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Thesis Outline

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Chapters 1 and 2: General Introduction and Literature Review

The tropical river-lake floodplain system is one of the most diverse and significant ecosystems for wildlife and humans. Such a system is fundamentally characterized by the flood pulse, principally affecting the biota (e.g., aquatic life and flooded plants) and humans through its hydrological process. However, our understanding of the ecosystem services (ES) of tropical floodplain systems concerning the economic value, social importance, and perception of local communities of ES remains scarce and fragmented. Further, due to the recent hydrological change, it is required to identify suitable ecohydrological conditions to maintain the provisional service of the floodplain (e.g., fish production). Therefore, this study aimed to comprehensively elucidate the ES of a floodplain and its response to changing hydrological regimes in a large tropical lake-floodplain system, with Tonle Sap Lake (TSL) in Cambodia as an internationally important ecosystem. The specific objectives of this research are:

1. To understand the response of the TSL-floodplain ES to changing hydrological regimes;
2. To elucidate the ES of the TSL-floodplain and its economic valuation and relation to people;
3. To investigate the response of the ES to hydrological and environmental changes in the TSL-floodplain system.

In this thesis, "inundated forest" refers to the forest that is inundated in the floodplain (the area of inundated forest is determined by the condition of annual maximum water level and does change as long as the annual maximum water level changes), while "flooded forest" refers to the forest in the floodplain that is inundated or used to be inundated under the condition of maximum water level (their distribution does not change on a yearly basis even when the annual maximum water level changes).

This thesis is structured into six chapters. Chapter 1 provides a general introduction comprising the background, knowledge gaps, and objectives of the study. Chapter 2 consists of a body of literature regarding floodplains and their service (i.e., fish production) associated with the changing hydrological regimes. Chapter 3 investigates the response of migratory fishes to changing hydrological regimes, employing the integration of life cycle and habitation conditions in modeling the fish biomass, as their production is one of the major ES of floodplains. Chapter 4 elucidates the major ES of floodplains, their economic valuation, and their relation to local communities based on the questionnaire survey. Chapter 5 examines the response of ES to hydrological and environmental changes in the TSL-floodplain system. Then, Chapter 6 summarizes the major findings from this study and provides key recommendations, contributing to effective measures for sustainable environmental management of TSL and the Lower Mekong Basin, as well as future research in the tropical river-lake-floodplain systems.

Chapter 3: Integration of Life Cycle and Habitat Conditions in Modeling Fish Biomass in the Floodplain of the Lower Mekong Basin

The objective of this chapter aimed to model the fish biomass based on their life cycle and habitat conditions in order to investigate their response to changing hydrological regimes by focusing on the floodplain of TSL and its associated ecosystems within the Lower Mekong Basin. The objective of this chapter corresponds to the first specific objective of this thesis. To achieve its objective, this chapter hypothesized that the integration of life cycle and habitat conditions significantly improves the model performance for describing the biomass of migratory fishes. To test this hypothesis, this Chapter analyzed and modeled the temporal dynamics of the overall catches of the migratory fish species in the Tonle Sap River (TSR), of which six migratory fish species were individually investigated in this study based on the observation over 15 years (2000 – 2015) in the river-lake-floodplain system of the Mekong River, TSR, TSL, and its floodplain.

The study area covers specifically the section from Phnom Penh to Stung Treng, and the TSR and TSL floodplain system in Cambodia. The study targeted the migratory white fishes (i.e., 74 species), of which six species are additionally investigated individually. The six species are two large-sized species (river catfish *Pangasianodon hypophthalmums* and carp *Cyclocheilichthys enoplos*), two medium-sized carps (*Cirrhinus microlepis* and *Osteochilus melanopleurus*), and two small-sized mud carps (*Henicorhynchus lobatus* and *Labiobarbus lineatus*) which are planktivorous fishes. The other four individual species are piscivorous fishes.

In this study, the overall approach of modeling fish biomass was based on the full life cycle and habitat conditions of the migratory fishes. We modeled the total biomass of the 74 migratory fishes in the river-lake-floodplain system of Mekong River, TSR, and TSL, in association with the life cycle and the environmental factors of the fish habitats over 15 years (2000–2015). The model integrates hydrological factors (i.e., water level regime indices), climatic factors (i.e., water temperature), and physical habitat factors (i.e., inundated forest cover) to describe fish biomass.

This study modeled the fish biomass based on their life cycles in the river-lake-floodplain system using multiple linear regression, generalized linear model, generalized additive regressions (Hastie and Tibshirani, 1990; Wood, 2006) and random forests. The target variables were the total biomass of all the migratory fishes (i.e., 74 species) and biomasses of the individual six migratory species. This study assumed that the total weight of the annual catch of migratory fishes in TSR is proportional to and indicates the fish biomass, given that TSR is the only passing route for all the migratory fishes from TSL back to the Mekong River.

As a result, the models and their performance indicate that the integration of the life cycle and seasonal habitat conditions in modeling biomass is significantly important for migratory fishes. The results further showed that changing ecohydrological indices in the feeding and refuge seasons negatively affected fish biomass. Those indices were

hydrological factors (i.e., maximum water level, mean water level, the start date of the flood, and the end date of the flood), and climate factors (water temperature). Interestingly, the models indicated that the total area of inundated forests negatively influences the biomass of planktivorous fishes while it positively affects the biomass of piscivores. These results clearly showed the importance of the natural flow regime to ensure the fish life cycle and biomass production in the Lower Mekong Basin. The findings of this study enhance our understanding of the effects of shifting ecohydrological conditions on the fish life cycle and biomass production, which are critically important for fish conservation and management.

Chapter 4: Ecosystem Services of Flooded Forests and Their Relations to Characteristics of Local Communities in the Tonle Sap Lake-Floodplain System

This chapter aimed to achieve the second objective of the thesis, with two specific objectives: (1) to quantitatively describe the ES of the flooded forests in the tropical floodplains and (2) to elucidate the relation of local community characteristics to those ES by focusing on the TSL floodplain. Through intensive site investigation and detailed analysis of ninety-seven surveyed households, randomly selected from 22 villages in nine communes, this chapter elucidated all four main types of ES of the flooded forests in the TSL floodplain. This chapter employed the local market value approach for provisioning services, the contingent valuation method with the double-bounded dichotomous choice for cultural services on willingness to pay, and structural equation modeling for regulating services and supporting services.

As a result, the total economic valuation of provisioning and cultural services of the total population living in 170 floating villages in the Tonle Sap Lake floodplains was estimated approximately at US$ 106 million/year. The provisioning service was estimated to be US$655/person/year on average. The majority of cultural service was ecotourism, followed by social relations, religious, aesthetic, cultural heritage, and inspirational services. The estimates of the willingness to pay for these services were heavily influenced by the community characteristics, namely distance, sex, household size, and age. The regulating service comprised air temperature regulation, water purification, storm regulation, flood control, and carbon fixation, whereas the supporting service included fish spawning grounds and waterbird habitats. This study for the first time elucidated the importance of the four main ES categories of the flooded forests of the tropical floodplain system to the local communities. However, those services have been deteriorated by the ecohydrological change and anthropogenic activities. The applied and developed approaches provide scientific-based evidence for policymakers to incorporate ES in the conservation and management of flooded forests of tropical floodplains.

Chapter 5: Response of Ecosystem Services to Hydrological and Environmental Changes in the Tonle Sap Lake-Floodplain System

This chapter aimed to investigate the response of ecosystem service of the TSL-Floodplain system to hydrological and environmental changes with the application of the fish biomass model integrating life cycle and habitat conditions developed in Chapter 3. This model application utilized the fish biomass determinants, namely, the maximum water level, total area of inundated forests, and water temperature in the Mekong River refuges of the previous hydrological year.

This study for the first time presented the effects of changing hydrological regimes on ES. The applied biomass models of integrating life cycle and habitat conditions showed a high accuracy, enabling to prediction of the biomass of migratory fishes and the six individuals across a wide range of changing habitat conditions. The predicted results of the applied models demonstrated and reflected the general conceptual understanding of the influences of changing hydrological regimes on fish production. Such a reflection highlights the high reliability of the applied models in showcasing the consistency between the theoretical concept and practical application. In addition, the applied models schematically illustrated the variation of predicted biomass according to actual changing hydrological regimes. This manner provides a feasible condition for managing the ES based on a preferred environmental condition.

The findings of this chapter brought us new insights into the understanding of the relationships between the changing hydrological regimes and the ES provided by a large floodplain system. Changing hydrological regimes (e.g., the maximum water level, the end date of a flood, the area of inundated forests, and the water temperature in the refuge season) may limit the ES for people; however, the people need to have a comprehensive understanding of their relationship to have those changing indices in check, e.g., their regime connectivity. Regarding regime connectivity, strong cooperation among the Mekong member states is required to ensure that a hydrological regime is provided for the biota (e.g., fish) in the Mekong basin. This manner may increase their responsiveness to the changing climate and hydrological regimes and improve the livelihoods of communities. Natural flow is critical to maintaining the ecosystem functions and services of the TSL floodplains; however, it is challenging to have a natural flow given the current development in the Mekong River Basin. Nonetheless, the Mekong countries may decide to identify a threshold where the hydrological system can function and energy production can still be sufficiently generated. In such a context, a good case would be when the water level at Kampong Luong station is > 8 m.

Chapter 6: Conclusions and Recommendations

The objective of this study was to comprehensively understand the ES of a floodplain and its response to changing hydrological regimes in a large tropical lake-floodplain system, with TSL in Cambodia as a globally important ecosystem.

The integration of the life cycle and seasonal habitat conditions in modeling biomass is significantly important for migratory fishes. The applied models showed that changing hydrological indices in the feeding and refuge seasons negatively affected fish biomass.

Those indices were hydrological factors (i.e., maximum water level, mean water level, the start date of the flood, and the end date of the flood), and climate factors (i.e., water temperature). Interestingly, the applied models for the first time distinctly illustrate the response of the biomass of different fish species to changing areas of inundated forests, in particular, between piscivorous and planktivorous fishes. Such findings reflected the reliability of the application of the applied models in predicting biomass, being consistent with the biological features of the fish species. In addition, the applied model underscored the importance of habitat conditions in the fish life cycle to fish production (e.g., the water temperature of the previous year in the refuge season). As such, it requires complete attention to all life stages of different hydrological indices to maintain ES, as those indices revealed connectivity.

The findings of this study brought us new insights into our understanding of the relationships between the changing hydrological regimes and the ecosystem services provided by the TSL floodplain system. In particular, this study elucidated the response of migratory fishes to changing ecohydrology within their life cycle in the Lower Mekong Basin. The elucidation of the integration of life cycle and habitat conditions in modeling ecosystem services (e.g., the biomass of migratory fishes) enhances our understanding of their responses to ecohydrological regime shifts in the freshwater environment.

The high-water level is necessary to ensure habitat/regime connectivity in fish migrating seasons, which helps maintain fish recruitment production in the Lower Mekong Basin. Regarding this connectivity, strong cooperation among the Mekong member states is required to ensure that a hydrological regime is provided for the biota (e.g., fish) in the Mekong basin. As such, a working group on integrated water resource management aiming to ensure a sufficient flow for habitat/regime connectivity needs to be established and on board among the Mekong member countries, including community riverine organizations.

As the study of this thesis addressed only the migratory fishes in the Lower Mekong Basin floodplain to elucidate their responses to changing hydrological regimes using the biomass model of integrating life cycle and habitat conditions, future research may apply this model to investigate the responses of non-migratory, short-distant migratory, and long-distant migratory fishes in other tropical river-lake floodplain systems to those changes.