Managing Hydropower Under Climate Change in the Mekong Tributaries. *In:* SHRESTHA, S., ANAL, A. K., SALAM, P. A. & VAN DER VALK, M. (eds.) *Managing Water Resources under Climate Uncertainty: Examples from Asia, Europe, Latin America, and Australia.* Cham: Springer International Publishing.

PIMAN, T., LENNAERTS, T. & SOUTHALACK, P. 2013. Assessment of hydrological changes in the lower Mekong Basin from Basin-Wide development scenarios. *Hydrological Processes,* 27**,** 2115-2125.

PITTOCK, J. 2019. Trade-Offs Between Hydropower Development and Food Security in River Management. *In:* JAMES, H. (ed.) *Population, Development, and the Environment: Challenges to Achieving the Sustainable Development Goals in the Asia Pacific.* Singapore: Springer Singapore.

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.

PRADHAN, P. 2019. Antagonists to meeting the 2030 Agenda. *Nature Sustainability,* 2**,** 171-172.

PREMSTALLER, G., CAVEDON, V., PISATURO, G. R., SCHWEIZER, S., ADAMI, V. & RIGHETTI, M. 2017. Hydropeaking mitigation project on a multi-purpose hydro-scheme on Valsura River in South Tyrol/Italy. *Science of The Total Environment,* 574**,** 642-653.

RÄSÄNEN, T. A., SOMETH, P., LAURI, H., KOPONEN, J., SARKKULA, J. & KUMMU, M. 2017. Observed river discharge changes due to hydropower operations in the Upper Mekong Basin. *Journal of Hydrology,* 545**,** 28-41.

RIBOLZI, O., EVRARD, O., HUON, S., DE ROUW, A., SILVERA, N., LATSACHACK, K. O., SOULILEUTH, B., LEFÈVRE, I., PIERRET, A., LACOMBE, G., SENGTAHEUANGHOUNG, O. & VALENTIN, C. 2017. From shifting cultivation to teak plantation: effect on overland flow and sediment yield in a montane tropical catchment. *Scientific Reports,* 7**,** 3987.

ROSSEL, V. & DE LA FUENTE, A. 2015. Assessing the link between environmental flow, hydropeaking operation and water quality of reservoirs. *Ecological Engineering,* 85**,** 26-38.

ROUNSEVELL, M. D. A. & METZGER, M. J. 2010. Developing qualitative scenario storylines for environmental change assessment. *WIREs Climate Change,* 1**,** 606-619.

SABO, J. L., RUHI, A., HOLTGRIEVE, G. W., ELLIOTT, V., ARIAS, M. E., NGOR, P. B., RÄSÄNEN, T. A. & NAM, S. 2017. Designing river flows to improve food security futures in the Lower Mekong Basin. *Science,* 358**,** eaao1053.

SAM, T. T., KHOI, D. N., THAO, N. T. T., NHI, P. T. T., QUAN, N. T., HOAN, N. X. & NGUYEN, V. T. 2019. Impact of climate change on meteorological, hydrological and agricultural droughts in the Lower Mekong River Basin: a case study of the Srepok Basin, Vietnam. *Water and Environment Journal,* 33**,** 547-559.

SHARVINI, S. R., NOOR, Z. Z., CHONG, C. S., STRINGER, L. C. & YUSUF, R. O. 2018. Energy consumption trends and their linkages with renewable energy policies in East and Southeast Asian countries: Challenges and opportunities. *Sustainable Environment Research,* 28**,** 257-266.

SHRESTHA, S., BACH, T. V. & PANDEY, V. P. 2016. Climate change impacts on groundwater resources in Mekong Delta under representative concentration pathways (RCPs) scenarios. *Environmental Science & Policy,* 61**,** 1-13.

SILVA, J. D., FERNANDES, V., LIMONT, M., DZIEDZIC, M., ANDREOLI, C. V. & RAUEN, W. B. 2020. Water sustainability assessment from the perspective of sustainable development capitals: Conceptual model and index based on literature review. *Journal of Environmental Management,* 254**,** 109750.

SINGH, D. 2009. Resource assessment handbook. *Asian and Pacific Centre for Transfer of Technology of the United Nations, Economic and Social Commission for Asia and the Pacific (ESCAP): New Delhi, India***,** 16-34.

SINGH, P., SINGH, S., VARDHAN, S. & PATNAIK, A. 2020. Sustainability of maintenance management practices in hydropower plant: A conceptual framework. *Materials Today: Proceedings,* 28**,** 1569-1574.

SORACHAMPA, P., TIPPAYAWONG, N. & NGAMSANROAJ, K. 2020. Optimizing multiple reservoir system operation for maximum hydroelectric power generation. *Energy Reports,* 6**,** 67-75.

SOUKHAPHON, A., BAIRD, I. G. & HOGAN, Z. S. 2021. The Impacts of Hydropower Dams in the Mekong River Basin: A Review. *Water,* 13**,** 265.

SOVACOOL, B. & WALTER, G. 2017. Major hydropower states, sustainable development, and energy security: Insights from a preliminary cross-comparative assessment. *Energy,* 142.

SPARKES, S. 2014. Sustainable hydropower development: Theun-Hinboun expansion project case study, Laos. *Water Resources and Rural Development,* 4**,** 54-66.

STOTT, P. 2016. How climate change affects extreme weather events. *Science,* 352**,** 1517.

STRATON, A. T., JACKSON, S., MARINONI, O., PROCTOR, W. & WOODWARD, E. 2011. Exploring and Evaluating Scenarios for a River Catchment in Northern Australia Using Scenario Development, Multi-criteria Analysis and a

Deliberative Process as a Tool for Water Planning. *Water Resources Management,* 25**,** 141-164.

SUHARDIMAN, D., WICHELNS, D., LEBEL, L. & SELLAMUTTU, S. S. 2014. Benefit sharing in Mekong Region hydropower: Whose benefits count? *Water Resources and Rural Development,* 4**,** 3-11.

SUKHWANI, V., THAPA, K., SHAW, R., DESHKAR, S., MITRA, B. K. & YAN, W. 2020. Addressing Urban–Rural Water Conflicts in Nagpur through Benefit Sharing. *Water,* 12**,** 2979.

SUN, H., HE, D., SUI, X. & CHEN, Y. 2020. Predicting impacts of future climate change and hydropower development towards habitats of native and non-native fishes. *Science of The Total Environment,* 707**,** 135419.

SWETNAM, R. D., FISHER, B., MBILINYI, B. P., MUNISHI, P. K. T., WILLCOCK, S., RICKETTS, T., MWAKALILA, S., BALMFORD, A., BURGESS, N. D., MARSHALL, A. R. & LEWIS, S. L. 2011. Mapping socio-economic scenarios of land cover change: A GIS method to enable ecosystem service modelling. *Journal of Environmental Management,* 92**,** 563-574.

TANG, W., LI, Z. & TU, Y. 2018. Sustainability Risk Evaluation for Large-Scale Hydropower Projects with Hybrid Uncertainty. *Sustainability,* 10**,** 138.

THILAKARATHNE, M. & SRIDHAR, V. 2017. Characterization of future drought conditions in the Lower Mekong River Basin. *Weather and Climate Extremes,* 17**,** 47-58.

THOMPSON, J. R., GREEN, A. J., KINGSTON, D. G. & GOSLING, S. N. 2013. Assessment of uncertainty in river flow projections for the Mekong River using multiple GCMs and hydrological models. *Journal of Hydrology,* 486**,** 1-30.

TILT, B., BRAUN, Y. & HE, D. 2009. Social impacts of large dam projects: A comparison of international case studies and implications for best practice. *Journal of Environmental Management,* 90**,** S249-S257.

TONOLLA, D., BRUDER, A. & SCHWEIZER, S. 2017. Evaluation of mitigation measures to reduce hydropeaking impacts on river ecosystems – a case study from the Swiss Alps. *Science of The Total Environment,* 574**,** 594-604.

TRAN, T. A. & SUHARDIMAN, D. 2020. Laos' hydropower development and cross-border power trade in the Lower Mekong Basin: A discourse analysis. *Asia Pacific Viewpoint,* 61**,** 219-235.

TRUNG, L. D., DUC, N. A., NGUYEN, L. T., THAI, T. H., KHAN, A., RAUTENSTRAUCH, K. & SCHMIDT, C. 2020. Assessing cumulative impacts of the proposed Lower Mekong Basin hydropower cascade on the Mekong River floodplains and Delta – Overview of integrated modeling methods and results. *Journal of Hydrology,* 581**,** 122511.

UMMENHOFER, C. C. & MEEHL, G. A. 2017. Extreme weather and climate events with ecological relevance: a review. *Philosophical Transactions of the Royal Society B: Biological Sciences,* 372**,** 20160135.

UNESCAP 2021. Country SDG Profiles. Bangkok, Thailand: UNESCAP.

UNITED NATIONS 2018. Sustainable Development Goals. *In:* AFFAIRS, D. O. E. A. S. (ed.).

UTHAI, S. 2018. Hydropower Dams on the Mekong River: Changes in Food Security and Chiang Khong Women's Adaptation. *Journal of Mekong Societies,* 14**,** 125-147.

VAN CLEEF, A. 2016. Hydropower development and involuntary displacement: Toward a global solution. *Ind. J. Global Legal Stud.,* 23**,** 349.

VÄSTILÄ, K., KUMMU, M., SANGMANEE, C. & CHINVANNO, S. 2010. Modelling climate change impacts on the flood pulse in the Lower Mekong floodplains. *Journal of Water and Climate Change,* 1**,** 67-86.

VERICAT, D., VILLE, F., PALAU-IBARS, A. & BATALLA, R. J. 2020. Effects of Hydropeaking on Bed Mobility: Evidence from a Pyrenean River. *Water,* 12**,** 178.

WHEELER, K. G., ROBINSON, C. J. & BARK, R. H. 2018. Modelling to bridge many boundaries: the Colorado and Murray-Darling River basins. *Regional Environmental Change,* 18**,** 1607-1619.

WILD, T. B., REED, P. M., LOUCKS, D. P., MALLEN-COOPER, M. & JENSEN, E. D. 2019. Balancing Hydropower Development and Ecological Impacts in the Mekong: Tradeoffs for Sambor Mega Dam. *Journal of Water Resources Planning and Management,* 145**,** 05018019.

WILLIAMS, J. M. 2019. The hydropower myth. *Environmental Science and Pollution Research*.

WOOLSON, R. 2007. Wilcoxon signed-rank test. *Wiley encyclopedia of clinical trials***,** 1-3.

WORLD BANK GROUP 2015. World Bank Open Data.

XU, C., XU, Z. & YANG, Z. 2020. Reservoir operation optimization for balancing hydropower generation and biodiversity conservation in a downstream wetland. *Journal of Cleaner Production,* 245**,** 118885.

YEOPHANTONG, P. 2014. China’s Lancang Dam Cascade and Transnational Activism in the Mekong Region: Who’s Got the Power? *Asian Survey,* 54**,** 700-724.

YOSHIDA, Y., LEE, H. S., TRUNG, B. H., TRAN, H.-D., LALL, M. K., KAKAR, K. & XUAN, T. D. 2020. Impacts of Mainstream Hydropower Dams on Fisheries and Agriculture in Lower Mekong Basin. *Sustainability,* 12**,** 2408.

YU, Y., ZHAO, J., LI, D. & WANG, Z. 2019. Effects of Hydrologic Conditions and Reservoir Operation on Transboundary Cooperation in the Lancang–Mekong River Basin. *Journal of Water Resources Planning and Management,* 145**,** 04019020.

YÜKSEL, I. 2010. Hydropower for sustainable water and energy development. *Renewable and Sustainable Energy Reviews,* 14**,** 462-469.

YUN, X., TANG, Q., WANG, J., LIU, X., ZHANG, Y., LU, H., WANG, Y., ZHANG, L. & CHEN, D. 2020. Impacts of climate change and reservoir operation on streamflow and flood characteristics in the Lancang-Mekong River Basin. *Journal of Hydrology,* 590**,** 125472.

ZHANG, L., PANG, M., WANG, C. & ULGIATI, S. 2016. Environmental sustainability of small hydropower schemes in Tibet: An emergy-based comparative analysis. *Journal of Cleaner Production,* 135**,** 97-104.

ZHANG, X. & LIU, H. 2020. Analysis of drought character in the Mekong River Basin. *Flood Prevention and Drought Relief in Mekong River Basin.* Springer.

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. *Proceedings of the National Academy of Sciences,* 109**,** 5609-5614.

Appendix 5: Chapter 5's Supplementary Information (SI)

Appendix 5.A: Existing hydropower projects in the LMB as of 2015

Table A.1: Existing hydropower project in the LMB as of 2015

Specifications	Unit	FNP		FPS		FST	
		TB	MS	TB	MS	TB	MS
No. of Project	No.	33	0	7	0	28	0
Average designed discharge	m3/s	250.7	-	243.3	-	252.1	-
Average full supply level (FSL)	mamsl	509.5	-	272.4	-	426.5	-
Average minimum storage level (MSL)	mamsl	494.4	-	263.3	-	414.2	-
Total installed capacity	MW	5415.2	-	249.7	-	4939.5	-
Total mean annual energy	GWh	25438.1	-	555.5	-	20563.2	-
Total live reservoir storage	1000 m3	21931.1	-	3277.1	-	10351.0	-
Total resevoir area at live storage	km2	1069.5	-	558.2	-	607.7	-
Total reservoir area at full supply level	km2	1399.7	-	664.5	-	750.2	-
No. with installed capacity of ≥ 100 MW	No.	16	-	1	-	14	-
Average designed discharged of projects with installed capacity ≥ 100 MW	m3/s	369.9	-	1320.0	-	311.6	-
Total live reservoir storage of projects with installed capacity ≥ 100 MW	km2	19106.6	-	125.0	-	9005.6	-

Appendix 5.B: Key Development Strategies and Policies of the LMB Countries

Table A.2: Relevant Cambodia's Development Strategies

Outputs	Targets
Achieve food security and improved nutrition and promote sustainable agriculture	• Accelerate agriculture development, including enhanced agricultural productivity, diversification and commercialization, promotion of livestock farming and aquaculture, land reform and sustainable management of natural resources. • By 2030 double the agricultural productivity and incomes of small-scale food producers
Ensure access to affordable, reliable, sustainable and modern energy for all	• Increase the share of renewable energy in the global energy mix substantially by 2030 including hydropower, biomass, solar, wind. • Ensure universal access to affordable reliable and modern energy services. • Double the global rate of improvement in energy efficiency by 2030
Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation	• Raise industry's share of employment and gross domestic product by 2030 • Develop reliable and quality infrastructure to support industrial development
Make cities, and human settlements inclusive, safe, resilient and sustainable	• Reduce negative environmental impacts per capita of cities' dwellers

Table A.3: Relevant Lao PDR's Development Strategies

Outputs	**Target**
Ensuring sustained and inclusive economic growth	• Strive to increase the industrial sectors to the growth rate of 15% per annum on average • Strive to complete 15 hydropower projects to increase electricity consumption cover rate of 95% • Develop industrial zone to attract foreign investment. • Focusing rice production in 10 provinces to achieve 2.5 million tons of rice production on 600,000 ha by 2020 • Increase irrigated rice production area from about 300,000 to 400,000 ha by 2020 • Restore production forest of 500,000 ha
Environmental protection and sustainable natural resources management	• Complete the reforestation to achieve forest cover over 70% of the total country area. • Improve mineral resources management by the conservation of about 30,000 square km for mineral protection. • Promote green and sustainable rural development by establishing a system for the management and reduction of waste and chemicals

Table A.4: Relevant Thailand's Development Strategies

Outputs	Targets
Strengthening the Economy, and Underpinning Sustainable Competitiveness	• Developing and maintaining water storage systems for agriculture, and planning the crop planting systems to match the availability of wate • Protecting potential agricultural land and expanding opportunities for farmers to access land for their livelihood. • Developing infrastructure and technology capabilities to support the development of future industries
Advancing Infrastructure and Logistics	• Increase the share of alternative energy in final energy consumption; and to reduce the dependency on natural gas for electricity generation.
Regional, Urban, and Economic Zone Development	• Increasing the capacity of existing water storage facilities and natural water resources and developing new water resources in the Loei, Chi, and Mun river basins, constructing small Kaem-Ling reservoirs in high potential areas for agriculture, promoting reforestation and encouraging participatory resources management in local communities. • Developing the Thung Kula Rong Hai plateau in Yasothon, Surin, Roi-Et, Maha Sarakham, and

Outputs	Targets
	Sisaket, and including other high-potential areas, to become a premium Thai jasmine rice production. • Developing Nakhon Ratchasima to become the center of agro-processing and food industries.

Table A.5: Relevant Viet Nam's Development Strategies

Outputs	Targets
Ensure environmental sustainability	• Increase forest coverage by 45%. • Increase proportion of protected land where biodiversity is preserved.
Reduction of greenhouse gas emissions, increase energy efficiency and efficient shift in fuel	• Prioritise renewable electricity development and increase its share to 4.5% and 6% by 2020 and 2030, respectively by increasing the capacity of hydroelectricity nearly twofold by 2020. • Changes in agricultural cultivation methods, management and use of livestock breeding waste.

Appendix 5.C: Narrative descriptors of future hydropower development scenarios

Table A.6: Longer narrative descriptors of the four plausible hydropower development scenarios

No.	Hydropower development scenarios	Narratives
1	No more hydropower development (Baseline Scenario) (NH)	This scenario is derived by prioritising the protection of water resources of the Mekong River and its tributaries and the ecosystem services it provided. Under this scenario, no additional hydropower development would develop moving forward. This baseline scenario does consist of 68 hydropower project that were developed by 2015. Of these 68 stations, none is located in the Mekong mainstream. The scenario also assumed that alternative energy sources can be harvested to compensate for any energy shortage.
2	Only planned mainstream projects are developed (MS)	This scenario considered the need of the LMB countries in achieving access to affordable, reliable and modern energy for their citizens while concurrently considering the potential adverse cumulative impacts of having all planned hydropower projects developed. Under this scenario, only the 11 planned mainstream projects would be allowed to be developed from 2016 to 2040. They potential effects on streamflow and instream concentrations of nitrate and TSS will be

		examined to quantify magnitude of changes from the baseline (no more hydropower development) scenarios. The scenario also assumed that alternative energy sources can be harvested to compensate for any energy shortage.
3	Only planned tributaries projects are developed (TB)	Similar to the MS only scenario, this scenario takes into consideration the needs of the LMB Countries in achieving SDG goal # 7 in ensuring access to affordable, reliable and modern energy to their citizens. Under this scenario, only the planned 57 stations would be allowed to be developed from 2016 to 2050. The accumulative impacts of the development of these tributary hydropower projects on streamflow and instream concentrations of TSS and nitrate of the Mekong River are assessed to quantity their magnitude of changes from the baseline scenarios. The scenario also assumed that alternative energy sources can be harvested to compensate for any energy shortage
4	Both planned tributaries and mainstream projects are developed (TB+MS)	This final scenario made assumption that the only way to achieve SDG # 7 is through the development of all planned mainstream and tributary hydropower projects. In this scenario additional 68 projects (11 mainstream and 57 tributary projects) would be developed from 2016

		to 2050. Similar to the two previous scenarios their accumulative effects on streamflow and instream concentration of nitrate and TSS will be examined to quantify their magnitude of changes from the baseline scenarios.

Appendix 5.D: Summary of main drivers and associated policy setting assumptions

Table A.7: Summary of main drivers and associated policy setting assumptions for future scenarios development

Drivers	No.	Uncertainties	Attribute (Unit)	Assumption/policy	Baseline condition (2015)	Plausible 2016 - 2040 future scenarios				Sources
						S1 (BAU)	S2 (TB)	S3 (MS)	S4 (MS+TB)	
Economic growth	1	Sustaining rate of economic growth for individual riaparian countries	% annual GDP growth	Assumption	Cambodia (7.1) Lao PDR (4.7) Thailand (2.4) Viet Nam (7.0)	Cambodia (6.7) Lao PDR (6) Thailand (3.5) Viet Nam (4.2)	Same as S1	Same as S1	Same as S1	World Bank (2015)
	2	Changes in income per capita	GDP per capita (US$)	Assumption	Cambodia (1643) Lao PDR (2534) Thailand (7800) Viet Nam (2715)	Cambodia (2,375) Lao PDR (3,649) Thailand (17,000) Viet Nam (5,870)	Same as S1	Same as S1	Same as S1	
	3	Domestic energy generation	Amount of energy supplied (Mtoe)	Assumption	Cambodia (5.9) Lao PDR (6.4) Thailand (122.5) Viet Nam (78.9)	Cambodia (33.27) Lao PDR (11.9) Thailand (277.6) Viet Nam (293)	Increase from S1 by 4,300 MW	Increase from S1 by 15,000 MW	Increase from S1 by 19,000 MW	Kimura and Phoumin (2020)

Drivers	No.	Uncertainties	Attribute (Unit)	Assumption/policy	Baseline condition (2015)	Plausible 2016 - 2040 future scenarios S1 (BAU)	S2 (TB)	S3 (MS)	S4 (MS+TB)	Sources
	4	Energy export	% of electricity	Policy	Cambodia (0) Lao PDR (80) Thailand (0.8) Viet Nam (0.5)	Same as baseline	Decrease from baseline by 4300 MW	Decrease from baseline by 15,000 MW	Decrease from baseline by 19,000 MW	
	5	Total electricity supplied to support domestic demand (both renewable and non-renewable sources)	Total electricity generated (TWh)	Policy	Cambodia (8.48) Lao PDR(63) Thailand (167.5) Viet Nam (193)	Cambodia (99.56) Lao PDR (70) Thailand (402) Viet Nam (734)	Increase from S1 by 21 TWh	Increase from S1 by 66 TWh	Increase from S1 by 87 Twh	
	6	Domestic energy demand	Amount of energy demand (Mtoe)	Assumption	Cambodia (4.3) Lao PDR (3.1) Thailand (85.3) Viet Nam (63.8)	Cambodia (22.3) Lao PDR (8.8) Thailand (212) Viet Nam (191)	Same as S1	Same as S1	Same as S1	
Changes in population	7	Population growth	Population growth rate (%)	Assumption	Cambodia (1.54) Lao PDR (1.73) Thailand (0.22) Viet Nam (1.05)	Cambodia (1.5) Lao PDR (3.5) Thailand (-0.4) Viet Nam (1.6)	Same as S1	Same as S1	Same as S1	World Bank (2015)
	8	Urban population (2015)	Proportion of tolal population (%)	Assumption	Cambodia (23) Lao PDR (31) Thailand (48) Viet Nam (34)	Cambodia (42) Lao PDR (55) Thailand (70) Viet Nam (67)	Same as S1	Same as S1	Same as S1	

Drivers	No.	Uncertainties	Attribute (Unit)	Assumption/policy	Baseline condition (2015)	Plausible 2016 - 2040 future scenarios				Sources
						S1 (BAU)	S2 (TB)	S3 (MS)	S4 (MS+TB)	
Electricity demand	9	Change in electricity demand at the country level	Amount of electricity consumed nationally (Mtoe)	Assumption	Cambodia (0.74) Lao PDR (0.47) Thailand (15) Viet Nam (14.9)	Cambodia (7.7) Lao PDR (2.7) Thailand (40.1) Viet Name (56.8)	Same as S1	Same as S1	Same as S1	Kimura and Phoumin (2020) GMS (2016) ADB (2019) IRENA (2017) U.S.EIA (2021) World Bank (2015)
	10	Level of energy consumed per capita	Amount of electricity consumed per person (toe per capita)	Assumption	Cambodia (0.4) Lao PDR (0.9) Thailand (1.8) Viet Nam (0.8)	Cambodia (1.2) Lao PDR (1.0) Thailand (3.6) Viet Nam (2.23)	Same as S1	Same as S1	Same as S1	
	11	Operational variation in electricity generation	Time required to get electricity (day)	Policy	Cambodia (179) Lao PDR (105) Thailand (37) Viet Nam (49)	Same as baseline	Cambodia (123) Lao PDR (16) Thailand (10) Viet Nam (31)	Cambodia (116) Lao PDR (16) Thailand (6) Viet Nam (31)	Cambodia (107) Lao PDR (3) Thailand (1) Viet Nam (7)	
	12	Energy supplied by hydropower to support national demand	Proportion of total energy supplied (%)	Policy	Cambodia (50) Lao PDR (59.7) Thailand (4) Viet Nam (39.8)	Same as baseline	Cambodia (+ 17,000 MW) Lao PDR (+ 17,000 MW) Thailand (+ 0) Viet Nam (+ 49 MW)	Cambodia (+ 4,300 MW) Lao PDR (+ 18,000 MW) Thailand (+ 0) Viet Nam (+ 0 MW)	Cambodia (+ 21,300 MW) Lao PDR (+ 35,000 MW) Thailand (+ 0) Viet Nam (+ 49 MW)	

Drivers	No.	Uncertainties	Attribute (Unit)	Assumption/policy	Baseline condition (2015)	Plausible 2016 - 2040 future scenarios				Sources
						S1 (BAU)	S2 (TB)	S3 (MS)	S4 (MS+TB)	
	13	Electricity imported to support domestic demand	Proportion of electricity produced domestically (%)	Assumption	Cambodia (27) Lao PDR (46) Thailand (11) Viet Nam (2)	Same as baseline	Decrease from S1 by 4,300 MW	Decrease from S1 by 15,000 MW	Decrease from S1 by 19,000 MW	
Development goals of countries	14	All gross domestic product continue to increase	Annual GDP (billion US$)	Assumption	Cambodia(18.1) Lao PDR (14.4) Thailand (401) Viet Nam (193)	Cambodia () Lao PDR (81) Thailand (1,305) Viet Nam (995.7)	Same as S1	Same as S1	Same as S1	Sachs et al. (2020) World Bank (2015) Mekong River Commission (2018)
	15	Achievement of all SDG	Overall progress (%)	Policy	Cambodia (64.4) Lao PDR (62.1) Thailand (74.5) Viet Nam (73.8)	100%	Same as S1	Same as S1	Same as S1	
	16	Extend of electricity coverage in individual riparian countries	Proportion of population with electricity (%)	Policy	Cambodia (92) Lao PDR (97.9) Thailand (100) Viet Nam (100)	100%	Same as S1	Same as S1	Same as S1	
	17	Flood/drought management	Live reservoir storage in the basin (m3)	Policy	33,000 million	Same as baseline	Increase from S1 by 40 million m3	Increase from S1 by 10 million m3	Increase from S1 by 50 million m3	
	18	Availability of water supply for	Dry season irrigated	Policy	5.1 million	Same as baseline	Increase from S1 with 40 million m3 of	Decrease from S2 with 30 million m3 less	Increase from S1 with addition 10	

Drivers	No.	Uncertainties	Attribute (Unit)	Assumption/policy	Baseline condition (2015)	Plausible 2016 - 2040 future scenarios				Sources
						S1 (BAU)	S2 (TB)	S3 (MS)	S4 (MS+TB)	
		dry season irrigation	areas in the basin (ha)				live reservior storage	reservoir live storage then S2	million m3 of reservoir live storage than S2	
	19	Achievement of poverty reduction	Poverty headcount ratio at $3.20/day	Policy	Cambodia (31.2) Lao PDR (50.9) Thailand (0.1) Viet Nam (9.3)	0%	Same as S1	Same as S1	Same as S1	
Water resources conservation goals	20	Water quality of the Mekong River meets guidelines for the protection of human health, aquatic life and agricultural use	Proporation of station received classification of "good" water quality or above (%)	Policy	Protection of Aquatic Life (95) Protection of Human Health (100) Agricultural use (100)	Decrease from the baseline with increase population, LULC, industrial effluents	Decrease from S3	Decrease from S1	Decrease from S2	Mekong River Commission (2018) Mekong River Commission (2016) Mekong River Commission (1995)
	21	Good ambient water quality to support the maintenance of freshwater ecosystem	Number of basin-wide fish species (No.)	Policy	1,148	Decrease from baseline with increase water pollution and harvesting	Decrease from S3	Decrease from S1	Decrease from S2	
	22	Good ambient water quality to provide food and livelihood security	Annual volume of basin-wide inland capture	Policy	2.3	Decrease from baseline with increase water pollution and harvesting	Decrease from S3	Decrease from S1	Decrease from S2	

Drivers	No.	Uncertainties	Attribute (Unit)	Assumption/policy	Baseline condition (2015)	Plausible 2016 - 2040 future scenarios				Sources
						S1 (BAU)	S2 (TB)	S3 (MS)	S4 (MS+TB)	
			fisheries (million tones)							
	23	Incountry water scarity and stress	Renewable internal freshwater resources per capita (m3 per capita)	Policy	Cambodia (7,500) Lao PDR (27,400) Thailand (3,200) Viet Nam (3,800)	Same as baseline	Improve during dry season but decrease wet season	Improve during dry season but decrease wet season	Decrease from S1	
	24	Ensure sufficient flow to support downstream ecosystem and water security	Annual freshwater withdrawal (% of renewable freshwater volume)	Assumption	Cambodia (2) Lao PDR (4) Thailand (26) Viet Nam (23)	Same as baseline	40 million m3 of withheld	5 million m3 withheld	45 million m3 withheld	
	25	Protection of the Mekong River systems and its resources within national boundary	Proportion of national conservation projects with basin-wide implication (%)	Policy	Cambodia (12) Lao PDR (12) Thailand (11) Viet Nam (14)	Same as baseline	Increase from S1 with additional revenue from TB hydropower	Increase from S2 with revenue from MS hydropower	Increase from S3 with revenue from MS+TB hydropower	

Drivers	No.	Uncertainties	Attribute (Unit)	Assumption/policy	Baseline condition (2015)	Plausible 2016 - 2040 future scenarios				Sources
						S1 (BAU)	S2 (TB)	S3 (MS)	S4 (MS+TB)	
	26	Cooperation between countries on joint projects	Total basin-wide budget ($US)	Policy	11.0 million	Same as baseline	Small risk of decrease from S1	Medium risk of decrease from S1	High risk of decrease from S1	
Climate change	27	Change in river flow regimed due to increase temperature	% changes of the Mekong River flow at Kratie (% Change)	Assumption	Q5: 38,302 m3/s Q95: 1560 m3/s	Q5: -8.8% Q95: 15.0%	Q5: Decrease from S1 Q5 Q95: Increase from S1 Q95	Q5: Decrease from S1 Q5 Q95: Increase from S1 Q95	Q5: Decrease from S1 Q5 Q95: Increase from S1 Q95	Thompson et al. (2013) Kimura and Phoumin (2020) GMS (2016) ADB (2019) IRENA (2017) U.S.EIA (2021) 28 and 29: S1 increase from baseline due to the continuous use of fossil fuel to meet energy demand 30: S1
	28	Cost of climate change	Emission per unit of GDP (tones per million US$)	Assumption	Cambodia (155) Lao PDR (445) Thailand (132) Viet Nam (311)	Cambodia (173) Lao PDR (158) Thailand (114) Viet Nam (181)	Decrease from baseline	Decrease from S2	Decrease from S3	
	29	Investment in renewable energy	Emission per unit of primary energy consumed (t-C/toe)	Assumption	Cambodia (0.51) Lao PDR (0.88) Thailand (0.46) Viet Nam (0.7)	Cambodia (0.75) Lao PDR (0.75) Thailand (0.54) Viet Nam (0.74)	Decrease from baseline	Decrease from S2	Decrease from S3	
	30	Access to reliable and clean energy	Renewable energy supply (% of total energy)	Policy	Cambodia (51) Lao PDR (60) Thailand (16) Viet Nam (40)	Cambodia (54.3) Lao PDR (74.6) Thailand (36.8) Viet Nam (51.6)	Cambodia (S1 + 17,000 MW) Lao PDR (S1+ 17,000 MW) Thailand (Same as S1)	Cambodia (S1 + 4,300 MW) Lao PDR (S1 + 18,000 MW) Thailand (Same as S1)	Cambodia (S1 + 21,300 MW) Lao PDR (S1 + 35,000 MW) Thailand (Same as S1)	

Drivers	No.	Uncertainties	Attribute (Unit)	Assumption/policy	Baseline condition (2015)	Plausible 2016 - 2040 future scenarios				Sources
						S1 (BAU)	S2 (TB)	S3 (MS)	S4 (MS+TB)	
							Viet Nam (S1 + 49 MW)	Viet Nam (Same as S1)	Viet Nam (S1 + 49 MW)	increase from basline due to addition supply from ohter renewable sources (excluding hydropower)
Alternative renewable energy	31	Energy supplied by other renewable energy resources (wind, solar, biomass, waste to energy)	Proportion of total energy supplied by renewable resources (% of total energy)	Policy	Cambodia (1) Lao PDR (0.3) Thailand (12) Viet Nam (0.2)	Cambodia (3.3) Lao PDR (14.6) Thailand (20.8) Viet Nam (11.6)	Decrease from baseline by 4,300 MW	Decrease from baseline by 15,000 MW	Decrease from baseline by 19,000 MW	Kimura and Phoumin (2020) GMS (2016) ADB (2019) ADB (2015) IRENA (2017) U.S.EIA (2021)
	32	Regional energy supplied by other renewable energy resources (wind, solar, biomass, waste to energy)	Proportion of total energy supplied by renewable resources (% of total electricity generation)	Policy	23.55	12.65	Decrease from baseline by 4,300 MW	Decrease from baseline by 15,000 MW	Decrease from baseline by 19,000 MW	

Drivers	No.	Uncertainties	Attribute (Unit)	Assumption/policy	Baseline condition (2015)	Plausible 2016 - 2040 future scenarios				Sources
						S1 (BAU)	S2 (TB)	S3 (MS)	S4 (MS+TB)	
Depletion of non-renewable energy source	33	National level of non-renewable energy consumed (heavy fuel oil and diesel, natural gas, fossil)	Proportion of primary energy consumption from non-renewable sources (% of total energy consumed)	Assumption	Cambodia (58.3) Lao PDR (87) Thailand (80) Viet Nam (73.8)	Cambodia (87.5) Lao PDR (78) Thailand (79.5) Viet Nam (88.3)	Decrease from baseline by 4,300 MW	Decrease from baseline by 15,000 MW	Decrease from baseline by 19,000 MW	
	34	Non-renewable resources consumption measures as energy generation input	Amount of non-renewable resource used as measure by power generation (Mtoe)	Assumption	Cambodia (30.8) Lao PDR (4.4) Thailand (42) Viet Nam (20.7)	Cambodia (41.2) Lao PDR (7.2) Thailand (97.4) Viet Nam (11.7)	Decrease from baseline by 4,300 MW	Decrease from baseline by 15,000 MW	Decrease from baseline by 19,000 MW	
Technology change	35	Reduce operational cost for non-renewable electricity generation	Energy consumption per unit GDP (tones/million US$)	Assumption	Cambodia (155) Lao PDR (445) Thailand (132) Viet Nam (311)	Cambodia (173) Lao PDR (158) Thailand (114) Viet Nam (181)	Decrease from baseline by 4,300 MW	Decrease from baseline by 15,000 MW	Decrease from baseline by 19,000 MW	

Drivers	No.	Uncertainties	Attribute (Unit)	Assumption/policy	Baseline condition (2015)	Plausible 2016 - 2040 future scenarios				Sources
						S1 (BAU)	S2 (TB)	S3 (MS)	S4 (MS+TB)	
	36	Energy saving	Energy intensity measure amount of energy consumed (toe per GDP)	Policy	Cambodia (301) Lao PDR (505) Thailand (289) Viet Nam (450)	Cambodia (230) Lao PDR (137) Thailand (213) Viet Nam (244)	Reduce from baseline	reduce from S2	Reduce from S3	
	37	Improve thermal efficiency	Efficiency level	Assumption	Cambodia (30.8) Lao PDR (27) Thailand (43.8) Viet Nam (40.2)	Cambodia (41.2) Lao PDR (32) Thailand (47.5) Viet Nam (54.6)	Same as S1	Same as S1	Same as S1	
	38	Reduce emission levels associated with the operation of non-renewable electricity generation facilities	Emission per unit of primary energy consumed (t-C/toe)	Assumption	Cambodia (0.51) Lao PDR (0.88) Thailand (0.46) Viet Nam (0.7)	Cambodia (0.75) Lao PDR (0.75) Thailand (0.54) Viet Nam (0.74)	Reduce from baseline	reduce from S2	Reduce from S3	

*BAU - Business as usual

*MS - Mainstream Hydropower Project

*TB - Tributary Hydropower Project

*MS+TB - Mainstream and tributary projects

*Mtoe - million tons of oil equivalences

Annex 5.E: Previous applications of climate change scenarios in the LMB

Table A.8: Analyses of climate variabilities and their effects across the LMB

Research focus	Methods used/Source	Temperature	Rainfall
Management of hydropower in the tributaries of the LMB (Piman et al., 2015).	Downscaling of GCM data based on two approaches – (i) precise regional climate model (A2 and B2 emissions scenarios from MPI-ECHAM4 of GCM); and (ii) delta change method (using projected climate data of A2 emission scenarios) to generate future climate data from 2010 to 2040.	Drier (increase annual temperature) Wetter (increase annual temperature Increased seasonality (Increase annual temperature)	Drier overall (decrease in annual rainfall) Wetter (increase annual rainfall) Increased seasonality (11% decreased in dry season, 8% increase in wet season)
Groudwater resources management (Shrestha et al., 2016b)	Downscaling five GCM datasets using pattern scaling technique by linking Simple Climate Model (SCM) with the GCM response pattern.	Increase in seasonal and annual	Decrease in mean dry season rainfall and increase wet season and annual rainfall

Research focus	Methods used/Source	Temperature	Rainfall
Floods and droughts (Sam et al., 2019)	Downscaling of HadGEM2-AO GCM data by four different regional climate models (HadGEM3-RA, SNU-MM5, RegCM4 and YSU-RSM) to generate climate data for the 2016–2040 period.	Increase temperature	Decrease rainfall (both wet and dry season)
Floods and droughts (Thilakarathne and Sridhar, 2017).	Downscaling of 15 GCM datasets by NASA Earth Exchange Global Daily Downscaled to obtained precipitation data for the period from 2016 to 2099.	-	Decrease dry season precipitation but increase wet season precipitation

Research focus	Methods used/Source	Temperature	Rainfall
Changes in streamflow regimes (Thompson et al., 2013)	Downscaling of GCM data by ClimGen pattern scaling technique to generate 30 years climate scenarios for temperature and precipitation.	-	All scenarios show increase rainfall in upper part of the basin, but as the temperature increases, rainfall decreased in the lower part of the basin
Floods and droughts (Västilä et al., 2010)	Downscaling of GCM ECHAM4 atmospheric-ocean data by the PRECIS regional climate model.	Increase in daily minimum and maximum temperatures.	Increase annual rainfall in the northern part of the LMB but decrease in the floodplains.

Chapter 6. Thesis discussion and conclusion

Kongmeng Ly

Chapter 6. Thesis discussion and conclusion

6.1 Introduction

This final Chapter provides a synthesis of the results from the previous chapters which contain answers to my research questions (RQs) that were formulated at the beginning to support the achievement of my overall objectives of my thesis. These results highlight the knowledge gaps identified during initial literature review on drivers that influence hydrological and water quality conditions of Mekong River, a large-scale transboundary river basin that is shared by four developing countries with uneven geographical attributes and natural resources endowments resulting in divergent economic development pathways.

As a transboundary river that flows through six countries, the Mekong River water and resources are shared across the basin and have historically been vital for the countries' economic development and water and food security (see Chapter 1). Therefore, any changes in streamflow and water quality stemming from rapid economic development, population growth, and land use/land cover (LULC) could affect the integrity and the usability of the Mekong River, diminishing its ability to maintain diverse ecosystems and adequate supply for agricultural production. As the Lower Mekong River Basin (LMB) countries continue to embark on divergent development and conservation pathways, it is essential that potential consequences of these development on streamflow and water quality of the Mekong River at both temporal and spatial scales are well understood. This enhanced understanding can lead to a proper identification of basin specific management challenges and therefore management tools to support water resources managers in solving complex water resources development and conflicts, and in negotiation of international agreements on water usage.

Key findings from each of the previous chapters are presented in the following sections. Each chapter making up this thesis has been conceptualised to gain answers to the RQs that would allow for a better understanding of the basin specific spatiotemporal dynamics and relationships between land-based characteristics and instream integrity indicators of the Mekong River which can advance knowledge on how the Mekong River may be protected through appropriate management practices and development interventions. Along with these findings, each chapter also reviews the significance of the research in the context of advancing science for the sustainable development of the Mekong River and its water resources with final conclusions and recommendation for future research in the LMB.

6.2 Synthesis of research findings

6.2.1 Research Question RQ1 – Chapter 2

Question: Have there been significant changes in streamflow and water quality of the Mekong River? If so, what are the drivers of these changes?

The initial review of scientific literature revealed that the Mekong streamflow and water quality are strongly influenced by a variety of biophysical and economic factors (Ribolzi et al., 2011; Wilbers et al., 2014; Chea et al., 2016) and that they are changing due to the increase economic development and population growth. Prior studies in the LMB have linked streamflow and sediment regimes to hydropower operations (Fan et al., 2015; Shrestha et al., 2016a; Hecht et al., 2019) and instream nutrient levels to the expansion of urban and agricultural areas (Li and Bush, 2015; Whitehead et al., 2019; Yadav et al., 2019). Chapter 1 and Chapter 2 evidence that many studies have examined the status of water scarcity and pollutants in the LMB, though focusing predominantly on a single development factor (Cenci and Martin, 2004; Sudaryanto et al., 2011; Guédron et al., 2014; Wilbers et al., 2014; Chea et al., 2016), instead of a holistic examination of drivers of change and their integrated impact on freshwater resources of the LMB (e.g. increased economic development and population effects).

Understanding how increased economic development and population growth affect streamflow and water quality at spatial and temporal scales is vital for the development of appropriate water resources management measures (Lee et al., 2010a; Kauffman, 2015; Hobbie et al., 2017). Addressing this knowledge gap while answering RQ1, Chapter 2 presents my research findings undertaken in the LMB. Using environmental monitoring records gathered between 1985 and 2015 at 14 monitoring stations located along the Lower Mekong River (LMR), the objectives of the research were to:

1. conduct a spatiotemporal exploratory analysis of how these changes affected water quality indicators,
2. identify trends and observed seasonality of historical TSS and nitrate concentrations, and
3. conduct analysis and interpretation of the afore mentioned data sets to ascertain whether changes in LULC affect the river streamflow and instream TSS and nitrate levels.

Total suspended solids (TSS) and nitrate were used as proxies for water quality due to their documented ecological importance for sustaining the Mekong River functions (Trung et al., 2018; Intralawan et al., 2019; Wild et al., 2019). Temporal and spatial LULC patterns in the LMB were also investigated using the European Space Agency (ESA) Annual Global Land Cover Time Series (AGLCTS) from 1993 to 2015 (European Space Agency, 2017). The ESA dataset was aggregated into nine main LULC types for further assessment of their influence on streamflow and water quality of the Mekong River.

Results of this research revealed that instream TSS concentrations exhibited decreasing temporal trends at nine of the 14 stations considered, while an increasing trend was detected at one station. For instream nitrate concentrations, temporal changes varied from station to station, with significant increasing trends detected at five stations of the upper section of the LMB. Instream concentrations of nitrate and TSS were highly correlated with the river discharge and exhibited clear seasonality patterns, and their historical trends appear to be related to the distinctive wet and dry seasons of the region.

The primary drivers of change appear related to human disturbance through traditional land use practices, such as shifting cultivation, and instream infrastructure development. Our results evidence, for example, that decreases in TSS levels at stations located in the upper section of the LMR coincided with the operation of the Manwan Hydropower. The results provided by the Seasonal Mann-Kendall test confirm that changes in TSS levels in the upper part of the basin were statistically significant and suggested that the progressive development and operation of dams in the Upper Mekong River Basin (UMB) may have influenced the TSS levels at these stations. The operational influences of the mainstream dams located in the UMB on TSS appear to be less profound at stations located in the Mekong Delta (MD), as these stations exhibited increasing trends during the same time period.

Temporal analyses of the time series data for the Vientiane sub-catchment (SVT in Section 2.4.5) further confirmed the influence of land use practices on TSS. At the SVT, the proportion of forest, agriculture, and urban land cover types increased from 1993 to 2015, while the opposite trend occurred with grasslands. These dynamics of LULC change coincided with decreased instream TSS levels, and our analysis shows a positive relationship between instream TSS and grassland, but significant negative relationships with agriculture, forest, and urban land use types. Conversely, the historic trend of instream nitrate concentration increased, suggesting that the increased level was driven by the expansion of urban and agricultural areas at the expenses of grasslands. These changes appear to increase nitrate-laden runoff in the basin, while, at the same time, reducing the basin's natural filtering capacity (Okamoto et al., 2014; Sonnenborg et al., 2017; Zhang et al., 2017; Valera et al., 2019b).

At a spatial level, the values of year 2010 for the proxies representing water quality were compared with the 2010 LULC surface areas. The results (Section 2.4.2.2) suggest that as the proportion of forest areas increased, instream concentrations for both TSS and nitrate also increased. For nitrate, its instream concentrations also increased as the proportion of grassland increased. These results contradicted findings from other studies (Lee et al., 2010a; Mouri et al., 2011; Valera et al., 2019b) and suggest that water quality of the LMR is influenced by LULC and other factors, such as soil type, topography, hydropower development, and land cultivation practices.

The results of our research ascertain that TSS and nitrate levels were highest in sub-catchments dominated by forest land cover, steep slopes, and easily erodible soil types, as well as those exposed to illegal logging and intensive shifting cultivation practices involving vegetation clearance at the onset of the Wet season. The strong relationships found between mean slope percentages of sub-catchments and instream concentration of TSS and nitrate suggest that the detachment and runoff of sediment-laden nutrients from forest-dominated areas (Ribolzi et al., 2017; Lacombe et al., 2018) led to increases of instream concentrations of TSS and nitrate. These results confirmed that a combination of landform, topography, and human disturbances through land use practices influenced the instream levels of these water quality indicators.

A holistic identification of factors influencing changes in the condition of streamflow and water quality is vital for sustaining development of land and water resources, particularly in the context of the LMB, where different types of development are undertaken at an unprecedentedly rapid pace. This study has enhanced understanding of spatiotemporal dynamics and relationships between LULC and water quality in the LMB, and it advances knowledge on how water quality of the LMR may be better protected through appropriate integrated water resources management.

6.2.2 Research Question RQ2 – Chapter 3

Question: Is there an available watershed management tool that has been successfully used to assess the effects of development on streamflow and water quality of a large transboundary river basin the LMB?

Over the past 30 years, interests on the effects of LULC and economic development has led to a proliferation of many watershed models (WMs) (Crawford and Linsley, 1966; Arnold et al., 2012a; Golmohammadi et al., 2014; Ly et al., 2019). While having different interface and capability, the intention of these models has been to assist water resources managers in better understanding the behaviours of the watersheds (João and Walsh, 1992; Singh and Woolhiser, 2002; Baffaut et al., 2015), and therefore, better able to make decisions on the beneficial use of watershed resources for sustainable development (Barlow et al., 2011; Mannik et al., 2012; Motew et al., 2019; de Oliveira Serrão et al., 2021).

Building on findings from Chapter 2 where challenges of integrated water resources management were framed, Chapter 3 developed selection criteria that were used for the identification of watershed models that can be used as management tools to support decision-making, sensitive to the socio-ecological context of the LMB. Using these criteria, this research reviewed and examined 14 event-based, physical and distributed, and process-based watershed models for their comparative suitability to support decision making on large-scale transboundary river basin of developing countries. Each MW was assessed against the established criteria which included the model ability to:

- Simulate continuous records of water quality indicators and instream discharge,
- Address challenges associated with large transboundary river basin (e.g. data gaps; different human resources capacity for implementing the model, vast topographical different within the basin),
- Proven record of successful implementation to support decision making;

To ensure a comprehensive inventory of existing watershed models, journals covering topics related to water science, watershed modelling, hydrology, water resources management and water management technology were searched within Web of Science, Google Scholar, and Science Direct. The screening resulted in about 250 peer-reviewed journals that were reviewed in detail, examining MWs' capability, performance, and geographical, academic and real-world applications.

Against the established set of criteria, the eWater Source model (eWater Ltd., 2018) was selected as the most appropriate due to its capability to simulate instream hydrologic and instream water quality dynamics. Further, it was chosen for its ease of use and ability to deal with the issues of data scarcity and incompatibility associated with large transboundary river basins. With its adoption as the watershed modelling platform to support decision making in Australia (Welsh et al., 2013), Source's proven record in supporting decision makers in the management and development of water resources was also extremely beneficial.

The review findings revealed that while all models have been reported as successful in their prior applications (Section 3.4), the degree of their success depends greatly on data availability. For example, the review of AnnAGNPS, SWAT and HSPF have revealed that these models demand a great number of input data (Chong, 2010; Crossette et al., 2015; Luo et al., 2015; Adu and Kumarasamy, 2018). This can be problematic in large transboundary river basins where long term monitoring data may not be available, may contain gaps and may have insufficient frequency and/or in comparable due to different monitoring objectives of the countries making up the basin, as discussed in Section 3.2.2. Given that these are sophisticated models that required a large amount of data input, they may not be suitable for a large transboundary river basin where data scarcity and incompatibility are major issues (see Section 3.2.1).

While most models reviewed perform satisfactorily when simulating the effects of land use change on water quality and quantity, only a few have been applied in a large transboundary river basin such the Lower Mekong River. More to the point, only SWAT and Source were found to have been applied in transboundary river catchments. Of relevance is that SWAT was used in the Lower Mekong River (Rossi et al., 2009), though pollutant loading simulation was excluded from the study (see Section 3.4.3); unlike Source which was applied in transboundary river catchments to simulate both hydrologic processes and nutrient and sediment transport, as summarised in Section 3.4.4. With a history of successful application in the Australian Murray-Darling River Basin (Dutta et al., 2012) —a transboundary river basin expanding across five states, over an area of more than one million square kilometres, Source was assessed as an IWM tool capable of handling challenges associated with the diverse LULC and topographic patterns that characterise the LMB, and hence with potential for adaptation and transfer to conditions of the LMB.

The findings of this research provide water resource decision makers at both national and transboundary levels with new and advanced scientific tool for the LMB. Further, its flexibility which allows for customization and updating based on emerging policies and information can be valuable as an integrated water resource management tool for large transboundary basins of developing countries like the LMB where different development and conservation priorities can lead to long-term water conflicts.

6.2.3 Research Question RQ3 – Chapter 4

Question: How will the identified tool perform when applied in the LMB, considering challenges associated to its management?

While prior research and governmental policy implementation have revealed the Source modelling framework to have high level of performance when simulating hydrologic processes and instream water quality dynamics of the studied basins, regardless of areas (Chong, 2010; Carr and Podger, 2012; Dutta et al., 2012; Mannik et al., 2012; Waters et al., 2012), the application of Source for the LMB as part of this research is first of the kind. Therefore, its performances in simulating watershed behaviours, hydrologic responses and overland generation and overland runoff of water quality indicators of the LMB have largely unknown. To answer this question, a research was carried out with the main objective of evaluating the performance of Source in simulating hydrological processes and instream water quality dynamics of the LMB. As part of the research experiments, the set up *LMB-Source* model was reconfigurated with the LMB specific physical attributes, hydrological response characteristics, and overland generation and runoff characteristics of water quality indicators, as well as historical environmental monitoring data.

Due to its novel application in the LMB, numerical values of several hydrological response characteristic (HRC) parameters that govern various aspects of rainfall-runoff relationships of the model (Abushandi and Merkel, 2013) were unavailable and had to be estimated based on available historical climatic and streamflow data. Likewise, integral to the simulation of instream TSS and nitrate dynamics are the overland generation and removal dynamic (GRD) parameters for each LULC. LMB specific values for these parameters were estimated using available historical water quality and land use data (Chiew et al., 2002), and that was done as part of this research. These parameters and their values are crucial for the model calibration and optimisation (eWater Ltd., 2018).

The model performance was evaluated using a combination of predictive performance metrics (PPMs) that include NSE, R^2, and %PBIAS (Arnold et al., 2012b; Moriasi et al., 2015) and novel application of hydrologic signatures to diagnose and improve specific aspects of the model that performed poorly (Yilmaz et al., 2008; McMillan, 2019).

Results of this first ever application of Source in the LMB (Chapter 4) revealed the model to perform exceptionally well when simulating the Mekong River streamflow and instream TSS and nitrate loads, with strong similarity between the simulated and observed time series during calibration period of 2003 to 2008. Comparing against performance criteria recommended by Moriasi et al. (2015) for WMs, the *LMB-Source* model was considered to perform at “good” to “very good” levels. Encouragingly, the *LMB-Source* model was able to replicate its performance during the validation period of 2009 to 2012 with similar levels achieves for PPMs. The improvement made through model calibration and validation processes allow final hydrologic signatures of simulated streamflow time series to be closely correlated to their observed counterparts. The calibration and validation results also confirmed hydrologic signatures as powerful calibration and validation techniques for improving model performance.

Compared to other WMs applied in the LMB, either at the entire basin scale or smaller sub-basin scale, the *LMB-Source* model was found to perform on par if not better than those high demanded data. These studies cited low frequency of monitoring data as a contributing factor for their WMs' poor performances. In contrast, the simulation exercise of this research revealed no influence of monitoring data frequency on the performance of the *LMB-Sources*. Instead, the *LMB-Source* model places focus on the topographic characteristics and human disturbance aspects of the modelled basins when generating and removing overland flow and TSS and nitrate runoff.

Instream water quality processes were modelled using the eWater's Fully Mixed Model (eWater Ltd., 2018). While eWater's Source Model is equipped with a number of instream water quality processing models including the Exponential Decay Constituent Processing Model, which allow for the simulation of decay and deposition processes of water quality at the point of simulation represented by storage nodes, instream water quality simulation using Fully Mixed Model was considered to be more appropriate considering the instream hydrological characteristics of the Mekong River at the chosen points of simulation for this study (i.e., no storage, fast flowing, and well mixed) (eWater Ltd., 2018). As these points represent gauging nodes with no storage, mass balance of TSS and nitrate, the two proxies of water quality being modelled, are maintained with no deposition or decay processes (eWater Ltd., 2018)."

Through our reconfiguration of the Source modelling framework in setting up the *LMB-Source* model (Chapter 4), we confirmed the capability of Source as a scientific and integrated water resource management tool for large-scale transboundary river basin of developing countries, using the LMB as case study. Furthermore, the findings of this research illustrate the important LULC and human disturbance as key factors influencing streamflow and instream TSS and nitrate dynamics.

In addition to confirming the capability of the Source modelling framework as a tool for management of developing transboundary river basin and its water resources, through the undertaking of this research, the study generated LMB specific parameter values of HRCs and TSS and nitrate GRDs. These were previously unavailable but important for the characterisation of LULC behaviours for generating and removing TSS and nitrate during overland runoff processes (Mannik et al., 2012; Dutta et al., 2013; Yu et al., 2016; Ribolzi et al., 2018). In total, numerical values of parameters governing overland HRCs and GRDs of nine LULC types were generated as part of this research which are valuable with basin-wide important implications. For example, this information can be utilised for estimating streamflow, TSS and nitrate data of the ungauged sub-basins using a top-down technique of parameters regionalisation as illustrated by Post (2009) and Ragettli et al. (2017). Together, valuable data essential for decision making and establishing baseline conditions for impacts assessment of future development activities (Biber, 2013) can be obtained without the added cost associated with establishing and operating ambient monitoring programmes.

6.2.4 Research question RQ4 – Chapter 5

<u>Question:</u> What are the national and regional development priorities of the LMB and what are the environmental consequences of the implementation of these priorities?

Building on findings to the first three questions and to answer this final research question, this research explored how future development in the basin could affect streamflow and instream TSS and nitrate loads of the Mekong River. To ensure that the pathways reflect actual development strategies, this research required the collation of exiting national and regional socio-economic development plans of the LMB Countries (Government of the Lao PDR, 2016; Government of Viet Nam, 2016; Government of Thailand, 2017; Government of Cambodia, 2019). The analyses of these existing plans revealed that while countries are embarking on different socio-economic development pathways, ensuring access to affordable, reliable and modern energy has been identified as the main catalyse for sustaining countries' economic development. With the abundant of water resources and topography suitable for the development of hydropower, the LMB has seen a boom in hydropower development with Lao PDR, for example, adding about 1,900 MW of installed capacity in 2019, third behind Brazil and China in 2019 (IHA, 2020). Hydropower development is rapidly becoming the main source of energy in the Lower Mekong Basing (LMB), supplying not only energy for the expanding urban population but also boosting the growing economies of the countries that make the basin (Suhardiman et al., 2014). In parts of the basin, hydropower is seen as an avenue for poverty reduction where the generated electricity is not only exported to generate earnings but also to increase electricity coverage to villages and households without electricity (Chattranond, 2018; Tran and Suhardiman, 2020; Atkinson, 2021).

While hydropower operation for electricity generation is considered as clean energy, their operations have also evidenced irreversible environmental and social impacts. A review of the basin hydropower development revealed that additional 68 hydropower projects are planned for development between 2016 to 2040, providing additional 15,000 GWh of energy annually (Mekong River Commission, 2016). With these projects being planned as both mainstream and tributary projects, improper management and operation could result in cross-border impacts outweighing the benefits provided and leading to water diplomacy conflicts.

Using exploratory scenario narrative approach (Rounsevell and Metzger, 2010; Gorgoglione et al., 2019), this research constructed four future hydropower development scenarios for the LMB. Among them, the business-as-usual scenario represents a baseline scenario (S1) where no additional hydropower development would be allowed. The other three plausible future scenarios represent pathway for the development of either projects located on the tributary (S2), mainstream (S3), or both (S4). The cumulative effects of each development scenario on streamflow and instream TSS and nitrate loads of the Mekong River were predicted using the LMB-Source model, previously successfully set up for the LMB (Chapter 3 and Section 6.2.3). The results of the modelling revealed that exclusive development of either tributary (S2) or mainstream (S3) could result in the reduction of mean annual and wet season flow but increase dry season flow which are beneficial for flood/drought management and dry season irrigation. However, electricity generation pathway of developing both tributary and mainstream projects (S4) could result in a reduction of dry season streamflow in relation to the baseline scenario (S1). The results further revealed that increased rainfall (under an alternative scenario of wettest conditions) could improve dry season flow project for S4. However, the improvement was found would not offset the cumulative impacts of S4 development pathway. Both instream TSS and nitrate loads were also predicted to decrease with all three scenarios in relative to the baseline one.

The findings of this research also revealed that improvement of dry season flow could be realised by modify hydropeaking operation hours of large-scale tributary and mainstream projects. However, the modification was found to have little impact on instream TSS and nitrate loads indicating different operational optimization may be required for downstream sediment and nitrate management strategies. Overall, the results of hydropower operational modification from this study provide an insight into the importance of basin-wide integrated management and cooperation approach for sustainable hydropower development. The positive outcomes on dry season flow improvement from modifying operational period of electricity generation illustrates the importance of operational alternatives as management and mitigation options for the sustainable hydropower development. For the LMB where hydropower development and operation are inevitable, operational alternatives could be effective transboundary cooperation and management pathways for balancing electricity generation and downstream protection of riverine ecology, water and food security, and people livelihoods.

6.3 Finding implications of this thesis

6.3.1 Identification of management challenges through enhanced understanding of factors influencing streamflow and instream water quality

As noted in Chapter 1, an initial review of scientific research yielded an abundance of results on studies examining the status of water scarcity and pollutants in the LMB. These studies tend to focus on the influences of a single development factor rather than a holistic examination of the impacts resulting from economic development and population growth (Chapter 1 and Chapter 2).

As part of this thesis, we conducted a research to explore relationships between past development and changes observed in streamflow and water quality of the Mekong River and found changes in LULC influenced instream TSS and nitrate levels differently over time and space (Chapter 2). On a temporal scale, our findings were consistent with studies from other regions where forest LULC type was found to have a negative relationship with instream TSS and nitrate levels (Uriarte et al., 2011; Yu et al., 2016; Valera et al., 2019b). Conversely, positive relationship was detected between forest LULC type and instream TSS and nitrate levels on spatial scale, contracting not only results from prior studies, but also signifying the unique characteristics of the LMB as a developing large-scale transboundary river basin where a combination of landform, topography, and human disturbances through land use practices influenced the Mekong River streamflow and instream levels of TSS and nitrate.

This enhanced understanding of spatiotemporal dynamics and relationships between LULC and water quality paved ways for the identification of management challenges specific to the LMB. Using these specific challenges as criteria, the study was able to identify appropriate management tool (Chapter 3) that can be used to support transboundary river basin development decision makings of not only the LMB but of other similar large-scale ones with similar management challenges including different economic development and environmental conservation pathways which resulted in gaps of available data and human and technical capacities. When considering its flexibility which allows for customization and updating based on emerging policies and information, this novice to the basin WM – Source modelling framework - can proof to be even more valuable as an integrated water resource management tool for large transboundary basins of developing countries like the LMB where development dynamics are interconnected with uncertain future of climate variability, water scarcity and ecosystem services.

6.3.2 Basin-specific parameterisation and implications for transboundary river basin management

This thesis has not only enhanced knowledge on the spatiotemporal relationships between watershed characteristics and streamflow and water quality to support the sustainable development and management of the LMB, but also has also confirmed the Source modelling framework (eWater Ltd., 2018) as a scientific-based decision support tool that can be used for the integrated water resources management of large-scale transboundary basin of developing countries, including the LMB. As a first to apply the modelling framework in the LMB, this thesis has validated the capabilities of the *LMB-Source* to:

(i) satisfactory simulate hydrological processes and pollutant loadings in a time continuous manner;

(ii) simulate the effects of various land use/land cover (LULC) change scenarios; and

(iii) handle issues of data scarcity and compatibility stemming from different development policies and priorities of each administrative jurisdiction.

Through the successful calibration and validation processes where the LMB-Source model performances were assessed using a combined PPMs and diagnostic approaches (Chapter 4), useful and reliable information pertaining to the behaviours of the LMB watershed systems were quantified for future use. For example, the successful calibration and validation of streamflow modelling produced parameter values that represent the HRCs and GRDs specific to the LMB. In transboundary river basins of developing countries — such as the LMB— limited information pertaining watershed functions is available; therefore, the parameter values derived by this thesis provide valuable information that can be applied in further research and management for long-term sustainability of the basin water resources use.

Specific to the management of the LMB, differences in capacities and priorities for collecting and analysing long-term streamflow and water quality data among countries sharing the basin have resulted in data scarcity and uncertainty at many sub-basins. This has challenged strategies aimed at management for development, as long-term hydrological and environmental monitoring data are required for a wide range of reasons, including civil infrastructure development (e.g. siting of hydropower dams, environmental impact assessment), flood and drought forecasting, instream ecological habitat assessment, and assessment of LULC best management practices (Post, 2009; McMillan, 2020). For example, the lack of quantitative values specific to the biophysical context of the LMB for all calibration parameters was a challenge that this research had to overcome. Through the successful implementation of the *LMB-Source*, information derived from this study can be used to predict streamflow, TSS and nitrate data of the ungauged sub-basins using a top-down technique of parameters regionalisation as suggested by Post (2009) and Ragettli et al. (2017). Specifically, relationships can be established between physical attributes (e.g. slope, drainage area, LULC, soil, etc.) of LMB and the HRCs and GRDs derived from this study. The relationships established can then be transferred to un-monitored tributaries sub-basins where streamflow and instream TSS and nitrate data can be estimated based on the similarity of the physical attributes (Kokkonen et al., 2003). Also, the relationships can be used to evaluate overland generation and removal dynamic (GRD) parameters for LULC and to improve broader development policies. Consequently, the improved insights and understanding on the functions and behaviours of the basin provided by this thesis will help better evaluate the effects of development and their management practices.

6.3.3 Toward energy security and sustainable economic development

The overall aim of this thesis was to advance scientific knowledge and understanding on the potential effects of future development on streamflow and instream water quality dynamics of the Mekong River, which has seen its basin undergoing LULC changes due to rapid economic development and population growth (Chapter 1). Sustainable development of large-scale transboundary river basin of developing countries, such as the LMB, has been documented to be challenging due to its size, diverse topography and LULC, and divergent data governance arrangements and policies resulting from differences in political, cultural, economic and environmental conservation priorities of the countries making up the basin (Yeophantong, 2014; De Stefano et al., 2017; Wheeler et al., 2018; Gorgoglione et al., 2019; Ahmadov, 2020).

With LMB countries continue to embark on divergent economic development pathways, ensuring access to affordable, reliable and modern energy has been identified as the main catalyse for sustaining countries' economic growth (Government of the Lao PDR, 2016; Government of Viet Nam, 2016; Government of Thailand, 2017; Government of Cambodia, 2019). Combined with other added known water management benefits, such as flood and drought control, irrigation, and greenhouse gas reduction (Branche, 2017; Sovacool and Walter, 2017; Tang et al., 2018), hydropower is quickly becoming core energy security strategies of the LMB countries to support continuous economic development, poverty reduction, and electricity coverage (Chapter 5). However, with more than 70 hydropower projects already in operation across the basin, their environmental and social impacts have been documented (Kummu and Varis, 2007; Arias et al., 2012; Räsänen et al., 2017). As such, the development of new hydropower is more challenging with intense debates and growing concerns over the long-term and irreversible environmental and social impacts (Fan et al., 2015; Pokhrel et al., 2018; Hecht et al., 2019).

Despite these growing concerns, for most of the LMB countries hydropower development remains an obvious and sometimes the only solution to the region energy requirements with 68 projects planned from 2016 to 2040 (Olson and Gareau, 2018). Development of all planned hydropower projects in the basin is likely unavoidable, and as the narrative on hydropower development in the LMB becomes more centred on the costs and benefits trade-off (Ziv et al., 2012; Intralawan et al., 2019; Wild et al., 2019), this study has provided evidence (Chapter 5) to argue that focus should be shifted to sustainable hydropower development that promotes economic development and protects the environment and social values, as suggested also by (Tang et al., 2018).

As LMB countries continue to embark on the development of both mainstream and tributary hydropower, basin-wide integrated management and cooperative approach for sustainable hydropower development can provide transparency on transboundary environmental and social impacts of individual hydropower development, regardless of location. Past experiences of early high levels basin-wide cooperation have evidenced greater basin-wide net benefits in addition to the benefits realized by individual countries (Bhagabati et al., 2017; Xu et al., 2020). This is because countries can jointly identify cross-boundary impacts of development on the ecological, food and water security, and livelihood interests of the downstream countries (Bao et al., 2017). With early impact identification, appropriate optimization measures can be explored and incorporated into project operational rules to balance electricity generation and downstream environmental and social interests (Yüksel, 2010; Liu et al., 2013; Singh et al., 2020). Depending on the downstream conservation objectives, one such optimization measure can include modification of hydropeaking operations, as illustrated by this study, where changes in mean annual flow and dry season flow in relative to baseline condition were reduced (Chapter 5 and Section 6.2.4).

6.4 Recommendation on future research direction

6.4.1 Enhancing knowledge on factors influencing water quality of the LMB

This research has advanced scientific and local knowledge useful to support the sustainable economic development of the LMB (Sections 6.3.1 to 6.3.3).

Specifically, this thesis has increased understanding of the relationship between land-based attributes, and streamflow and instream TSS and nitrate dynamics of the LMB. As discussed in Chapter 1, TSS and nitrate were selected as proxies for water quality due their documented importance for appraising the state of ecosystem functions (Tchobanoglous and Schroeder, 1985; Hounslow, 2018; Boyd, 2019).

With the rapid pace economic development, uncertain climatic variability, and changes to streamflow regimes, the Mekong River's natural capacity to dilute pollutants has been affected; changes in the physical condition of the river during the dry season have been observed, which are reducing the usability of its waters and increasing the vulnerability of aquatic fauna (Mekong River Commission, 2019). The continuity of this trend could affect water and food security of the basin (Hecht et al., 2019; Intralawan et al., 2019). Future studies could build upon the findings of this thesis by not only focusing on pinpointing the specific source of instream TSS and nitrate changes once more LULC, development and accepted downscaling climate models become available[1], but also on analysing impacts of a growing population and climatic extremes on instream flow quality, exploring whether additional proxies for water quality estimation could be derived from the database of Water Quality Monitoring Network of the Mekong River Commission. Further research could also explore whether a proxy indicator of human disturbance could enhance the initial findings provided in this thesis in relation to the links between water quality and LULC[2]. Such additional research could strengthen the management of the LMB through the implementation of issue-specific measures (e.g. strategies for sustainable urbanization; management resilient to increasing water scarcity; amount and pattern of environmental flows vital to supporting the river's ecological processes), to foster economic development, while maintaining the

[1] My sincere gratitude for Dr. Peter N. King for reviewing this thesis and offering this meaningful insight for the future research work in the LMB.

[2] My sincere gratitude for Dr. Peter N. King for reviewing this thesis and offering this meaningful insight for the future research work in the LMB.

ecosystem health of the Mekong River to ensure it continues functioning and delivering the services that are needed for nature and human wellbeing.

6.4.2 Enhancing knowledge on the significance of tributaries on the overall health of the Mekong River mainstream

Findings from this research demonstrate the likely operational impacts of mainstream and tributary hydropower projects on the streamflow and instream water quality of the Mekong River. Specifically, scenario modelling revealed that the Mekong River streamflow and instream water quality were affected differently as function of the flow contribution from the tributaries (Section 5.4). This highlights the significant influence of healthy tributaries to the overall ecological integrity of the Mekong River, and it raises the hypothesis that the overall health of the LMB could be promoted through a basin-wide coordination approach on hydropower operation. Under such premise projects may be more concentrated in certain tributaries, in order to limit a 'systems' impact on the Mekong River. This alternative approach would require increasing —and strategically positioning— the number monitoring stations, to gather fundamental data for formulating interventions that minimise environmental externalities of hydropower operation on the river health; in essence trading-off the negative impact in some tributaries for the positive impact on the overall health of the mainstream. The current data is not rich enough to allow any such insights. The exploratory scenarios developed in this research (Chapter 5) point that optimisation should be possible and beneficial, though it should be explored in future research.

6.4.3 Further strengthening of regional cooperation in the LMB

This research confirms the importance of WMs as an integrated water resources management tool for the assessment and management of water flows across the LMB, and for the exploration and evaluation of potential effects of plausible future development in the LMB. As highlighted in Chapter 3, while many WMs exists, finding one with capability to handle the physical characteristics and management complexity often associated with a large-scale transboundary river basin, such as the LMB, can be challenging. In the LMB, where countries are embarking on different development pathways, all countries could benefit from a single and focussed approach to capture and model data, as it could ultimately promote greater cooperation between countries, and allow for standardised mechanisms to resolve disputes which will increasingly arise with increasing water utilization (and likely water scarcity). The findings of the study provide evidence for these countries to understand the importance of a shared WM, which could lead to a coordinated adoption of a uniform, transboundary WM – or at least a co-designed methodology to develop one – whose predictive value will increase as more coordinated data is generated for the model inputs. As such, this study proposes a pathway for future cooperative research into water management of LMB (e.g. a joint undertaken of LMB countries), to enable a comprehensive, holistic assessment of future development projects. New research can focus on the parameters that such shared model would require to reflect the policies and priorities of each country, and to allow quantification and informed debate on to the implications of disparate water management policies. Specific to the anticipated increase development and operation of hydropower dams, the shared model can be used to support transboundary dialogues on the various management options, ranging from dam designs to operations to decommission once their economic values have been depleted.[3]

Future research could also explore if existing transboundary governance arrangements amongst countries of the Upper and Lower Mekong River Basins are sufficient to implement the findings of this research[4].

6.4.4 Future development of the LMB

Despite the abundance and diverse natural resources (Chapter 1), the LMB still ranks as one of the poorest region in the world, with wide ranging socioeconomic

---

[3] My sincere gratitude for Dr. Peter N. King for reviewing this thesis and offering this meaningful insight for the future research work in the LMB.

[4] My sincere gratitude for Dr. Peter N. King for reviewing this thesis and offering this meaningful insight for the future research work in the LMB.

disparities among its four countries (Cosslett and Cosslett, 2018). These disparities, along with the basin topographic characteristics, have led divergent economic development priorities among the LMB countries, as discussed in Chapter 5. While this thesis placed focus on advancing scientific understanding of the effects of different future hydropower development pathways on streamflow and instream TSS and nitrate loads of the Mekong River, future studies should extend concerns related to transboundary management, and examine the transboundary effects of hydropower auxiliary development and operation projects, including high voltage transmission lines and sub-stations, on water quantity and quality of the Mekong River.[5]

Other future studies in the LMB should examine the potential effects of other type of development in the basin. Of significant importance — and as highlighted in the existing national and regional socioeconomic development plans—, are key development activities such as:

- prioritisation of industrialisation and modernisation that can result in increased land conversion for urban areas at the expense of other land use types, and changes of lifestyle of the basin population;
- increase of agriculture productivity through expansion of irrigated agricultural areas and intensive and diversified agricultural activities; and
- exploitation of natural forest resources to promote economic growth and revenue generation.

National strategies for implementation of these activities need to be appraised for the potential negative impacts on streamflow and water quality of the Mekong River. With findings from this thesis revealing significant relationships between LUCL and streamflow and instream TSS and nitrate levels of the Mekong River (Chapter 2), cumulative effects of these developments —together with the effects of hydropower development and operation—, on water resources of the Mekong River

[5] My sincere gratitude for Dr. Peter N. King for reviewing this thesis and offering this meaningful insight for the future research work in the LMB.

could be devastating if no proper management is put in place. Using the *LMB-Source* model implemented in this research, future studies can explore the effects future urbanization scenarios on streamflow and water quality of the Mekong River as the basin population is forecasted to continue growing (Jones, 2015; Kimura and Phoumin, 2021). Additional knowledge that may be gained from these recommended future studies, along with finding from this thesis, can be used to support decision making in the basin, that ensures the sustainable protection and conservation of riverine ecology, water and food security, and maintains people livelihoods.

6.5 References

ABBASPOUR, K. C., ROUHOLAHNEJAD, E., VAGHEFI, S., SRINIVASAN, R., YANG, H. & KLØVE, B. 2015. A continental-scale hydrology and water quality model for Europe: Calibration and uncertainty of a high-resolution large-scale SWAT model. *Journal of Hydrology,* 524**,** 733-752.

ABBOTT, M. B., BATHURST, J. C., CUNGE, J. A., O'CONNELL, P. E. & RASMUSSEN, J. 1986. An introduction to the European Hydrological System — Systeme Hydrologique Europeen, "SHE", 1: History and philosophy of a physically-based, distributed modelling system. *Journal of Hydrology,* 87**,** 45-59.

ABELL, J. M., ÖZKUNDAKCI, D., HAMILTON, D. P. & MILLER, S. D. 2011. Relationships between land use and nitrogen and phosphorus in New Zealand lakes. *Marine and Freshwater Research,* 62**,** 162-175.

ABUSHANDI, E. & MERKEL, B. 2013. Modelling Rainfall Runoff Relations Using HEC-HMS and IHACRES for a Single Rain Event in an Arid Region of Jordan. *Water Resources Management,* 27**,** 2391-2409.

ADB 2018. Cambodia: Energy sector assessment, strategy, and road map. Mandaluyong City, Philippines: Asian Development Bank.

ADB 2019. Lao People's Democratic Republic Engergy Sector Assessment, Strategy, and Road Map. *Country Sector and Thematic Assessments.* The Asian Development Bank.

ADU, J. T. & KUMARASAMY, M. V. 2018. Assessing Non-Point Source Pollution Models: a Review. *Polish Journal of Environmental Studies,* 27**,** 1913-1922.

AFZAL, M., BATTILANI, A., SOLIMANDO, D. & RAGAB, R. 2016. Improving water resources management using different irrigation strategies and water qualities: Field and modelling study. *Agricultural Water Management,* 176**,** 40-54.

AGARWAL, A., DELOS ANGELES, M. S., BHATIA, R., CHÉRET, I., DAVILA-POBLETE, S., FALKENMARK, M., VILLARREAL, F. G., JØNCH-CLAUSEN, T., KADI, M. A. & KINDLER, J. 2000. *Integrated water resources management*, Global water partnership.

AHMADI, S. H., AMIN, S., REZA KESHAVARZI, A. & MIRZAMOSTAFA, N. 2006. Simulating Watershed Outlet Sediment Concentration using the ANSWERS Model by applying Two Sediment Transport Capacity Equations. *Biosystems Engineering,* 94**,** 615-626.

AHMADOV, E. 2020. Water resources management to achieve sustainable development in Azerbaijan. *Sustainable Futures,* 2**,** 100030.

AI, L., SHI, Z. H., YIN, W. & HUANG, X. 2015. Spatial and seasonal patterns in stream water contamination across mountainous watersheds: Linkage with landscape characteristics. *Journal of Hydrology,* 523**,** 398-408.

AL-ABED, N. & AL-SHARIF, M. 2008. Hydrological Modeling of Zarqa River Basin – Jordan Using the Hydrological Simulation Program – FORTRAN (HSPF) Model. *Water Resources Management,* 22**,** 1203-1220.

AL BAKRI, D., RAHMAN, S. & BOWLING, L. 2008. Sources and management of urban stormwater pollution in rural catchments, Australia. *Journal of Hydrology,* 356**,** 299-311.

ALLAN, D., ERICKSON, D. & FAY, J. 1997. The Influence of Catchment Land Use on Stream Integrity Across Multiple Spatial Scales. *Freshwater Biology,* 37**,** 149-161.

ALLEN, C., METTERNICHT, G. & WIEDMANN, T. 2019. Prioritising SDG targets: assessing baselines, gaps and interlinkages. *Sustainability Science,* 14**,** 421-438.

AMMANN, L., FENICIA, F. & REICHERT, P. 2019. A likelihood framework for deterministic hydrological models and the importance of non-stationary autocorrelation. *Hydrology and Earth System Sciences,* 23**,** 2147-2172.

ANG, R. & OEURNG, C. 2018. Simulating streamflow in an ungauged catchment of Tonlesap Lake Basin in Cambodia using Soil and Water Assessment Tool (SWAT) model. *Water Science,* 32**,** 89-101.

ARHEIMER, B. & LIDÉN, R. 2000. Nitrogen and phosphorus concentrations from agricultural catchments—influence of spatial and temporal variables. *Journal of Hydrology,* 227**,** 140-159.

ARIAS, M. E., COCHRANE, T. A., KUMMU, M., LAURI, H., HOLTGRIEVE, G. W., KOPONEN, J. & PIMAN, T. 2014. Impacts of hydropower and climate change on drivers of ecological productivity of Southeast Asia's most important wetland. *Ecological Modelling,* 272**,** 252-263.

ARIAS, M. E., COCHRANE, T. A., PIMAN, T., KUMMU, M., CARUSO, B. S. & KILLEEN, T. J. 2012. Quantifying changes in flooding and habitats in the Tonle Sap Lake (Cambodia) caused by water infrastructure development and climate change in the Mekong Basin. *Journal of Environmental Management,* 112**,** 53-66.

ARIAS, M. E., HOLTGRIEVE, G. W., NGOR, P. B., DANG, T. D. & PIMAN, T. 2019. Maintaining perspective of ongoing environmental change in the Mekong floodplains. *Current Opinion in Environmental Sustainability,* 37**,** 1-7.

ARNOLD, J. G., MORIASI, D. N., GASSMAN, P. W., ABBASPOUR, K. C., WHITE, M. J., SRINIVASAN, R., SANTHI, C., HARMEL, R. D., VAN GRIENSVEN, A., VAN LIEW, M. W., KANNAN, N. & JHA, M. K. 2012a. SWAT: Model use, calibration, and validation. *Transactions of the ASABE,* 55**,** 1491-1508.

ARNOLD, J. G., MORIASI, D. N., GASSMAN, P. W., ABBASPOUR, K. C., WHITE, M. J., SRINIVASAN, R., SANTHI, C., HARMEL, R. D., VAN GRIENSVEN, A.,

W. VAN LIEW, M., KANNAN, N. & K. JHA, M. 2012b. SWAT: Model Use, Calibration, and Validation. *Transactions of the ASABE,* 55**,** 1491.

ATKINSON, C. L. 2021. Hydropower, development, and poverty reduction in Laos: promises realized or broken? *Asian Journal of Political Science,* 29**,** 67-87.

AUNG, T. S., FISCHER, T. B. & AZMI, A. S. 2020. Are large-scale dams environmentally detrimental? Life-cycle environmental consequences of mega-hydropower plants in Myanmar. *The International Journal of Life Cycle Assessment,* 25**,** 1749-1766.

BADIGER, S., GOPALAKRISHNAN, S. & PATIL, I. 2018. Contextualizing Rural–Urban Water Conflicts: Bio-Physical and Socio-Institutional Issues of Domestic Water Scarcity. *Globalization of Water Governance in South Asia.* Routledge India.

BAFFAUT, C., M. DABNEY, S., D. SMOLEN, M., A. YOUSSEF, M., V. BONTA, J., L. CHU, M., A. GUZMAN, J., S. SHEDEKAR, V., K. JHA, M. & G. ARNOLD, J. 2015. Hydrologic and Water Quality Modeling: Spatial and Temporal Considerations. *Transactions of the ASABE,* 58**,** 1661.

BAGINSKA, B., MILNE-HOME, W. & CORNISH, P. S. 2003. Modelling nutrient transport in Currency Creek, NSW with AnnAGNPS and PEST. *Environmental Modelling & Software,* 18**,** 801-808.

BAKER, A. 2003. Land use and water quality. *Hydrological Processes,* 17**,** 2499-2501.

BAKER, D. B., RICHARDS, R. P., LOFTUS, T. T. & KRAMER, J. W. 2004. A NEW FLASHINESS INDEX: CHARACTERISTICS AND APPLICATIONS TO MIDWESTERN RIVERS AND STREAMS. *Journal of the American Water Resources Association,* 40**,** 503-522.

BAO, P. N., MITRA, B. K. & KUYAMA, T. 2017. Integrated approach for sustainable hydropower development in the Mekong River basin. *Environment and Natural Resources Research.,* 7**,** 60-75.

BARAN, E. 2006. *Fish migration triggers in the Lower Mekong Basin and other freshwater tropical systems. Technical paper # 14. Mekong River Commission. 2006.*

BARLOW, K., WEEKS, A., F., G., CHRISTY, B. & CHENG, X. 2011. A Source model of the Ovens River Catchment in Victoria - Northen Victoria Project. eWater CRC Application Report: eWater.

BARROS, M. T. L., TSAI, F. T.-C., YANG, S.-L., LOPES, J. E. G. & YEH, W. W.-G. 2003. Optimization of Large-Scale Hydropower System Operations. *Journal of Water Resources Planning and Management,* 129**,** 178-188.

BAUER, S., OLSON, J., COCKRILL, A., VAN HATTEM, M., MILLER, L., TAUZER, M. & LEPPIG, G. 2015. Impacts of Surface Water Diversions for Marijuana Cultivation on Aquatic Habitat in Four Northwestern California Watersheds. *PLOS ONE,* 10**,** e0120016.

BEASLEY, D. B., HUGGINS, L. F. & MONKE, E. J. 1980. ANSWERS: A Model for Watershed Planning. *Transactions of the ASAE,* 23**,** 938.

BEJARANO, M. D., JANSSON, R. & NILSSON, C. 2018. The effects of hydropeaking on riverine plants: a review. *Biological Reviews,* 93**,** 658-673.

BENESTY, J., CHEN, J., HUANG, Y. & COHEN, I. 2009. Pearson correlation coefficient. *Noise reduction in speech processing.* Springer.

BERGMAN, M. J., GREEN, W. & DONNANGELO, L. J. 2002. Calibration of Storm Loads in the South Prong Watershed, Florida, Using BASINS/HSPF1. *JAWRA Journal of the American Water Resources Association,* 38**,** 1423-1436.

BETRIE, G. D., MOHAMED, Y. A., VAN GRIENSVEN, A. & SRINIVASAN, R. 2011. Sediment management modelling in the Blue Nile Basin using SWAT model. *Hydrology and Earth System Sciences,* 15**,** 807.

BHAGABATI, S. S., KAWASAKI, A. & BABEL, M. S. 2017. A cooperative framework for optimizing transboundary hydropower development. *Water International,* 42**,** 945-966.

BHUYAN, S. J., KOELLIKER, J. K., MARZEN, L. J. & HARRINGTON, J. A. 2003. An integrated approach for water quality assessment of a Kansas watershed. *Environmental Modelling & Software,* 18**,** 473-484.

BIBER, E. 2013. The Challenge of Collecting and Using Environmental Monitoring Data. *Ecology and Society,* 18.

BICKNELL, B., IMHOFF, J., KITTLE, J., JOBES, T. & DONIGIAN, A. 2001. HSPF, Version 12, User's Mannual. Athens, GA: U.S. Environmental Protection Agency.

BIN, K. S. & ALOUNSAVATH, O. 2016. Factors influencing the increase of forest cover in Luang Prabang Province, Northern Laos. *Forest Science and Technology,* 12**,** 98-103.

BINGNER, R. L., THEURER, F. D. & YUAN, Y. 2009. *AnnAGNPS Technical Processes: Documentation Version 5* [Online]. Available: ftp://199.133.90.201/pub/outgoing/AGNPS/AGNPS_Web_Files/pdf_files/AnnAGNPS_Technical_Documentation.pdf [Accessed 3 December 2009].

BINH, D. V., KANTOUSH, S. & SUMI, T. 2020. Changes to long-term discharge and sediment loads in the Vietnamese Mekong Delta caused by upstream dams. *Geomorphology,* 353**,** 107011.

BLEVINS, R., LAL, R., DORAN, J., LANGDALE, G. & FRYE, W. 2018. Conservation tillage for erosion control and soil quality. *Advances in soil and water conservation.* Routledge.

BOAVIDA, I., CAETANO, L. & PINHEIRO, A. N. 2020. E-flows to reduce the hydropeaking impacts on the Iberian barbel (Luciobarbus bocagei) habitat. An effectiveness assessment based on the COSH Tool application. *Science of The Total Environment,* 699**,** 134209.

BOONSONG, K., PIYATIRATITIVORAKUL, S. & PATANAPONPAIBOON, P. 2003. Potential use of mangrove plantation as constructed wetland for municipal wastewater treatment. *Water Sci Technol,* 48**,** 257-66.

BORAH, D. K. 2011. Hydrologic procedures of storm event watershed models: a comprehensive review and comparison. *Hydrological Processes,* 25**,** 3472-3489.

BORZÌ, I., BONACCORSO, B. & FIORI, A. 2018. A Modified IHACRES Rainfall–Runoff Model for Predicting Hydrologic Response of a River Basin System with a Relevant Groundwater Component. *Proceedings,* 7**,** 24.

BOTELHO, A., FERREIRA, P., LIMA, F., PINTO, L. M. C. & SOUSA, S. 2017. Assessment of the environmental impacts associated with hydropower. *Renewable and Sustainable Energy Reviews,* 70**,** 896-904.

BOYD, C. E. 2019. *Water quality: an introduction*, Springer Nature.

BRANCHE, E. 2017. The multipurpose water uses of hydropower reservoir: The SHARE concept. *Comptes Rendus Physique,* 18**,** 469-478.

BREWER, J., LANGSTON, J. D., FERRETTI-GALLON, K., INNES, J. L., XIN, S., ZHAI, H. & WANG, G. 2020. Alleviating forest degradation in the Lancang-Mekong Region requires closing management—measurement gaps. *Journal of Forestry Research,* 31**,** 2033-2051.

BRIDHIKITTI, A., PRABAMROONG, T., GAOHUAN, L. & GUO-AN, Y. 2021. Best management practices for mitigating agricultural nutrient pollution in the Mun River Basin, Thailand. *Soil and Water Research,* 16**,** 121-128.

BROWNE, D., DELETIC, A., MUDD, G. M. & FLETCHER, T. D. 2008. A new saturated/unsaturated model for stormwater infiltration systems. *Hydrological Processes,* 22**,** 12.

BRUN, S. E. & BAND, L. E. 2000. Simulating runoff behavior in an urbanizing watershed. *Computers, Environment and Urban Systems,* 24**,** 5-22.

BUCK, O., NIYOGI, D. K. & TOWNSEND, C. R. 2004. Scale-dependence of land use effects on water quality of streams in agricultural catchments. *Environmental Pollution,* 130**,** 287-299.

BUSSI, G., DARBY, S. E., WHITEHEAD, P. G., JIN, L., DADSON, S. J., VOEPEL, H. E., VASILOPOULOS, G., HACKNEY, C. R., HUTTON, C., BERCHOUX, T., PARSONS, D. R. & NICHOLAS, A. 2021. Impact of dams and climate change on suspended sediment flux to the Mekong delta. *Science of The Total Environment,* 755**,** 142468.

CAMPBELL, I. C. 2016. Integrated management in the Mekong River Basin. *Ecohydrology & Hydrobiology,* 16**,** 255-262.

CARR, R. & PODGER, G. eWater source - Australia's next generation IWRM modelling platform. Water Resources Symposium, 2012 Barton, ACT. Engineers Australia, 742-749.

CENCI, R. M. & MARTIN, J. M. 2004. Concentration and fate of trace metals in Mekong River Delta. *Science of The Total Environment,* 332**,** 167-182.

CEPF 2012. Ecosystem profile: Indo-Burma biodiversity hotspot. Critical Ecosystem Partnership Fund.

CETRULO, T. B., MARQUES, R. C., MALHEIROS, T. F. & CETRULO, N. M. 2020. Monitoring inequality in water access: Challenges for the 2030 Agenda for Sustainable Development. *Science of The Total Environment,* 727**,** 138746.

CHAHOR, Y., CASALÍ, J., GIMÉNEZ, R., BINGNER, R. L., CAMPO, M. A. & GOÑI, M. 2014. Evaluation of the AnnAGNPS model for predicting runoff and sediment yield in a small Mediterranean agricultural watershed in Navarre (Spain). *Agricultural Water Management,* 134**,** 24-37.

CHAN, B., BROSSE, S., HOGAN, Z. S., NGOR, P. B. & LEK, S. 2020. Influence of Local Habitat and Climatic Factors on the Distribution of Fish Species in the Tonle Sap Lake. *Water,* 12**,** 786.

CHANG, H. 2008. Spatial analysis of water quality trends in the Han River basin, South Korea. *Water Research,* 42**,** 3285-3304.

CHAPLOT, V., KHAMPASEUTH, X., VALENTIN, C. & BISSONNAIS, Y. L. 2007. Interrill erosion in the sloping lands of northern Laos subjected to shifting cultivation. *Earth Surface Processes and Landforms,* 32**,** 415-428.

CHATTRANOND, O. Battery of Asia? The Rise of Regulatory Regionalism and Transboundary Hydropower Development in Laos. 2018.

CHEA, R., GRENOUILLET, G. & LEK, S. 2016. Evidence of Water Quality Degradation in Lower Mekong Basin Revealed by Self-Organizing Map. *PLoS One,* 11.

CHEN, G., FANG, X. & DEVKOTA, J. 2016. Understanding flow dynamics and density currents in a river-reservoir system under upstream reservoir releases. *Hydrological Sciences Journal,* 61**,** 2411-2426.

CHEN, X., ZHENG, Y., XU, B., WANG, L., HAN, F. & ZHANG, C. 2020. Balancing competing interests in the Mekong River Basin via the operation of cascade hydropower reservoirs in China: Insights from system modeling. *Journal of Cleaner Production,* 254**,** 119967.

CHEREMISINOFF, N. P. 1997. 2 - Relationship Between Groundwater and Surface Water. *In:* CHEREMISINOFF, N. P. (ed.) *Groundwater Remediation and Treatment Technologies.* Westwood, NJ: William Andrew Publishing.

CHIEW, F., SCANLON, P., VERTESSY, R. & WATSON, F. 2002. Estimation of pollutant concentrations for EMSS modelling of the South-East Queensland region. *Technical Report* [Online], Report 02/1. Available: https://ewater.org.au/archive/crcch/archive/pubs/pdfs/technical200201.pdf [Accessed 15 June 2019].

CHINYAMA, A., OCHIENG, G. M., NHAPI, I. & OTIENO, F. A. 2014. A simple framework for selection of water quality models. *Reviews in Environmental Science and Biotechnology,* 13**,** 109-119.

CHONG, L. 2010. Nattai River Catchment Source Catchments Application Project. *eWater Technical Report*.

CHRISTIAENSEN, L. & MARTIN, W. 2018. Agriculture, structural transformation and poverty reduction: Eight new insights. *World Development,* 109**,** 413-416.

CHU, X. & STEINMAN, A. 2009. *Event and continuous modeling with HEC_HMS*.

CLEVELAND, R. B., CLEVELAND, W. S., MCRAE, J. E. & TERPENNING, I. 1990. STL: A seasonal-trend decomposition. *Journal of official statistics,* 6**,** 3-73.

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.

COHEN, A. & DAVIDSON, S. 2011. The watershed approach: Challenges, antecedents, and the transition from technical tool to governance unit. *Water alternatives,* 4**,** 1.

CONNOLLY, N. M., PEARSON, R. G., LOONG, D., MAUGHAN, M. & BRODIE, J. 2015. Water quality variation along streams with similar agricultural development but contrasting riparian vegetation. *Agriculture, Ecosystems & Environment,* 213**,** 11-20.

COOPER, R. J., BATTAMS, Z. M., PEARL, S. H. & HISCOCK, K. M. 2019. Mitigating river sediment enrichment through the construction of roadside wetlands. *Journal of Environmental Management,* 231**,** 146-154.

COSSLETT, T. L. & COSSLETT, P. D. 2018. The Lower Mekong Basin: Rice Production, Climate Change, ENSO, and Mekong Dams. *In:* COSSLETT, T. L. & COSSLETT, P. D. (eds.) *Sustainable Development of Rice and Water Resources in Mainland Southeast Asia and Mekong River Basin.* Singapore: Springer Singapore.

COWIE, A. L., ORR, B. J., CASTILLO SANCHEZ, V. M., CHASEK, P., CROSSMAN, N. D., ERLEWEIN, A., LOUWAGIE, G., MARON, M., METTERNICHT, G. I., MINELLI, S., TENGBERG, A. E., WALTER, S. & WELTON, S. 2018. Land in balance: The scientific conceptual framework for Land Degradation Neutrality. *Environmental Science & Policy,* 79**,** 25-35.

COX, B. A. 2003. A review of currently available in-stream water-quality models and their applicability for simulating dissolved oxygen in lowland rivers. *Science of The Total Environment,* 314-316**,** 335-377.

CRAWFORD, N. H. & LINSLEY, R. K. 1966. Digital Simulation in Hydrology'Stanford Watershed Model 4.

CREWS-MEYER, K. A. 2004. Agricultural landscape change and stability in northeast Thailand: historical patch-level analysis. *Agriculture, Ecosystems & Environment,* 101**,** 155-169.

CROKE, B. F., ANDREWS, F., JAKEMAN, A., CUDDY, S. & LUDDY, A. Redesign of the IHACRES rainfall-runoff model. 29th Hydrology and Water Resources Symposium: Water Capital, 20-23 February 2005, Rydges Lakeside, Canberra, 2005. Engineers Australia, 333.

CROKE, B. F. W. & JAKEMAN, A. J. 2004. A catchment moisture deficit module for the IHACRES rainfall-runoff model. *Environmental Modelling & Software,* 19**,** 1-5.

CROSSETTE, E., PANUNTO, M., KUAN, C. & MOHAMOUD, Y. 2015. Application of BASINS/HSPF to Data Scarce Watersheds. *In:* AGENCY, U. S. E. P. (ed.). Washington, DC: EPA/600/R-15/007.

CUI, Y., FANG, L., GUO, X., HAN, F., JU, W., YE, L., WANG, X., TAN, W. & ZHANG, X. 2019. Natural grassland as the optimal pattern of vegetation restoration in arid and semi-arid regions: Evidence from nutrient limitation of soil microbes. *Science of the total environment,* 648**,** 388-397.

DANG, T. D., COCHRANE, T. A., ARIAS, M. E. & TRI, V. P. D. 2018. Future hydrological alterations in the Mekong Delta under the impact of water resources development, land subsidence and sea level rise. *Journal of Hydrology: Regional Studies,* 15**,** 119-133.

DANIELS, R. B. & GILLIAM, J. W. 1996. Sediment and Chemical Load Reduction by Grass and Riparian Filters. 60**,** 246-251.

DAS, G. G. 2015. Why some countries are slow in acquiring new technologies? A model of trade-led diffusion and absorption. *Journal of Policy Modeling,* 37**,** 65-91.

DE OLIVEIRA SERRÃO, E. A., SILVA, M. T., FERREIRA, T. R., DE ATAIDE, L. C. P., WANZELER, R. T. S., DA SILVA, V. D. P. R., DE LIMA, A. M. M. & DE SOUSA, F. D. A. S. 2021. Large-Scale hydrological modelling of flow and hydropower production, in a Brazilian watershed. *Ecohydrology & Hydrobiology,* 21**,** 23-35.

DE STEFANO, L., PETERSEN-PERLMAN, J. D., SPROLES, E. A., EYNARD, J. & WOLF, A. T. 2017. Assessment of transboundary river basins for potential hydro-political tensions. *Global Environmental Change,* 45**,** 35-46.

DEPARTMENT OF FOREIGN AFFAIRS AND TRADE 2016. Final Evaluation of the MRC Integrated Capacity Building Programme (ICBP). Canberra: DFAT.

DEVIA, G. K., GANASRI, B. & DWARAKISH, G. 2015. A review on hydrological models. *Aquatic Procedia,* 4**,** 1001-1007.

DUAN, Q., SOROOSHIAN, S. & GUPTA, V. 1992. Effective and efficient global optimization for conceptual rainfall-runoff models. *Water Resources Research,* 28**,** 1015-1031.

DUTTA, D., HUGHES, J., VAZE, J., KIM, S., YANG, A. & PODGER, G. A daily river system model for the Murray-Darling basin: Development, testing and implementation. Hydrology and Water Resources Symposium, 2012 Barton, ACT. Engineers Australia, 1057-1066.

DUTTA, D., WILSON, K., WELSH, W. D., NICHOLLS, D., KIM, S. & CETIN, L. 2013. A new river system modelling tool for sustainable operational management of water resources. *Journal of Environmental Management,* 121**,** 13-28.

EDMONDS, C. 2004. Rice Production, Land Use Dynamics, and Infrastructure Development in Viet Nam's Mekong River Delta. *Asian Development Review,* 21**,** 57-78.

EL-KHOURY, A., SEIDOU, O., LAPEN, D. R., QUE, Z., MOHAMMADIAN, M., SUNOHARA, M. & BAHRAM, D. 2015. Combined impacts of future climate and land use changes on discharge, nitrogen and phosphorus loads for a Canadian river basin. *Journal of Environmental Management,* 151**,** 76-86.

ELGUETA, A., GÓRSKI, K., THOMS, M., FIERRO, P., TOLEDO, B., MANOSALVA, A. & HABIT, E. 2021. Interplay of geomorphology and hydrology drives macroinvertebrate assemblage responses to hydropeaking. *Science of The Total Environment,* 768**,** 144262.

ELLIS, R. & SEARLE, R. 2013. An Integrated Water Quality Modelling Framework for Reporting on Great Barrier Reef Catchments. *20th International Congress on Modelling and Simulation.* Adelaide, Australia.

ESEN, E. & USLU, O. 2008. Assessment of the effects of agricultural practices on non-point source pollution for a coastal watershed: A case study Nif Watershed, Turkey. *Ocean & Coastal Management,* 51**,** 601-611.

EUROPEAN SPACE AGENCY 2017. Land Cover Newsletter.

EVANS, J. P. & JAKEMAN, A. J. 1998. Development of a simple, catchment-scale, rainfall-evapotranspiration-runoff model. *Environmental Modelling & Software,* 13**,** 385-393.

EWATER 2019. Source User Guide 4.7. *In:* DAVIS, G. (ed.).

EWATER LTD. 2018. Source User Guide 4.7. Available: https://wiki.ewater.org.au/display/SD47/Source+User+Guide+4.7 [Accessed 03 November 2018].

FAN, H., HE, D. & WANG, H. 2015. Environmental consequences of damming the mainstream Lancang-Mekong River: A review. *Earth-Science Reviews,* 146**,** 77-91.

FOLEY, A. & OLABI, A. G. 2017. Renewable energy technology developments, trends and policy implications that can underpin the drive for global climate change. *Renewable and Sustainable Energy Reviews,* 68**,** 1112-1114.

FORTIN, J.-P., TURCOTTE, R., MASSICOTTE, S., MOUSSA, R., FITZBACK, J. & VILLENEUVE, J.-P. 2001. Distributed Watershed Model Compatible with Remote Sensing and GIS Data. I: Description of Model. *Journal of Hydrologic Engineering,* 6**,** 91-99.

FOX, J., VOGLER, J. B., SEN, O. L., GIAMBELLUCA, T. W. & ZIEGLER, A. D. 2012. Simulating Land-Cover Change in Montane Mainland Southeast Asia. *Environmental Management,* 49**,** 968-979.

FRANCESCONI, W., SRINIVASAN, R., PÉREZ-MIÑANA, E., WILLCOCK, S. P. & QUINTERO, M. 2016. Using the Soil and Water Assessment Tool (SWAT) to model ecosystem services: A systematic review. *Journal of Hydrology,* 535**,** 625-636.

FRERE, M. H., ONSTAD, C. A. & HOLTAN, H. 1975. ACTMO, an agricultural chemical transport model. Washington, DC.: USDA.

FU, L. & WANG, Y.-G. 2012. *Statistical Tools for Analyzing Water Quality Data* [Online]. InTech. Available: https://www.intechopen.com/books/water-quality-monitoring-and-assessment/statistical-tools-for-analyzing-water-quality-data [Accessed 11 November 2017].

GAIUS-OBASEKI, T. 2010. Hydropower opportunities in the water industry. *International Journal of Environmental Sciences,* 1**,** 392.

GAN, T. Y. & BIFTU, G. F. 1996. Automatic Calibration of Conceptual Rainfall-Runoff Models: Optimization Algorithms, Catchment Conditions, and Model Structure. *Water Resources Research,* 32**,** 3513-3524.

GARCIA, L. E. 2008. Integrated water resources management: a 'small'step for conceptualists, a giant step for practitioners. *International Journal of Water Resources Development,* 24**,** 23-36.

GARRICK, D., ANDERSON, G., CONNELL, D. & PITTOCK, J. 2014. *Federal rivers: Managing water in multi-layered political systems*.

GAUSEMEIER, J., FINK, A. & SCHLAKE, O. 1998. Scenario Management: An Approach to Develop Future Potentials. *Technological Forecasting and Social Change,* 59**,** 111-130.

GEHEB, K. & SUHARDIMAN, D. 2019. The political ecology of hydropower in the Mekong River Basin. *Current Opinion in Environmental Sustainability,* 37**,** 8-13.

GHARARI, S., CLARK, M., MIZUKAMI, N., WONG, J. S., PIETRONIRO, A. & WHEATER, H. 2019. Improving the representation of subsurface water movement in land models. *Journal of Hydrometeorology*.

GOHARIAN, E. & BURIAN, S. J. 2018. Developing an integrated framework to build a decision support tool for urban water management. *Journal of Hydroinformatics,* 20**,** 708.

GOLMOHAMMADI, G., PRASHER, S., MADANI, A. & RUDRA, R. 2014. Evaluating Three Hydrological Distributed Watershed Models: MIKE-SHE, APEX, SWAT. *Hydrology,* 1**,** 20.

GORGOGLIONE, A., CRISCI, M., KAYSER, R. H., CHRETIES, C. & COLLISCHONN, W. 2019. A New Scenario-Based Framework for Conflict Resolution in Water Allocation in Transboundary Watersheds. *Water,* 11**,** 1174.

GOVERNMENT OF CAMBODIA 2019. National Strategic Development Plan (2019-2023). Phnom Penh, Cambodia: Ministry of Planning, The Royal Government of Cambodia.

GOVERNMENT OF SOCIALIST REPUBLIC OF VIET NAM 1998. Law on Water Resources. *In:* DEVELOPMENT, M. O. A. A. R. (ed.). Hanoi, Viet Nam.

GOVERNMENT OF THAILAND 2017. The 12th National Economic and Social Development Plan (2017 - 2021). *In:* OFFICE OF NATIONAL ECONOMIC AND SOCIAL DEVELOPMENT BOARD, O. O. T. P. M. (ed.). Bangkok, Thailand.

GOVERNMENT OF THE LAO PDR 2011. Renewable energy development strategy in the Lao PDR. Vientiane, Lao PDR.

GOVERNMENT OF THE LAO PDR 2016. 8th Five-Year National Socio-Economic Development Plan (2016-2020). Vientiane, Lao PDR: Ministry of Planning and Investiment.

GOVERNMENT OF VIET NAM 2015. Decision No. 2068/QD-TTg dated 02 November 2015 of the Prime Minister Approving the Viet Nam Renewable Energy Development Strategy to 2030, Outlook Up to 2050. . Ha Noi, Viet Nam.

GOVERNMENT OF VIET NAM 2016. The Five Year Socio-Economic Development Plan (2016-2020). Hanoi, Viet Nam.

GREIMEL, F., SCHÜLTING, L., GRAF, W., BONDAR-KUNZE, E., AUER, S., ZEIRINGER, B. & HAUER, C. 2018. Hydropeaking Impacts and Mitigation.

In: SCHMUTZ, S. & SENDZIMIR, J. (eds.) *Riverine Ecosystem Management: Science for Governing Towards a Sustainable Future.* Cham: Springer International Publishing.

GU, Q., HU, H., MA, L., SHENG, L., YANG, S., ZHANG, X., ZHANG, M., ZHENG, K. & CHEN, L. 2019. Characterizing the spatial variations of the relationship between land use and surface water quality using self-organizing map approach. *Ecological Indicators,* 102**,** 633-643.

GUÉDRON, S., TISSERAND, D., GARAMBOIS, S., SPADINI, L., MOLTON, F., BOUNVILAY, B., CHARLET, L. & POLYA, D. A. 2014. Baseline investigation of (methyl)mercury in waters, soils, sediments and key foodstuffs in the Lower Mekong Basin: The rapidly developing city of Vientiane (Lao PDR). *Journal of Geochemical Exploration,* 143**,** 96-102.

GULSEVEN, O. 2020. Measuring achievements towards SDG 14, life below water, in the United Arab Emirates. *Marine Policy,* 117**,** 103972.

GUNAWARDANA, S. K., SHRESTHA, S., MOHANASUNDARAM, S., SALIN, K. R. & PIMAN, T. 2021. Multiple drivers of hydrological alteration in the transboundary Srepok River Basin of the Lower Mekong Region. *Journal of Environmental Management,* 278**,** 111524.

GUPTA, H. V., SOROOSHIAN, S. & YAPO, P. O. 1999. Status of Automatic Calibration for Hydrologic Models: Comparison with Multilevel Expert Calibration. *Journal of Hydrologic Engineering,* 4**,** 135-143.

GUPTA, H. V., WAGENER, T. & LIU, Y. 2008. Reconciling theory with observations: elements of a diagnostic approach to model evaluation. *Hydrological Processes,* 22**,** 3802-3813.

GUPTA, J. 2011. An essay on global water governance and research challenges. *Principles of good governance at different water governance levels,* 5.

HALLS, A. S. & HORTLE, K. G. 2021. Flooding is a key driver of the Tonle Sap dai fishery in Cambodia. *Scientific Reports,* 11**,** 1-4.

HARRIS, P., RILEY, E., DAWSON, A., FRIEL, S. & LAWSON, K. 2020. "Stop talking around projects and talk about solutions": Positioning health within infrastructure policy to achieve the sustainable development goals. *Health Policy,* 124**,** 591-598.

HE, C. 2003. Integration of geographic information systems and simulation model for watershed management. *Environmental Modelling & Software,* 18**,** 809-813.

HE, H., ZHOU, J. & ZHANG, W. 2008. Modelling the impacts of environmental changes on hydrological regimes in the Hei River Watershed, China. *Global and Planetary Change,* 61**,** 175-193.

HEALD, C. L. & SPRACKLEN, D. V. 2015. Land Use Change Impacts on Air Quality and Climate. *Chemical Reviews,* 115**,** 4476-4496.

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. *Journal of Hydrology,* 568**,** 285-300.

HER, Y., CHAUBEY, I., FRANKENBERGER, J. & JEONG, J. 2017. Implications of spatial and temporal variations in effects of conservation practices on water management strategies. *Agricultural Water Management,* 180**,** 252-266.

HEY, D. L., KENIMER, A. L. & BARRETT, K. R. 1994. Water quality improvement by four experimental wetlands. *Ecological Engineering,* 3**,** 381-397.

HIRSCH, R., R. SLACK, J. & SMITH, R. 1982. Techniques of Trend Analysis for Monthly Water Quality Data. *Water Resources Research,* 18**,** 107-121.

HJELMFELT ALLEN, T. 1991. Investigation of Curve Number Procedure. *Journal of Hydraulic Engineering,* 117**,** 725-737.

HOANG, L. P., VAN VLIET, M. T. H., KUMMU, M., LAURI, H., KOPONEN, J., SUPIT, I., LEEMANS, R., KABAT, P. & LUDWIG, F. 2019. The Mekong's future flows under multiple drivers: How climate change, hydropower developments and irrigation expansions drive hydrological changes. *Science of The Total Environment,* 649**,** 601-609.

HOANH, C. T., JIRAYOOT, K., LACOMBE, G. & SRINETR, V. 2010. Impacts of climate change and development on Mekong flow regimes. First assessment-2009. International Water Management Institute.

HOBBIE, S. E., FINLAY, J. C., JANKE, B. D., NIDZGORSKI, D. A., MILLET, D. B. & BAKER, L. A. 2017. Contrasting nitrogen and phosphorus budgets in urban watersheds and implications for managing urban water pollution. *Proceedings of the National Academy of Sciences*.

HOLLAND, J. H. 1975. Adaptation in natural and artificial systems. An introductory analysis with applications to biology, control, and artificial intelligence. Ann Arbor, Michigan: University of Michigan Press.

HOMESANA, C. 2019. Understanding the urban livelihoods and wellbeing of migrant women working in garment factories in Vientiane, Laos.

HOUNSLOW, A. W. 2018. *Water quality data: analysis and interpretation*, CRC press.

HOWARTH, R. W., BOYER, E. W., PABICH, W. J. & GALLOWAY, J. N. 2002. Nitrogen Use in the United States from 1961-2000 and Potential Future Trends. *Ambio,* 31**,** 88-96.

HUANG, Y., HUANG, J., ERVINIA, A. & DUAN, S. 2020. Tracking riverine nitrate sources under changing land use pattern and hydrologic regime. *Marine Pollution Bulletin,* 152**,** 110884.

IHA 2020. Hydropower status report 2020: Sector trends and insights. Romford, United Kingdom: International Hydropower Association.

IM, S., KIM, H., KIM, C. & JANG, C. 2008. Assessing the impacts of land use changes on watershed hydrology using MIKE SHE. *Environmental Geology,* 57**,** 231.

INTERNATIONAL HYDROPOWER ASSOCIATION 2020. Laos - the 2016 Hydropower Status Report.

INTRALAWAN, A., SMAJGL, A., MCCONNELL, W., AHLQUIST, D. B., WARD, J. & KRAMER, D. B. 2019. Reviewing benefits and costs of hydropower development evidence from the Lower Mekong River Basin. *WIREs Water,* 6**,** e1347.

INTRALAWAN, A., WOOD, D., FRANKEL, R., COSTANZA, R. & KUBISZEWSKI, I. 2018. Tradeoff analysis between electricity generation and ecosystem services in the Lower Mekong Basin. *Ecosystem Services,* 30**,** 27-35.

IRENA 2017. Renewable energy outlook: Thailand. *In:* AGENCY, I. R. E. (ed.) *Renewable Readiness Assessment and REmap analysis.* Abu Dhabi, United Arab Emirates: Thailand's Ministry of Energy.

IVANIC, M. & MARTIN, W. 2018. Sectoral Productivity Growth and Poverty Reduction: National and Global Impacts. *World Development,* 109**,** 429-439.

JABER, F. H. & SHUKLA, S. 2012. MIKE SHE: Model Use, Calibration, and Validation. *Transactions of the ASABE,* 55**,** 1479-1489.

JANTZ, S. M., BARKER, B., BROOKS, T. M., CHINI, L. P., HUANG, Q., MOORE, R. M., NOEL, J. & HURTT, G. C. 2015. Future habitat loss and extinctions driven by land-use change in biodiversity hotspots under four scenarios of climate-change mitigation. *Conservation Biology,* 29**,** 1122-1131.

JAYAKRISHNAN, R., SRINIVASAN, R., SANTHI, C. & ARNOLD, J. G. 2005. Advances in the application of the SWAT model for water resources management. *Hydrological Processes,* 19**,** 749-762.

JEON, J. H., YOON, C. G., JUNG, K. W. & JANG, J. H. 2007. HSPF-Paddy simulation of water flow and quality for the Saemangeum watershed in Korea. *Water Science and Technology,* 56**,** 123.

JIANCHANG, L., ZHANG, L., ZHANG, Y., HUASHENG, H. & HONGBING, D. 2008. Validation of an agricultural non-point source (AGNPS) pollution model for a catchment in the Jiulong River watershed, China. *Journal of Environmental Sciences,* 20**,** 599-606.

JOÃO, E. M. & WALSH, S. J. 1992. GIS implications for hydrologic modeling: Simulation of nonpoint pollution generated as a consequence of watershed development scenarios. *Computers, Environment and Urban Systems,* 16**,** 43-63.

JOHNSON, H. O., GUPTA, S. C., VECCHIA, A. V. & ZVOMUYA, F. 2009. Assessment of Water Quality Trends in the Minnesota River using Non-

Parametric and Parametric Methods. *Journal of Environmental Quality,* 38, 1018-30.

JONES, G. W. 2015. Population and Development in Lao PDR. *In:* UNFPA (ed.) *Understanding opportunities, challenges and policy options for socioeconomic development.*

JUNG, K.-W., YOON, C.-G., JANG, J.-H. & KONG, D.-S. 2008. Estimation of pollutant loads considering dam operation in Han River Basin by BASINS/Hydrological Simulation Program-FORTRAN. *Water Science and Technology,* 58, 2329.

KAINI, S., NEPAL, S., PRADHANANGA, S., GARDNER, T. & SHARMA, A. K. 2020. Representative general circulation models selection and downscaling of climate data for the transboundary Koshi river basin in China and Nepal. *International Journal of Climatology,* 40, 4131-4149.

KANNAN, N., SANTHI, C. & ARNOLD, J. G. 2008. Development of an automated procedure for estimation of the spatial variation of runoff in large river basins. *Journal of Hydrology,* 359, 1-15.

KARAKUS, C. B., CERIT, O. & KAVAK, K. S. 2015. Determination of Land Use/Cover Changes and Land Use Potentials of Sivas City and its Surroundings Using Geographical Information Systems (GIS) and Remote Sensing (RS). *Procedia Earth and Planetary Science,* 15, 454-461.

KARKI, R., TAGERT, M. L. M., PAZ, J. O. & BINGNER, R. L. 2017. Application of AnnAGNPS to model an agricultural watershed in East-Central Mississippi for the evaluation of an on-farm water storage (OFWS) system. *Agricultural Water Management,* 192, 103-114.

KAUFFMAN, G. J. 2015. Governance, Policy, and Economics of Intergovernmental River Basin Management. *Water Resources Management,* 29, 5689-5712.

KELLY, R. A., JAKEMAN, A. J., BARRETEAU, O., BORSUK, M. E., ELSAWAH, S., HAMILTON, S. H., HENRIKSEN, H. J., KUIKKA, S., MAIER, H. R., RIZZOLI, A. E., VAN DELDEN, H. & VOINOV, A. A. 2013. Selecting among five common modelling approaches for integrated environmental assessment and management. *Environmental Modelling & Software,* 47**,** 159-181.

KIMURA, S. & PHOUMIN, H. 2021. Energy Outlook and Energy Saving Potential in East Asia 2020. Economic Research Institute for ASEAN and East Asia.

KING, M. D. 2018. Nutrient trading credits: best management practices and policy hurdles for non-point source polluters in the Chesapeake Bay. *Environmental Policy and the Pursuit of Sustainability.* Routledge.

KITE, G. 2001. Modelling the Mekong: hydrological simulation for environmental impact studies. *Journal of Hydrology,* 253**,** 1-13.

KITTIKHOUN, A. & STAUBLI, D. M. 2018. Water diplomacy and conflict management in the Mekong: From rivalries to cooperation. *Journal of Hydrology,* 567**,** 654-667.

KNISEL, W. G. 1980. CREAMS: A field-scale model for chemicals, runoff, and erosion from agricultural management systems. Washington, D.C.: USDA National Resources Conservation Service.

KOIRALA, S., HILL, D. & MORGAN, R. 2017. Impacts of the delay in construction of a large scale hydropower project on potential displacees. *Impact Assessment and Project Appraisal,* 35**,** 106-116.

KOKKONEN, T. S., JAKEMAN, A. J., YOUNG, P. C. & KOIVUSALO, H. J. 2003. Predicting daily flows in ungauged catchments: model regionalization from catchment descriptors at the Coweeta Hydrologic Laboratory, North Carolina. *Hydrological Processes,* 17**,** 2219-2238.

KONDOLF, G. M. & LOPEZ-LLOMPART, P. 2018. National-local land-use conflicts in floodways of the Mississippi River system. *AIMS Environmental Science,* 5**,** 47-63.

KRISTENSEN, P. The DPSIR Framework. Comprehensive/detailed assessment of the vlnerability of water resources to enviornmental change in Africa using river basin approach, 2004 UNEP Headquarters, Nairobi, Kenya.

KRULL, E., HAYNES, D., GELL, P., MCGOWAN, J. & LAMONTAGNE, S. 2008. Changes in organic matter chemistry in the Coorong Lagoons over space and time. *Biogeochemistry*.

KUMMU, M., LU, X. X., WANG, J. J. & VARIS, O. 2010. Basin-wide sediment trapping efficiency of emerging reservoirs along the Mekong. *Geomorphology,* 119**,** 181-197.

KUMMU, M. & SARKKULA, J. 2008. Impact of the Mekong River Flow Alteration on the Tonle Sap Flood Pulse. *AMBIO - A Journal of the Human Environment,* 37**,** 185-192.

KUMMU, M. & VARIS, O. 2007. Sediment-related impacts due to upstream reservoir trapping, the Lower Mekong River. *Geomorphology,* 85**,** 275-293.

LABORDE, A., HABIT, E., LINK, O. & KEMP, P. 2020. Strategic methodology to set priorities for sustainable hydropower development in a biodiversity hotspot. *Science of The Total Environment,* 714**,** 136735.

LACOMBE, G., DOUANGSAVANH, S., VOGEL, R. M., MCCARTNEY, M., CHEMIN, Y., REBELO, L.-M. & SOTOUKEE, T. 2014. Multivariate power-law models for streamflow prediction in the Mekong Basin. 2**,** 35-48.

LACOMBE, G., RIBOLZI, O., DE ROUW, A., PIERRET, A., LATSACHAK, K., SILVERA, N., PHAM DINH, R., ORANGE, D., JANEAU, J. L., SOULILEUTH, B., ROBAIN, H., TACCOEN, A., SENGPHAATHITH, P., MOUCHE, E., SENGTAHEUANGHOUNG, O., TRAN DUC, T. & VALENTIN, C. 2016. Contradictory hydrological impacts of afforestation in the humid tropics evidenced by long-term field monitoring and simulation modelling. *Hydrol. Earth Syst. Sci.,* 20**,** 2691-2704.

LACOMBE, G., VALENTIN, C., SOUNYAFONG, P., DE ROUW, A., SOULILEUTH, B., SILVERA, N., PIERRET, A., SENGTAHEUANGHOUNG, O. & RIBOLZI, O. 2018. Linking crop structure, throughfall, soil surface conditions, runoff and soil detachment: 10 land uses analyzed in Northern Laos. *Science of The Total Environment,* 616-617**,** 1330-1338.

LANGE, K., MEIER, P., TRAUTWEIN, C., SCHMID, M., ROBINSON, C. T., WEBER, C. & BRODERSEN, J. 2018. Basin-scale effects of small hydropower on biodiversity dynamics. *Frontiers in Ecology and the Environment,* 16**,** 397-404.

LANZANTE, J. R., DIXON, K. W., NATH, M. J., WHITLOCK, C. E. & ADAMS-SMITH, D. 2018. Some Pitfalls in Statistical Downscaling of Future Climate. *Bulletin of the American Meteorological Society,* 99**,** 791-803.

LAWNICZAK, A. E., ZBIERSKA, J., NOWAK, B., ACHTENBERG, K., GRZEŚKOWIAK, A. & KANAS, K. 2016. Impact of agriculture and land use on nitrate contamination in groundwater and running waters in central-west Poland. *Environmental Monitoring and Assessment,* 188**,** 172.

LE, N. D., LE, T. P. Q., PHUNG, T. X. B., DUONG, T. T. & DIDIER, O. 2020. Impact of hydropower dam on total suspended sediment and total organic nitrogen fluxes of the Red River (Vietnam). *Proc. IAHS,* 383**,** 367-374.

LE, T. N., BREGT, A. K., VAN HALSEMA, G. E., HELLEGERS, P. J. G. J. & NGUYEN, L.-D. 2018. Interplay between land-use dynamics and changes in hydrological regime in the Vietnamese Mekong Delta. *Land Use Policy,* 73**,** 269-280.

LEE, J., KIM, J., JANG, W. S., LIM, K. J. & ENGEL, B. A. 2018. Assessment of Baseflow Estimates Considering Recession Characteristics in SWAT. *Water,* 10**,** 371.

LEE, J. Y., YANG, J. S., KIM, D. K. & HAN, M. Y. 2010a. Relationship between land use and water quality in a small watershed in South Korea. *Water Science and Technology,* 62**,** 2607.

LEE, S.-B., YOON, C.-G., JUNG, K. W. & HWANG, H. S. 2010b. Comparative evaluation of runoff and water quality using HSPF and SWMM. *Water Science and Technology,* 62**,** 1401.

LEKAVIČIUS, V., GALINIS, A. & MIŠKINIS, V. 2019. Long-term economic impacts of energy development scenarios: The role of domestic electricity generation. *Applied Energy,* 253**,** 113527.

LERCH, R., LIN, C., GOYNE, K., KREMER, R. & ANDERSON, S. 2017. Vegetative buffer strips for reducing herbicide transport in runoff: Effects of buffer width, vegetation, and season. *JAWRA Journal of the American Water Resources Association,* 53**,** 667-683.

LÉVESQUE, É., ANCTIL, F., VAN GRIENSVEN, A. N. N. & BEAUCHAMP, N. 2008. Evaluation of streamflow simulation by SWAT model for two small watersheds under snowmelt and rainfall. *Hydrological Sciences Journal,* 53**,** 961-976.

LI, D., LONG, D., ZHAO, J., LU, H. & HONG, Y. 2017. Observed changes in flow regimes in the Mekong River basin. *Journal of Hydrology,* 551**,** 217-232.

LI, S. & BUSH, R. T. 2015. Rising flux of nutrients (C, N, P and Si) in the lower Mekong River. *Journal of Hydrology,* 530**,** 447-461.

LI, Y., ZHANG, Q., LIU, X. & YAO, J. 2020. Water balance and flashiness for a large floodplain system: A case study of Poyang Lake, China. *Science of The Total Environment,* 710**,** 135499.

LI, Z., LUO, C., XI, Q., LI, H., PAN, J., ZHOU, Q. & XIONG, Z. 2015. Assessment of the AnnAGNPS model in simulating runoff and nutrients in a typical small watershed in the Taihu Lake basin, China. *CATENA,* 133**,** 349-361.

LIAO, H., SARVER, E. & KROMETIS, L.-A. H. 2018. Interactive effects of water quality, physical habitat, and watershed anthropogenic activities on stream ecosystem health. *Water Research,* 130**,** 69-78.

LICCIARDELLO, F., A. ZEMA, D., M. ZIMBONE, S. & L. BINGNER, R. 2007. Runoff and Soil Erosion Evaluation by the AnnAGNPS Model in a Small Mediterranean Watershed. *Transactions of the ASABE,* 50**,** 1585.

LIGMANN-ZIELINSKA, A. & JANKOWSKI, P. 2010. Exploring normative scenarios of land use development decisions with an agent-based simulation laboratory. *Computers, Environment and Urban Systems,* 34**,** 409-423.

LIU, B., CHENG, C., WANG, S., LIAO, S., CHAU, K.-W., WU, X. & LI, W. 2018a. Parallel chance-constrained dynamic programming for cascade hydropower system operation. *Energy,* 165**,** 752-767.

LIU, J., SHEN, Z. & CHEN, L. 2018b. Assessing how spatial variations of land use pattern affect water quality across a typical urbanized watershed in Beijing, China. *Landscape and Urban Planning,* 176**,** 51-63.

LIU, J., ZHANG, L., ZHANG, Y., HONG, H. & DENG, H. 2008. Validation of an agricultural non-point source (AGNPS) pollution model for a catchment in the Jiulong River watershed, China. *Journal of Environmental Sciences,* 20**,** 599-606.

LIU, J., ZUO, J., SUN, Z., ZILLANTE, G. & CHEN, X. 2013. Sustainability in hydropower development—A case study. *Renewable and Sustainable Energy Reviews,* 19**,** 230-237.

LIU, S. A., LI, X., CHEN, D., DUAN, Y., JI, H., ZHANG, L., CHAI, Q. & HU, X. 2020. Understanding Land use/Land cover dynamics and impacts of human activities in the Mekong Delta over the last 40 years. *Global Ecology and Conservation,* 22**,** e00991.

LIU, Z. & TONG, S. T. Y. 2011. Using HSPF to Model the Hydrologic and Water Quality Impacts of Riparian Land-Use Change in a Small Watershed. *Journal of Environmental Informatics,* 17**,** 1-14.

LONERGAN, S. C. 2018. Water and conflict: Rhetoric and reality. *Environmental conflict.* Routledge.

LÓPEZ-MORENO, J. I., ZABALZA, J., VICENTE-SERRANO, S. M., REVUELTO, J., GILABERTE, M., AZORIN-MOLINA, C., MORÁN-TEJEDA, E., GARCÍA-RUIZ, J. M. & TAGUE, C. 2014. Impact of climate and land use change on water availability and reservoir management: Scenarios in the Upper Aragón River, Spanish Pyrenees. *Science of The Total Environment,* 493**,** 1222-1231.

LU, H. & XIE, H. 2018. Impact of changes in labor resources and transfers of land use rights on agricultural non-point source pollution in Jiangsu Province, China. *Journal of Environmental Management,* 207**,** 134-140.

LUO, C., LI, Z., LI, H. & CHEN, X. 2015. Evaluation of the AnnAGNPS model for predicting runoff and nutrient export in a typical small watershed in the hilly region of Taihu Lake. *International journal of environmental research and public health,* 12**,** 10955-10973.

LWIN, M. T. 2019. LABOUR MARKET IN MAE SOT 1990–2017 AND THAILAND'S NEW SPECIAL ECONOMIC ZONE POLICY. *Hue University Journal of Science: Economics and Development,* 128**,** 95–109-95–109.

LY, K., METTERNICHT, G. & MARSHALL, L. 2019. Transboundary river catchment areas of developing countries: Potential and limitations of watershed models for the simulation of sediment and nutrient loads. A review. *Journal of Hydrology: Regional Studies,* 24**,** 100605.

LY, K., METTERNICHT, G. & MARSHALL, L. 2020a. Linking Changes in Land Cover and Land Use of the Lower Mekong Basin to Instream Nitrate and Total Suspended Solids Variations. *Sustainability,* 12**,** 2992.

LY, K., METTERNICHT, G. & MARSHALL, L. 2020b. Simulation of streamflow and instream loads of total suspended solids and nitrate in a large transboundary river basin using Source model and geospatial analysis. *Science of The Total Environment***,** 140656.

MA, L., HE, C., BIAN, H. & SHENG, L. 2016. MIKE SHE modeling of ecohydrological processes: Merits, applications, and challenges. *Ecological Engineering,* 96**,** 137-149.

MANH, N. V., DUNG, N. V., HUNG, N. N., KUMMU, M., MERZ, B. & APEL, H. 2015. Future sediment dynamics in the Mekong Delta floodplains: Impacts of hydropower development, climate change and sea level rise. *Global and Planetary Change,* 127**,** 22-33.

MANNIK, R., BORONKAY, A., JORDAN, P., CHURCH, T., HUGHES, D. & BLOCKWELL, S. 2012. Applying eWater source as the catchment model for the Hawkesbury-Nepean water quality model system. *Hydrology and Water Resources Symposium 2012.* Barton, ACT: Engineers Australia.

MARANDA, B. & ANCTIL, F. 2015. SWAT Performance as Influenced by Potential Evapotranspiration Formulations in a Canadian Watershed. *Transactions of the ASABE,* 58**,** 1585.

MARTHALER, F., GESK, J. W., SIEBE, A. & ALBERS, A. 2020. An explorative approach to deriving future scenarios: A first comparison of the consistency matrix-based and the catalog-based approach to generating future scenarios. *Procedia CIRP,* 91**,** 883-892.

MARTÍNEZ-MENA, M., CARRILLO-LÓPEZ, E., BOIX-FAYOS, C., ALMAGRO, M., GARCÍA FRANCO, N., DÍAZ-PEREIRA, E., MONTOYA, I. & DE VENTE, J. 2019. Long-term effectiveness of sustainable land management practices to control runoff, soil erosion, and nutrient loss and the role of rainfall intensity in Mediterranean rainfed agroecosystems. *CATENA***,** 104352.

MATHWORKS. R2010a. *MATLAB version 7.10.0*

MCMILLAN, H. 2020. Linking hydrologic signatures to hydrologic processes: A review. *Hydrological Processes,* 34**,** 1393-1409.

MCMILLAN, H. K. 2019. Process-based diagnostics for hydrologic models. *AGUFM,* 2019**,** H42B-01.

MCPHERSON, M. & KARNEY, B. 2014. Long-term scenario alternatives and their implications: LEAP model application of Panama's electricity sector. *Energy Policy,* 68**,** 146-157.

MEHDI, B., LUDWIG, R. & LEHNER, B. 2015. Evaluating the impacts of climate change and crop land use change on streamflow, nitrates and phosphorus: A modeling study in Bavaria. *Journal of Hydrology: Regional Studies,* 4**,** 60-90.

MEKONG RIVER COMMISSION 1995. Agreement on the Cooperation for the Sustainable Development of the Mekong River Basin. *In:* COMMISSION, T. M. R. (ed.). Vientiane, Lao PDR.

MEKONG RIVER COMMISSION 2009. The flow of the Mekong. *In:* BURNHILL, T. (ed.) *MRC management informantion booklet series.* Vientiane, Lao PDR: MRC Secretariat.

MEKONG RIVER COMMISSION 2010. Land use and land cover lower Mekong Basin parts in Laos, Thailand, Cambodia and Vietnam. *In:* COMMISSION, M. R. (ed.). Vientiane, Laos.

MEKONG RIVER COMMISSION 2011. Planning Atlas of the Lower Mekong River Basin. Vientiane, Lao PDR: Mekong River Commission.

MEKONG RIVER COMMISSION 2014. Multi-media (water, sediment, biota) monitoring and assessment report. *In:* KONGMENG LY, H. L., NGUYEN VAN DUYEN (ed.) *MRC Technical Paper.* Vientiane, Lao PDR: The Mekong River Commission Secretariat.

MEKONG RIVER COMMISSION 2016. Basin Development Strategy. Vientiane, Lao PDR: The Mekong River Commission.

MEKONG RIVER COMMISSION 2018. State of the Basin Report 2018. Vientiane, Lao PDR: The Mekong River Commission Secretariat.

MEKONG RIVER COMMISSION 2019. Mekong River's aquamarine hue likely to occur elsewhere due to low flows, bringing possible risks. Vientiane, Lao PDR: The Mekong River Commission Secretariat.

MEKONG RIVER COMMISSION 2020. Understanding the 1995 Mekong Agreement and the MRC Procedures: A handbook. Vientiane, Lao PDR: The Mekong River Commission Secretariat.

METTERNICHT, G. 2018. *Land use and spatial planning: Enabling sustainable management of land resources*, Springer.

METZ, A. & HARTLEY, P. 2020. Scenario development as valuation: Opportunities for reflexivity. *Technological Forecasting and Social Change,* 155**,** 120027.

MIHALICZ, J. E., JARDINE, T. D., BAULCH, H. M. & PHILLIPS, I. D. 2019. Seasonal effects of a hydropeaking dam on a downstream benthic macroinvertebrate community. *River Research and Applications,* 35**,** 714-724.

MIRCHI, A., WATKINS, D. J. & MADANI, K. 2009. Modeling for watershed planning, management, and decision making. *In:* VAUGHN, J. C. (ed.) *Watersheds: Management, Restoration and Environmental Assessment.* Nova Science Publishers, Inc.

MIRJAT, N. H., UQAILI, M. A., HARIJAN, K., WALASAI, G. D., MONDAL, M. A. H. & SAHIN, H. 2018. Long-term electricity demand forecast and supply side scenarios for Pakistan (2015–2050): A LEAP model application for policy analysis. *Energy,* 165**,** 512-526.

MIRZAEI, M., JAFARI, A., GHOLAMALIFARD, M., AZADI, H., SHOOSHTARI, S. J., MOGHADDAM, S. M., GEBREHIWOT, K. & WITLOX, F. 2019. Mitigating environmental risks: Modeling the interaction of water quality parameters and land use cover. *Land Use Policy***,** 103766.

MISIGO, A. W. & SUZUKI, S. 2018. Spatial-Temporal Sediment Hydrodynamics and Nutrient Loads in Nyanza Gulf, Characterizing Variation in Water Quality. *World Journal of Engineering and Technology,* 6**,** 98.

MITCHELL, B. 2005. Integrated water resource management, institutional arrangements, and land-use planning. *Environment and Planning A,* 37**,** 1335-1352.

MITIC, V., KANKARAS, M., NIKOLIC, D., DIMIC, S. & KOVAC, M. 2020. Rationalization of the scenario development process under conditions involving extensive dynamics. *Futures*.

MOALLEMI, E. A. & MALEKPOUR, S. 2018. A participatory exploratory modelling approach for long-term planning in energy transitions. *Energy Research & Social Science,* 35**,** 205-216.

MOHER, D., LIBERATI, A., TETZLAFF, J., ALTMAN, D. G. & THE, P. G. 2009. Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA Statement. *PLOS Medicine,* 6**,** e1000097.

MOLLE, F., FORAN, T. & KÄKÖNEN, M. 2009. *Contested Waterscapes in the Mekong Region: Hydropower, Livelihoods and Governance*.

MONAGHAN, R. M., WILCOCK, R. J., SMITH, L. C., TIKKISETTY, B., THORROLD, B. S. & COSTALL, D. 2007. Linkages between land management activities and water quality in an intensively farmed catchment in southern New Zealand. *Agriculture, Ecosystems & Environment,* 118**,** 211-222.

MOORE, R. 2006. Watershed Models. Edited by VP Singh and DK Frevert. Boca Raton, FL, USA: CRC Press,(2006), pp. 653,£ 79.99. ISBN 0-8493-3609-0. *Experimental Agriculture,* 42**,** 370.

MORÁN-TEJEDA, E., ZABALZA, J., RAHMAN, K., GAGO-SILVA, A., LÓPEZ-MORENO, J. I., VICENTE-SERRANO, S., LEHMANN, A., TAGUE, C. L. & BENISTON, M. 2015. Hydrological impacts of climate and land-use changes in a mountain watershed: uncertainty estimation based on model comparison. *Ecohydrology,* 8**,** 1396-1416.

MORAN, E. F., LOPEZ, M. C., MOORE, N., MÜLLER, N. & HYNDMAN, D. W. 2018. Sustainable hydropower in the 21st century. *Proceedings of the National Academy of Sciences,* 115**,** 11891.

MOREIRA, M., HAYES, D. S., BOAVIDA, I., SCHLETTERER, M., SCHMUTZ, S. & PINHEIRO, A. 2019. Ecologically-based criteria for hydropeaking mitigation: A review. *Science of The Total Environment,* 657**,** 1508-1522.

MORIASI, D. N., GITAU, M. W., PAI, N. & DAGGUPATI, P. 2015. Hydrologic and Water Quality Models: Performance Measures and Evaluation Criteria. *Transactions of the ASABE,* 58**,** 1763.

MORITZ, S. & BARTZ-BEIELSTEIN, T. 2017. imputeTS: Time Series Missing Value Imputation in R. *R Jounal 9.1*.

MOTEW, M., CHEN, X., CARPENTER, S. R., BOOTH, E. G., SEIFERT, J., QIU, J., LOHEIDE, S. P., TURNER, M. G., ZIPPER, S. C. & KUCHARIK, C. J. 2019. Comparing the effects of climate and land use on surface water quality using future watershed scenarios. *Science of The Total Environment,* 693**,** 133484.

MOURI, G., TAKIZAWA, S. & OKI, T. 2011. Spatial and temporal variation in nutrient parameters in stream water in a rural-urban catchment, Shikoku, Japan: Effects of land cover and human impact. *Journal of Environmental Management,* 92**,** 1837-1848.

MRC 1995. Agreement on the Cooperation for the Sustainable Development of the Mekong River Basin. *In:* COMMISSION, T. M. R. (ed.). Vientiane, Lao PDR.

NASH, J. E. & SUTCLIFFE, J. V. 1970. River flow forecasting through conceptual models part I — A discussion of principles. *Journal of Hydrology,* 10**,** 282-290.

NATIONAL ASSEMBLY 2017. Law on Water and Water Resources. *In:* DEPARTMENT OF WATER RESOURCES, M. O. N. R. A. E. (ed.). Vientiane Lao PDR.

NDOMBA, P., MTALO, F. & KILLINGTVEIT, A. 2008. SWAT model application in a data scarce tropical complex catchment in Tanzania. *Physics and Chemistry of the Earth, Parts A/B/C,* 33**,** 626-632.

NEEF, A., HAGER, J., WIRTH, T., SCHWARZMEIER, R. & HEIDHUES, F. 2018. Land tenure and water rights in Thailand and Vietnam: Challenges for ethnic minorities in mountainous forest regions. *Geographica Helvetica,* 61**,** 255-265.

NELDER, J. A. & MEAD, R. 1965. A Simplex Method for Function Minimization. *The Computer Journal,* 7**,** 308-313.

NELSON, E. J. & BOOTH, D. B. 2002. Sediment sources in an urbanizing, mixed land-use watershed. *Journal of Hydrology,* 264**,** 51-68.

NGO, L. A., MASIH, I., JIANG, Y. & DOUVEN, W. 2018. Impact of reservoir operation and climate change on the hydrological regime of the Sesan and Srepok Rivers in the Lower Mekong Basin. *Climatic Change,* 149**,** 107-119.

NGOR, P. B., LEGENDRE, P., OBERDORFF, T. & LEK, S. 2018. Flow alterations by dams shaped fish assemblage dynamics in the complex Mekong-3S river system. *Ecological Indicators,* 88**,** 103-114.

NGUYEN, C. V. & PHAM, N. M. 2018. Economic growth, inequality, and poverty in Vietnam. *Asian-Pacific Economic Literature,* 32**,** 45-58.

NGUYEN, H. H., RECKNAGEL, F., MEYER, W., FRIZENSCHAF, J. & SHRESTHA, M. K. 2017. Modelling the impacts of altered management practices, land use and climate changes on the water quality of the Millbrook catchment-reservoir system in South Australia. *Journal of Environmental Management,* 202**,** 1-11.

NGUYEN, H. H., RECKNAGEL, F., MEYER, W., FRIZENSCHAF, J., YING, H. & GIBBS, M. S. 2019. Comparison of the alternative models SOURCE and SWAT for predicting catchment streamflow, sediment and nutrient loads under the effect of land use changes. *Science of The Total Environment,* 662**,** 254-265.

NGUYEN, Q. H., TRAN, D. D., DANG, K. K., KORBEE, D., PHAM, L. D., VU, L. T., LUU, T. T., HO, L. H., NGUYEN, P. T. & T. NGO, T. T. 2020. Land-use dynamics in the Mekong delta: From national policy to livelihood sustainability. *Sustainable Development,* 28**,** 448-467.

NIETO-ROMERO, M., MILCU, A., LEVENTON, J., MIKULCAK, F. & FISCHER, J. 2016. The role of scenarios in fostering collective action for sustainable development: Lessons from central Romania. *Land Use Policy,* 50**,** 156-168.

NOBRE, R. L. G., CALIMAN, A., CABRAL, C. R., ARAÚJO, F. D. C., GUÉRIN, J., DANTAS, F. D. C. C., QUESADO, L. B., VENTICINQUE, E. M., GUARIENTO, R. D., AMADO, A. M., KELLY, P., VANNI, M. J. & CARNEIRO, L. S. 2020. Precipitation, landscape properties and land use interactively affect water quality of tropical freshwaters. *Science of the Total Environment,* 716.

O'CONNOR, J. E., DUDA, J. J. & GRANT, G. E. 2015. 1000 dams down and counting. *Science,* 348**,** 496-497.

OEURNG, C., COCHRANE, T. A., ARIAS, M. E., SHRESTHA, B. & PIMAN, T. 2016. Assessment of changes in riverine nitrate in the Sesan, Srepok and Sekong tributaries of the Lower Mekong River Basin. *Journal of Hydrology: Regional Studies,* 8**,** 95-111.

OKAMOTO, K., SHARIFI, A. & CHIBA, Y. 2014. The Impact of Urbanization on Land Use and the Changing Role of Forests in Vientiane. *In:* YOKOYAMA, S., OKAMOTO, K., TAKENAKA, C. & HIROTA, I. (eds.) *Integrated Studies of Social and Natural Environmental Transition in Laos.* Tokyo: Springer Japan.

OLSON, K. A. & GAREAU, B. J. 2018. Hydro/power? Politics, discourse and neoliberalization in Laos's hydroelectric development. *Sociology of Development,* 4**,** 94-118.

OLSON, K. R. & MORTON, L. W. 2018. Water rights and fights: Lao dams on the Mekong River. *Journal of Soil and Water Conservation,* 73**,** 35A.

OYEBODE, O., BABATUNDE, D. E., MONYEI, C. G. & BABATUNDE, O. M. 2019. Water demand modelling using evolutionary computation techniques: integrating water equity and justice for realization of the sustainable development goals. *Heliyon,* 5**,** e02796.

PÁEZ, A. M. & VALLEJO PIEDRAHÍTA, C. 2021. Channeling Water Conflicts through the Legislative Branch in Colombia. *Water,* 13**,** 1214.

PANAGOPOULOS, Y., MAKROPOULOS, C. & MIMIKOU, M. 2012. Decision support for diffuse pollution management. *Environmental Modelling & Software,* 30**,** 57-70.

PARISI, D., TAQUINO, M., GRICE, S. M. & DUANE, G. A. 2003. Promoting Enviornmental Democracy Using GIS as a Means to Integrate Community into the EPA-BASINS Approach. *Society and Natural resources,* 16,**,** 205-219.

PARMESAN, C., ROOT, T. L. & WILLIG, M. R. 2000. Impacts of Extreme Weather and Climate on Terrestrial Biota. *Bulletin of the American Meteorological Society,* 81**,** 443-450.

PEASE, L. M., ODUOR, P. & PADMANABHAN, G. 2010. Estimating sediment, nitrogen, and phosphorous loads from the Pipestem Creek watershed, North Dakota, using AnnAGNPS. *Computers & Geosciences,* 36**,** 282-291.

PECH, S. & SUNADA, K. 2008. Population Growth and Natural-Resources Pressures in the Mekong River Basin. *Ambio,* 37**,** 219-224.

PETERSEN, C. M., RIFAI, H. S., VILLARREAL, G. C. & STEIN, R. 2011. Modeling <i>Escherichia Coli</i> and Its Sources in an Urban Bayou with Hydrologic Simulation Program—FORTRAN. *Journal of Environmental Engineering,* 137**,** 487-503.

PETERSON, H. M., NIEBER, J. L. & KANIVETSKY, R. 2011. Hydrologic regionalization to assess anthropogenic changes. *Journal of Hydrology,* 408**,** 212-225.

PHAM, H. T., MIYAGAWA, S. & KOSAKA, Y. 2015. Distribution patterns of trees in paddy field landscapes in relation to agro-ecological settings in northeast Thailand. *Agriculture, Ecosystems & Environment,* 202**,** 42-47.

PHUNG, D., HUANG, C., RUTHERFORD, S., DWIRAHMADI, F., CHU, C., WANG, X., NGUYEN, M., NGUYEN, N. H., DO, C. M., NGUYEN, T. H. & DINH, T. A. D. 2015. Temporal and spatial assessment of river surface water quality using multivariate statistical techniques: a study in Can Tho City, a Mekong Delta area, Vietnam. *Environmental Monitoring and Assessment,* 187**,** 229.

PIMAN, T., COCHRANE, T. A., ARIAS, M. E., DAT, N. D. & VONNARART, O. 2015. Managing Hydropower Under Climate Change in the Mekong Tributaries. *In:* SHRESTHA, S., ANAL, A. K., SALAM, P. A. & VAN DER VALK, M. (eds.) *Managing Water Resources under Climate Uncertainty: Examples from Asia, Europe, Latin America, and Australia.* Cham: Springer International Publishing.

PIMAN, T., LENNAERTS, T. & SOUTHALACK, P. 2013. Assessment of hydrological changes in the lower Mekong Basin from Basin-Wide development scenarios. *Hydrological Processes,* 27**,** 2115-2125.

PITTOCK, J. 2019. Trade-Offs Between Hydropower Development and Food Security in River Management. *In:* JAMES, H. (ed.) *Population, Development, and the Environment: Challenges to Achieving the Sustainable Development Goals in the Asia Pacific.* Singapore: Springer Singapore.

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.

POST, D. A. 2009. Regionalizing rainfall–runoff model parameters to predict the daily streamflow of ungauged catchments in the dry tropics. 40**,** 433.

POTTER, C. & HIATT, S. 2009. Modeling river flows and sediment dynamics for the Laguna de Santa Rosa watershed in Northern California. *Journal of Soil and Water Conservation,* 64**,** 383.

PRADHAN, P. 2019. Antagonists to meeting the 2030 Agenda. *Nature Sustainability,* 2**,** 171-172.

PREMSTALLER, G., CAVEDON, V., PISATURO, G. R., SCHWEIZER, S., ADAMI, V. & RIGHETTI, M. 2017. Hydropeaking mitigation project on a multi-purpose hydro-scheme on Valsura River in South Tyrol/Italy. *Science of The Total Environment,* 574**,** 642-653.

PRICE, W. L. 1987. Global optimization algorithms for a CAD workstation. *Journal of Optimization Theory and Applications,* 55**,** 133-146.

PROSSER, P., RUSTOMJI, P., YOUNG, B., MORAN, C. & HUGHES, A. 2001. Constructing river basin sediment budgets for the National Land and Water Resources Audit. *CSIRO Land and Water.*

PUSHPALATHA, R., PERRIN, C., MOINE, N. L. & ANDRÉASSIAN, V. 2012. A review of efficiency criteria suitable for evaluating low-flow simulations. *Journal of Hydrology,* 420-421**,** 171-182.

RAGETTLI, S., ZHOU, J., WANG, H., LIU, C. & GUO, L. 2017. Modeling flash floods in ungauged mountain catchments of China: A decision tree learning approach for parameter regionalization. *Journal of Hydrology,* 555**,** 330-346.

RÄSÄNEN, T. A., SOMETH, P., LAURI, H., KOPONEN, J., SARKKULA, J. & KUMMU, M. 2017. Observed river discharge changes due to hydropower operations in the Upper Mekong Basin. *Journal of Hydrology,* 545**,** 28-41.

RATHA, C., GRENOUILLET, G. & LEK, S. 2016. Evidence of Water Quality Degradation in Lower Mekong Basin Revealed by Self-Organizing Map. *PLoS One,* 11.

RENARD, K. G., FOSTER, G. R., WEESIES, G. A., MCCOOL, D. K. & YODER, D. C. 1996. *Predicting soil erosion by water: a guide to conservation planning with the Revised Universal Soil Loss Equation (RUSLE).*

RIBAROVA, I., NINOV, P. & COOPER, D. 2008. Modeling nutrient pollution during a first flood event using HSPF software: Iskar River case study, Bulgaria. *Ecological Modelling,* 211**,** 241-246.

RIBOLZI, O., CUNY, J., SENGSOULICHANH, P., MOUSQUÈS, C., SOULILEUTH, B., PIERRET, A., HUON, S. & SENGTAHEUANGHOUNG, O. 2011. Land Use and Water Quality Along a Mekong Tributary in Northern Lao P.D.R. *Environmental Management,* 47**,** 291-302.

RIBOLZI, O., EVRARD, O., HUON, S., DE ROUW, A., SILVERA, N., LATSACHACK, K. O., SOULILEUTH, B., LEFÈVRE, I., PIERRET, A., LACOMBE, G., SENGTAHEUANGHOUNG, O. & VALENTIN, C. 2017. From shifting cultivation to teak plantation: effect on overland flow and sediment yield in a montane tropical catchment. *Scientific Reports,* 7**,** 3987.

RIBOLZI, O., LACOMBE, G., PIERRET, A., ROBAIN, H., SOUNYAFONG, P., DE ROUW, A., SOULILEUTH, B., MOUCHE, E., HUON, S., SILVERA, N., LATXACHAK, K. O., SENGTAHEUANGHOUNG, O. & VALENTIN, C. 2018. Interacting land use and soil surface dynamics control groundwater outflow in a montane catchment of the lower Mekong basin. *Agriculture, Ecosystems & Environment,* 268**,** 90-102.

RICHTER, B. D., BAUMGARTNER, J. V., POWELL, J. & BRAUN, D. P. 1996. A Method for Assessing Hydrologic Alteration within Ecosystems. *Conservation Biology,* 10**,** 1163-1174.

ROEBELING, P., ALVES, H., ROCHA, J., BRITO, A., ALMEIDA, P. & MAMEDE, J. 2014. Gains from trans-boundary water quality management in linked catchment and coastal socio-ecological systems: A case study for the Minho region. *Water Resources and Economics,* 8**,** 32-42.

ROLLE, K., GITAU, M. W., CHEN, G. & CHAUHAN, A. 2012. Assessing fecal coliform fate and transport in a coastal watershed using HSPF. *Water Science and Technology,* 66**,** 1096.

ROMERO-ZALIZ, R. & REINOSO-GORDO, J. F. 2018. An Updated Review on Watershed Algorithms. *In:* CRUZ CORONA, C. (ed.) *Soft Computing for Sustainability Science.* Cham: Springer International Publishing.

ROSSEL, V. & DE LA FUENTE, A. 2015. Assessing the link between environmental flow, hydropeaking operation and water quality of reservoirs. *Ecological Engineering,* 85**,** 26-38.

ROSSI, C. G. 2009. Hydrologic evaluation of the lower Mekong River basin with the soil and water assessment tool model. *International agricultural engineering journal,* v. 18**,** pp. 1-13-2009 v.18 no.1-2.

ROSSI, C. G., SRINIVASAN, R., JIRAYOOT, K., LE DUC, T., SOUVANNABOUTH, P., BINH, N. & GASSMAN, P. W. 2009. Hydrologic evaluation of the lower Mekong River basin with the soil and water assessment tool model. *International agricultural engineering journal,* v. 18**,** pp. 1-0-2009 v.18 no.1-2.

ROSSMAN, L. A. 2004. SWMM (Storm Water Management Model). *User Mannual.* Washington , DC.: Environmental Protection Angency.

ROUNSEVELL, M. D. A. & METZGER, M. J. 2010. Developing qualitative scenario storylines for environmental change assessment. *WIREs Climate Change,* 1**,** 606-619.

RUTTEN, M., VAN DIJK, M., VAN ROOIJ, W. & HILDERINK, H. 2014. Land Use Dynamics, Climate Change, and Food Security in Vietnam: A Global-to-local Modeling Approach. *World Development,* 59**,** 29-46.

SABO, J. L., RUHI, A., HOLTGRIEVE, G. W., ELLIOTT, V., ARIAS, M. E., NGOR, P. B., RÄSÄNEN, T. A. & NAM, S. 2017. Designing river flows to improve food security futures in the Lower Mekong Basin. *Science,* 358**,** eaao1053.

SACHS, J. D. 2012. From Millennium Development Goals to Sustainable Development Goals. *The Lancet,* 379**,** 2206-2211.

SAFEEQ, M. & HUNSAKER, C. T. 2016. Characterizing Runoff and Water Yield for Headwater Catchments in the Southern Sierra Nevada. *JAWRA Journal of the American Water Resources Association,* 52**,** 1327-1346.

SALEH, A. & GALLEGO, O. 2007. Application of SWAT and APEX Using the SWAPP (SWAT-APEX) Program for the Upper North Bosque River Watershed in Texas. *Transactions of the ASABE,* 50**,** 1177.

SALEH, D. K., KRATZER, C. R., GREEN, C. H. & EVANS, D. G. 2009. Using the Soil and Water Assessment Tool (SWAT) to simulate runoff in Mustang Creek Basin, California. *U.S. Geological Survey Scientific Investigations Report 2009-5031.*

SALVIA-CASTELLVÍ, M., FRANÇOIS IFFLY, J., VANDER BORGHT, P. & HOFFMANN, L. 2005. Dissolved and particulate nutrient export from rural catchments: A case study from Luxembourg. *Science of The Total Environment,* 344**,** 51-65.

SAM, T. T., KHOI, D. N., THAO, N. T. T., NHI, P. T. T., QUAN, N. T., HOAN, N. X. & NGUYEN, V. T. 2019. Impact of climate change on meteorological, hydrological and agricultural droughts in the Lower Mekong River Basin: a case study of the Srepok Basin, Vietnam. *Water and Environment Journal,* 33**,** 547-559.

SANDU, M.-A. & VIRSTA, A. 2015. Applicability of MIKE SHE to Simulate Hydrology in Argesel River Catchment. *Agriculture and Agricultural Science Procedia,* 6**,** 517-524.

SARANGI, A., COX, C. A. & MADRAMOOTOO, C. A. 2007. Evaluation of the AnnAGNPS Model for prediction of runoff and sediment yields in St Lucia watersheds. *Biosystems Engineering,* 97**,** 241-256.

SAWICZ, K., WAGENER, T., SIVAPALAN, M., TROCH, P. A. & CARRILLO, G. 2011. Catchment classification: empirical analysis of hydrologic similarity based on catchment function in the eastern USA. *Hydrology and Earth System Sciences,* 15**,** 2895-2911.

SCHALTEGGER, S. & SYNNESTVEDT, T. 2002. The link between 'green' and economic success: environmental management as the crucial trigger between environmental and economic performance. *Journal of Environmental Management,* 65**,** 339-346.

SCHILLING, K. E. 2002. Chemical transport from paired agricultural and restored prairie watersheds. *Journal of Environmental Quality,* 31**,** 1184-93.

SCHWEIKHARD, J., KASPER, K., EBERT, C., LEHMANN, M., ERBE, P. & ZIEGLER, T. 2019. Investigations into the illegal wildlife trade in central Lao PDR. *Traffic Bulletin,* 31**,** 19-25.

SEARCHINGER, T., HEIMLICH, R., HOUGHTON, R. A., DONG, F., ELOBEID, A., FABIOSA, J., TOKGOZ, S., HAYES, D. & YU, T.-H. 2008. Use of U.S. Croplands for Biofuels Increases Greenhouse Gases Through Emissions from Land-Use Change. *Science,* 319**,** 1238.

SHARVINI, S. R., NOOR, Z. Z., CHONG, C. S., STRINGER, L. C. & YUSUF, R. O. 2018. Energy consumption trends and their linkages with renewable energy policies in East and Southeast Asian countries: Challenges and opportunities. *Sustainable Environment Research,* 28**,** 257-266.

SHAW, M., SILBURN, D. M., ELLIS, R., R., S., BIGGS, J., THORBURN, P. & WHISH, G. Paddock scale modelling to assess effectiveness of agricultural management practice in improving water quality in the Great Barrier Reef Catchments. 10th International Congress on Modelling and Simulation, 1-6 December 2013 2013 Adelaide, Australia.

SHRESTHA, B., BABEL, M., MASKEY, S., VAN GRIENSVEN, A., UHLENBROOK, S., GREEN, A. & AKKHARATH, I. 2013. Impact of climate change on sediment yield in the Mekong River basin: a case study of the Nam Ou basin, Lao PDR. *Hydrology and Earth System Sciences,* 17**,** 1.

SHRESTHA, B., COCHRANE, T. A., CARUSO, B. S., ARIAS, M. E. & PIMAN, T. 2016a. Uncertainty in flow and sediment projections due to future climate scenarios for the 3S Rivers in the Mekong Basin. *Journal of Hydrology,* 540**,** 1088-1104.

SHRESTHA, B., MASKEY, S., BABEL, M. S., VAN GRIENSVEN, A. & UHLENBROOK, S. 2018. Sediment related impacts of climate change and reservoir development in the Lower Mekong River Basin: a case study of the Nam Ou Basin, Lao PDR. *Climatic Change,* 149**,** 13-27.

SHRESTHA, S., BACH, T. V. & PANDEY, V. P. 2016b. Climate change impacts on groundwater resources in Mekong Delta under representative concentration pathways (RCPs) scenarios. *Environmental Science & Policy,* 61**,** 1-13.

SILVA, J. D., FERNANDES, V., LIMONT, M., DZIEDZIC, M., ANDREOLI, C. V. & RAUEN, W. B. 2020. Water sustainability assessment from the perspective of sustainable development capitals: Conceptual model and index based on literature review. *Journal of Environmental Management,* 254**,** 109750.

SINGH, D. 2009. Resource assessment handbook. *Asian and Pacific Centre for Transfer of Technology of the United Nations, Economic and Social Commission for Asia and the Pacific (ESCAP): New Delhi, India***,** 16-34.

SINGH, P., SINGH, S., VARDHAN, S. & PATNAIK, A. 2020. Sustainability of maintenance management practices in hydropower plant: A conceptual framework. *Materials Today: Proceedings,* 28**,** 1569-1574.

SINGH, R., TIWARI, K. N. & MAL, B. C. 2006. Effect of spatial resolution on watershed characteristics and the ANSWERS model hydrological simulations for a small watershed. *In:* KULIGOWSKI, R. J., PARIHAR, J. S. & SAITO, G. (eds.) *Agriculture and Hydrology Applications of Remote Sensing.* Bellingham: Spie-Int Soc Optical Engineering.

SINGH, V. P. & WOOLHISER, D. A. 2002. Mathematical Modeling of Watershed Hydrology. *Journal of Hydrologic Engineering,* 7**,** 270-292.

SITHIRITH, M. 2021. Transboundary River Basin Governance: A Case of the Mekong River Basin. *River Basin Management-Sustainability Issues and Planning Strategies*.

SITHONG, T. & YAYOI, F. 2006. Recent Land Use and Livelihoods Transitions in Northern Laos. *Mountain Research and Development,* 26**,** 237-244.

SOKOLOV, V. 2011. Integrated Water Resources Management. *Water and Food Security in Central Asia.* Springer.

SOLAR, R. R. D. C., BARLOW, J., ANDERSEN, A. N., SCHOEREDER, J. H., BERENGUER, E., FERREIRA, J. N. & GARDNER, T. A. 2016. Biodiversity consequences of land-use change and forest disturbance in the Amazon: A multi-scale assessment using ant communities. *Biological Conservation,* 197**,** 98-107.

SONNENBORG, T. O., CHRISTIANSEN, J. R., PANG, B., BRUGE, A., STISEN, S. & GUNDERSEN, P. 2017. Analyzing the hydrological impact of afforestation and tree species in two catchments with contrasting soil properties using the spatially distributed model MIKE SHE SWET. *Agricultural and Forest Meteorology,* 239**,** 118-133.

SORACHAMPA, P., TIPPAYAWONG, N. & NGAMSANROAJ, K. 2020. Optimizing multiple reservoir system operation for maximum hydroelectric power generation. *Energy Reports,* 6**,** 67-75.

SOUKHAPHON, A., BAIRD, I. G. & HOGAN, Z. S. 2021. The Impacts of Hydropower Dams in the Mekong River Basin: A Review. *Water,* 13**,** 265.

SOVACOOL, B. & WALTER, G. 2017. Major hydropower states, sustainable development, and energy security: Insights from a preliminary cross-comparative assessment. *Energy,* 142.

SPARKES, S. 2014. Sustainable hydropower development: Theun-Hinboun expansion project case study, Laos. *Water Resources and Rural Development,* 4**,** 54-66.

SPERA, S. A., GALFORD, G. L., COE, M. T., MACEDO, M. N. & MUSTARD, J. F. 2016. Land-use change affects water recycling in Brazil's last agricultural frontier. *Global Change Biology,* 22**,** 3405-3413.

SRIDHAR, V., KANG, H. & ALI, S. A. 2019. Human-Induced Alterations to Land Use and Climate and Their Responses for Hydrology and Water Management in the Mekong River Basin. *Water,* 11**,** 1307.

STOTT, P. 2016. How climate change affects extreme weather events. *Science,* 352**,** 1517.

STRATON, A. T., JACKSON, S., MARINONI, O., PROCTOR, W. & WOODWARD, E. 2011. Exploring and Evaluating Scenarios for a River Catchment in Northern Australia Using Scenario Development, Multi-criteria Analysis and a Deliberative Process as a Tool for Water Planning. *Water Resources Management,* 25**,** 141-164.

SUDARYANTO, A., ISOBE, T., TAKAHASHI, S. & TANABE, S. 2011. Assessment of persistent organic pollutants in sediments from Lower Mekong River Basin. *Chemosphere,* 82**,** 679-686.

SUHARDIMAN, D., WICHELNS, D., LEBEL, L. & SELLAMUTTU, S. S. 2014. Benefit sharing in Mekong Region hydropower: Whose benefits count? *Water Resources and Rural Development,* 4**,** 3-11.

SUIF, Z., FLEIFLE, A., YOSHIMURA, C. & SAAVEDRA, O. 2016. Spatio-temporal patterns of soil erosion and suspended sediment dynamics in the Mekong River Basin. *Science of The Total Environment,* 568**,** 933-945.

SUKHWANI, V., THAPA, K., SHAW, R., DESHKAR, S., MITRA, B. K. & YAN, W. 2020. Addressing Urban–Rural Water Conflicts in Nagpur through Benefit Sharing. *Water,* 12**,** 2979.

SUN, H., HE, D., SUI, X. & CHEN, Y. 2020. Predicting impacts of future climate change and hydropower development towards habitats of native and non-native fishes. *Science of The Total Environment,* 707**,** 135419.

SUTTLES, B. J., VELLIDIS, G., BOSCH, D. D., LOWRANCE, R., SHERIDAN, M. J. & USERY, L. E. 2003. Watershed-Scale Simulation of Sediment and Nutrient Loads in Georgia Coastal Plain Streams Using the Annualized AGNPS Model. *Transactions of the ASAE,* 46**,** 1325.

SWETNAM, R. D., FISHER, B., MBILINYI, B. P., MUNISHI, P. K. T., WILLCOCK, S., RICKETTS, T., MWAKALILA, S., BALMFORD, A., BURGESS, N. D., MARSHALL, A. R. & LEWIS, S. L. 2011. Mapping socio-economic scenarios of land cover change: A GIS method to enable ecosystem service modelling. *Journal of Environmental Management,* 92**,** 563-574.

TANG, W., LI, Z. & TU, Y. 2018. Sustainability Risk Evaluation for Large-Scale Hydropower Projects with Hybrid Uncertainty. *Sustainability,* 10**,** 138.

TAS, E. 2013. Integrated water resources management. *Aerul si Apa. Componente ale Mediului***,** 217.

TAYLOR, S. D., HE, Y. & HISCOCK, K. M. 2016. Modelling the impacts of agricultural management practices on river water quality in Eastern England. *Journal of Environmental Management,* 180**,** 147-163.

TCHOBANOGLOUS, G. & SCHROEDER, E. E. 1985. Water quality: characteristics, modeling, modification.

THE ROYAL GOVERNMENT OF CAMBODIA 2007. Law on water resources management of the Kingdom of Cambodia. *In:* METEOROLOGY, M. O. W. R. A. (ed.). Phnom Penh, Cambodia.

THE ROYAL THAI GOVERNMENT 2018. Water Resources Act. *In:* COMMISSION, N. W. R. (ed.). Bangkok, Thailand.

THEURER, F. D. & CLARKE, C. D. Wash load component for sediment yield modeling. The Fifth Federal Interagency Sedimentation Conference, 1991.

THILAKARATHNE, M. & SRIDHAR, V. 2017. Characterization of future drought conditions in the Lower Mekong River Basin. *Weather and Climate Extremes,* 17**,** 47-58.

THOMPSON, J. R., GREEN, A. J., KINGSTON, D. G. & GOSLING, S. N. 2013. Assessment of uncertainty in river flow projections for the Mekong River using multiple GCMs and hydrological models. *Journal of Hydrology,* 486**,** 1-30.

TIAN, Y., HUANG, Z. & XIAO, W. 2010. Reductions in non-point source pollution through different management practices for an agricultural watershed in the Three Gorges Reservoir Area. *Journal of Environmental Sciences,* 22**,** 184-191.

TILT, B., BRAUN, Y. & HE, D. 2009. Social impacts of large dam projects: A comparison of international case studies and implications for best practice. *Journal of Environmental Management,* 90**,** S249-S257.

TONOLLA, D., BRUDER, A. & SCHWEIZER, S. 2017. Evaluation of mitigation measures to reduce hydropeaking impacts on river ecosystems – a case study from the Swiss Alps. *Science of The Total Environment,* 574**,** 594-604.

TRAMBAUER, P., MASKEY, S., WINSEMIUS, H., WERNER, M. & UHLENBROOK, S. 2013. A review of continental scale hydrological models and their suitability for drought forecasting in (sub-Saharan) Africa. *Physics and Chemistry of the Earth, Parts A/B/C,* 66**,** 16-26.

TRAN, T. A. & SUHARDIMAN, D. 2020. Laos' hydropower development and cross-border power trade in the Lower Mekong Basin: A discourse analysis. *Asia Pacific Viewpoint,* 61**,** 219-235.

TRANG, N. T. T., SHRESTHA, S., SHRESTHA, M., DATTA, A. & KAWASAKI, A. 2017. Evaluating the impacts of climate and land-use change on the hydrology and nutrient yield in a transboundary river basin: A case study in the 3S River Basin (Sekong, Sesan, and Srepok). *Science of The Total Environment,* 576**,** 586-598.

TROCH, P. A., CARRILLO, G., SIVAPALAN, M., WAGENER, T. & SAWICZ, K. 2013. Climate-vegetation-soil interactions and long-term hydrologic partitioning: signatures of catchment co-evolution. 17, 2209-2217.

TRUNG, L. D., DUC, N. A., NGUYEN, L. T., THAI, T. H., KHAN, A., RAUTENSTRAUCH, K. & SCHMIDT, C. 2018. Assessing cumulative impacts of the proposed Lower Mekong Basin hydropower cascade on the Mekong River floodplains and Delta – Overview of integrated modeling methods and results. *Journal of Hydrology*.

TRUNG, L. D., DUC, N. A., NGUYEN, L. T., THAI, T. H., KHAN, A., RAUTENSTRAUCH, K. & SCHMIDT, C. 2020. Assessing cumulative impacts of the proposed Lower Mekong Basin hydropower cascade on the Mekong River floodplains and Delta – Overview of integrated modeling methods and results. *Journal of Hydrology,* 581, 122511.

TU, J. 2013. Spatial Variations in the Relationships between Land Use and Water Quality across an Urbanization Gradient in the Watersheds of Northern Georgia, USA. *Environmental Management,* 51, 1-17.

ULÉN, B., STENBERG, M. & WESSTRÖM, I. 2016. Use of a flashiness index to predict phosphorus losses from subsurface drains on a Swedish farm with clay soils. *Journal of Hydrology,* 533, 581-590.

UMMENHOFER, C. C. & MEEHL, G. A. 2017. Extreme weather and climate events with ecological relevance: a review. *Philosophical Transactions of the Royal Society B: Biological Sciences,* 372, 20160135.

UNEP-DHI & UNEP 2016. Transboundary River Basins: Status and Trends. Nairobi: United Nations Environment Programme (UNEP).

UNESCAP 2021. Country SDG Profiles. Bangkok, Thailand: UNESCAP.

UNITED NATIONS 2018. Sustainable Development Goals. *In:* AFFAIRS, D. O. E. A. S. (ed.).

URIARTE, M., YACKULIC, C. B., LIM, Y. & ARCE-NAZARIO, J. A. 2011. Influence of land use on water quality in a tropical landscape: a multi-scale analysis. *Landscape Ecology,* 26**,** 1151.

USDA 1972. National Engineering Handbook. Washington, DC: Soil Conservation.

USEPA 2015. Application of BASINS/HSPF to Data-scarce Watersheds. Washington, DC: Office of Research and Development.

UTHAI, S. 2018. Hydropower Dams on the Mekong River: Changes in Food Security and Chiang Khong Women's Adaptation. *Journal of Mekong Societies,* 14**,** 125-147.

VALERA, C. A., PISSARRA, T. C. T., FILHO, M. V. M., VALLE JÚNIOR, R. F. D., OLIVEIRA, C. F., MOURA, J. P., SANCHES FERNANDES, L. F. & PACHECO, F. A. L. 2019a. The Buffer Capacity of Riparian Vegetation to Control Water Quality in Anthropogenic Catchments from a Legally Protected Area: A Critical View over the Brazilian New Forest Code. *Water,* 11**,** 549.

VALERA, C. A., PISSARRA, T. C. T., VALLE JÚNIOR, R. F. D., OLIVEIRA, C. F., MOURA, J. P., SANCHES FERNANDES, L. F. & PACHECO, F. A. L. 2019b. The buffer capacity of riparian vegetation to control water quality in anthropogenic catchments from a legally protected area: A critical view over the Brazilian new forest code. *Water,* 11**,** 549.

VAN CLEEF, A. 2016. Hydropower development and involuntary displacement: Toward a global solution. *Ind. J. Global Legal Stud.,* 23**,** 349.

VAN DER STERREN, M., RAHMAN, A. & RYAN, G. 2014. Modeling of a lot scale rainwater tank system in XP-SWMM: A case study in Western Sydney, Australia. *Journal of Environmental Management,* 141**,** 177-189.

VASILIADES, L., SARAILIDIS, G. & LOUKAS, A. 2017. Hydrological modelling of low flows for operational water resources management.

VÄSTILÄ, K., KUMMU, M., SANGMANEE, C. & CHINVANNO, S. 2010. Modelling climate change impacts on the flood pulse in the Lower Mekong floodplains. *Journal of Water and Climate Change,* 1**,** 67-86.

VERICAT, D., VILLE, F., PALAU-IBARS, A. & BATALLA, R. J. 2020. Effects of Hydropeaking on Bed Mobility: Evidence from a Pyrenean River. *Water,* 12**,** 178.

VU, T. T. H., TIAN, G., KHAN, N., ZADA, M., ZHANG, B. & NGUYEN, T. V. 2019. Evaluating the International Competitiveness of Vietnam Wood Processing Industry by Combining the Variation Coefficient and the Entropy Method. *Forests,* 10**,** 901.

WALTON, C. R., ZAK, D., AUDET, J., PETERSEN, R. J., LANGE, J., OEHMKE, C., WICHTMANN, W., KREYLING, J., GRYGORUK, M. & JABŁOŃSKA, E. 2020. Wetland buffer zones for nitrogen and phosphorus retention: impacts of soil type, hydrology and vegetation. *Science of the Total Environment,* 727**,** 138709.

WANG, X. & YIN, Z.-Y. 1997. Using GIS to assess the relationship between land use and water quality at a watershed level. *Environment International,* 23**,** 103-114.

WATERS, D., CARROLL, C., ELLIS, R., MCCLOSKEY, G., HATELEY, L., DOUGALL, C. & FENTIE, B. 2013. Catchment modelling scenarios to inform GBR water quality targets. *20th Internation Congress on Modelling and Simulation.* Adelaide, Australia.

WATERS, D. K., JIAO, F., CHEN, M., YNG, J., PAPE, S., ZHANG, H., LI, J. & NASH, D. 2012. Application of Source to investigate nutrient management options for the Dongshan Peninsula, Suzhou China. eWater Cooperative Research Centre.

WELSH, W. D., VAZE, J., DUTTA, D., RASSAM, D., RAHMAN, J. M., JOLLY, I. D., WALLBRINK, P., PODGER, G. M., BETHUNE, M., HARDY, M. J., TENG, J. & LERAT, J. 2013. An integrated modelling framework for regulated river systems. *Environmental Modelling & Software,* 39**,** 81-102.

WESSTRÖM, I., JOEL, A. & MESSING, I. 2014. Controlled drainage and subirrigation – A water management option to reduce non-point source pollution from agricultural land. *Agriculture, Ecosystems & Environment,* 198**,** 74-82.

WHEELER, K. G., ROBINSON, C. J. & BARK, R. H. 2018. Modelling to bridge many boundaries: the Colorado and Murray-Darling River basins. *Regional Environmental Change,* 18**,** 1607-1619.

WHITEHEAD, P. G., JIN, L., BUSSI, G., VOEPEL, H. E., DARBY, S. E., VASILOPOULOS, G., MANLEY, R., RODDA, H., HUTTON, C., HACKNEY, C., TRI, V. P. D. & HUNG, N. N. 2019. Water quality modelling of the Mekong River basin: Climate change and socioeconomics drive flow and nutrient flux changes to the Mekong Delta. *Science of The Total Environment,* 673**,** 218-229.

WILBERS, G.-J., BECKER, M., NGA, L. T., SEBESVARI, Z. & RENAUD, F. G. 2014. Spatial and temporal variability of surface water pollution in the Mekong Delta, Vietnam. *Science of The Total Environment,* 485–486**,** 653-665.

WILD, T. B., REED, P. M., LOUCKS, D. P., MALLEN-COOPER, M. & JENSEN, E. D. 2019. Balancing Hydropower Development and Ecological Impacts in the Mekong: Tradeoffs for Sambor Mega Dam. *Journal of Water Resources Planning and Management,* 145**,** 05018019.

WILLIAMS, J. M. 2019. The hydropower myth. *Environmental Science and Pollution Research*.

WILLIAMS, J. R. & BERNDT, H. D. 1997. Sediment yield prediction based on watershed hydrology. *Trans. ASAE,* 20**,** 1100-1104.

WILLIAMS, J. R., NICKS, A. D. & ARNOLD, J. G. 1985. Simulator for Water Resources in Rural Basins. *Journal of Hydraulic Engineering,* 111**,** 970-986.

WOOLSON, R. 2007. Wilcoxon signed-rank test. *Wiley encyclopedia of clinical trials***,** 1-3.

WORLD BANK GROUP 2015. World Bank Open Data.

WU, J. C. 2021. Asia and the Pacific. *USGS minerals yearbook 2017-2018.* USGS National Minerals and Information Center.

XIE, M. Integrated water resources management (IWRM)–introduction to principles and practices. Africa Regional Workshop on IWRM, Nairobi, Oct, 2006.

XU, C., XU, Z. & YANG, Z. 2020. Reservoir operation optimization for balancing hydropower generation and biodiversity conservation in a downstream wetland. *Journal of Cleaner Production,* 245**,** 118885.

XU, T. & VALOCCHI, A. J. 2015. Data-driven methods to improve baseflow prediction of a regional groundwater model. *Computers & Geosciences,* 85**,** 124-136.

XU, Z. X., PANG, J. P., LIU, C. M. & LI, J. Y. 2009. Assessment of runoff and sediment yield in the Miyun Reservoir catchment by using SWAT model. *Hydrological Processes,* 23**,** 3619-3630.

YADAV, S., BABEL, M. S., SHRESTHA, S. & DEB, P. 2019. Land use impact on the water quality of large tropical river: Mun River Basin, Thailand. *Environmental Monitoring and Assessment,* 191.

YAEGER, M. A., SIVAPALAN, M., MCISAAC, G. F. & CAI, X. 2013. Comparative analysis of hydrologic signatures in two agricultural watersheds in east-central Illinois: legacies of the past to inform the future. 17**,** 4607-4623.

YAN, Q., LEI, T., YUAN, C., LEI, Q., YANG, X., ZHANG, M., SU, G. & AN, L. 2015. Effects of watershed management practices on the relationships among rainfall, runoff, and sediment delivery in the hilly-gully region of the Loess Plateau in China. *Geomorphology,* 228**,** 735-745.

YASMI, Y., DURST, P., HAQ, R. U. & BROADHEAD, J. 2017. Forest change in the Greater Mekong Subregion (GMS): An overview of negative and positive drivers. Bangkok, Thailand: The Food and Agriculture Organization of the United Nations (FAO).

YEOPHANTONG, P. 2014. China's Lancang Dam Cascade and Transnational Activism in the Mekong Region: Who's Got the Power? *Asian Survey,* 54, 700-724.

YILMAZ, K. K., GUPTA, H. V. & WAGENER, T. 2008. A process-based diagnostic approach to model evaluation: Application to the NWS distributed hydrologic model. *Water Resources Research,* 44, n/a-n/a.

YOSHIDA, Y., LEE, H. S., TRUNG, B. H., TRAN, H.-D., LALL, M. K., KAKAR, K. & XUAN, T. D. 2020. Impacts of Mainstream Hydropower Dams on Fisheries and Agriculture in Lower Mekong Basin. *Sustainability,* 12, 2408.

YOUNG, R. A., ONSTAD, C. A., BOSCH, D. D. & ANDERSON, W. P. 1989. AGNPS: A nonpoint-source pollution model for evaluating agricultural watersheds. *J. SOIL WATER CONSERVAT.,* 44, 168-173.

YOUNG, R. A. & SHEPHERD, R. G. AGNPS - Agricultural Nonpoint Source Model. Workshop on Computer Applications in Water Management, 1995 Fort Collins, Colorado.

YU, D., SHI, P., LIU, Y. & XUN, B. 2013. Detecting land use-water quality relationships from the viewpoint of ecological restoration in an urban area. *Ecological Engineering,* 53, 205-216.

YU, S., XU, Z., WU, W. & ZUO, D. 2016. Effect of land use types on stream water quality under seasonal variation and topographic characteristics in the Wei River basin, China. *Ecological Indicators,* 60, 202-212.

YU, Y., ZHAO, J., LI, D. & WANG, Z. 2019. Effects of Hydrologic Conditions and Reservoir Operation on Transboundary Cooperation in the Lancang–Mekong River Basin. *Journal of Water Resources Planning and Management,* 145, 04019020.

YÜKSEL, I. 2010. Hydropower for sustainable water and energy development. *Renewable and Sustainable Energy Reviews,* 14, 462-469.

YUN, X., TANG, Q., WANG, J., LIU, X., ZHANG, Y., LU, H., WANG, Y., ZHANG, L. & CHEN, D. 2020. Impacts of climate change and reservoir operation on streamflow and flood characteristics in the Lancang-Mekong River Basin. *Journal of Hydrology,* 590**,** 125472.

ZHANG, L., PANG, M., WANG, C. & ULGIATI, S. 2016. Environmental sustainability of small hydropower schemes in Tibet: An emergy-based comparative analysis. *Journal of Cleaner Production,* 135**,** 97-104.

ZHANG, M., LIU, N., HARPER, R., LI, Q., LIU, K., WEI, X., NING, D., HOU, Y. & LIU, S. 2017. A global review on hydrological responses to forest change across multiple spatial scales: Importance of scale, climate, forest type and hydrological regime. *Journal of Hydrology,* 546**,** 44-59.

ZHANG, X. & LIU, H. 2020. Analysis of drought character in the Mekong River Basin. *Flood Prevention and Drought Relief in Mekong River Basin.* Springer.

ZHOU, T., HU, W. & YU, S. 2019. Characterizing interactions of socioeconomic development and environmental impact at a watershed scale. *Environmental Science and Pollution Research*.

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. *Proceedings of the National Academy of Sciences,* 109**,** 5609-5614.