Environmental Changes in Tonle Sap Lake and its Floodplain

Status and Policy Recommendations

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Tonle Sap Lake

Establishment of Environmental Conservation Platform of Tonle Sap Lake

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Editors

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Although every effort is made to ensure objectivity and balance, the results, conclusion and recommendations in this publication should be understood to be those of the authors and editors and do not imply endorsement or acquiescence by JICA, JST, IGES, Tokyo Tech, ITC or any other agencies.

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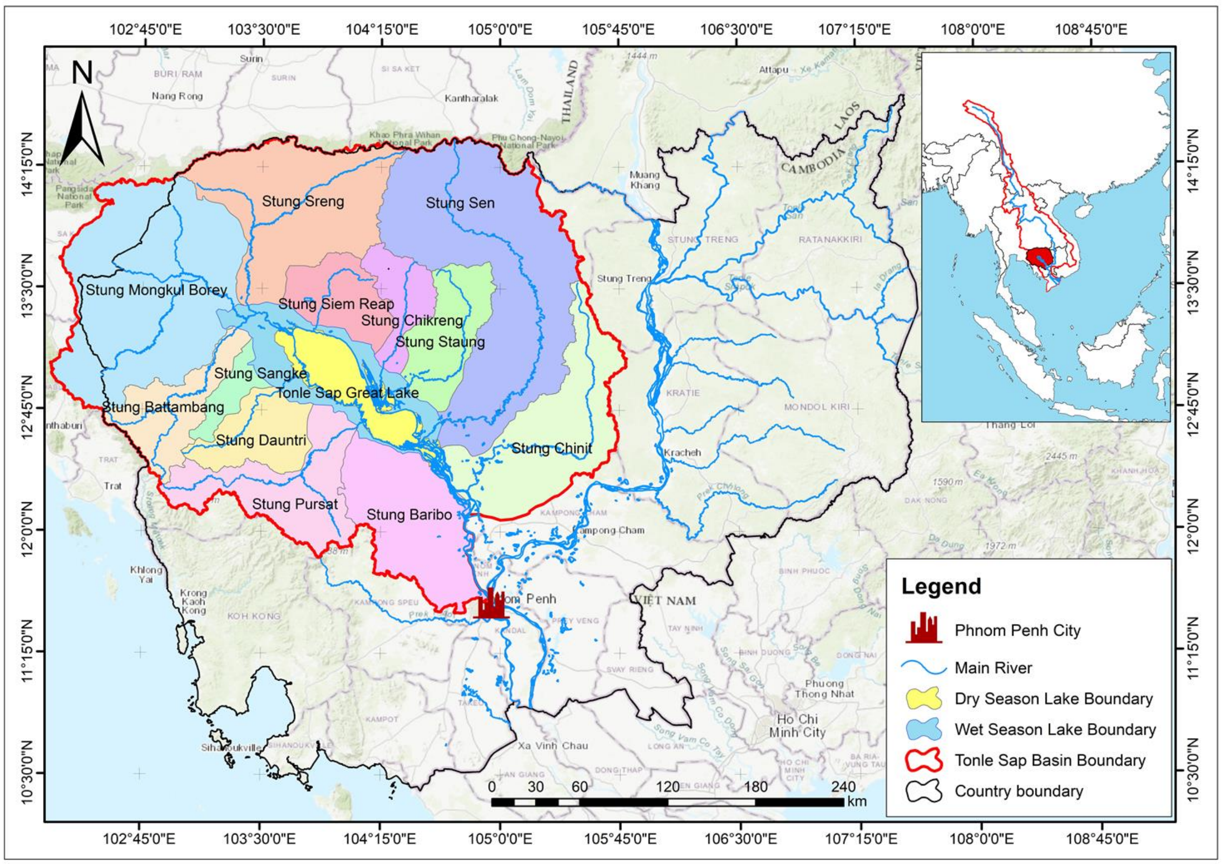
FACTSHEET OF TONLE SAP LAKE

General	Dry season	Wet season
Area (km^2)	~ 2,500	~15,278
Length (km)	~120	~250
Width (km)	3–35	~100
Depth (m)	1–2	8–11
Volume (million m^3)	1300	80,000
Average rainfall (mm/year)	1300–1500	
Discharge (m^3/sec)	380–8176 (outflow)	104–7032 (inflow)
Total suspended solids (mg/l)	4–652	3–126

General	
Size	Largest in SE Asia
Water sources (Rainfall, %)	12.5
Water sources (Mekong River inflow, %)	53.5
Water sources (Tributaries, %)	34
Residence time (year)	<1
Sediment (million ton/year)	7–9
Unique characteristics	Flood pulse (reverse flow)
UNESCO Tonle Sap Biosphere Reserve	



Basins' profile	
Area (km^2)	~85,786
# of sub-basins/ main tributaries	11
Forest (%)	~55
Flooded Forests (ha)	608,188 (~3%)
Agriculture (%)	~45
Urban (%)	<0.5

Biodiversity	
Fish species	175
Reptiles	42
Birds	225
Mammals	46
Plant species	~370

Socio-economy	
Population living around the lake (millions)	~5
Fishing families	135,000
# Land based villages	948
# Land and water based villages	36
# of floating (water based) villages	53
Fish catch (1000 tons/year)	289–431

(Data sources: Tonle Sap Authority website, project publications)

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Table of Contents

FOREWORD

Tonle Sap Lake is the largest freshwater lake in South East Asia, and is instrumental in Cambodia's social, economic, cultural, and environmental development. The lake's tremendous natural capital provides food security and supports the lives of the people throughout Cambodia. The lake is also a cultural heritage and part of the history defining the national identity of Cambodia.

Today, the lake is under multiple pressures from population growth, development activities, forest degradation and land cover changes, exploitation of its resources and disposal of waste. Furthermore, transboundary impacts such as climate change and unwise development of water infrastructure in upstream countries could seriously disrupt the unique flood-pulse system and threaten the integrity of this massive wetland system and the overall sustainable development of the country. Escalation of negative impacts on the lake's ecosystem and environment might eventually be linked to increasing poverty and vulnerability of the people who are directly dependent on the lake resources for their livelihoods.

The role of research, scientific innovation and advancement of in-house research capacity are crucial for strengthening the sustainable management and conservation of the lake's environment and its natural resources. In order to address environmental problems through research and capacity building, the project "Establishment of Environmental Conservation Platform of Tonle Sap Lake" under the Science and Technology Research Partnership for Sustainable Development (SATREPS) program with support from the Japan International Cooperation Agency (JICA) and Japan Science and Technology Agency (JST) has been initiated for the period 2016 to 2020. Under the project, researchers and students in Japan and Cambodia as well as staff and experts from key agencies in Cambodia such as the Ministry of Environment (MOE), Tonle Sap Authority (TSA), and Ministry of Water Resources and Meteorology (MOWRM) and other organizations have been directly involved in research collaboration, capacity building and various consultations.

This policy report aims to disseminate the research accomplishments and share policy-relevant findings of the project to the relevant decision makers and stakeholders. The report introduces the major issues of environmental impact on the livelihoods of the local residents on and around the lake, using the latest research methods that have been developed or applied in this project to examine and address the environmental problems. It covers hydrology and hydrodynamics, water quality assessment, micro-pollutants (heavy metals and pesticides), and microbial pollution. The report stresses the need to pursue solution-oriented research; to use the scientific findings and tools for decision making; and to find measures to reduce health risks from microbes, pesticides and potential blooms of toxic cyanobacteria.

We hope that the recommendations in this report will support the policy and administrative efforts for the conservation and management of the lake. We believe it provides a substantial contribution to the understanding of environmental problems and challenges faced by Tonle Sap Lake, and provides useful countermeasures.

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LIST OF FIGURES, TABLES AND BOXES

ABBREVIATIONS AND ACRONYMS

1D	One Dimensional
2D	Two Dimensional
2D-ILE	Two Dimensional Local Inertial Model
3D	Three Dimensional
ADCP	Acoustic Doppler Current Profiler
AIQS-DB	Automated Identification and Quantification System with a Database
BOD	Biological Oxygen Demand
CFU	Colony Forming Unit
COD	Chemical Oxygen Demand
CS	Cross Section
DDT	Dichlorodiphenyltrichloroethane
DEM	Digital Elevation Model
DVEL	Difference Between EVI and LSWI
DO	Dissolved Oxygen
DR	Dynamic Ratio
EC	Electrical Conductivity
ELC	Economic Land Concession
EVI	Enhanced Vegetation Index
GAP	Good Agricultural Practices
GBHM	Geomorphology-based Hydrological Model
GC-MS	Gas Chromatography–Mass Spectrometry
I-geo	Geo-accumulation Index
IPM	Integrated Pest Management
ITC	Institute of Technology Cambodia
JICA	Japan International Cooperation Agency
JST	Japan Science and Technology Agency
LIE	Local Inertial Equation
LSWI	Land Surface Water Index
MODIS	Moderate Resolution Imaging Spectroradiometer
MRC	Mekong River Commission
MOE	Ministry of Environment
MOEYS	Ministry of Education, Youth and Sports
MOWRM	Ministry of Water Resource and Meteorology
NGS	Next-Generation Sequencing
ORP	Oxidation-Reduction Potential
PLI	Pollution Load Index
RUPP	Royal University of Phnom Penh

SAR	Synthetic Aperture Radar
SATREPS	Science and Technology Research Partnership for Sustainable Development
SS	Suspended Solids/Sediments
SWAT	Soil and Water Assessment Tools
TD	Total Depth
TDS	Total Dissolved Solid
TP	Total Phosphorus
TSA	Tonle Sap Authority
TSL	Tonle Sap Lake
TSS	Total Suspended Sediments
TSWEP	Tonle Sap Water Environmental Platform
WASH	Water, Sanitation and Hygiene
WHO	World Health Organization

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EXECUTIVE SUMMARY

Sustainability and resilience of local livelihoods in and around Tonle Sap Lake depend on the state of the lake's environment

Tonle Sap Lake (TSL) is under increasing pressure from pollution, land-use change, climate change, and development activities in the lake, its basin and the Mekong Basin. Recent changes in the lake hydrological system and its floodplains are becoming a great concern for hundreds of communities relying on the lake resources for their livelihoods. The lake has already been experiencing abnormal fluctuation of its unique inflow-outflow system. This has been affecting the inflow of water, sediments, nutrients and migratory aquatic animals which are essential for the ecosystem productivity and fishery-based livelihoods. The lowered fish catch directly impacts the economic profile of the low-income fishing communities living in the lake's floating villages and increases their vulnerability. Pollution from point and non-point sources, eutrophication, poor sanitation, and disposal of untreated wastewater has caused deterioration of water quality in certain parts of the lake. This was found to increase incidences of water-borne diseases, and impact on the ecosystem and the fishery.

The science-policy gap in the conservation and sustainable development of Tonle Sap Lake needs to be filled through a scheme for research collaboration and co-design

Advancing our understanding of the interlinkages between the lake's environment and community livelihood is critical to ensure sustainable development, conserve the ecosystem, and enhance the resilience of the communities that are dependent on the lake's resources. Updated approaches to scientific investigation and use of the latest and most effective techniques should be applied to assess existing and emerging environmental challenges, while findings and potential countermeasures should be conveyed to decision makers and relevant stakeholders. Under the SATREPS project "Establishment of Environmental Conservation Platform of Tonle Sap Lake", an attempt was made to fill the existing knowledge gaps on key environmental issues through research collaboration and technology transfers among the participating institutions and researchers in Cambodia and Japan. This report synthesises the policy relevant achievements and findings of the project, as a means to address the existing science-policy gap.

Hydrological assessments need to be the basis for decision making on a number of environmental issues around TSL including climate change

For a large and hydro-ecologically complex lake, such as TSL, a multi-level hydrological assessment is necessary to visualise changes and impacts at the basin scale. The proposed multi-level modelling has been established and utilised as a useful tool for analysing the inundation, water quality and the water environment in the lake and its floodplain, which allows a comprehensive assessment of changes and impacts on the lake in one (longitudinal), two (longitudinal and lateral), and three dimensions (mixing along longitudinal, lateral and vertical). At the same time, use of the latest environmental data and analysis by combining remote sensing and ground monitoring tools can fill information gaps for executing the above-mentioned modelling tool. The scientific approach developed under this project could be utilised as a solid basis for progressing discussions among riparian countries on transboundary impacts on the lake and assessing future scenarios of changes due to human and climate change factors. In the meantime, it is also essential to advance the capacity for environmental assessment at key research institutions and relevant agencies in Cambodia.

A comprehensive and continuous assessment of water quality is necessary to detect and address problems, while water quality monitoring requires optimisation because of the extensive and complex nature of the lake ecosystem

The availability of scientific data at multiple scales and time periods is key for water quality management for an extensive and complex lake ecosystem like TSL. Monitoring and assessment of water quality requires a standardised and regular process. It has to be guided not only to address short-term and localised pollution, but also to understand long-term trends over several decades. Water quality assessments therefore need to employ a dynamic monitoring protocol (e.g., remote sensing) that is designed to suit a wide range of updated environmental parameters and best available methods to account for their spatio-temporal variabilities.

Ensuring sound sediment dynamics in the lake and its basins is vital for maintaining their physical properties and productivity, and for controlling eutrophication

Heavy sedimentation in the wet season, and resuspension and discharge of sediments in the dry season, are two important processes that define sediment dynamics in TSL. The role of flood plain vegetation is important to reduce sediment resuspension intensity, implying the need to control forest degradation and encroachment of the flooded forest areas. A holistic approach to the management of sediments and nutrients will be necessary to understand and manage its sources, paths and sinks. In the case of TSL, a transboundary approach will be useful to deal with the sediment load caused by soil erosion in China, Lao PDR and western Vietnam, as well as the impacts of water storage dam construction in those areas.

Pesticide contamination in the lake needs policy attention to avoid serious negative impacts on human health and ecosystems

The detection of pesticides in water, sediment and fish samples confirmed their uses and occurrences in TSL and its floodplains. Heavy metal concentration was not found high in water and sediments. Obviously, water is the main exposure pathway due to people's direct interactions and its uses on daily basis such as for transport, swimming, washing, bathing, cooking, and drinking. The detection of pesticides in fish samples, including the banned DDT, are of a serious concern for public health, given the fact that a large number of people consume fish from TSL. In order to formulate preventive measures to reduce the health risks, understanding of the pesticides in TSL environment need to be improved. Continuous monitoring and improvement in research capacity will be necessary to properly assess contamination pathways and health impacts on the people living around the lake as well as through fish consumption. Because of the persistent nature of certain pesticides, efforts need to be enhanced by strengthening regulations on markets and distributions, as well as on how to appropriately use pesticides in an environmentally sustainable manner.

Sufficient policy attention is necessary to find and develop approaches to determine and reduce health risks caused by microbial contamination

Harmful bacteria and algae have been detected in the lake and surrounding waters with the help of a novel analytical approach developed in this project. Their extended survival in the lake water increases the vulnerability of the people living in floating villages. In addition to the intensive investigation of those pathogenic microbes in different seasons, appropriate removal mechanisms should be explored to reduce health risks. Alternatives for safe drinking water, sanitation, hygiene (WASH) and safer disposal of human waste, should be given high priority for floating villages. Proper consideration should be given also to emerging problems such as antibiotic-resistant bacteria, which arise from the increased uses of antibiotics by people, aquaculture and livestock.

An integrated approach for maintaining a unique and precious lake environment needs to be implemented through smooth communication among stakeholders, experts and residents in relevant fields

Environmental problems in TSL are complex and inter-connected. A holistic approach for solving them needs to be implemented for ensuring sustainability and avoiding trade-offs based on the characteristics of TSL and its changing realities, needs, and priorities. Further research activities should be guided on the basis of actual problems and potential scenarios that are critical for the wellbeing and sustainable development of the region. It is advisable to develop appropriate channels and modes of communication to integrate the research outcomes with community livelihoods as well through awareness raising and capacity development, for example by setting up “a committee for environment management of TSL” with stakeholders, experts and residents. In addition, transfer of the research findings in a timely manner is important for meeting needs at national level and improving the resilience and adaptive capacity of the local communities to cope with unexpected environmental changes, including climate change impacts. Advancement of the multi-level hydrodynamic models used in this SATREPS project and their planned integration into Water Environmental Analytical Tool (WEAT), is expected to address multiple environmental issues such as water resources management, sedimentation, eutrophication, organic pollution, microbial contamination, pathogens, and other ecological problems in the future.

In the long term, it is advisable for relevant agencies and stakeholders to provide strong leadership to come up with an integrated perspective that is suitable for TSL to address various environmental issues in a coordinated and sustainable manner.

CHAPTER 1 INTRODUCTION

Binaya Raj Shivakoti[1], Pham Ngoc Bao[1], Hul Seingheng[2], Yoshimura Chihiro[3]

Tonle Sap Lake and its importance for sustainable development of Cambodia

Tonle Sap Lake (TSL) in Cambodia is the largest freshwater body in Southeast Asia. It is a biodiverse natural habitat that is home to a variety of fish, birds, reptiles, mammals, and plants. The lake is an integral part of the Mekong River Basin, which originates in the Himalayas and flows through six riparian countries in Southeast and East Asia: Cambodia, China, Lao PDR, Myanmar, Thailand, and Vietnam. The hydrological cycle of the lake is unique due to a reverse flood pulse into the lake during the peak flood season (May–June) (Uk, et al., 2018). This reverse flow through the Tonle Sap River brings in huge mass of water, sediments, nutrients and migratory fish. The discharge from the lake is virtually blocked by the flood pulse until the flow in the Mekong River subsides (September-October). Such hydrological cycle expands the water surface of TSL by five to six fold on average due to the accumulation of water entering from the Tonle Sap River as well as the inflows from tributaries of the lake basin (TSA, 2015). During the seasonal expansion of the lake surface, vast areas of forests (i.e., flooded forests), wetlands, grassland and fields are inundated, which provides sanctuary and breeding grounds for the migratory fish and other aquatic organisms as well as terrestrial wildlife such as birds, reptiles and mammals. The normal discharge from the Tonle Sap River into the Mekong River restarts during September or October when the water level in the Mekong River starts receding. This gradual discharge from TSL in the dry season is vital for maintaining environmental flows in the downstream areas of the Mekong River.

The hydrological and environmental conditions of TSL and its basins are crucial for sustainable development in Cambodia and the lower Mekong Region, covering more than 47% of the country's surface area. The productivity of TSL and the state of the ecosystem are critical for a number of people who are dependent on fisheries for their livelihood. People living in floating

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villages are directly impacted by changes in the environmental condition of the lake due to their high reliance on the fisheries. Similarly, the fertile floodplains in TSL and its basin are important for a number of farming communities for growing rice, vegetables, and crop fruits. Maintaining a healthy environmental condition in the lake, flooded forests, and farm land is therefore indispensable to sustainable and harmonious balances among aquatic ecosystem, rich biodiversity, and livelihood of the local residents.

Environmental changes in and around Tonle Sap Lake

Numerous human-induced activities are driving rapid changes in the hydrological and ecological condition of TSL. Construction of water storage dams in the upstream area and climate change are transboundary issues, which affect TSL (Uk, et al., 2018). A cascade of hydrological dams are planned or under construction in the upstream countries in addition to the existing dams under the operation in Lao PDR or China. Climate change influences seasonal flow pattern in the Mekong River, directly affecting the water level in the lake (Uk, et al., 2018; Oeurng, et al., 2019). The changing flow conditions, especially the lower flood water level, are threatening the usual reverse hydrological flow, which is crucial for lake productivity due to its effects on inflow of sediment, nutrients, and fish catch.

The increased human activities in the lake and its basins are also directly impacting the lake's environment. With approximately five million people living around the lake (MOP, 2013), population growth and economic activities have resulted in increasing competition among local

fishermen, and the expansion of floating villages and farmlands. As a result, the environmental condition of the lake is negatively impacted by soil erosion, runoff of agrochemicals from fields and deforestation, and fires in flooded forest areas, especially, during dry season. Similarly, disposal of untreated wastewater and solid waste into the tributaries, and improper sanitation in the floating villages, pollute the lake and decrease the water quality in certain areas of the lake. High nutrient loads from point and non-point sources are responsible for the proliferation of algae and water hyacinth. The polluted water poses diversified health risks to the people who are directly interacting with the lake. These environmental changes are likely to intensify unless timely counter-measures are introduced through appropriate policies and programs.

Purpose of the report

Inadequate scientific information is a major barrier to the sustainable management of TSL. Despite a number of studies of TSL, considerable gaps remain between science and policy, especially with regard to the aquatic environment. The knowledge gaps hamper the formulation of science-based mitigation measures and decision making capacity. Research and scientific studies are necessary to narrow the knowledge gaps, for instance, for identifying the root causes and severity of the environmental problems mentioned above. An understanding of the scale and extent of the environmental degradation, and the spread and intensity of the negative impacts on the aquatic ecosystem and dependent livelihoods is essential for articulating mitigation strategies. From a long-term perspective, a systematic mechanism is needed to sustainably manage the lake's aquatic environment by gathering, maintaining, sharing, and discussing the knowledge generated by research, in addition to building up research capacity of relevant institutes and universities in Cambodia.

Japan International Cooperation Agency (JICA) and Japan Science and Technology Agency (JST) have supported the project *"Establishment of Environmental Conservation Platform of Tonle Sap Lake"* under the Science and Technology Research Partnership for Sustainable Development (SATREPS) program of the Japanese government. Under the scheme, a transdisciplinary research consortium involving universities and research institutes in Japan and Cambodia and governmental agencies in Cambodia has implemented the project. In Japan, the project is led by

Tokyo Institute of Technology (Tokyo Tech) in collaboration with the Institute for Global Environmental Strategies (IGES) and Yamagata University (YU). In Cambodia, the Institute of Technology of Cambodia (ITC) is leading the project in collaboration with the Ministry of Environment (MOE), Tonle Sap Authority (TSA), the Ministry of Water Resource and Meteorology (MOWRM), Ministry of Education, Youth and Sports (MOEYS), and the Royal University of Phnom Penh (RUPP). The project aimed at developing a Water Environment Analytical Tool (WEAT) for TSL and establishing an environmental conservation platform. The outcomes of the project, in the long term, are expected to contribute towards establishing state-of-the-art research-oriented facilities in ITC, promoting science-based decision making practices by the Royal Government of Cambodia in managing TSL, and creating a benchmark in freshwater ecology and management studies in Southeast Asia through the proposed Tonle Sap Water Environmental Platform (TSWEP). The research collaboration between Cambodia and Japan provides leverage to enhance the scientific research capability of researchers and technical institutes, such as ITC, in Cambodia. The project has begun to fill the knowledge gaps through various research activities and knowledge outputs - both tacit and explicit - to examine and assess the problems, develop scenarios, find solutions, reach out to the public (through project video and social media), and share the findings.

One of the activities of the project is to engage regularly with policy makers and decision makers of relevant line agencies, such as Tonle Sap Authority (TSA), Mekong River Commission (MRC), MOWRM, and MOE, and communicate the latest research findings of the project to them. The research findings are the basis for relevant policy recommendations to advance the scientific understanding and effectively solve the environmental problems in TSL. As a part of this activity, the objective of this policy report is to share and disseminate policy relevant research findings of the project, up until September 2019, with relevant stakeholders in Cambodia and Japan, as well as other countries facing environmental challenges similar to TSL.

Structure of the report

This report is divided into seven chapters, beginning with this introductory chapter. The second chapter discusses the close relationship between the socio-economic conditions of the local communities and TSL environment, including the impact of environmental changes on livelihoods and fisheries. It also touches on the impacts of climate change on both water security and fishing productivity. The environmental issues identified in the second chapter form the basis for the rest of chapters, which elaborate the state of problems, impacts, and risks. The third chapter discusses hydrological changes in the Mekong River as well as in TSL Basin. The chapter introduces multi-level hydrological modeling for simulating changes in water flows and quality. The fourth chapter highlights the general condition of water quality in TSL and its river basin at different locations and periods. The fifth chapter focuses on the heavy metal and pesticide contamination in different profiles such as water, sediment, and biota (only for pesticides). The sixth chapter assesses health and ecological risks due to microbial contamination. The seventh and final chapter synthesises major findings and key policy recommendations for integrated management of TSL and its basin.

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CHAPTER 2 SOCIO-ECONOMIC DEPENDENCY OF LOCAL COMMUNITIES ON TONLE SAP LAKE

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The environmental status of Tonle Sap Lake (TSL) and its basin is directly related to the socio-economic conditions of the people dependent on the lake's resources. An insightful understanding of socio-economic and environmental changes in the lake and its basin, as well as their causes and the threats they pose to the people's livelihoods is critical for the sustainable management of TSL and its basin as well as for the enhancement of resilience of the related communities.

Communities and their livelihoods

About 1.7 million people are living in 1037 villages of TSL and surrounding floodplains. Fishing villages in TSL can be classified into three types based on their location: water-based village (53 villages), land-based village (948 villages), and water-land based village (36 villages) (**Figure 2.1**). People living in TSL and surrounding floodplains have learned to adapt to the hydrological changes in the lake (Sithirith, 2011).

In the water-based villages, often referred to as floating villages, local people primarily rely on fishing for their livelihoods, due to their physical disconnect from the land. In floating villages, the

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principal mode of transportation for fishing, business, and access to public and private facilities (health care facilities, markets, schools etc.) is boats. Floating villages are mobile throughout the year, and their communities depend on the lake in their day-to-day activities. It is where they drink water, cook food, wash clothes, bathe, and dispose of waste. It is common for the owners of floating houses to shift their location to new fishing areas or to track changes in water level over the year.

(a) (b)

Figure 2.1 (a) Water-land based and (b) water-based communities in and around Tonle Sap Lake (Source: author)

In water-land based villages, people may spend half the year on land during dry season and half on water during the wet season, depending on the seasonal hydrological changes in the lake. In the wet season, the floodwater surrounds the stilt houses that compose these settlements, which are normally built several meters above the ground. During the flooding season, they resemble the water-based floating villages. Although fishing is the primary occupation for local livelihoods, villagers also supplement their incomes through small-scale farming or aquaculture.

In land-based villages, people are primarily engaged in farming as well as occasional fishing activities depending on the water level. While land-based communities benefit from resources of the lake, their activities such as farming, uses of agro-chemicals including pesticides, and disposal of waste and wastewater, negatively affect the environmental condition of the lake.

The livelihood setting in three kinds of villages are well adapted to the dynamics of the flood pulse and the subsequent water drainage in the dry season. Local residents in all three kinds of villages are heavily dependent on the resources and services that the lake and its floodplains provide, such as agricultural products, fish, other aquatic animals, and plants. As a result, these people are also vulnerable to the negative pressures on lake resources, degradation of flooded forests, and resulting changes.

Impacts of climate change and upstream dams on water security and fishing

The livelihoods and lifestyles of the local residents of TSL could be directly affected by the impacts of climate change, especially, those caused by disruptions in the hydrological cycle of TSL. Extreme weather conditions or unexpected events such as heavy storms causing high waves and severe floods (e.g. the flood events in 2000 and 2011), and droughts, occur more frequently and cause considerable economic impacts on particularly poorer households, according to local communities living in and around TSL. This is critical for a large population depending on the resources and services of TSL basin, the national agriculture and food security, terrestrial and freshwater ecosystems, and human health. Among the three types of surveyed villages, the water-based communities (e.g. Kampong Luong) are physically less affected than land-based and water-land based communities. However, high waves caused by heavy storms add new challenges to small-scale fishing activities and houses in floating villages and water-land based villages. The higher tides could also damage and displace floating houses.

Meanwhile, an assessment of climate change impact on river flows in 11 sub-basins contributing to TSL, using the Soil and Water Assessment Tool (SWAT) model, indicated a likely decrease in flows in both the wet and dry seasons (Oeurng et al., 2019). The projected river flows from three General Circulation Models (GFDL-CM3, GISS-E2-R-CC and IPSL-CM5A-MR) for three time horizons (2030s, 2060s and 2090s) indicate a likely decrease in both the wet and dry season flows. The mean annual flow reductions range from 9 to 29% for the 2030s, 10 to 35% for the 2060s, and 7 to 41% for the 2090s projections, respectively. A decrease in extreme river flows is also expected, implying a decline in flood magnitudes and an increase in drought occurrences throughout the lake basin. Reduced flood peaks and decreasing base flows could threaten not only river ecosystems but also socio-economic development, particularly in agriculture and aquaculture. These results have provided an insight that could inform planning and adaptation strategies.

In addition, Suif et al. (2017) have analysed the impacts of climate change, under different dam construction scenarios, on discharge and suspended sediment load and its concentration in the Mekong River Basin using a distributed process-based model. The study examined climate change scenarios of integrating increased radiative forcing values for the near (2041-2050) and far (2090-2099) future. According to results based on outputs from MIROC and HadGem2 climate models, climate change may increase the average annual river discharge at Phnom Penh in both the near and far future. In addition, for a given number of dams, suspended solid load and its concentration at the Phnom Penh station increased with the escalating impact of climate change. For a given climate change scenario, load and concentration decreased with an increasing number of dams. However, it was noted that differences in projections by climate models caused considerable uncertainties in the projected variables (rainfall, sediments and discharge). Such uncertainties should be well considered when sediment management strategies are formulated. Since sediment dynamics in shallow lakes greatly influence nutrient dynamics (as described further in Chapter 4), the implications of this study are useful for understanding the influence of climate change on ecosystem productivity in the lake.

Declining fish catch and socio-economic impacts

In this project, social surveys were conducted - in land based villages in Kampong Luong, water based villages in Chhnok Tru and land-water based villages in Muk Wat - to understand the relationship between people's livelihoods and the lake environment. Results of the surveys indicated that fisheries are crucial and form either the primary or secondary income source in all surveyed communities. For example, the results from the household survey in Chhnok Tru in 2018 revealed that 74% of the households relied on small-scale fishing as the main source for income and nutrition. Their income is directly dependent on the value of daily fish catch, which typically ranges between 3 and 20 USD/day. For many households, fishing is the only revenue stream to support essential household expenditures. Meanwhile, rice cultivation is the main livelihood and income source for the majority of households in land-based and water-land based villages. Although fishing is the secondary source of income, it is still a vital source of regular revenue, as well as nutrition, to the households

The rapid fall in quantity and quality of fish catch is making it difficult to support essential household expenses. The intensification of fishing efforts by several fishermen has led to a vicious circle, exerting increasing pressure on fishing grounds. Decreased catch also means wasted time and increased financial burden due to the cost of fuel for fishing boats and lost opportunity costs. According to local communities, the decline in fish catch can be attributable to several factors. Inappropriate fishing methods (ex. illegal fishing gear) and unequal access to fishing grounds are responsible for imbalanced fish catches. Environmental and hydrological factors are exacerbating the declined fish catches. The deterioration of fish habitat due to pollution, eutrophication, and forest degradation in seasonally inundated area contributes to lower fish catches. Through focus group discussion, we found that the communities are also experiencing decreased fish catches due to inadequate water levels and consequently increasing pressure on adjacent fishing grounds. Water is reportedly shallower than the typical level (i.e. 9-10 meters) during the peak flooding season, with the deeper water being ideal for a normal to good harvest.

It is evident that the fishing communities lack good sources for alternative income other than selling the lake's fish. Because of their high dependency on fish catch for the daily income, these communities are increasingly vulnerable to the consequences of continuous disruption to the hydrological cycle. A hydrological assessment is necessary to determine how the water level affects sedimentation and nutrient transport in TSL and to determine its links with the reported decline in fish catch.

Impacts of environmental changes on health and livelihoods

The lifestyles of the local residents of TSL are intimately connected with the lake environment. Our social survey revealed that pollution and deterioration of water quality in both TSL and Tonle Sap River, and its effect on health and their living environment, greatly concerned local communities. The main causes of this water quality decline include the discharge of untreated wastewater and the disposal of solid waste into tributaries, runoff of agro-chemicals, poor sanitation and hygiene conditions near floating villages, and direct waste disposal in the vicinity of the floating houses. The main reason for poor sanitation and hygiene and disposal of wastes could be attributed to a lack of affordable and effective countermeasures.

Effluent from toilets in floating villages is discharged directly into the lake due to the lack of facilities for safe storage, treatment and disposal. Due to the nature of housing and lifestyle, people have direct contact with the polluted water, including through washing raw food and fish

(**Figure 2.2**), bathing, hand washing, and swimming. They face high risk of infection from waterborne diseases particularly during the dry season (Ung, et al. 2019). Due to the primary and secondary contamination, we found that at least some household members, especially children, had water borne illnesses and needed to frequently visit clinics or hospitals. These medical costs drain their hard-earned income, which further increases their financial vulnerability.

Figure 2.2 Chhnok Tru village (Source: authors)

Severe water pollution in certain locations intensifies during dryer periods with low water levels (Nov-April), and also affects fish population due to the proliferation of algae and water hyacinth. The communities have to travel in search of better fishing grounds due to pollution in nearby waters, raising fuel cost for the fishing boats, requiring extra physical labor, and risking boat accidents during wind tides.

It is essential for local communities in and around TSL to improve their livelihood condition and environment. Some of the common and simple options adopted by households are seasonal migration to cities and industrial estates for part-time or short-term employment, work in other villages or provinces, or off-farm businesses (e.g. running grocery stores). Improving and strengthening housing structures, using either bamboo or wood, is another measure adopted to cope with high tides and storms. The study found that villagers can access micro-credit from institutions with low interest rates, which can help them to finance or invest in supplementary livelihoods and buy new fishing gear. We did not investigate the effectiveness of micro-finance in detail, including potential negative impacts such as loan default and associated problems. Yet, it is obvious that the communities need to boost their resilience and adaptive capacity and diversify their income bases and livelihood support options to cope with unexpected environmental changes and climate change impacts.

Key findings and recommendations

- The socio-economic condition of the local residents of TSL directly depends on interlinked environmental and hydrological changes. Advancing our understanding on the interlinkages is critical to find better livelihood options and to ensure the sustainability of the local communities of TSL.
- It is important to integrate the identified socio-economic issues and challenges into the assessment of the lake environment in order to find scientific solutions to community problems, for example through the application of hydrological modelling, water quality monitoring and assessment, and assessment of health impacts.

- The findings suggest efficient measures for the prevention of environmental degradation are needed. Those measures could be better land-use and land-cover management in the basins, introduction of best management practices for clean water storage and distribution, improvement for accessing safe drinking water, sanitation and hygiene (WASH) and waste management.
- Awareness raising and capacity development of the local communities on effective measures to improve their resilience and adaptive capacity are necessary. That would allow the local residents to better cope with unexpected environmental changes and climate change, improve WASH conditions, diversify their income sources, and make resettlement in safer locations, which eventually reduces pressures on the lake.

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CHAPTER 3 HYDROLOGICAL CHANGES IN THE MEKONG RIVER AND TONLE SAP LAKE BASIN

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Tonle Sap Lake (TSL) is an integral part of the Mekong River Basin. Hydrological and land-use changes in the basin have a direct influence on the state of the lake. Cambodia, Lao PDR, Thailand and Vietnam jointly established the Mekong River Commission (MRC), aiming to manage shared water resources and to ensure the sustainable management of the Mekong River, including TSL. Despite past and on-going cooperation under the MRC, a focused collaboration to address the transboundary impacts on TSL environment is necessary. The Mekong Region is one of the fastest-growing regions in Asia and many development activities are ongoing along the Mekong River. For instance, development of a cascade of dams and extraction of water for irrigation and water supply are directly impacting river runoff, fish migration and breeding, and aquatic ecosystems. Land-use changes in the basin also have a significant impact on rainfall runoff such as extreme floods, or inflows of sediments, nutrients and other chemical substances. The changes also include rapid development along the stream and in the basin, and intensification of land-use and

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deforestation for agriculture. Climate change threatens the seasonal hydrological cycle of the Mekong River and TSL due to changes in the rainfall patterns such as frequency and intensity.

The extent of transboundary impacts on unique dynamics of the lake is yet to be fully understood. Despite a growing body of research, impacts on the hydrological and ecological balance (e.g. depth and dynamic area of the lake, sediment and nutrient transport, aquatic biodiversity and fish catch) needs further investigation. Improving the scientific understanding of the recent changes in the hydrological condition of the Mekong River and TSL is crucial to help policy makers to identify appropriate responses to minimise transboundary impacts and to devise appropriate integrated lake-basin management strategies. In particular, there is considerable uncertainty which can be resolved through mathematical modelling on direction and magnitude of the changes in river flow that may result from climate change. Hydrological studies will allow local authorities and governmental institutions to identify optimum environmental flow condition to be maintained, and could form a basis for the integrated management of river flows to allocate the limited supply of water to people, agriculture, industry, energy, and ecosystems. A better understanding of the changes within the lake is useful to assess the impacts on the lake ecosystem and capture fishery, upon which the livelihoods of millions of people depend.

A multi-level hydrological assessment was employed in the SATREPS project as shown in **Figure 3.1**. The main aim was to undertake a comprehensive assessment of the impacts on the lake at different scales, both laterally and vertically. The latest advanced tools for hydrological monitoring and assessment were used in the process of co-designing and implementing the research activities.

Changes in flow conditions and water level in the lake

A combination of the latest and advanced modelling, satellite remote sensing and in-situ

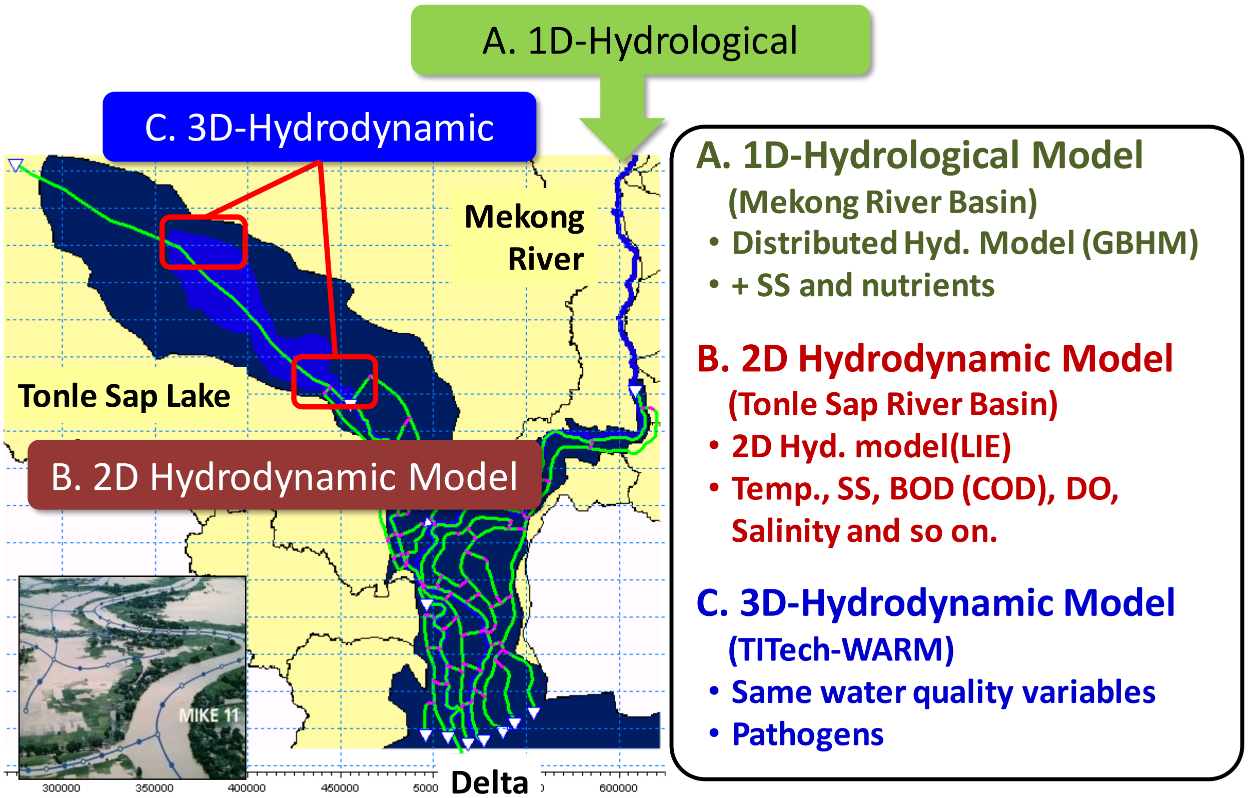


Figure 3.1 A multi-level hydrological assessment model employed in the SATREPS project (Source: author)

observation techniques provides an effective numerical simulation of surface water flows in both longitudinal and lateral dimensions. A single dimensional model, such as MIKE-11, was setup to simulate the time series of flow conditions with its upstream boundary at Kratie in the Mekong River, and its downstream boundaries at Tan Chau in the Mekong River and at Chau Doc in the Bassac in Vietnam as shown in **Figure 3.2**. We compared the simulated and observed water level data of 1998-2002 to evaluate the accuracy of simulation by the model. In order to ensure the applicability of the model to the most recent flow condition, direct observation of a time-series of water level was carried out for one year (March 2017 to March 2018) using an Acoustic Doppler Current Profiler (ADCP) (**Box 3.1**).

Similarly, we used Geomorphology-based Hydrological Model (GBHM) to simulate the flow from tributaries into the TSL Basin. Daily discharges were simulated over ten years and compared with the observations collected at the evaluation sites of the Chinit River and the Sen River. Through the integration of the GBHM for simulating inflows from tributaries and MIKE 11 for simulating longitudinal water flows as boundary condition, a two-dimensional local inertial model (2D-ILE) enables tracking dynamics of the surface water and flowing substances in both longitudinal and lateral dimensions.

The resultant integrated model allows capture of the temporal changes of water level and the seasonal backwater flows along the Tonle Sap River (**Figure 3.3**).

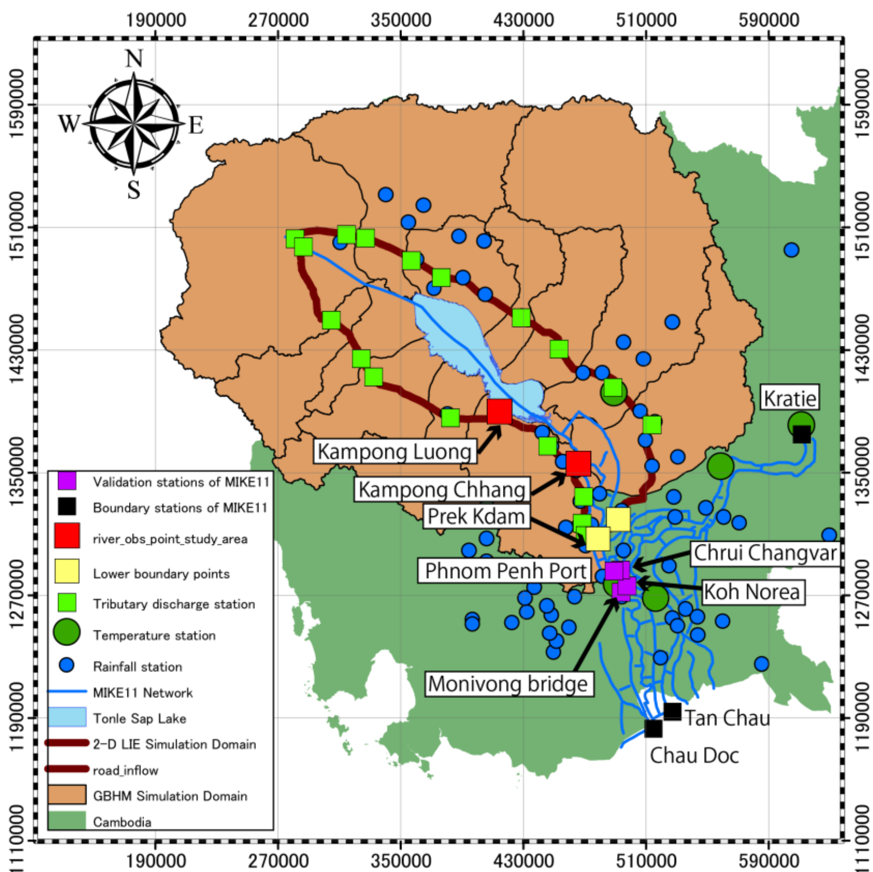


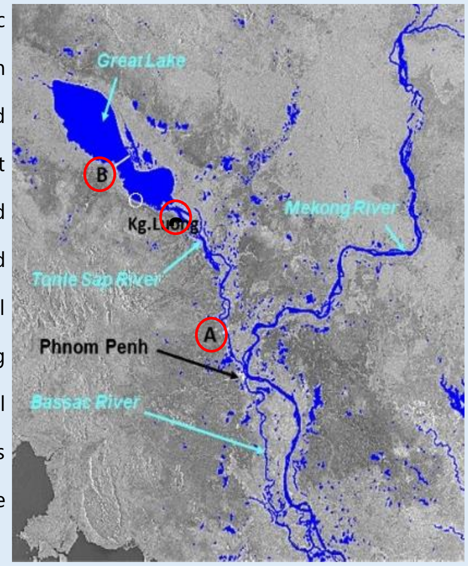
Figure 3.2. Simulation domain and cascade system among GBHM, MIKE 11 and 2D-LIE (Source: Tanaka et al., 2018)

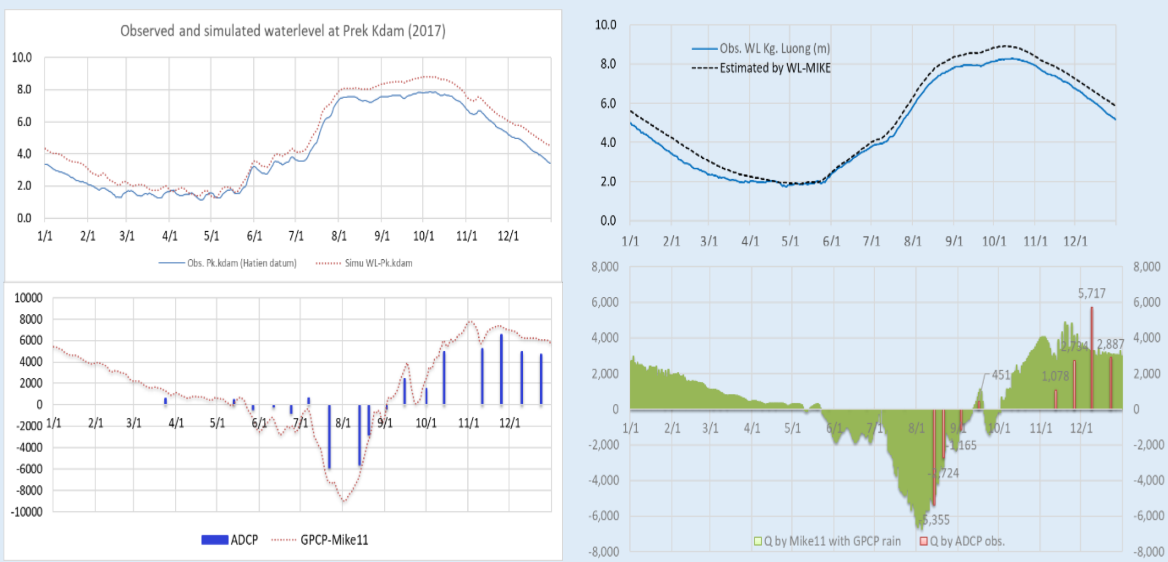
The Figure 3.3 shows that water-stage at the Kampong Luong station increased (solid line) and decreased (dashed line) by ±5% (red), ±10% (blue), ±20% (green), ±30% (yellow), and ±40%

(purple), indicating higher sensitivity of the water-stage to lake water level during the rainy season. The black lines show simulated results with original tributary discharges.

Box 3.1: Use of Acoustic Doppler Current Profiler (ADCP) (Source: authors)

ADCP is a multilayered flowmeter utilizing the Doppler Effect of ultrasonic wave. The ADCP used in this study is River Surveyor M9, of SonTek-Xylem Company. The M9 has eight transducers for flow velocity measurement and one transducer for water depth observation. The observation was carried out with a small boat towing a float (HydroBoard II) equipped with the ADCP and RTK-GPS. Three observation points, at Prek Kdam (A), Reang Til (B), and Chhnok Trou (C) were selected. Prek Kdam is an important water level observation station in the Tonle Sap River, connecting TSL with the Mekong River, and it is also the downstream boundary of the two-dimensional hydraulic model under development in the SATREPS project. Reang Til is located slightly south of the center of TSL and a short distance from the opposite shore in the dry season.





A. Prek Kdam

B. Reang Til

Comparison of observed discharge by ADCP and simulated discharge by 1D model Mike11

The models, as an abstract representation of the reality, have several limitations and rely on assumptions about the unknown factors. One of the limitations affecting the efficacy and accuracy of the modelling approach in our case is unavailability of adequate hydrological observations in

TSL and its floodplain area. Our existing ability to understand hydrological characteristics based only on on-the-ground observations is quite limited because of the practical constrains of installing, operating and maintaining observation points in a large river basin system like that of the Mekong River and for an extensive lake system like TSL.

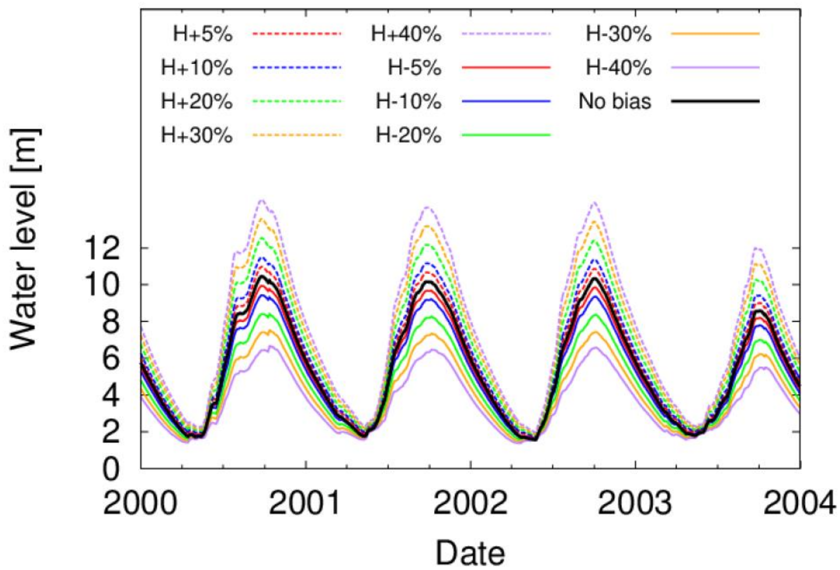


Figure 3.3 Water-stage at the Kampong Luong station (Source: Tanaka et al., 2018)

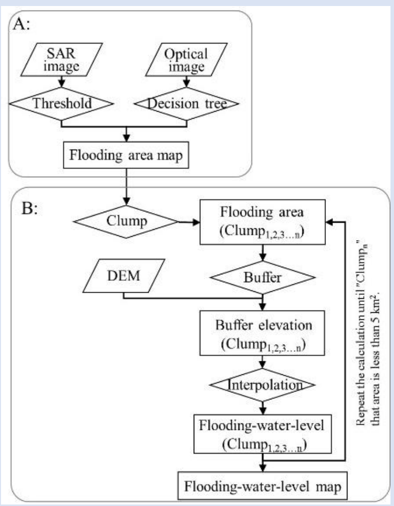
The processing of satellite images, including real-time images, and a Digital Elevation Model (DEM) is proposed as an alternative to address data limitations in understanding the spatial and temporal variability of flooding. A floodwater-level estimation method in TSL and its floodplain area was developed by using only satellite images and DEM. The process involves the use of two types of satellite images with different characteristics (Synthetic Aperture Radar [SAR] and optical remote sensing data) and verified by comparison with the ground-truthed floodwater levels (**Box 3.2**). The resultant estimated water level can be used to verify and adjust the models mentioned above.

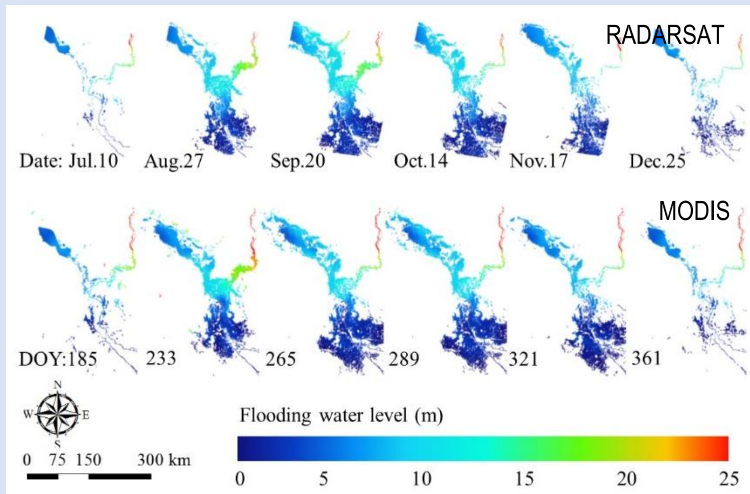
Assessing the impacts of land-use changes on hydrology

A study, conducted under the SATREPS project, focusses on the hydrological impacts of the change in the land use in the Stung Sen sub-basin of TSL in North West Cambodia (**Figure 3.4**).

This study analysed the hydrological problems due to land-cover changes in the future. It uses the land system change model, “CLUMondo” (van Asselen & Verburg, 2012), to make projections of land-use change between 2014 and 2030 under two different scenarios. The first is a GREEN scenario set for situation when dense forests are preserved in the country. The second is an ELC (Economic Land Concession) scenario, resembling “business-as-usual”, which allows the studied

Box 3.2: Flooding area and flood water-level analysis using satellite image and DEM (Source: authors)





Methodology to analyse flooding area

Distribution of floodwater level by RADARSAT and MODIS

Only the satellite images and the DEM were used in these analyses. RADARSAT was selected as a SAR image, MODIS was selected as an optical image, and SRTM was used as a DEM. Available field information was used to separate “flooded area” from “non-flooded area.” When using optical images, the flood areas are identified by an Enhanced Vegetation Index (EVI), Land Surface Water Index (LSWI), and the difference between them (DVEL). Floodwater level was calculated based on the relation between the extent of the flood area and the elevation. This process can be divided into three steps. The first step is a clumping procedure, which is used for classifying data of the flood area into unique categories by grouping grids that form physically discrete areas. The second step is the extraction of edges of the flood area by using a buffering technique. The third step is spatial interpolation to estimate flood levels (flood stages). The results of the RADARSAT and MODIS images were considerably similar at floodplain points, as indicated by the similar RMSE values. The developed method has good accuracy when the target area is whole floodplain area including TSL and Phnom Penh. The estimated flood area (flood extent) is useful for validating the 2-dimensional hydraulic model, which can simulate longitudinal and horizontal flows.

areas to be patched for businesses without restrictions on environmental or conservation. The two land use change scenarios are analysed in the tool, ArcSWAT, to assess implications on hydrology.

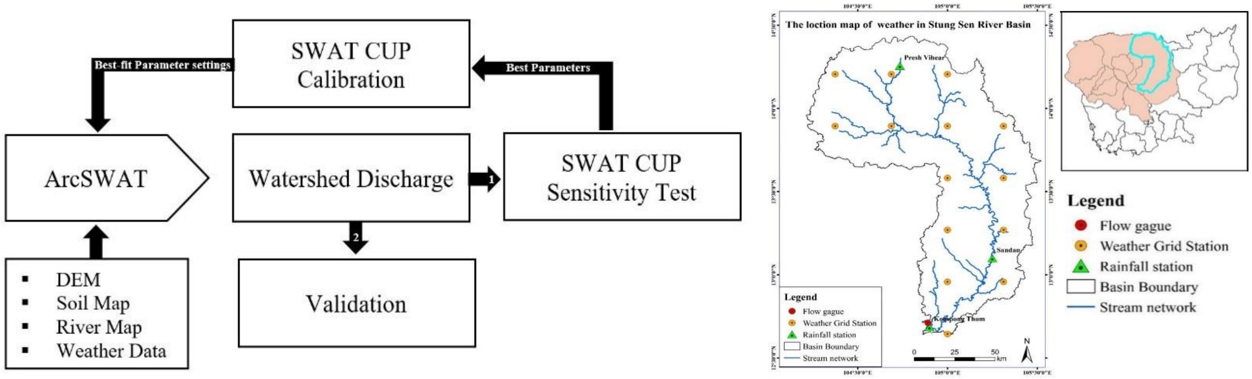


Figure 3.4 Assessment methodology of future land use change scenario impact on hydrology in Stung Sen sub-basin of TSL (Source: authors)

Three-dimensional assessment of lake hydro dynamics

A three-dimensional (3D) hydraulic model was developed to further understand the process of vertical mixing of water and other substances in the lake. The vertical distribution of substances is crucial for understanding temperature changes and behaviors of toxic substances, pathogens, and nutrients such as settlements and elution between water and the river/lake bed. A pilot application of the 3D model was trailed in Chhnok Tru's floating villages (**Figure 3.5**).

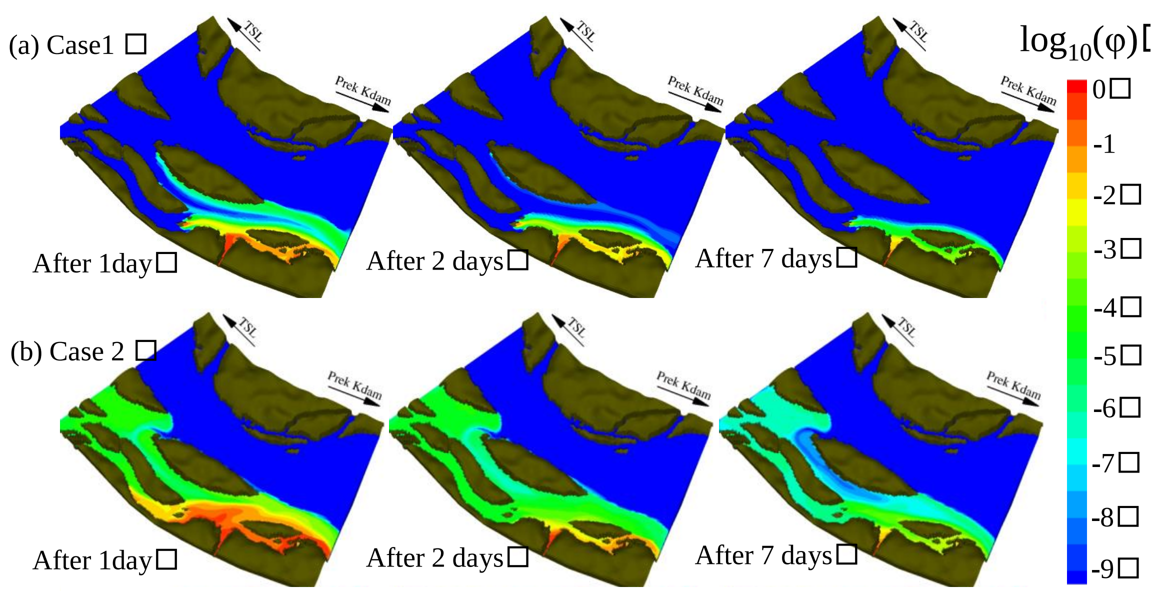


Figure 3.5 Calculated results of tracer concentration with different boundary conditions. Case 1 (a) shows inflow from both the main and sub-channels; Case 2 (b) shows inflow from only the main channel (Source: authors)

As shown in the figures, we can get information about the spreading/dilution process by taking account of the local conditions such as the shape and the inflow/outflow of the channels. The 3D model is a powerful tool with various applications. It can, for example, be employed to facilitate understanding of localised impacts, visualise the spread of pollution and microbial contamination over time, and examine changes in temperature profile or sedimentation in the lake system at different times of the year.

Key findings and recommendations

- Although hydrological assessments are technically intensive, a good understanding of hydrological conditions is a primary requirement for informed decision making to address a variety of problems resulting from the fluctuation of flows and storage of water. For a large and hydrologically complex lake like TSL, a multi-level hydrological assessment is necessary to visualise the changes and impacts at the basin level.
- We propose multi-level modelling for a comprehensive assessment of the changes in, and impacts on, the lake in one (longitudinal), two (longitudinal and lateral), and three (mixing along longitudinal, lateral and vertical) dimensions.
- We analysed the latest data combining hydrological, remote sensing and ground monitoring tools to tackle the data gaps. The process forms a solid basis for discussions with policymakers in riparian countries on the transboundary impacts on the lake, and assesses future scenarios of changes due to human activity and climate change. It is highly advisable to use the latest data acquisition methods available for the such assessments.
- It is also essential to advance hydrological monitoring capacity by the use of remote sensing as a cost-effective alternative to ground-based monitoring stations, while setting-up ground-based monitoring at critical observation points to verify the accuracy of the

estimation. The application of the latest tools, such as ADCP, or real-time water level for ground-based monitoring, should be promoted for more precise information.

– An integrated model with a cascading structure that consists of the three hydrological and hydraulic sub-models (namely GBHM, Mike11 and the 2-D LIE), has been established and utilised as a useful tool for the analysis of floods as well as water environmental assessment in and around TSL. The application of this integrated model for the assessment of fisheries in and around TSL is also important, especially with regard to the impacts caused by the hydrological and hydraulic changes on the seasonal migration of the key freshwater fish species. The research under this SATREPS project is a first attempt to operate the present model under realistic conditions offering flexibility and versatility of the model components.

– The discharge into tributaries flowing into TSL is very sensitive to land-use changes, particularly during low flow in the dry season. In some parts of TSL, flows from connected tributaries need to be regulated to support ecosystem such as Boeng Chmar Lake. It is relevant to the assessment of environmental flows to determine requirements for different competing needs (such as nature, energy, food and water supply). Results from such assessments could inform multi-stakeholders and concerned authorities to enable the monitoring of flows and to enact concrete regulations for maintaining the environmental flows in all TSL tributaries.

CHAPTER 4 PHYSICOCHEMICAL WATER QUALITY, SEDIMENTATION AND NUTRIENT DYNAMICS IN TONLE SAP LAKE

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Seasonal water quality monitoring and spatial interpolation

Assessing the state of the environment of TSL is challenging because of its sheer size, shallow depths (0.7-9 m on average), relatively low residence time of water (less than a year), high mixing rate and resuspension of sediments and nutrients, and large number of environmental parameters involved such as sediments, chemical constituents, microbes, algae, and other aquatic flora and fauna. Regular assessment of the environmental state of the lake and its ecosystems is important for its sustainable management. However, establishing and maintaining water quality monitoring sites is resource-intensive and time-consuming due to the need to cover a large area, and different depths, at regular intervals. The monitoring program should be optimised in an efficient and cost-effective manner to account for spatial (in both vertical and horizontal dimensions) and temporal variability of environmental parameters. Water quality of the lake and its tributaries was assessed using a broad range of methods, including spatial surveys (longitudinal, horizontal and vertical) of physio-chemical parameters in the key seasons (**Box 4.1**). Such a broad scale water quality survey was necessary to get a snapshot of the state of water quality, which is governed by a wide

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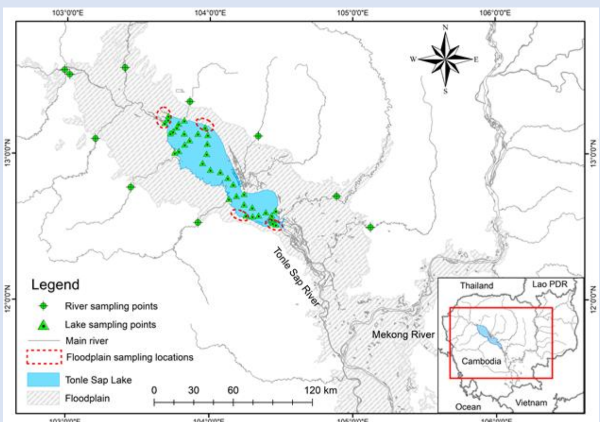
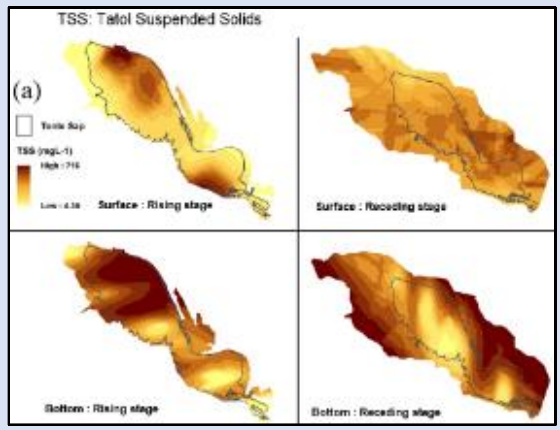
number of factors. For instance, the seasonal hydrology of the lake and its basins is responsible for the inflow of chemical substances, sediments and nutrients into the lake, and mixing of the constituents. Similarly, anthropogenic activities are responsible for the disposal of chemical substances and direct interference in the lake ecosystem. Therefore, the basic purpose of water quality surveys was to understand water quality profile of the lake to account for various locations and time periods. The collected data serve as baseline information for the future assessment of water quality.

Box 4.1. Water quality monitoring and spatial water quality maps for TSL (Source: authors)





(a) (b)

(a) Sampling locations in TSL and (b) spatial variability map of TSS using ordinary kriging (Source: chapter authors)

The lake was sampled at 37 sampling stations (a) during six sampling campaigns covering the period from December 2016 to March 2018 and corresponding with receding and rising stages of lake volume, respectively. The exact sample locations were geo-coded by GPS and projected on a cross-section (CS) line passing through the entire lake. Samples were collected from both surface and bottom water layers. The targeted parameters included total depth (TD) (m), water temperature (Temp) (°C), Oxidation-Reduction Potential (ORP) (mV), Electrical Conductivity (EC) (µS/cm), pH, Dissolved Oxygen (DO) (mg/l), Total Dissolved Solid (TDS), Turbidity (Turb) (NTU), Total Suspended Solid (TSS) (mg/l), Chlorophyll (µg/L).

Water quality analysis was conducted using the latest analytical methods and lab instruments set up by the SATREPS project at ITC as well as in the labs of participating universities in Japan. This process was part of research capacity development of the project and involves participation of students, faculty and researchers in Japan and Cambodia. Multivariate statistical techniques were employed to analyse the water quality parameters sampled at different locations and temporal frequencies. The multivariate statistical techniques allow for grouping or segregating of water quality parameters showing similar or distinct behaviors such as occurrences and concentration profile. In addition to that, interpolation techniques, such as ordinary kriging, were used to map and understand the likely distribution of specific water quality parameters across the lake (Box 4.1). Ordinary kriging helped to visualise the spatial variability in both surface and bottom water layers during rising and receding stages of the lake. The analysis of the water quality data not only helped to understand the spatial and temporal changes in water quality but also could be effectively used for identifying locations and frequency for conducting future monitoring activities. For instance, months were grouped based on the similarity of water quality by using a cluster analysis of 17 water quality parameters observed in Kampong Luong by monthly sampling (Ich, et al. 2018). The first cluster covered four months of dry season and early monsoon (February-June) when the water level was at its lowest (1.05-1.57m). The second cluster covered three months (Sept-Nov) which marks the time for peak flood in the Mekong River and the highest water level at the sampling point (7.49-8.43m). The final cluster had four months coinciding with the rising (July-August) and falling (December-January) of the water level but in the moderate range (3.59-5.77m). The continuation of similar analyses helps progressively improve our understanding of water quality variation trends and guides the design of appropriate water quality monitoring.

Sediment dynamics

Seasonal dynamics of sediments was examined, considering its importance to the sustainability of the lake's ecology. Sedimentation is directly related to the nutrient cycling, geomorphology, and ecosystem productivity (for example, plankton and fish) of the lake and its waterways. The Mekong River is the principle contributor to sediments in the lake via the Tonle Sap River during the peak flooding season in addition to tributaries and internal resuspension. In addition to direct observation, we applied remote sensing techniques to examine seasonal sediment dynamics.

An extensive and seasonal sampling survey was conducted between September 2016 and June 2017 to measure texture, composition and size of the sediment, total suspended solid (TSS) concentrations (i.e., the amount of undissolved solid particles in the water column), and sedimentation and resuspension rates of TSL and its floodplain areas for three different types of vegetation (grassland, shrub, flooded forest). More details about sampling and analysis methods can be found in Siev et al. (2018). The sediment grain size in TSL and its floodplain is relatively fine and mainly composed of silt (4–63µm). The median grain size (D50) was approximately 7µm. The textural composition of sediments explains the patterns of deposition and the hydrodynamic conditions of TSL and its floodplains.

TSS concentration ranged from 3 to 652 mg/L during the sampling period (**Figure 4.1**). The average TSS concentration was highest in March (low-water period), followed by June (rising water period), September (high-water period), and December (receding water period).

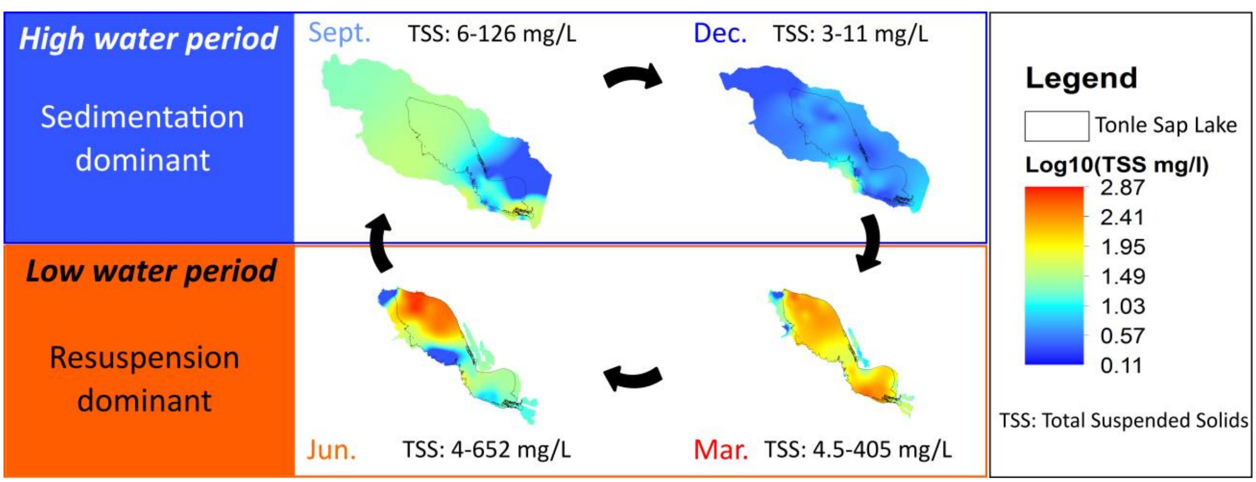


Figure 4.1. Sediment distribution in TSL during high- and low-water periods (Source: Siev et al. (2018))

The textural composition of sediments explained the patterns of deposition and the hydrodynamic conditions of TSL and its floodplain. TSL demonstrated high and very high (turbulent) conditions while the floodplain area showed calmer hydrodynamic conditions. Calmer hydrodynamic conditions facilitate the sedimentation process and retard resuspension. While sedimentation and resuspension took place simultaneously, sediment dynamics in TSL were influenced by the seasonal fluctuation of water level and sediment load brought in through tributaries and the Tonle Sap River. In the rising flood period (September), a large amount of sediment flowing into the lake results in a larger net sedimentation rate in the floodplain. In December, the water level starts receding due to outflow into the Tonle Sap River along with sediments. According to Kummu et al. (2008), the amount of sediment flowing out of the lake was lower than that flowing in. The difference could be attributed to the entrapment of sediment by vegetation on the edge of the lake and the floodplain, the lower velocity of outflowing water, and less turbulent flow. In March, when the water depth was at its lowest (dry season), resuspension was found to escalate TSS concentration to the highest level. In June, when the water depth is rising, TSS concentration is subjected to dilution, resulting in lower TSS concentrations (Siev et al., 2018).

The measured resuspension rate could explain the resuspension process and the reason why the sediment accumulation rate in TSL is very low (0.05 - 2.55 mm/year) (Kummu et al., 2008; Penny, Cook, & Sok, 2005; Tsukawaki, 1997). Furthermore, the use of Dynamic Ratio (DR), which is an indicator of the degree of sediment suspension in a lake, can further explain the seasonal sediment resuspension in TSL. As higher DR indicates higher resuspension, the DR of TSL varies greatly from 12.9 to 34.3 due to the changing shape, surface area and depth of the lake. Results in **Figure 4.2** indicated that sedimentation was dominant in the high-water period (September–December), while resuspension was dominant only in the low-water period (March–June) (Figure 4.1). TSL and its floodplain thus act as a sediment sink during the rainy season by facilitating sedimentation and as a source during the subsequent dry season by suspending the previously deposited sediments back into the water column. The understanding of TSL's sedimentation rates is a substantial improvement of our knowledge on the sediment dynamics of TSL. The findings could be used to assess the lake's productivity as well as its contribution to sediment load in the Mekong River during the dry season. Moreover, the research clarifies the important role of vegetation in reducing resuspension of the sediment in the water up to 26.3% (Siev et al., 2018), while resuspension itself could be the key factor for internal nutrient loading (Havens et al., 2007; Horppila & Nurminen, 2003; Qin et al., 2006; Zhu et al., 2015).

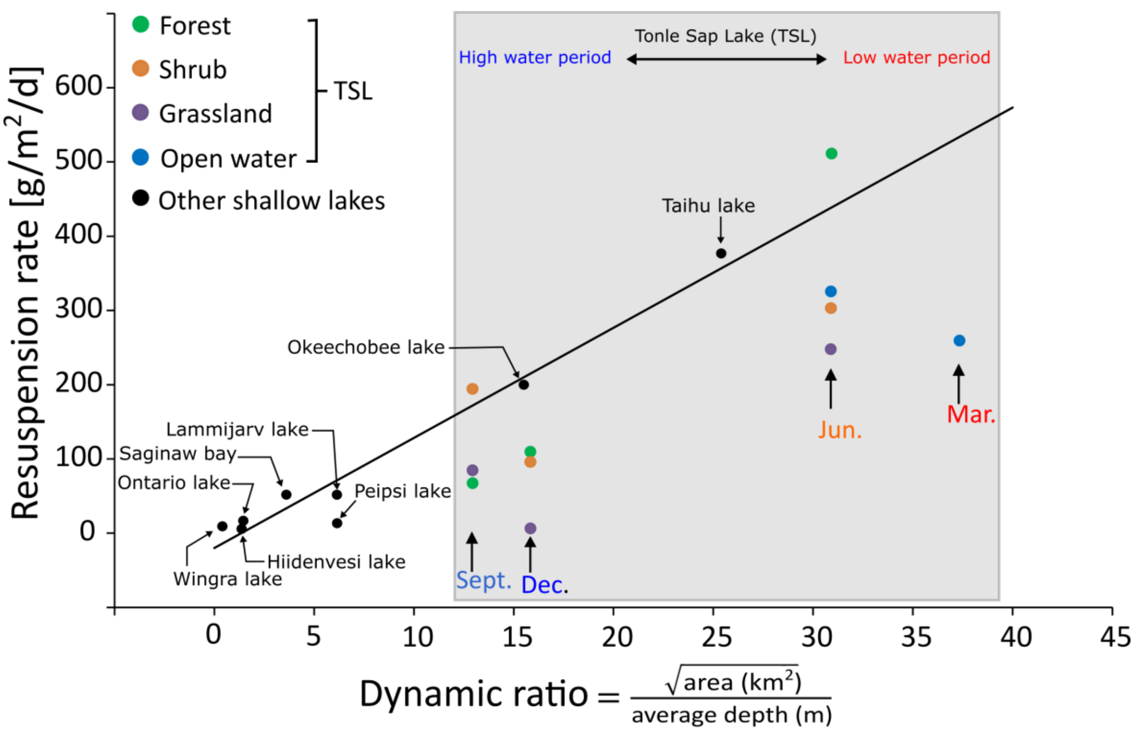


Figure 4.2 Dynamic ratio (DR) and resuspension rate in different shallow lakes, including TSL (Figure adopted from Siev et al., 2018)

Application of remote sensing for monitoring sediment dynamics

Remote sensing was used as an indirect method for assessing short- and long-term dynamics of TSS concentration and for estimating factors that determine TSS concentration. Moderate

Resolution Imaging Spectroradiometer (MODIS) Aqua, which provides daily reflectance of TSL since 2002, was used. A regression analysis was applied to establish the relationship between TSS based on the reflectance of MODIS images and TSS obtained through water sampling. Thus, the output regression equation was used to estimate daily spatial distribution of TSS from 2003 to 2017.

Water level plays a key role in determining TSS concentration, as pointed out earlier. **Figure 4.3** shows a simplified model of annual TSS concentration cycle, suggesting that, during outflow period when the water is discharged from TSL through the Tonle Sap River, TSS increases with the decrease of water depth along a single path. Resuspension of the bottom sediment could be the main factor in the increase of TSS. During the inflow period, TSS concentration is governed by both wind and inflow from the Mekong River. Resuspension of sediment fluctuates year by year depending on the amount of inflow from the Mekong River, while wind-induced resuspension is almost constant.

An integrated framework for the assessment of sediment dynamics in the Mekong River Basin was proposed to understand the source and pathways of sediments in the basin (Suif et al., 2016). The study used GIS based on "Revised Universal Soil Loss Equation (RUSLE)" in the integration of a sediment accumulation and routing scheme to study suspended sediment load. The framework also analysed Landsat images along with ground observations to obtain the spatial and temporal patterns of suspended sediment concentration (**Figure 4.4**). The results revealed that severe soil erosion in China and Lao PDR (upper part of the Mekong River Basin) and in western Vietnam (lower part of the Mekong River Basin) was the main contributor, and hence to be given priority in basin-wide soil and water management.

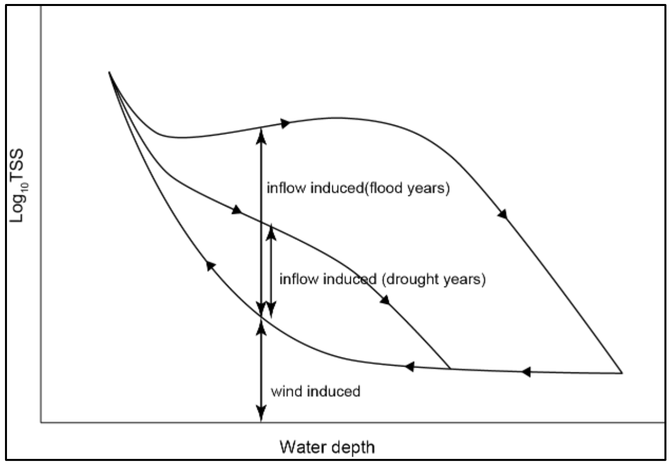


Figure 4.3 Simplified model for annual cycle of TSS concentration (sedimentation and dilution are not included in this model) (Source: authors)

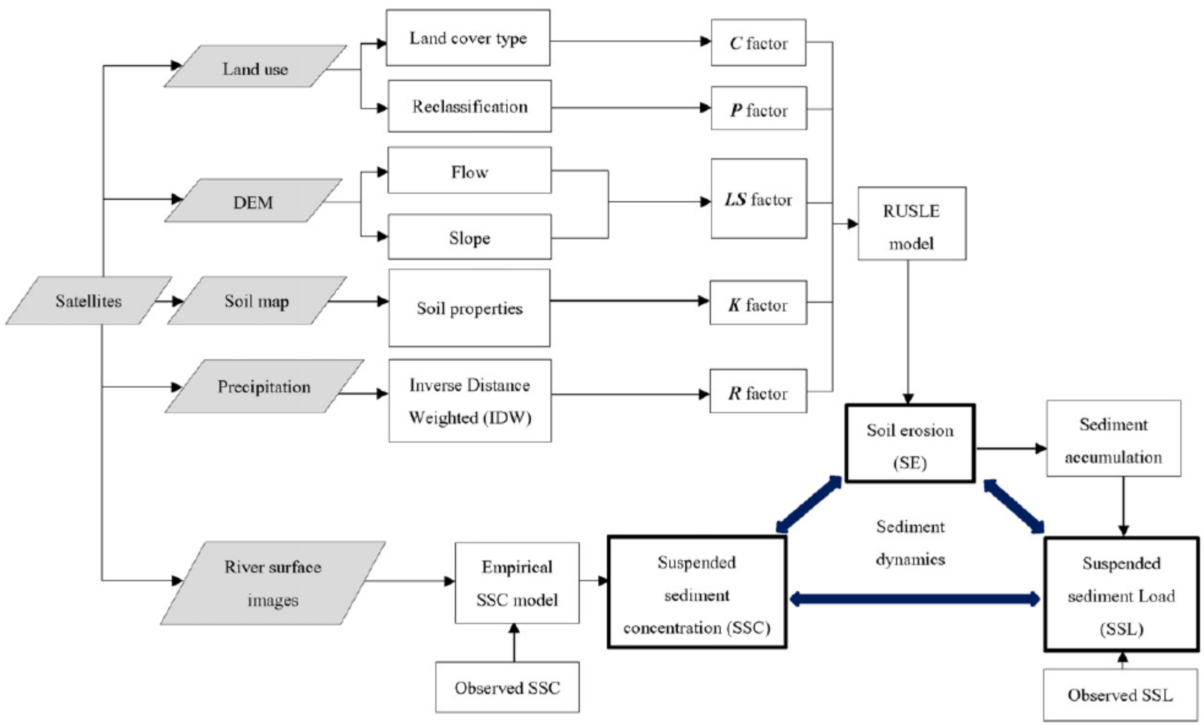
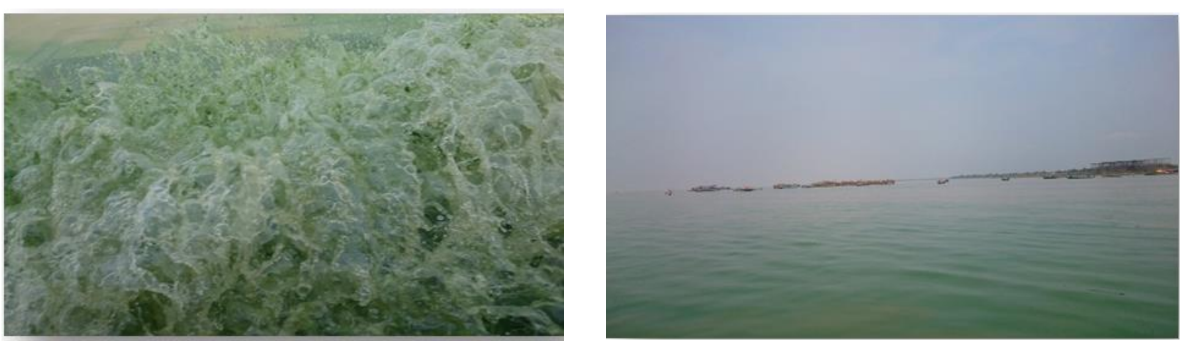


Figure 4.4 Integrated framework of spatio-temporal sediment dynamics analysis (Source: Suif et al., 2016)

The suspended sediment concentration showed increasing trends longitudinally in China and Lao PDR and decreasing trends longitudinally in Cambodia in the rainy season. Importantly, the suspended sediment concentration exhibited a decreasing trend from Kratie to Phnom Penh between June and August and between September and November. This trend attributed to falling water velocity in the mainstream Mekong which allowed more deposition (Suif et al., 2016). The findings clearly suggest that a holistic strategy for the management of sedimentation will be necessary, combining in-situ (within TSL and its basin) and transboundary approaches.

Nutrient dynamics in Tonle Sap Lake and eutrophication

Over the past few decades the ecosystem of TSL has been affected by multiple drivers, most notably anthropogenic activities both within and outside its watershed (Uk, et al. 2018). Water pollution in TSL threatens the drinking water supply for local people and eutrophication has led to explosive increase in the area covered by invasive plant species such as water hyacinth (Kuenzer, 2013). Eutrophication of water bodies is caused by excessive enrichment of nutrients and organic matter input. This stimulates phytoplankton growth, leading to changes in ecosystem functions, water quality deterioration and ecological degradation (National Academy of Sciences, 1969; Rabalais, Turner, Díaz, & Justić, 2009). We observed algal blooms in TSL (e.g., March and June 2017, **Figure 4.5**) during sampling campaigns in the dry season, while none were apparent during the wet season.



(a) (b)

Figure 4.5 Algal blooms in Tonle Sap Lake in (a) March 2017 and (b) June 2017 (Source: authors)

The seasonal water exchange between TSL and the Mekong River via the 120km-long Tonle Sap River underpins the uniqueness not only in hydrology but also water quality, productivity, and biodiversity of TSL (Campbell et al., 2006; Uk et al., 2018). The nutrient dynamics in TSL are complex in terms of both internal processes and exchanges with adjacent systems. Although the annual floodwater from the Mekong River and the tributaries are undoubtedly important nutrient sources for TSL, the nutrient dynamics in the lake are dominated by internal loading in the low-water period (Campbell et al. 2009).

Phosphorus (P) is a key factor limiting biological productivity in most freshwater ecosystems including TSL (Burnett et al., 2017) and is a key determinant of eutrophication. It has been observed that the concentration of phosphorus in the TSL water column has increased. The average annual yields of total phosphorus in TSL basins were estimated to increase from 42 $kg/km^2.yr$ in 1990–1994 to 55 $kg/km^2.yr$ in 1995–2010, increasing the average annual total phosphorus (TP) loading per lake area from 942 to 1257 $kg/km^2.yr$ between the two periods (Fink, Alcamo, Flörke, & Reder, 2018).

During mixing and resuspension, sediments can release nutrients, such as phosphorus, which could contribute to cyanobacteria blooms in the lake during the low-water period. According to a study by Uk et al. (2017) during the low-water period (December 2016 and March 2017), total phosphorus concentration in TSL sediments varied greatly between the two seasons and throughout the lake; 500-1467 mg/kg in December 2016 and 497-1481 mg/kg in March 2017. The findings imply that control of phosphorous inflow into the lake should be seriously considered such as by preventing the runoffs from agricultural fields, wastewater discharges and inflow from the transboundary sources (such as soil erosion).

Key findings and recommendations

- The research activities carried out under the SATREPS project have contributed towards creating a baseline information for understanding water quality variability, introducing the latest analytical methods, as well as improving our understanding of sediment and nutrient dynamics in TSL.
- Availability of scientific data at multiple scales and time periods is key for the water quality management of an extensive lake ecosystem like TSL. Monitoring and assessment of water quality have to be guided and regularly undertaken not only to address the short-term and localised pollution, but also to understand long-term trends.

- It is critical to determine what, where, when, and how to monitor water quality based on updated research outcomes, and for the cost-effective long-term environmental management of TSL.
- In TSL, sedimentation is dominant during the high-water period when the lake acts as sink. In contrast, resuspension is dominant during the low-water period when drainage from the lake is a source of sediment downstream. Vegetation in the floodplains plays an important role in maintaining natural sediment dynamics by reducing the intensity of sediment resuspension.
- Sediments play a crucial role in the overall nutrient dynamics of shallow lakes, for example as a sink and source of phosphorus. An understanding of sedimentation processes would therefore be valuable for estimating lake productivity and nutrient management.
- Overall, a holistic approach to the management of sediments and nutrients is required to understand and manage the sources, paths and sinks, and to ensure the sustainability of the lake and its basins. A transboundary approach is also necessary to monitor and deal with the sediment load from soil erosion in the Mekong River Basin, as well as the impacts of dam construction and water resource development upstream.

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CHAPTER 5 MICROPOLLUTANTS IN WATER, SEDIMENT AND BIOTA

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Health and ecological risks are the most pressing issues for the people who are directly dependent on Tonle Sap Lake (TSL) for their livelihood. The vast expanse of the lake and its basin acts as a big sink of anthropogenic activities. The lake is under pressure due to the inflow of sewage from cities, human waste from floating villagers, industrial waste, agricultural fertiliser and pesticides, as well as illegal activities impacting the lake's ecosystem and environment (Bonheur and Lane, 2002; Lin and Qi, 2017). The disposal of wastes and pollutants into the lake influences not only chemical and biological water quality but also increases exposure to, and vulnerability of, the lake's communities to the health hazards. The inhabitants of floating villages, who are in direct interactions with the lake environment on daily basis, are particularly vulnerable to the impacts of pollution, as explained in Chapter 2. Inasmuch as communities' health is of great concern, understanding the causal effects between the change of TSL ecosystem and communities' livelihood is essential to address the health risks. Hence, the impacts of pollution on the lake's ecology should be assessed as part of TSL management policy.

In the SATREPS project, sources and pathways responsible for increasing health and ecological risks were investigated. The project has targeted main areas of health or ecological risks that are closely related to the day-to-day life of the local residents of the lake. The three most important

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areas are: pollution due to heavy metals; pesticide contamination of the land and lake due to improper pesticide use and its persistence as residues from agricultural activities; and microbial risk due to improper sanitation and waste disposal activities. This chapter reports on heavy metals and pesticide contamination, while Chapter 6 focuses on microbial risks.

Heavy metal contamination in Tonle Sap Lake

Heavy metals are naturally present in soil. They are generally derived from parent material in bedrock. It is quite common that most heavy metals are associated with agricultural activities, disposal of industrial wastes, landfills and mining leachate (Ahmed et al., 2005). Heavy metals discharging into a lake from both natural and anthropogenic sources are distributed between bed sediments and aqueous phases. Lake sediments are normally the final pathway of both the natural and anthropogenic components produced or derived to the environment. In fact, sediment quality can be used as an indicator of pollution in the water column. Polluted sediments, in turn, can act as sources of heavy metal contamination in water and sources debasing water quality (Zhong et al., 2006). Only limited surveys have been undertaken to measure heavy metals in the sediments of TSL. We collected 28 surface water samples and 39 sediment samples from TSL for the analysis of heavy metals, in both the dry and the rainy season (**Figure 5.1**). The samples were brought to the ITC laboratory and analysed for selected heavy metals such as Cadmium (Cd), Chromium (Cr), Cupper (Cu), Iron (Fe), Manganese (Mn), Lead (Pb), and Zinc (Zn) using an atomic adsorption spectrophotometer (AAS-7000) (**Figure 5.2**). The relative abundance of metals (mean concentration, mg/l) in water samples over the whole observation period (13-19 March 2017; 25-30 June 2017) was in the order of Fe > Mn > Pb > Cu > Cd > Cr. The present study indicated that TSL surface water has higher Fe, Mn, and Pb concentration than other metals analysed (**Figure 5.3**).

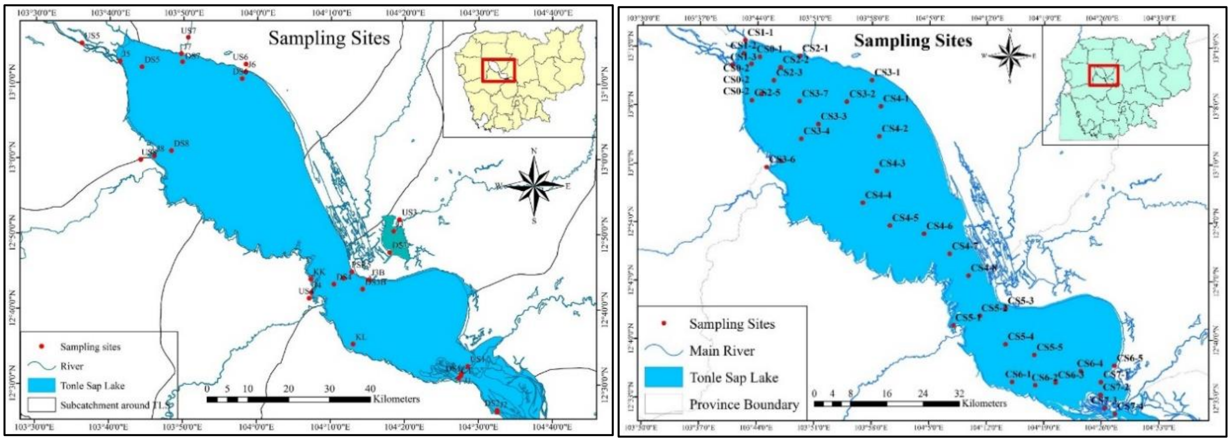

Figure 5.1 Sampling location for surface water samples (left) and bottom sediments (right) in Tonle Sap Lake. (Source: authors)

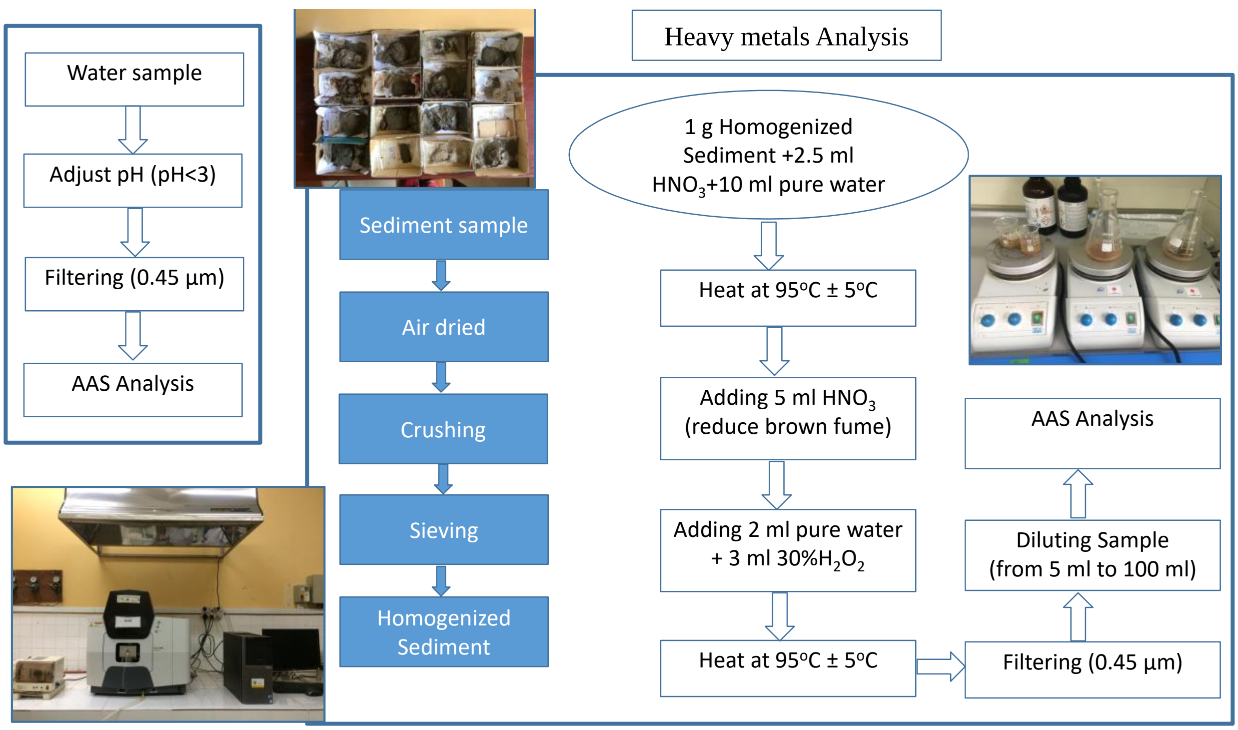

Figure 5.2 Methodology used in the project for heavy metal analysis in both sediments and water samples (Source: authors)

Cr was not detected in either season. Cu was found at very low concentrations with a mean value of 0.03 ± 0.01 mg/l during the rainy season.

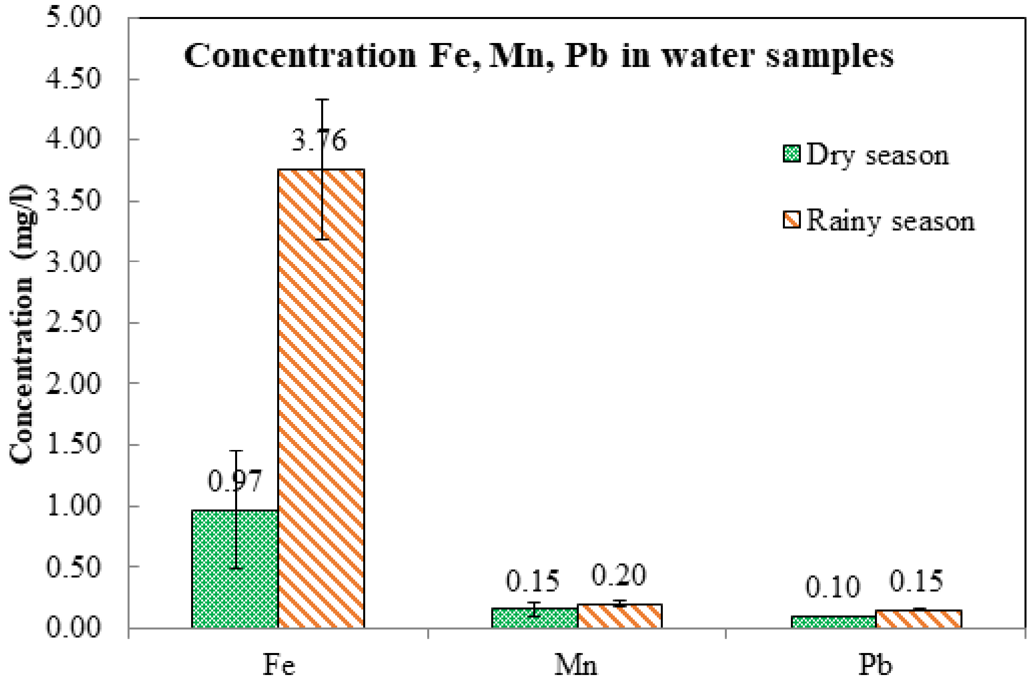

Figure 5.3 Fe, Mn, and Pb concentrations in surface water of Tonle Sap Lake (Source: authors)

Zn was not detected in the rainy season, but in the dry season it was detected with a mean value of 0.06 ± 0.04 mg/l. Cd was not detected in the rainy season, but in the dry season it was detected with a mean concentration of 0.003 mg/L. Most of the observed metals in water samples varied seasonally and were observed to be higher in the rainy season than in the dry season.

The study found concentrations of Cd (0.018 µg/g), Cr (0.83 µg/g), Cu (1.41 µg/g), Fe (35334.87 µg/g), Mn (212.49 µg/g), Pb (43.86 µg/g) and Zn (6.61 µg/g) in sediment samples. The pollution load index (PLI) and the geo-accumulation index (I-geo) were employed to assess the pollution of heavy metals in the sediment samples. In all samples, PLI values were less than 1, which indicates no cases of serious heavy metal pollution (**Table 5.1**). I-geo (a quantitative measure of contamination in aquatic sediments) (Muller, 1979), of most heavy metals in the sediments were found to be negative (**Figure 5.4**). This implies that the mean concentrations of heavy metals of TSL sediments are lower than the world surface rock average. I-geo values for only Pb were in the range between 0 and 1, while for the rest of the heavy metals the values were negative, indicating that Pb pollution was low to moderate. Overall, it could be inferred that heavy metal pollution was found not to be a serious concern.

Table 5.1 Pollution load indices of Tonle Sap Lake sediments

Sampling sites	PLI	Sampling sites	PLI	Sampling sites	PLI	Sampling sites	PLI
CS0-1	0.1	CS3-1	0.15	CS4-4	0.12	CS6-1	0.09
CS0-2	0.08	CS3-2	0.07	CS4-5	0.09	CS6-2	0.13
CS1-1	0.03	CS3-3	0.11	CS4-6	0.16	CS6-3	0.06
CS1-2	0.03	CS3-4	0.14	CS4-7	0.04	CS6-4	0.09
CS1-3	0.11	CS3-5	0.14	CS4-8	0.13	CS6-5	0.12
CS2-1	0.16	CS3-6	0.12	CS5-1	0.08	CS7-1	0.02
CS2-2	0.23	CS3-7	0.04	CS5-2	0.14	CS7-2	0.02
CS2-3	0.18	CS4-1	0.09	CS5-3	0.04	CS7-3	0.02
CS2-4	0.21	CS4-2	0.07	CS5-4	0.13	Cs7-4	0.03
CS2-5	0.1	CS4-3	0.12	CS5-5	0.06		

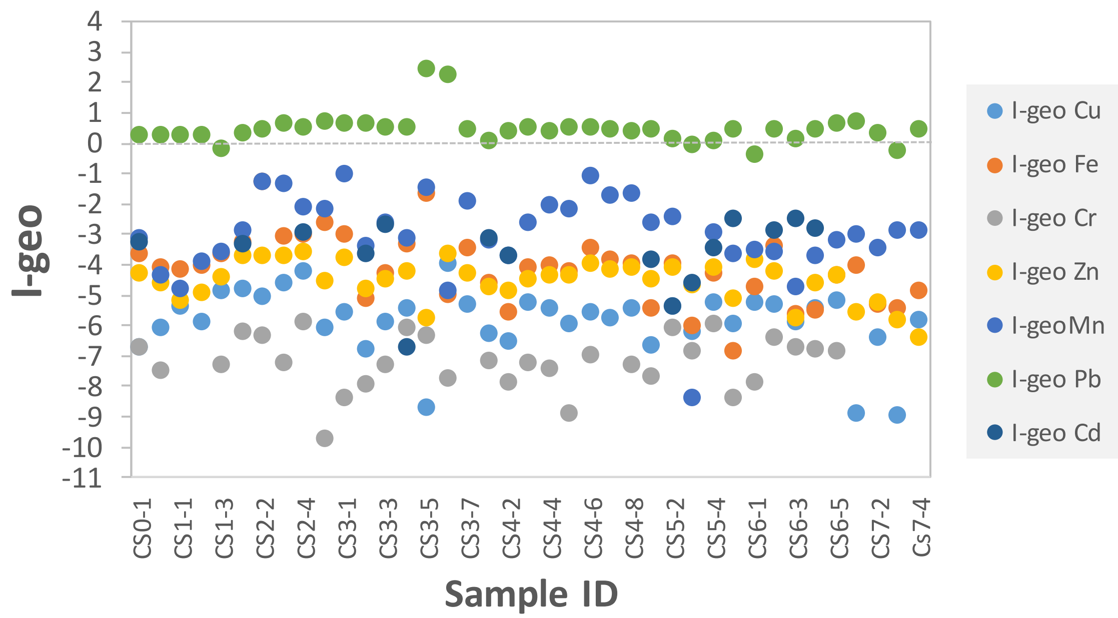

Figure 5.4 Geo-accumulation index (I-geo) of Tonle Sap Lake sediment

Impacts of pesticides uses in agriculture

Pesticide is a collective name for a group of organic compounds, generally used in agriculture, industry, and by households to kill unwanted biota such as weeds (herbicides), insects (insecticides), fungi (fungicides), rodents (rodenticides), round worms (nematocides), aphids (aphicides), and eggs (ovicides). They are also used as fumigants, attractants or repellent. Pesticides are hazardous to aquatic as well as human health.

The uses of pesticides is common in agricultural plains in Cambodia, including in TSL floodplains. The largest percentage of households using pesticides, herbicides, and fungicides are dominant in the floodplains zone. Many farmers living in TSL Basin commonly use insecticides to control pest insects and herbicide to kill weeds in field crops. Farmers are often found to mix together a number of pesticides and spray it in huge quantity on crops. Fishermen also reportedly apply pesticides to catch fish. In some cases, pesticides are found to be applied directly on the water surface to control aquatic insects. Despite directives from Ministry of Agriculture Forestry and Fisheries as well as Ministry of Environment to regulate their uses and to ban the imports and the uses of the pesticides such as Methylparathion, Mevinphos, Methamidiphos, Methomyl, Monocrotophos, Dichlophos, DDT, and Chlodane (Preap and Sareth 2015), farmers are still found to use a wide range of pesticides to prevent damage to, and loss of, crops. An estimated 1.3 million liters of the pesticide products was used in TSL basin in 2000 according to a previous study (WEPA 2019). Pesticides enter Cambodia mostly through illegal channels from neighboring countries such as Thailand and Vietnam, and other places such as China and the European Union, while 522 trade names of 133 types of mostly unregistered pesticides were available in local markets (Preap and Sareth 2015). Improper applications were reported to cause symptoms of poisoning such as impaired vision and lethargy, decline in fish numbers, and disappearance of some species of birds in the area.

Runoff from floodplains and the TSL catchment area could be the potential source of pesticide contamination in TSL. However, major active compositions of the pesticides and their fates in TSL are not well understood, and farmers have limited knowledge and skills on proper pest management. Since available pesticides are labeled in foreign languages (Preap and Sareth 2015), farmers tend to mix several on the hopes of making them stronger, and spray frequently to increase their effectiveness (Jensen, et al. 2011). Farmers also tend to apply insecticides and fungicides based on their judgment of field conditions, which could lead to overuse of these chemical substances (Matsukawa, et al. 2016). The mismanagement of pesticide storage and indiscriminate disposal of used containers further increase contamination risk to the environment.

Impact of pesticides use on human health and environment

Researchers in the SATREPS project investigated the fates of the pesticides in Chhnok Tru floating community of TSL (**Figure 5.5**).

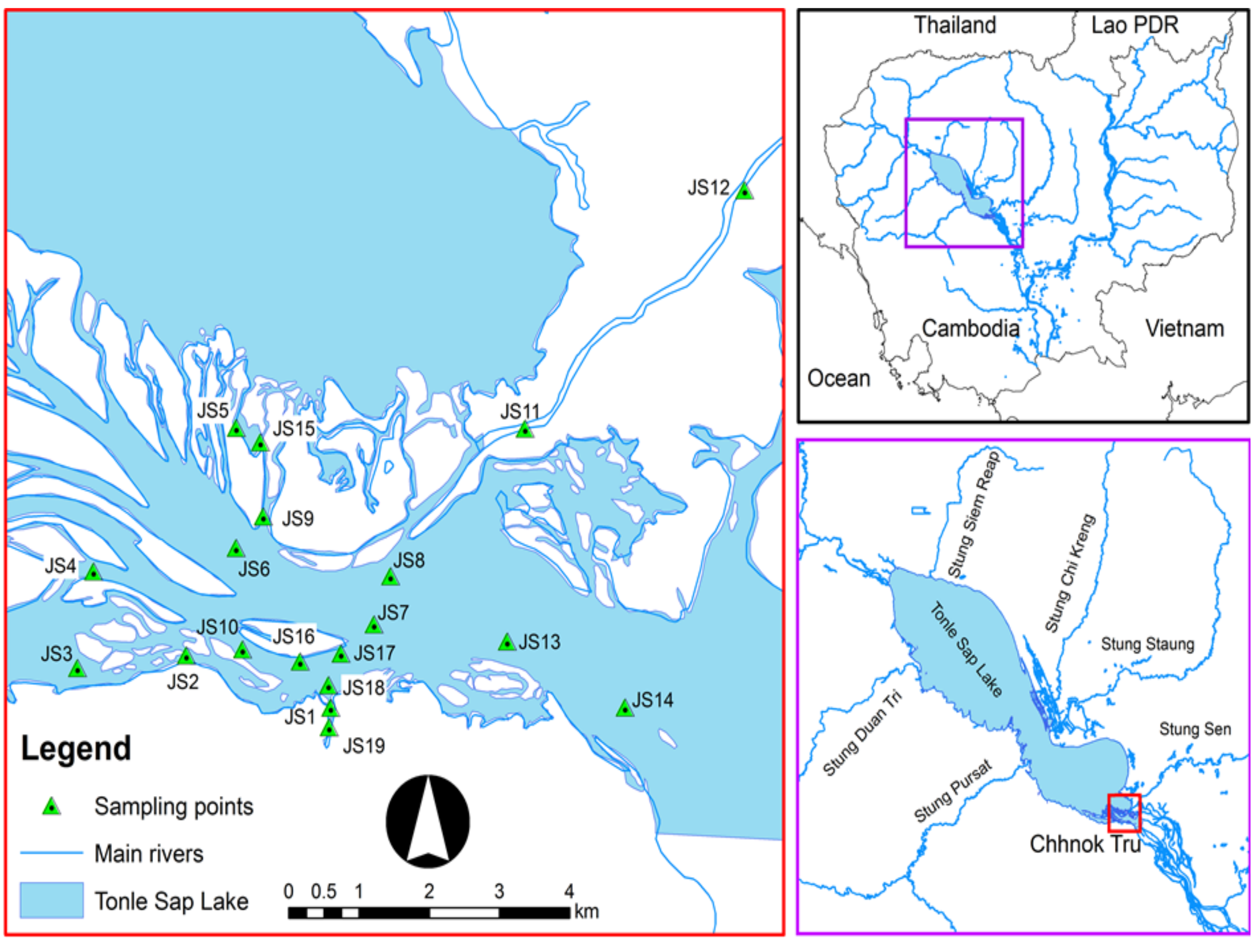

Figure 5.5 Sampling locations for pesticide residues analysis within Chhnok Tru floating community

This area is surrounded by a number of vegetable farms and rice fields. The pesticides concentration in water, sediment and fish samples were analysed to understand the potential pathways to human health risks (**Figure 5.6**). Samples were analysed in the advanced analytical laboratory at the ITC using the method shown in **Figure 5.7**. The analysis of pesticide residue at the ITC laboratory is a part of research collaboration and capacity building on the development and validation of the analytical techniques such as solid phase extraction and gas chromatography–mass spectrometry (GC-MS) for micropollutants analysis.

Figure 5.6 Sampling activities and collection of fish samples

Concentration profile of 451 common pesticides in water samples were analysed using GC-MS (TQ8040) equipped with an automated identification and quantification system with a database (AIQS-DB). The analysed pesticides included 19 compounds extremely hazardous to human health and environment. The targeted pesticides compounds were Aldrin, Anilofos, Chloroneb, Dieldrin, Endrin, Heptachlor, Hexachlorocyclohexane (Beta-HCH, Alpha-HCH), Isoxathion, Isazofos, Lindane, Mefenoxam, Methamidophos, Methyl parathions, Metalaxyl, Malathion, Parathion, Terbacil, Triadimefon, and 4,4′- Dichlorodiphenyltrichloroethane (DDT). The analysis detected 25 active compounds (six insecticides, 11 herbicides, seven fungicides and one other pesticide) in water samples. The most frequently detected compounds were Dimethomorph, Cinmethylin, and Oxabetrinil. In addition, all of 19 targeted pesticide compounds were also detected and quantified.

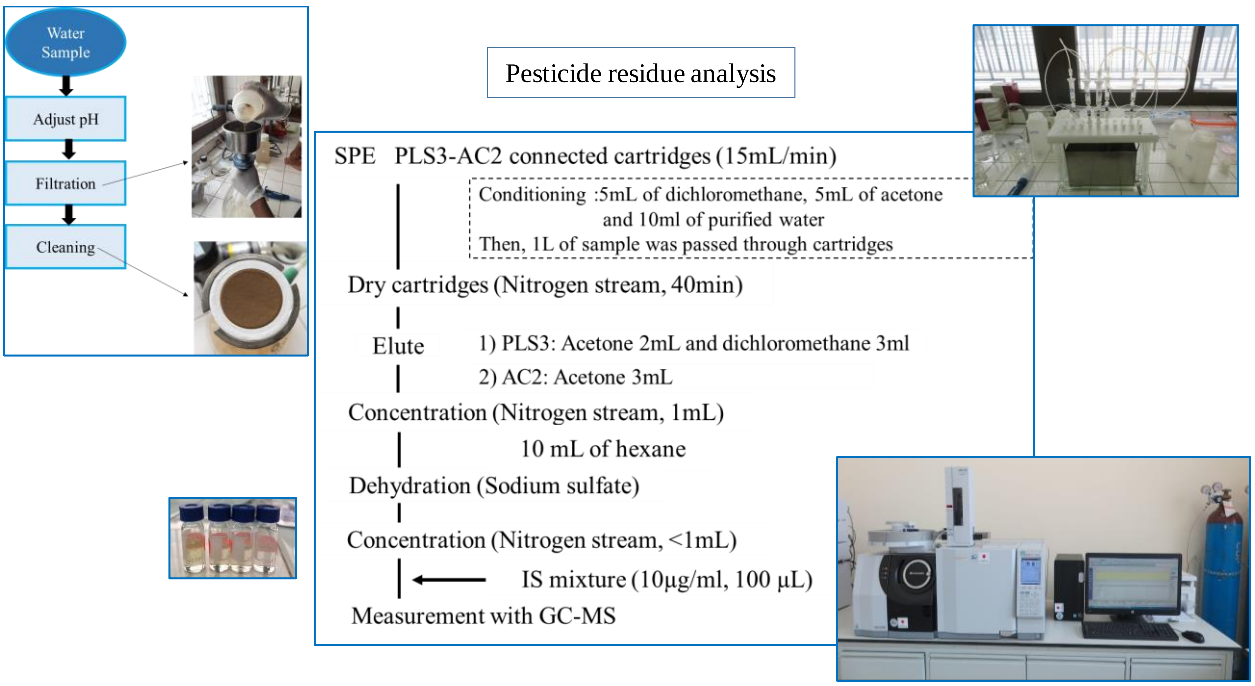

Figure 5.7 Methodology of pesticide residue analysis in the surface water

Among the targeted compounds for the present assessment, seven were detected of which four were fungicides (Mefenoxam, Metalaxyl, Chloroneb, and Triadimefon), two were insecticides (DDT, Malathion) and one was a herbicide (Atrazine). DDT, a persistent organic pollutant banned from import and use in Cambodia, was detected in surface water samples at Chhnok Trou floating community in the range of 1.35 - 2.32 µg/L. Overall, the Chhnok Tru floating community's water was significantly contaminated by pesticide residues, putting the health of this community at risk due to their frequent contact with the lake's water in their daily lives (Rann, et al. 2018).

As for the sediment samples, several insecticides (Pyridaben, Fenpropathrin, Bendiocarb and DCIP) were detected in the range from 0.4 to 96.8 ng/g-dry weight (dw) at various sampling sites (**Figure 5.8**).

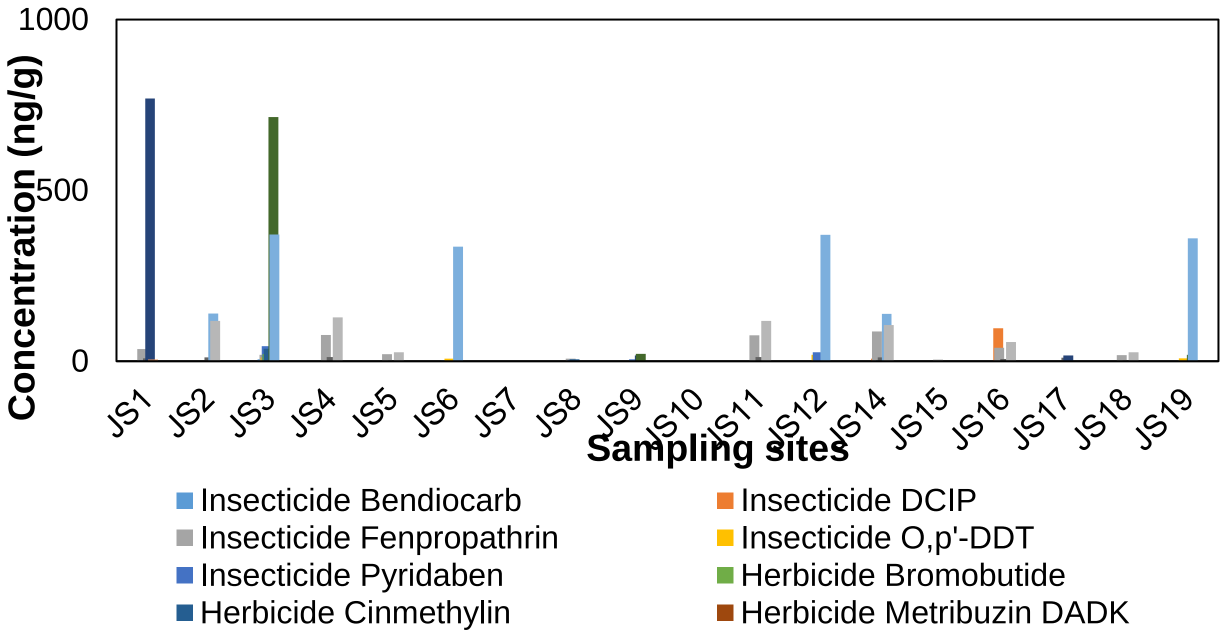

Figure 5.8. Levels of pesticide residues in sediment of TSL**.** (Source: authors)

Herbicide compounds found in the water samples included: Triclopyr, Metribuzin, Bromobutide, Cinmethylin, Chlorneb (max concentration 768.8 ng/g-dw), Dimethomorph Z (max concentration 714.5 ng/g-dw), and Hymexazol (max concentration 370.5 ng/g-dw). Usually, these herbicides are used to control pre- and post-emergence of weeds among soybeans, potatoes, tomatoes and sugarcane, while Bromobutide was used to control perennial weeds in rice paddies. Dimethomorph Z is a toxic compound that could contaminate ponds, dams, streams, waterways or drains.

For the SATREPS Project, ten fish species found in TSL were obtained for pesticide analysis. Eight pesticide compounds were detected in one or more of the ten fish species analysed. DDT was found in eight species. Pesticide residue was predominantly found in fish muscles, with concentrations between 8.7 to 147.8 ppb.

In particular, high concentrations of DDT were found in Slat Trey Slat (*N. notopterus*) (147.8 ppb), Trey Khmann (*H.dispar*) (131.8 ppb), and Trey Chrakaing (*P. proctozysron*) (88.7 ppb). Moreover, Pyridaben (13 - 106 ppb) was detected in four fish species and Dimetylvinphos (44 ppb) was detected in Trey Khmann. Five additional fungicides (chloroneb, dimethomorph, hymexazol, metalaxyl, and propiconazole), three types of insecticides (dimetylvinphos, DDTs, and pyridaben), and five types of herbicides (bromobutide, carbetamide, cinmethylin, dimethametryn, and simetryn) were also identified in fish samples. The presence of these pesticides in sediments and fish tissues is cause for serious concern about its impacts not only on the ecosystem but also on human health.

Key findings and recommendations

- Analysis of heavy metals in water and sediment samples from TSL did not show serious contamination.
- Detection of pesticide compounds in water, sediments and fish samples confirm their use in the TSL basin. This issue has to be taken seriously, considering its potential health risks to the people.
- Water is the obvious pathway for exposure due to direct contact and use on a daily basis. Lake sediment acts as a repository of pesticides in the bottom of the lake. The flood pulse, resuspension, and rapid mixing in the lake system could release heavy metals and pesticides from sediments and transport it to distant areas.

- Pesticides, such as DDT, in the fish samples from TSL is a serious concern for public health as many people consume fish and fish products from TSL. DDT can biomagnify and bioaccumulate in the environment.
- Understanding the fate of pesticides in the TSL environment is important to formulate preventive measures and to reduce aquatic and human health risks. Further improvements in continuous monitoring (covering more sampling sites, increased frequency, and fish and aquatic species) and research capacity is necessary to identify contamination pathways and health impacts, including through consumptions of fish.
- A survey to understand the practice of pesticide use (timing, quantity, and frequency of the application), and residues in soils, kitchen and food items, and products (vegetables, rice) is needed to identify sources and amount of pesticides applied. The findings from such an assessment is important in raising public awareness on occupational health hazards brought about by improper handling, use and dosing of pesticides.
- More efforts are necessary to control source and distribution of pesticides, and even its entry to the country such as by strengthening the regulation and having stringent standards on selling, and distribution. Users also need to be well informed on appropriate use of pesticides. In the longer-term, use of harmful pesticides should be phased out by providing environmentally sound alternatives to control pests such as Integrated Pest Management (IPM), organic farming, or good agriculture practices (GAP).

CHAPTER 6 MICROBIAL RISKS DUE TO POLLUTION AND DEGRADATION OF WATER QUALITY IN TONLE SAP LAKE

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The risk of microbial contamination due to poor sanitation and wastewater discharge

Many floating (water-based) and semi-floating (land-water based) villages are located on and around Tonle Sap Lake (TSL). People in floating and semi-floating villages are exposed to a number of health risks from anthropogenic pollutants. The discharge of untreated wastewater from the cities and unsafe sanitation and waste disposal from floating houses is one of the serious health concerns of the people living in these villages. Villagers usually defecate, urinate, and discard household waste directly into the lake without any treatment. An estimated 77 tons of faeces are discharged into the lake every day (Ung, 2018). Villagers have no better option than use of the contaminated lake water for bathing, washing, cooking, and drinking. Their kitchens and toilet rooms are installed near to each other at the rear of the floating houses and the villagers collect the lake water near to the houses for their daily activities. Water usage becomes more challenging for the villagers in the dry season when the lake area shrinks by almost one fifth. As a result of lower water volume, the concentration of contaminants increases, and the water quality worsens to the extent that it often smells bad. The villagers, particularly children, often suffer from

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waterborne diseases and families have to spend a significant amount of their income to pay for health care services.

Understanding the survival of pathogens and their distribution in the water environment is essential. The biological water quality and microbial consortia in the sewage of Phnom Penh, the Mekong River, Tonle Sap River, and TSL were determined by water quality sampling at different depths.

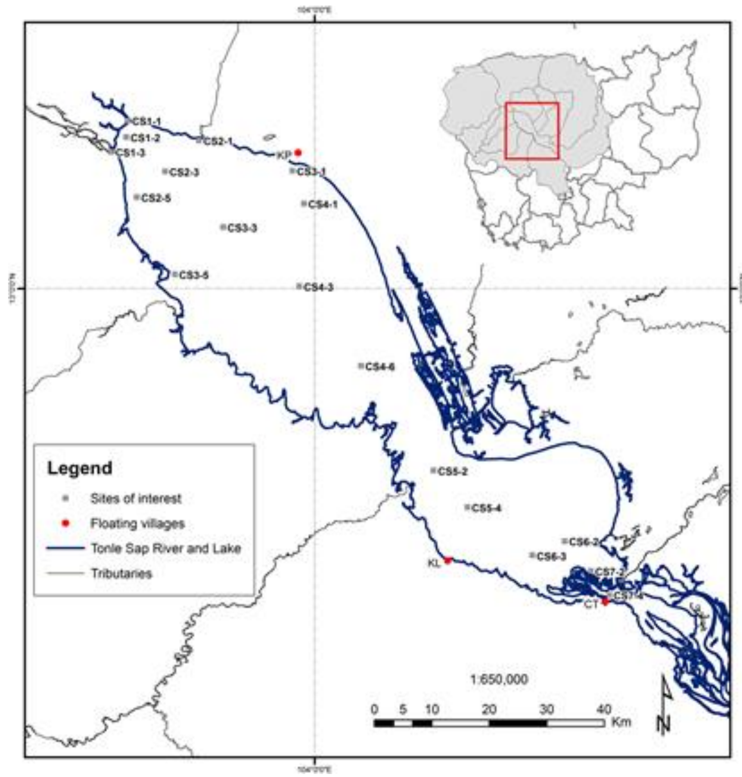


Figure 6.1. The sampling sites at seven cross-sections (CS) from the northwestern to the southeastern part of Tonle Sap Lake and in three floating villages [Kampong Plouk (KP), Kampong Luong (KL), and Chhnok Tru (CT)] and the Mekong River (Unit: Bacteria [CFU/mL]) (Source: authors)

A novel approach was developed to trace the fate of human intestinal bacteria and microbial communities in TSL using the following four steps (**Box 6.1**):

STEP I. Quantification of *E. coli*, coliform and microbial communities in sewage, the Tonle Sap River and the Mekong River.

STEP II. Assess spatiotemporal distribution of microbial community in different water depths and sediment of TSL (**Figure 6.1**)

STEP III. Introduction of a novel approach that uses a biologically stable dialysis membrane device to trace *E. coli*.

STEP IV. Use of a biologically stable dialysis device to trace human intestinal bacteria.

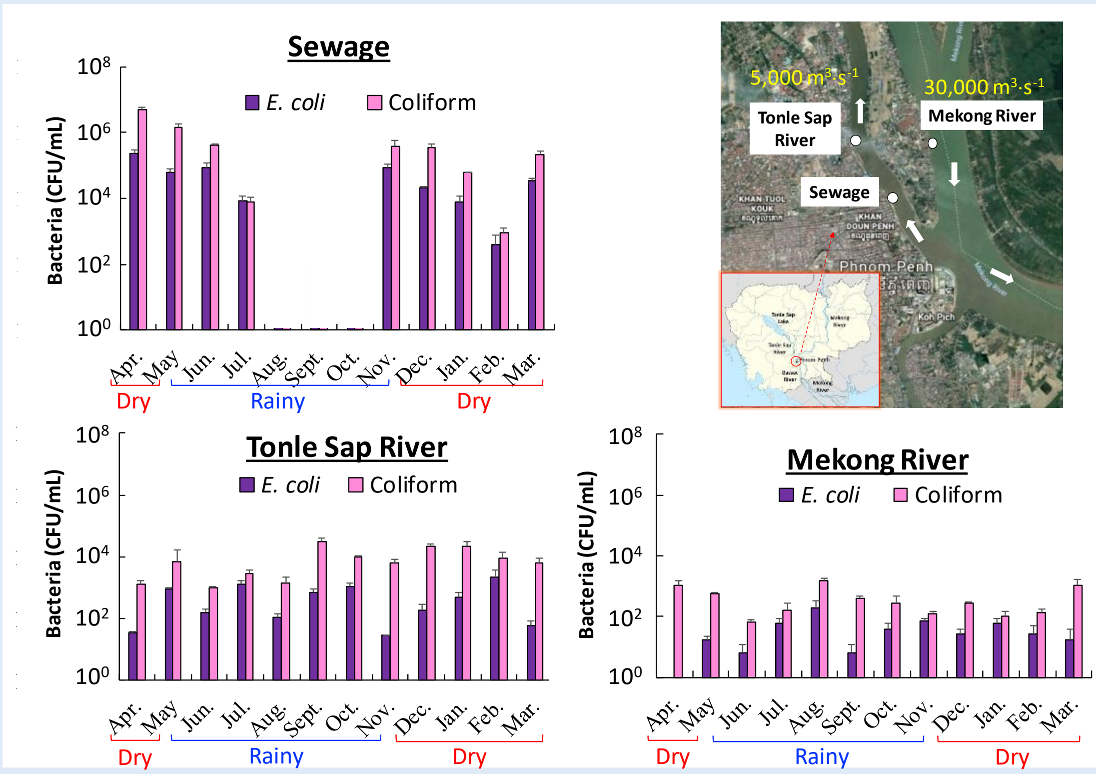
The presence of *E. coli* and coliform in the water environment confirms that the water is contaminated by human fecal waste. The coliform concentration was more than 10 times higher than that of *E. coli* in all samples (**Box 6.1, STEP I**). The concentration of *E. coli* and coliform in the sewage was more than 100 times higher than that of Tonle Sap River and more than 1000 times higher than that of Mekong River. *E. coli* and coliform concentrations in the sewage were highest in April and lowest in February. The biological water quality of both the Tonle Sap River and the Mekong River was influenced by discharge of sewage from cities. The higher contamination of the Tonle Sap River was due to higher discharge from the Mekong River and its location far from the populated Phnom Penh area.

Next-Generation Sequencing (NGS) was used to determine the spatiotemporal distribution of the microbial community structure in TSL, their diversity and their numbers at different water depths and sediment. The total bacterial concentration in the surface and sub-layer water was significantly different ($P < 0.01$) than in the sediment (**Figure 6.2**). Bacterial concentration in sediment was 100 times greater than concentration in the lake water. However, bacterial concentration in neither the surface and sub-layer water, nor in sediment, was significantly different among the sites.

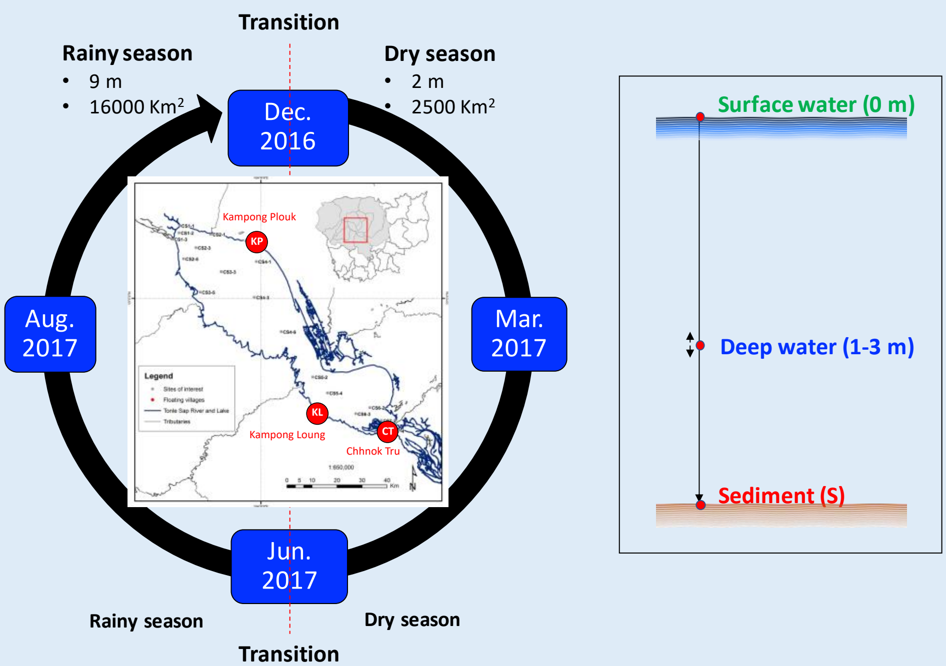
Interestingly, the relative abundance of microbial consortia near the floating villages was different from those measured at non-point sources. It was found that concentration of E. coli, as a hygiene indicator of the water around floating villages, was several hundreds of colony forming unit (CFU) per 1 mL. This value exceeds the safety guideline of the World Health Organization. On the other hand, in the lake water far from the villages, the concentration of *E. coli* was few CFU per 1 mL, or undetectable. Human waste could have strongly influenced the water environment near floating villages since the villagers usually defecate and urinate directly into the lake. In addition, the total bacterial concentration in water near the villages was about 108 copies/mL, which is 10 times

BOX 6.1 Determination of biological water quality and microbial consortia in sewage, the Mekong River, the Tonle Sap River, and Tonle Sap Lake and tracing the fate of human intestinal bacteria in the water environment (Source: authors)

STEP I: *Quantification of E. coli, coliform and microbial community in sewage, the Tonle Sap River and the Mekong River (Unit: Bacteria [CFU/mL])*



STEP II: *Assess spatiotemporal distribution of microbial community in different water depths and sediment of Tonle Sap Lake*

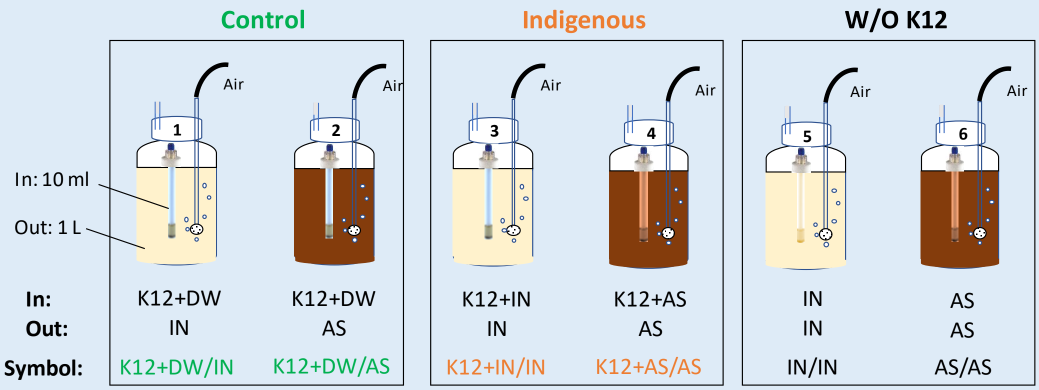


BOX 6.1 Determination of biological water quality and microbial consortia in sewage, the Mekong River, the Tonle Sap River, and Tonle Sap Lake and tracing the fate of human intestinal bacteria in the water environment (Continued..)

STEP III: *Develop a novel approach to trace the fate of E. coli in wastewater*

	1	2	3	4	5	6
E. coli **K12**	+	+	+	+	-	-
Inside	DW	DW	IN	AS	IN	AS
Outside	IN	AS	IN	AS	IN	AS
Condition	Control		Indigenous		W/O K12	

DW: Distilled Water
IN: Influent
AS: Activated Sludge



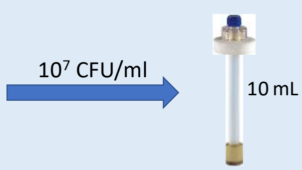
- 80 rpm, room temperature, no light, aerobic, 10-days incubation

STEP IV: *Use biologically stable dialysis device to trace the fate of human intestinal bacteria in Tonle Sap Lake*

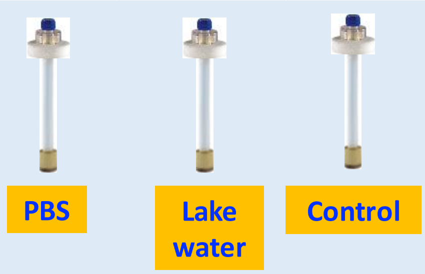
Field survey:

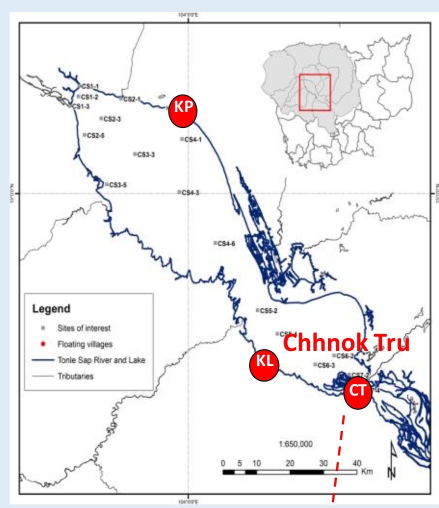
- Date: March 2018
- Site: Chhnok Tru floating village

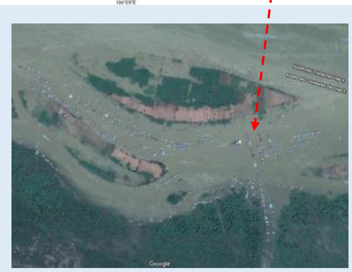
1. *E. coli* K12
2. *S. aureus* ATCC
3. *E. fergusonii*
4. *S. epidermidis*



	1	2	3
Condition	**PBS**	**Lake water**	**Lake water**
Strains	+	+	-







higher than that of the non-point source. In the dry season, most of villagers store the lake water treated by simple coagulation settling. Based on the measurement of total bacterial concentration, although it was lower than before treatment, it still remained ca.105 copies/mL. This indicates insufficient treatment of the water.

The most dominant bacterial phyla in TSL were Acidobacteria, Actinobacteria, Bacteroidetes, Chlorobi, Chlorofexi, Cyanobacteria, Firmicutes, Nitrospirae, Plantomycetes, Proteobacteria, and Verrucomicrobia (**Figure 6.3**). The bacterial community found in the surface and sub-layer water was not significantly different, but they differed from the bacterial community in sediment in all sampling dates. Actinobacteria, Proteobacteria, and Cyanobacteria were the most abundant in the water samples while Firmicutes and Chloroflexi were the two largest populations in the sediment samples.

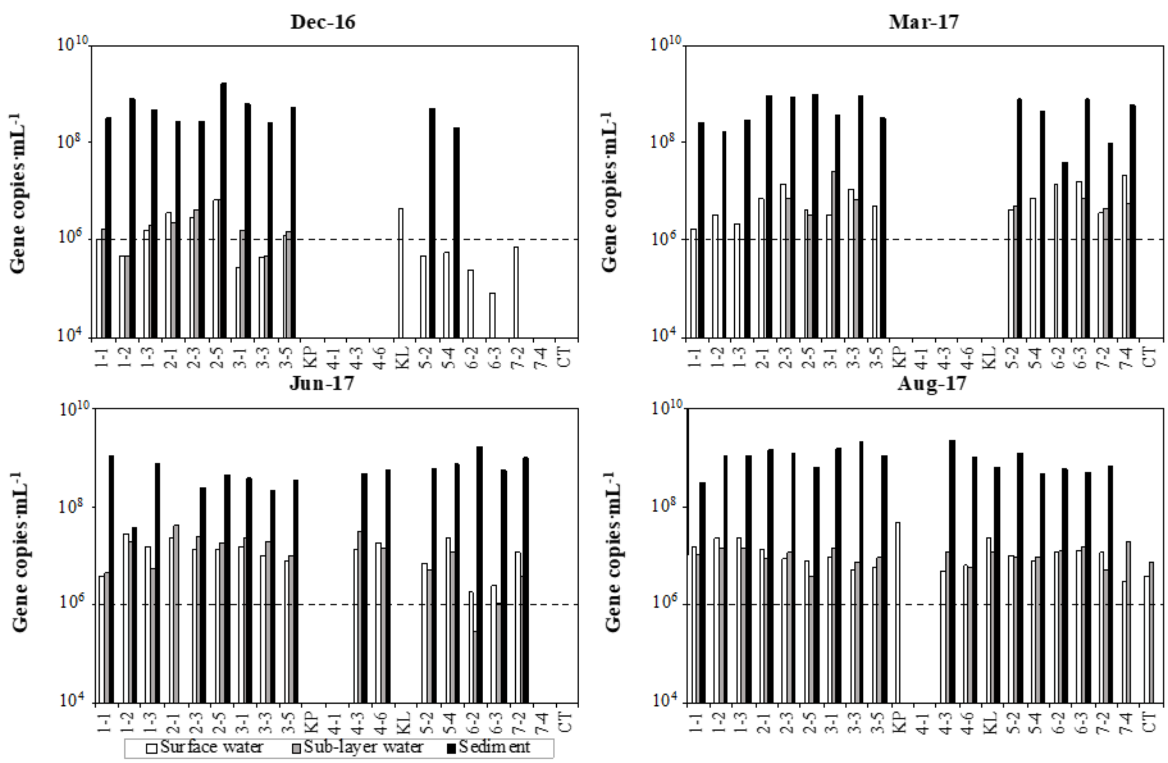


Figure 6.2 The total 16S rRNA gene copy number in the surface water (white bar), sub-layer water (grey bar), and sediment samples (black bar) in Dec-16, Mar-17, Jun-17, and Aug-17. The sites with bars missing have no data available. The dotted lines indicate the bacterial concentration of

106 gene copies/mL. The floating villages: Kampong Plouk (KP), Kampong Luong (KL), and Chhnok Tru (CT) (Source: authors)

The relative abundance of Cyanobacteria represented the highest proportion in the surface water compared to sub-layer water; and it was less abundance in sediment. High abundance of Actinobacteria and Proteobacteria were also found in sediment.

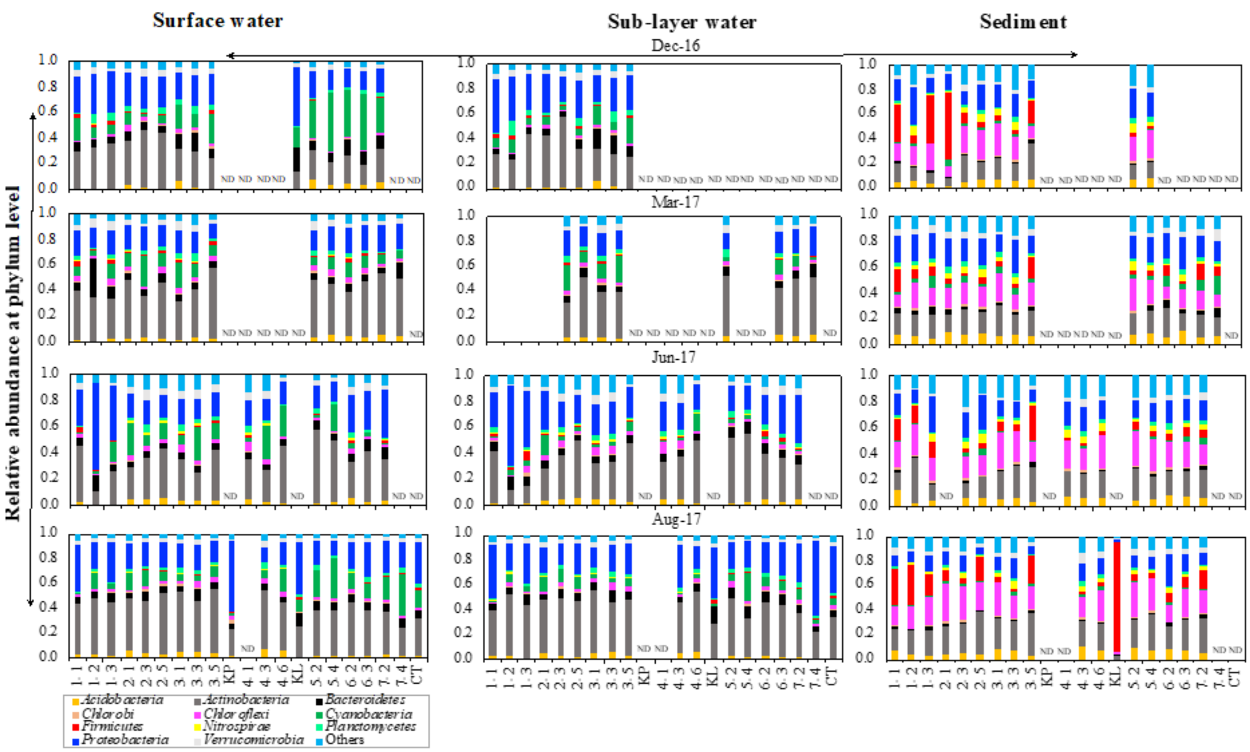


Figure 6.3 The relative abundance of the bacterial phyla in the surface water, sub-layer water, and sediment samples in Dec-16, Mar-17, Jun-17, and Aug-17. The floating villages: Kampong Plouk (KP), Kampong Luong (KL), and Chhnok Tru (CT). ND means not determined (Source: authors)

We also detected a high relative abundance of cyanobacterial toxin producing and pathogenic bacteria candidates, such as Mycobacterium, Microcystis, Dolichospermum, Flavobacterium, Sphingomonas, Clostridium, Streptomyces, Ralstonia, and Achromobacter. Compared to various high abundance species, Acidobacteria, Chlorobi, Planctomycetes, and Verrucomicrobia were widely distributed in both water and sediment samples. It is likely that dissolved oxygen and the pH of the lake water were responsible for the abundance of Cyanobacteria as well as the dominant phyla such as Acidobacteria, Actinobacteria, Chloroflexi, and Verrucomicrobia. The highly abundant and important phylum of Actinobacteria in the lake water were found to be dependent on total dissolved solids (TDS) and turbidity. The bacterial concentration in the lake water increased about 10 times in the dry season when the lake size decreased by several times. The bacterial concentration was still high during the wet season, most likely due to the resuspension of the bacterial community between sediment and water column. The findings of bacterial community dynamics also correspond well with the water quality data and natural phenomenon of the water cycle in TSL. An experimental protocol was developed to trace the fate of human intestinal bacteria in TSL (Ung, 2018; Ung, et al., 2019). Two standard strains (*E. coli* K12 W3110 and *S. aureus* ATCC 6538) and two environmental isolated strains (*E. fergusonii* ATCC 35469 and *S. epidermidis* NBRC 100911) from the lake samples taken in Kampong Luong floating village in September 2017 were used in this study. *E. fergusonii* was isolated from the lake water and *S. epidermidis* was isolated from the lake sediment. In the **Figure 6.4**, *E. coli* was classified as Enterobacteriaceae at the family level and *Staphylococcus aureus* was classified as Staphylococcus at the genus level.

In the raw lake water samples, Enterobacteriaceae (*E. coli*) had a relative abundance of about 5 % while that of Staphylococcus (*S. aureus*) was just 0.2 %. The most abundant communities in the lake water were Synechococcus, ACK-M1, C111, and Comamonadaceae. The abundance of community in the lake water changed when *E. coli* and *S. aureus* were introduced into the lake water sample. *E. coli* and *S. aureus* then dominated in the lake water sample with an abundance of 87% and 95%, respectively, of the total communities on day 0 of incubation. However, abundance of *E. coli* decreased after two days of incubation to the extent that it was almost undetectable. *S. aureus* also decreased, but more gradually in both the surface and bottom lake water samples, and was still detectable after 6 days of incubation. After two days of incubation, Rhodobacter, Comamonadaceae, and Hydrogenophaga appeared in *E.coli* inoculated samples and Rhodobacter and Comamonadaceae was also observed in *S. aureus* inoculated samples.

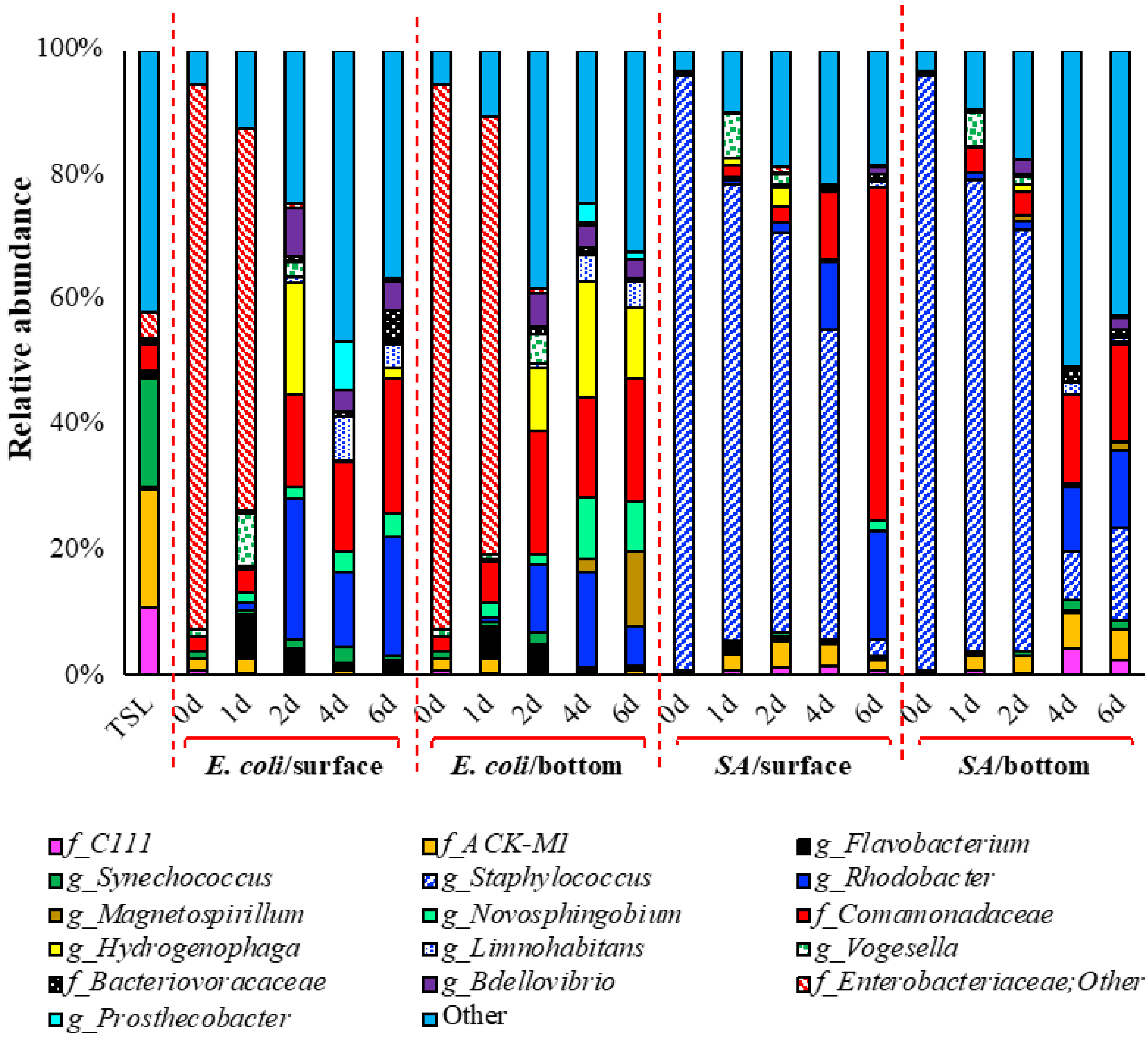


Figure 6.4 The relative abundance of the microbial community in Tonle Sap Lake and the relative abundance of inoculum (*E. coli* and *S. aureus*) incubated in the surface water and the bottom water layer of the lake for 6 days at Kampong Luong floating village in March 2017. f means family level classification, g means genus level classification, and other refers to less abundant communities and unassigned communities (Source: authors)

The extended survival of *Staphylococcus spp*. in the lake water indicates the vulnerability of people living in the floating villages, where human wastes are directly disposed without any treatment. The harmful bacteria were also detected in the water storage of floating villages even after coagulant treatment. Although a huge temperature difference between the human gut (warmer) and the water environment (cooler) makes it hard for the human gut bacteria's ability to grow and survive in the water environment, the persistence of the human gut bacteria in TSL suggests the fact that the survival could depend also on other factors.

Risk assessment of algal blooms

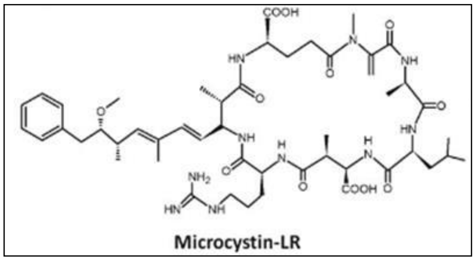
Cyanobacterial blooms in freshwater systems due to eutrophication (particularly high concentration of nitrogen and phosphorous) is a serious environmental and social problem, and a global issue. Some cyanobacteria produce toxins. *Microcystis aeruginosa* is one of the most predominant toxic cyanobacteria and can produce a hepatotoxin called microcystin. Microcystin is often reported in freshwater and the World Health Organization guideline on microcystin concentration is a maximum of 1 μg/L in drinking water. An understanding of the reason for, and timing of, toxin production is needed to reduce human and ecological risks. However, it still remains unclear why and when toxins are produced. In this study, we investigate the occurrences of cyanobacteria in TSL.

During the dry season, algal blooms are common in some areas around floating villages. An extremely high microcystin concentration (i.e., 70,692 ng/L), which exceeded WHO guideline, was detected near Kampong Phluk Port. In addition, microcystin was also detected from 191ng/L to 518ng/L in other parts of the lake. These results suggest that cyanotoxin can pose potential health risks if people in the floating villages directly access to the cyanobacteria-dominant toxic waters. Previous studies have suggested that cellular microcystin contents are higher under a stress condition such as high light intensity and low nutrient concentration (Nakatani, Nasukawa, & Fujii, 2018). It is suggested that future studies investigate microcystin production under different environmental and water quality condition to assess cellular stresses.

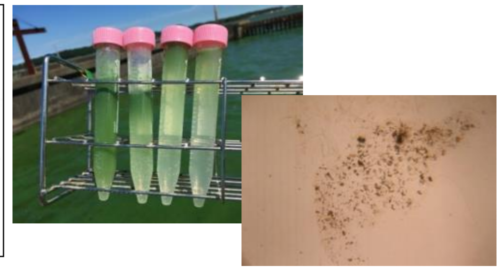
The interaction and diversity of microbes in the water environment depend on various factors such as landscape, soil, climate, water flow, abiotic, and biotic factors (Adrados, et al., 2014). The continuous introduction of nutrients, pollutants, and microbes from human sources into the water environment may impact the naturally occurring microbial diversity and its function and may lead to environmental problems. The concentrations of the three most abundant phyla - Cyanobacteria, Actinobacteria, and Proteobacteria - were averaged at the seven cross-sections on each sampling date (**Figure 6.5**).

The lowest bacterial concentrations were determined in Dec-16 sampling while the highest concentrations were recorded in Jun-17 sampling, with the exception of cross-section number 6. The bacterial concentration increased more than 10 times in the dry season (Mar-17) and reached to the peak during transition (Jun-17) from the dry to rainy season. However, their concentration reduced in Aug-17. The highest Proteobacteria concentration was determined in the lake water at the floating villages such as Kampong Plouk (KP) and Kampong Luong (KL), where concentration was more than 10 times higher than the samples from those measured at non-point sources. The concentration of Actinobacteria was also relatively higher near the floating villages. Firmicutes show their highest concentration in sediment at the Kampong Luong floating village – about 20 times higher than the samples from those measured at the non-point sources. Chloroflexi, Actinobacteria, and Proteobacteria showed higher concentration in the samples at the non-point sources than in the floating villages.

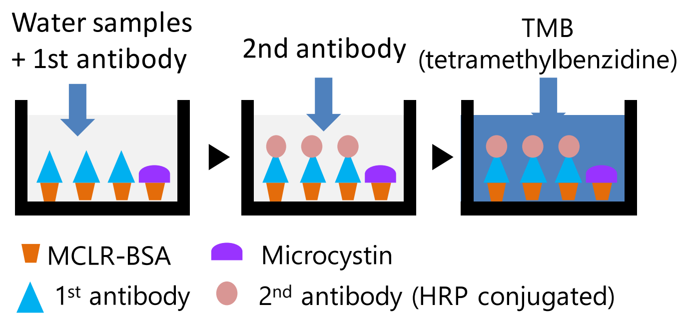
The above findings suggest that the direct use of the lake water during cyanobacterial blooms in the dry season is not recommended from the health perspective. Algae and cyanobacteria should be removed prior to the uses (for drinking or domestic) including by coagulation and filtration methods. Since cyanobacterial toxins in many cases are presents in the cyanobacterial cells, the removal of cells would be the most effective method to get rid of microcystin.



Microcystin-LR (MC), a hepato-toxin produced by freshwater cyanobacteria



Collection of water samples from cyanobacteria dominated lake



ELISA (Enzyme-Linked Immuno Sorbent Assay) method for microcystin detection

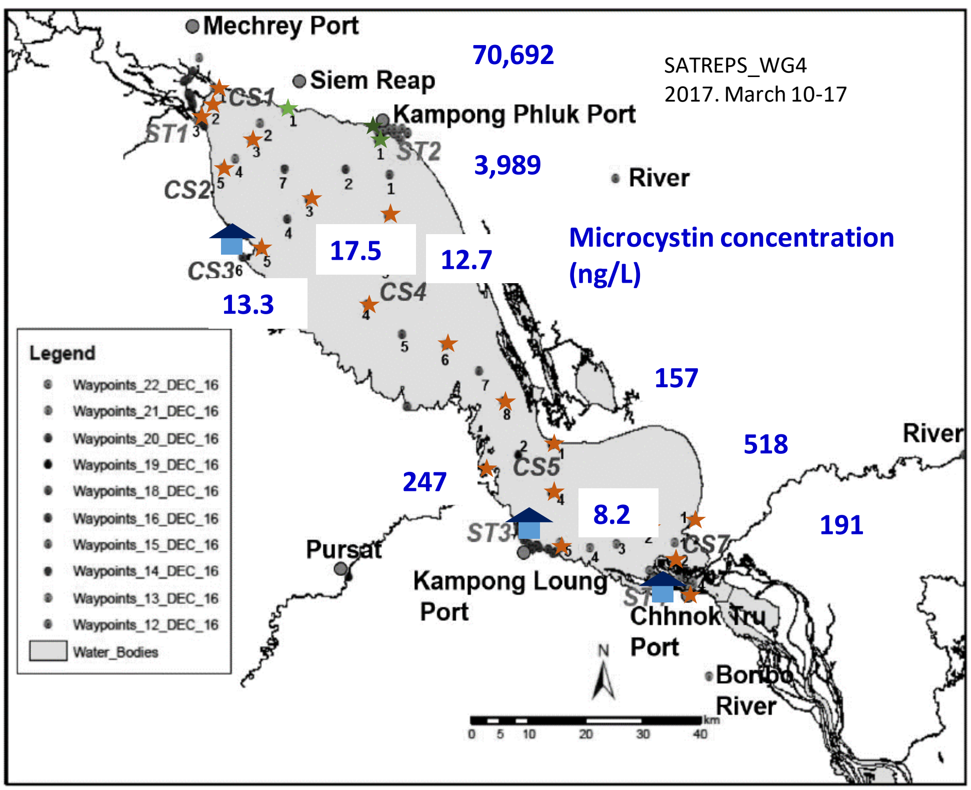


Figure 6.5 Spatial distribution of microcystin concentration on TSL. High microcystin concentratin was observed in the northwest of the lake (Kampong Phluk Port) exceeding WHO guideline. (Source: authors)

Recently, the emergence of antibiotic-resistant bacteria, especially multidrug resistant pathogens, has become a serious threat all over the world. It is thought that it is caused by the overuse and/or inappropriate uses of antibiotics. In TSL, antibiotics are used for the treatment of human illness, for livestock, and in fish feed in aquaculture farms. A preliminary assessment conducted under the SATREPS project found antibiotic-resistant bacteria in the lake environment. Future assessments will further elaborate on the risks posed by antibiotic resistant bacteria on human health.

Key findings and recommendations

- Microbial contamination of drinking water is a serious problem that has direct health implications for the people exposed to lake water on a daily basis. Harmful bacteria in human excreta and sewerage were found in the lake and surrounding waters, using a novel analytical approach developed in this project.
- These bacterial communities show a high level of persistence and their extended survival in the lake water increases the vulnerability of the people living in floating villages.
- The bacteria found in the water stored by villagers could not be effectively removed by coagulation methods only. Appropriate removal mechanisms should be further investigated. Similarly, safe drinking water, sanitation, hygiene (WASH) and safer disposal of human waste should be given a high priority to reduce the risk of contamination. For instance, a simple awareness of the importance of drinking only water that has been boiled could prevent the microbial health risks.
- The behavior of cyanobacteria, other indigenous bacteria, and phytoplankton in the changing water environment should be assessed as some cyanobacterial communities showed a risky level of the cyanotoxic concentration. Cyanobacterial cells should be

removed before using the contaminated water for domestic purposes. Similarly, proper consideration to emerging problems such as antibiotic resistant bacteria is needed due to an increased use of antibiotics by people, aquaculture and livestock.

CHAPTER 7 CONCLUSION AND POLICY RECOMMENDATIONS

Binaya Raj Shivakoti[1], Pham Ngoc Bao[1], Rajendra Khanal[2], Chihiro Yoshimura[2], Seingheng Hul[3]

Tone Sap Lake (TSL) is under various environmental pressures. Some are due to external factors across the Mekong River Basin, while the majority are related to changes within TSL Basin, which covers close to half of the landmass of Cambodia. Land-use changes, harvest of aquatic resources, disposal of waste, poor sanitation, surface- and agricultural runoff, erosion of sediments and pesticides, and constructions of dams along the Mekong Rivers and its tributaries, are the prominent drivers affecting environmental condition of TSL. Climate change, meanwhile, exacerbates and complicates the effects of these drivers.

Information on the hydrological condition and important environmental variables measuring the state and condition of TSL has been scarce and scattered. An improved scientific understanding of the causes of TSL's environmental is necessary for the conservation of the TSL environment and to minimise their impacts on the livelihoods of the millions of people who are directly or indirectly dependent on the lake's resources.

The SATREPS project "Establishment of Environmental Conservation Platform of Tonle Sap Lake" was initiated to fulfill the science and policy gap through a collaboration between researchers from Japan and Cambodia. The project utilised state-of-the art technologies and research methodology to address some of the prominent environmental challenges faced by the local

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communities living in the TSL basin. The collaborative research helped to transfer recent scientific advances in Japan. Graduate students (masters and PhDs) and other researchers were exchanged between the two countries and training opportunities were offered, including study exposure visits and thematic seminars in Japan and Cambodia for students, researchers, governmental officials and experts from Cambodia. The annual international lake symposium on conservation and management of tropical lakes and policy dialogues are organised regularly in Cambodia as well as at other international forum such as in the 17th World Lake Conference, Tsukuba, Japan.

This report presents the findings of the collaborative research activities which, it is hoped, will help to inform researchers, policy makers and decision makers, and other relevant stakeholders in Cambodia. The report focuses on the problems faced by local people due to recent environmental changes in the lake. It draws attention to both research gaps, and the scientific methods that can be used to address environmental problems in TSL.

Chapter 2 highlighted how the livelihoods and the wellbeing of the lake's communities are directly linked with the environmental condition of TSL. The communities are facing the impacts of hydrological changes due to construction of dams in the upstream Mekong River Basin and climate change. Hydrological changes have a visible impact on seasonal flood pulse and fisheries, which support the livelihoods of many local communities. Fish catches are declining which, in turn, is increasing pressure on the common fishing grounds and forcing fishermen to travel to look for the new fishing grounds. Meanwhile, the degraded water quality around the floating villages is causing water borne diseases frequently. The communities have to spend their hard-earned cash from fishing to cover medical expenses. It was evident that the environmental problems in the lake increased the vulnerability of the people, many of whom rely on daily earnings from fishing.

Chapter 3 demonstrated how hydrological modelling and the latest hydrological data acquisition methods could be used to examine and advance our understanding of hydrological changes in the lake. The chapter introduced a multi-level hydrological assessment involving one (1D), two (2D) and three (3D) dimensional modeling. The integration of 1D model with 2D model allows capture of temporal changes of the water level and the seasonal backwater flows along the Tonle Sap River. A three-dimensional (3D) hydraulic model is being developed to simulate the process of vertical mixing of water and other substances in the lake. The 3D model, which was trialed in the Chhnok Tru floating villages, will advance understanding of temperature changes and behavior of toxic substances, build-up, wash-off, and dispersion of harmful pathogens, nutrients and pollutants across TSL Basin. In addition, a land-use model was used to simulate impacts of land-use and land-cover changes on hydrology. Ground observation data and remote sensing data were used to estimate seasonal changes in the extent of water in the lake and its floodplains.

Chapter 4 provided a snapshot of water quality changes and the process of sedimentation in TSL based on water quality assessment of a broad range of parameters conducted across the lake and its tributaries, including spatial (longitudinal, horizontal and vertical) and seasonal surveys. This is expected to improve understanding of water quality profiles of the lake and spatio-temporal variation of water quality across TSL and its basin. The collected data serve as baseline information for the future assessment of water quality. Furthermore, the chapter examined seasonal dynamics of the sediment, which is important for the sustainability of the lake ecology. The findings suggest that the lake acts as sink during the high-water period while resuspension is dominant in the low-water period. The drainage from the lake in the dry season is a source of sediments to the downstream Mekong River. The role of floodplain vegetation is important to maintain the natural sediment dynamics. The characteristics of the sedimentation are influenced by the poor sanitation and the degradation of the water quality and the chemical pollution from the agriculture.

Chapter 5 discussed contamination of TSL water, sediments, and biota by heavy metals and pesticides. Advanced analytical techniques determined that, while contamination of heavy metals was found not to be dangerously high, pesticide levels in water, sediments and biota (fish) samples were a cause for concern.

Chapter 6 reported a novel approach that was developed in this project to trace the fate of the human intestinal bacteria and microbial communities in TSL. It was found that harmful human intestinal bacteria are likely to persist in the lake environment for an extended period. The study also found harmful cyanobacteria in the lake water, suggesting a health risk through direct use of the lake water during the dry season.

Based on the research findings, the following key policy recommendations are made for the attention of the relevant stakeholders in Cambodia:

1. Additional research and urgent action are needed to address the severe challenges faced by the communities living in and around TSL. Their livelihoods are intrinsically linked to environmental and hydrological changes in the lake. Addressing the lake's environmental problems is, therefore, critical to ensure sustainable development and to improve communities' quality of life.
2. It is advisable to find an appropriate channel and a mode of communication to link the research findings with community livelihoods though awareness raising and capacity development. The dissemination of research findings in a timely manner is important for

improving resilience and adaptive capacity of the communities to cope with unexpected environmental changes, including climate change.

3. Improvement in modeling capacity is highly desirable to more accurately estimate future scenarios, including the effects of climate change and the construction of dams on the hydrology and the hydrodynamics of the lake. Advancement of the multi-level hydrological assessment model employed in this study and its subsequent integration into Water Environmental Analytical Tool (WEAT) could help to find meaningful solutions to deal with sediment and nutrient dynamics, pollution, contamination of heavy metals, pesticides, harmful microbes or emerging pollutants, and ecological and hydrological issues.
4. The key factor in water quality management is the availability of data at multiple spatial scales and time periods. The monitoring and assessment of water quality required to find solutions to short-term and localised pollution, and to better understand long-term changes. Clarity on what, where, when, and how to monitor is critical, considering the massive size of TSL and the multi-dimensional nature of its environmental problems. A cost-effective and useful water quality assessment strategy is, therefore, needed.
5. Understanding the status of pesticides in TSL is important to formulate preventive measures to reduce aquatic and human health risks. Efforts are required at multiple levels to reduce the health risks ranging from upstream source control of pesticide distribution, prevention of inappropriate use and disposal of pesticides by the farmers, and promotion of good agricultural practices. Further improvements in the continuous monitoring and research capacity is necessary to assess spatial and seasonal distribution, contamination pathways, and health impacts on people living around the lake and consuming its fish.

6. Microbial pollution is a serious issue especially in TSL's floating villages due to contamination from in-situ as well as off-site sources. Because of high exposure to the contaminated water, better solutions to safe drinking water, sanitation, hygiene, and safer disposal of human waste are necessary. For instance, the simple raising of awareness about the need to boil water for drinking could reduce microbial health risks. Better alternatives to treat and disinfect drinking water should, however, also be investigated and introduced at the community scale.

7. Proper consideration should be given to blooms of toxic cyanobacteria and emerging problems such as antibiotic-resistant bacteria due to increased use of anti-biotic drugs by people and livestock. For the former, strategies to control excessive inflow and internal loading of sediments and nutrients (such as nitrogen and phosphorous) in localised cases has to be considered such as by the use of WEAT to simulate scenarios. Meanwhile, in addition to the research to understand the evolution, persistence and spread of antibiotic drug resistant, source control is important to prevent the overuse of antibiotic-resistant drugs from human treatment, livestock, or aquaculture.

These identified issues and recommendations are expected to be useful for advancing future research and monitoring of the state of the environment, while relevant agencies of the government could take necessary mitigation measures to solve these problems. In the long term, it is advisable to have an integrated perspective suitable for TSL to address various environmental issues in a coordinated manner. The generic principles of Integrated Lake Basin Management (ILBM) could be a useful framework for recognizing that lakes and their basins are a single and mutually-interacting management unit and for operationalizing the identified interventions and priorities in a coordinated manner. The design of ILBM should be guided by TSL's unique and changing realities, needs and priorities for the sustainable management of the lake.

This SATREPS project hopes to further investigate the environmental problems outlined here (such as heavy metals, water quality modeling, scenario analysis, antibiotic resistance, social implementation etc.) and integrate models such as WEAT, which will enable an integrated analysis of the different causal factors and impacts and helps to find alternative mitigation strategies and solutions scenarios. The project's major contribution will be the establishment of Tonle Sap Water Environmental Platform (TSWEP) as a repository of the information on TSL environment and for sharing the progress on the researches, decision making and the integrated management of this iconic lake.

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APPENDIX

List of Publications under the SATREPS Project

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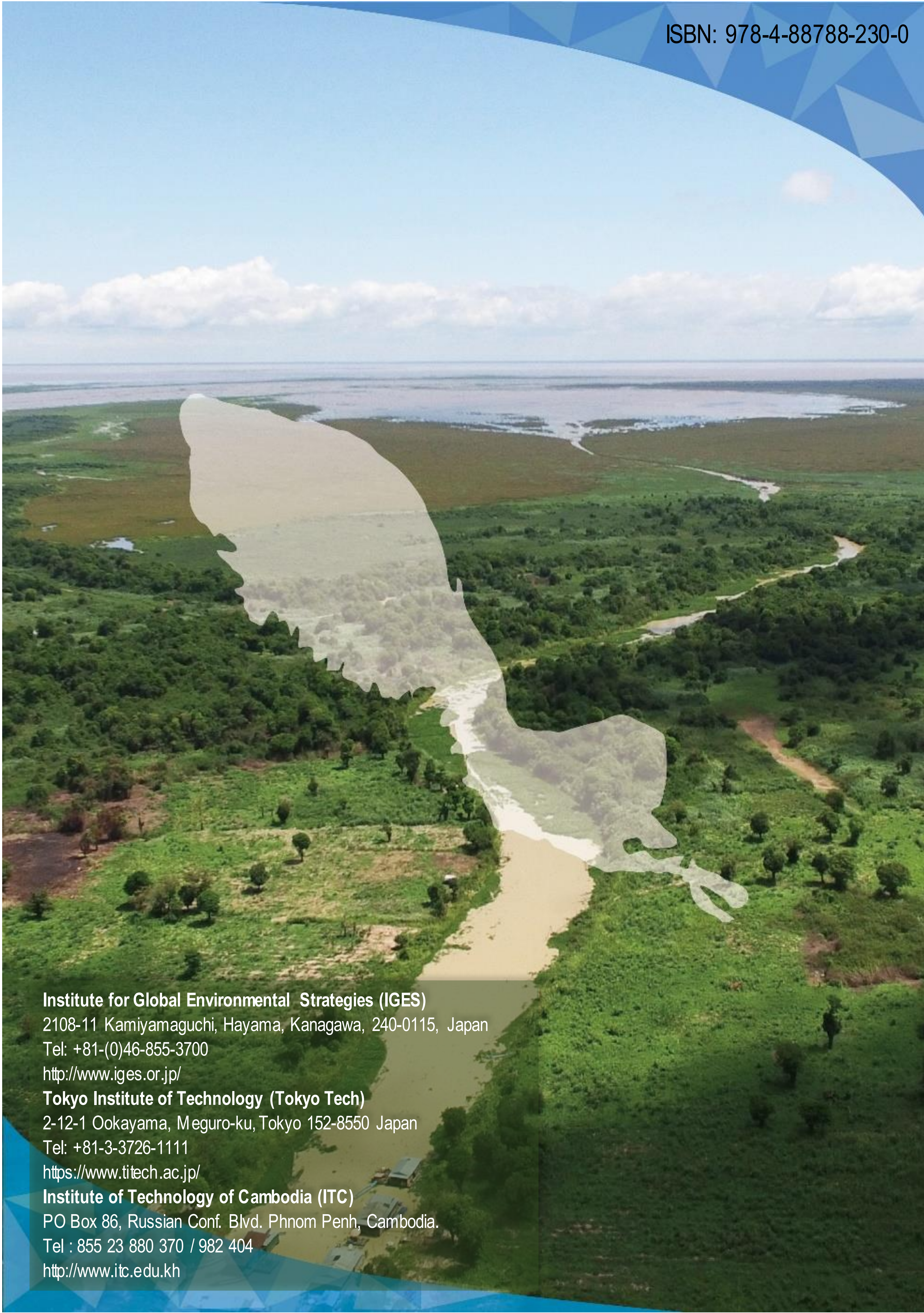

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