Chapter 50
Recommendations for Further Research and Environmental Management

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50.1 This Book and Steps Forward

This book compiles all the relevant available information, knowledge, and techniques to delineate the uniqueness and importance of the water and life of the Tonle Sap Lake (TSL). However, similar to other themes in environmental science, we have identified several knowledge gaps as described in each chapter. Thus, we sincerely hope that this book will be used as a solid and concise basis to further develop science on TSL in the general framework of tropical limnology and to

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develop substantial management policy and practices for wise use of this precious water body in domestic and international perspectives.

From this standpoint, we, all the part editors, carefully selected and concisely summarized the important remaining knowledge gaps and directions for lake environmental management in this chapter as our recommendation. We believe that this chapter will help you pick up the focuses of your research and policy development together with a good overview. In case some detailed explanation is required on each topic, please refer to the corresponding parts or chapters.

50.2 Recommendations for Further Research

50.2.1 Socioeconomics and Governance (Part I)

The livelihoods and well-being of the local communities in the TSL region are linked with the environmental conditions of the lake-floodplain system, which is one of the excellent research themes in cultural anthropology. To enhance the resilience of the local communities, it is important to further strengthen our understanding of the potential impacts of environmental and climate stresses on them. To achieve this goal, there is a strong and urgent need for further understanding of the relationship among the livelihoods, governance, and lake ecosystem based on accurate and reliable data of the lake ecosystem, particularly the fish community.

50.2.2 Climate and Hydrology (Part II)

It is necessary to enhance the network of climatic and hydrological observations in the lake basin as the current network is obviously insufficient in this large and dynamic basin. Such an observation network needs to be capable of monitoring climatic conditions and river discharge based on updated rating curves. Given the scale of the lake, we additionally recommend research and development to fully utilize satellite-based remote sensing techniques for monitoring hydrological processes together with a cloud-based platform for data sharing and modeling integrating ground observation. This approach for environmental monitoring together with the use of archived data will also help us understand the shifts in local climate, environment, and ecosystem covering the past few decades.

50.2.3 Hydrodynamics (Part III)

We should continue the use of observation-based approaches, such as a 1-year measurement of water velocity profile and time series analysis of lake water levels, for elucidating the unique hydrodynamics in TSL. With data integration, the 2D

hydrodynamic model should be used for longer periods and future climate change scenarios to project possible changes of hydrodynamics over the lake. At the village scale, the 3D hydrodynamic model can be combined with environmental assessments, in which a vertical profile of flow velocity is important (e.g., sediment dynamics and fate and transport of pollutants and pathogens). The integration of groundwater exchange and wind effect in hydrodynamic models would widen their applicability for broader issues related to hydrology and geochemistry.

50.2.4 Sediment Dynamics (Part IV)

Further research should be conducted to fully understand the sediment balance of TSL, the sedimentation–resuspension process, and those related to the Mekong River basin by integrating field observation, remote sensing, and modeling techniques. In particular, the relationship among wind conditions, turbulence, and sediment resuspension in the lake needs to be elucidated. Furthermore, the shift in sediment load and dynamics should be quantified and modeled in relation to forest cover change and water resource management in local basins and the Mekong River basin. This is because these factors will possibly cause an imbalance in the sediment dynamics in TSL and its floodplain, resulting in geomorphological shifts and environmental and ecological deteriorations in the lake in short- and long-term periods.

50.2.5 Physicochemical Water Quality (Part V)

The assessment of the historical and current trends of spatiotemporal variation in basic water quality, nutrients, and chlorophyll *a* indicated some hotspots in TSL where the water quality matrix significantly varies. In particular, areas of floating villages, hypoxia, and eutrophication are predominated. Nevertheless, further research is required to gain a full understanding of groundwater exchange, photochemical reactions, and biogeochemistry at the water–sediment interface in relation to the flow pattern, sediment dynamics, and primary production. We also need to cover the emission and absorption of greenhouse gases in this lake. These remaining knowledge gaps are possibly elucidated by the integration of isotopic analysis and process-based modeling of those water quality components.

50.2.6 Microbial Community (Part VI)

In general, physicochemical (e.g., aerobic/anaerobic, pH, temperature, and nutrients) and biological (e.g., prey–predator relationship) factors affect the microbial

consortia. Thus, it is important to investigate not only microbial community composition but also their interactions with the factors in the lake. Furthermore, the productivity and functional roles of bacterial and viral communities in the lake ecosystem are our next challenge, which will elucidate the importance of the microbial loop in biogeochemistry and the food web. For those challenges, culture- and gene-based approaches are available. Gene-based analysis can reveal the whole microbial consortia, including unculturable microbes. Thus, both approaches should be properly used and combined to gain a comprehensive understanding of the microbial community.

50.2.7 Flora and Fauna (Part VII)

Flooded forests and aquatic vegetation are ideal and important habitats for both aquatic and terrestrial biota. They are critically important to maintain intact ecosystems and ecosystem functions/services. However, their ecological role has been poorly investigated, and they are under imminent threat from anthropogenic pressures. Therefore, further research should be conducted to understand their spatio-temporal distribution, the ecological traits of key species including migration, and the multispecies interactions with the explicit linkage to physical and chemical conditions in the floodplain. For this purpose, it would be beneficial to combine models of hydrodynamics, water quality, primary production, and fish migration and production, together with other techniques, for example, using isotopes and environmental DNA.

50.2.8 Chemical Pollution (Part VIII)

Chemical pollution in TSL is caused mainly by heavy metals, pesticides, and antibiotics. These chemicals come from direct disposal from the floating villages and runoff via the tributaries. Persistent organic pollutants are evidently seeping into the food chain. In addition, plastic pollution is now apparent in TSL and is still critically understudied. The current status of the pollution highlights the importance of the establishment of standard analytical methods and strategic monitoring of the pollutants in TSL. Research on the understanding of their fates (e.g., distribution, bioaccumulation, biomagnification, biodegradation, photodegradation, and transport) in relation to the unique flood pulse is also required, which can help us develop and recommend pollution remediation techniques.

50.2.9 Sanitation and Health Risk (Part IX)

Almost all of the people living on TSL have frequently experienced diarrheal diseases probably due to the poor sanitary environment, which is characterized by the use of lake water as a source of drinking water and the absence of adequate toilet. The environmental sanitation can be improved by onsite treatments of lake water to provide safer drinking water as well as fecal matter to prevent lake water pollution. Therefore, the development of low-cost technologies is highly demanded for the safe use of lake water and the proper treatment of fecal matter. In addition, to gain public acceptance of the developed technologies, quantitative microbial risk assessment targeting not only *Escherichia coli* but also more emerging pathogens, such as norovirus, should be conducted with practical scenarios of implementing countermeasures.

50.2.10 Environmental Shifts and Management (Part X)

Environmental management should be implemented based on a sufficient understanding of the interrelations of environmental processes and human dimensions (e.g., socioeconomics, ecosystem service, climate change, land use, and waste management). In the case of TSL, we are still at the initial stage of the investigation to gain a comprehensive overview of such a complex system. Therefore, while knowledge and techniques are being updated as aforementioned, they need to be actively used for scenario analysis concerning climate change, land use/land cover, health risk, agriculture, and aquaculture for policy integration for realizing sustainable development. For this purpose, we highly recommend transdisciplinary research and science communication as described in Chap. 49.

50.3 Recommendations for Environmental Management

50.3.1 Socioeconomics and Governance (Part I)

The identified environmental and climate change impacts on the livelihoods and well-being of the local communities in the TSL region must be well addressed through collective actions among actors, including researchers, policymakers, environmentalists, relevant governmental agencies, and private sectors. Fair and open dialogs based on scientific evidence among local and international stakeholders must be considered, which could facilitate the scientific evidence-based policymaking process. The existing governance system is still complex and cannot guarantee sound environmental management and good governance of the lake ecosystem.

Therefore, government interventions need to be implemented to improve the performance of the current governance system.

50.3.2 Climate and Hydrology (Part II)

The development of the many hydropower dams on the upper reach of the Mekong River, together with the impacts of climate change, has greatly caused concerns over the potential threat to the biological diversity resulting from a significant change to the hydrological regimes in TSL. The development and integration of tools, management plans, and measures and policies about water resources management are required to rigorously evaluate and mitigate the abovementioned impacts on the TSL ecosystem for a sustainable regional development. Capacity building programs are also needed to secure sufficient human resources for the use of those tools. In addition, it is important to strengthen the cross-cutting collaboration among all stakeholders for the sake of the ease of data sharing.

50.3.3 Hydrodynamics (Part III)

The long-term monitoring of hydrodynamic processes is essential for determining hydrodynamic changes possibly due to climate change and the shifted flow regime in the Mekong River. With regard to the environmental management, the 2D-LIE model helps identify the hydrodynamic condition required for fishery, agriculture, and the unique ecosystem. This model suggested that the average retention time is approximately 4 months, which may be considered as the turnover time of the lake. In addition, local hydrodynamics at floating villages can be analyzed using the 3D non-hydrostatic hydraulic model as demonstrated at the floating village of Chhnok-Trou. The simulated flow field serves as a basis for understanding the water quality conditions and habitat conditions of aquatic flora and fauna.

50.3.4 Sediment Dynamics (Part IV)

TSL is extremely sensitive to sediment dynamics, while the available sediment data and knowledge are still limited. Therefore, we recommend the development of a system for monitoring sediment concentration, load, and quality in the scales of tributary basins and the whole lake. The monitored data are useful for further development of sediment transport models for the TSL basin, which are required for understanding sediment balance in TSL and implementing various scenario analyses concerning the shifting factors of land use/land cover, water resources, and climate change. Furthermore, the high concentration of lead in the sediment and

the lake water emphasized its potential risk to humans and the ecosystem. Thus, continuous monitoring of lead and the development of methods for mitigating its effect are necessary.

50.3.5 Physicochemical Water Quality (Part V)

For the effective management of the lake, continuous long-term monitoring of the water quality is deemed necessary. Considering the size of TSL, it is laborious and capital-intensive to continue frequent ground-based monitoring. Thus, it is highly recommended to integrate continuous monitoring by fixing multi-sensor probes at some points in the lake (ideally, real-time online system) and remote sensing techniques (i.e., satellite imagery) to minimize the cost of the ground survey. In addition, given the serious pollution at floating villages, the collection and treatment systems of solid waste and wastewater are urgently required for major floating villages. It is also important to restrict the number or density of the floating houses for maintaining a healthy environment and the unique ecosystem in TSL and its floodplain.

50.3.6 Microbial Community (Part VI)

The concentration of *E. coli* in the floating villages is higher than that in other areas of the lake. Moreover, microcystin that is produced by blue-green algae is strongly influenced by eutrophication and metal availability. To reduce the risk of waterborne disease, relatively simple treatment methods (e.g., sand filtration, flocculation, and chlorination) must be introduced to remove bacteria, algae, and viruses from the lake water for daily use at the village or household level. In addition, integrated lake basin management is highly recommended for controlling pollution and reducing the health risk of waterborne diseases. To this end, the key options are the introduction of wastewater treatment facilities in major communities in the lake basin and the reduction of loads of nutrients, pesticides, and antibiotics to the lake.

50.3.7 Flora and Fauna (Part VII)

Continuous monitoring of endemic species and their habitats in the flooded forests is necessary to understand the status of the floodplain ecosystems and develop preventive and adaptive measures against anthropogenic threats and climate change. Based on such understanding and development, a practical guideline for conservation and wise use of the floodplain ecosystem should be formulated and put into practice. Law enforcement needs to be strict against illegal activities so that the

guidelines and countermeasures can be effectively implemented. This will need strong and close collaborative work among relevant governmental agencies and institutions. Furthermore, such enforcement might lead to the identification of some potential wetlands for the conservation of flora and fauna, in particular, waterbirds.

50.3.8 Chemical Pollution (Part VIII)

The use of agrochemicals in Cambodia should be regulated. Based on their current distribution and risk, the current environmental legislation needs to expand the list of chemicals and establish standard analytical protocols for monitoring those chemicals. Urgently, farmers should be trained in good agricultural practices and proper use and handling of such chemicals. Capacity building is also vital for all the TSL stakeholders. In parallel, scientists, engineers, environmental managers, and policymakers should work together to address pollution problems through policy development, environmental monitoring, and remediation for conservation and sustainable use of the lake, avoiding serious degradation of the TSL ecosystem. Pollution prevention is fundamentally more desirable than pollution mitigation.

50.3.9 Sanitation and Health Risk (Part IX)

Hygienic behaviors are not commonly practiced among people living in the TSL region. For instance, washing hands with soap before eating and after defecation is easy and effective to avoid infection with pathogens originating from the lake. Hygienic behaviors eventually help people avoid lake water pollution. For this purpose, we strongly recommended the development of an educational program to promote hygienic behaviors. The educational program may use visualized materials based on 2D and 3D simulations of health risks under various scenarios, which can effectively help people understand the importance of hygienic practices. Such simulations tell us where and when people can obtain safe water and which countermeasure and treatment facility should be introduced to villages on TSL.

50.3.10 Environmental Shifts and Management (Part X)

To realize sustainable development of the TSL region, research and management strategies need to be strengthened to (1) bridge the gap between researchers and policymakers via a series of evidence-based policy dialogs; (2) promote appropriate technologies that are economic, effective, environmentally friendly, and locally implementable for water and wastewater treatment; (3) assess health and ecological

risks in the areas of floating villages; (4) remap the flooded forest, conservation area, and ecologically sensitive zones based on fundamental ecological understanding; and (5) develop and implement the policy framework for integrated lake basin management. On top of these, climate change needs to be additionally considered to develop mitigation and adaptation measures.

50.4 Final Remarks

At the same time, even after 5 years of intensive research combining literature survey, this book clearly highlights the limitation of our understanding of the TSL ecosystem. To take the next challenges, we humbly hope that the book will serve as a reference and encourage further investigations to improve our understanding of the ecosystem and our capacity for efficient evidence-based environmental management. Thus, we welcome any constructive feedback and comments, discussion, and collaboration on any topics related to the TSL ecosystem. Throughout the project, we have also confirmed again the importance of transdisciplinary research collaboration among various institutions and a network of scientists and researchers in various fields of expertise. We believe that transdisciplinary networks would advance our limnological knowledge, which would allow researchers, scientists, policymakers, and stakeholders to develop management strategies toward enhanced lake environmental sustainability.

Before closing, all the book editors and the part editors express sincere gratitude to all the authors who spent their substantial amount of time on writing and editing each corresponding chapter. We also appreciate the internal and external reviewers who provided us with their valuable expert comments to help us refine the quality of each chapter.