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Are freshwater systems in lower Mekong basin (southeast Asia) resilient? A synthesis of social-ecological system

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Abstract

Social-ecological resilience of freshwater systems in lower Mekong basin in southeast Asia is largely unknown. Over the recent past, the freshwater ecosystems in the region have gone through severe environmental stress. Climate change, sea level rise, over-extraction of water and eutrophication together have increased vulnerability to regime shifts of ecosystems in the region. Regime shifts can have long-lasting effects on social-ecological resilience. Response diversity plays a central role in linking ecological, social, and financial systems and enhances resilience. Documenting regime shifts and associated feedbacks as well as the role of response diversity in social-ecological resilience and ecosystem goods and services in the region is essential for future sustainability. In this study, primarily, I have described mechanisms behind emergence of feedback loops at a time of regime shifts and its impacts on ecological resilience. Secondly, I have developed a framework for social-ecological resilience of freshwater ecosystems for southeast Asian region. Thirdly, I have provided current contexts of social-ecological resilience of two of the most productive freshwater ecosystems in the lower Mekong basin of southeast Asia: the Tonle Sap Lake (Cambodia) and the Vietnamese Mekong Delta. Finally, in conclusion, I have outlined the key roles response diversity plays in showing the effects of environmental stress and maintaining social-ecological resilience in the region.

1. Introduction

Riverine landscapes of southeast Asia (figure 1) contain more than 25% of plant and animal species that are inherently linked to daily lives of the half billion people (Woodruff 2010). However, rapid clearance of trees has led to only 5%–7% remnant forests left in the region. Climate change has intensified the regional biodiversity and ecological conditions further (Steffen et al 2007). The forested watersheds have played an important role in maintaining biodiversity conservation and ecosystem functioning including water purification and carbon sequestration (Cardinale et al 2012, Muhamad et al 2014). However, meantime, the large-scale fish harvests in the region have threatened regional fish diversity and the supply of protein intakes among the populations (Orr et al 2012). Excessive consumption of freshwater resources with limited biodiversity conservation efforts has led to an imbalance of demand and supply of food and energy (Giam et al 2012, Kano et al 2016). For instance, the fish habitats of Tonle Sap Lake (TSL), an important water resource in the lower Mekong basin supporting large urban populations of Cambodia are threatened by upstream hydropower development consequently constraining the supply of fish protein (Keskinen et al 2015, Keskinen and Varis 2016). The withdrawal of water for energy has stretched the use of water resources for irrigation and drinking (Luck et al 2009) further exposing the river systems to social and ecological stressors (Zhang et al 2018).

Social-ecological system (SES) tends to undergo regime shifts in response to environmental changes including climate change and human disturbances (Scheffer et al 2012). Regime shifts can have long-lasting
effects on ecosystem goods and services and social-ecological resilience (Leadley et al 2014). Documenting the changes of social-ecological system, regime shifts and the regional environmental conditions of southeast Asia that provide information regarding the threshold and feedback of biodiversity and ecosystems is important for the regional scientific community, governments and international agencies such as the United Nations for formulating future research policies of freshwaters (Sonderegger et al 2009). The trajectory of temporal and spatial distribution patterns of natural and social phenomena of biodiversity and ecosystems goods and services can also reflect the future direction of the regional economy (Willis et al 2010).

Understanding the vulnerability of regime shifts and associated impacts on social-ecological resilience of freshwater systems and the consequences in goods and services and economic conditions of southeast Asia is very limited. An appropriate framework for the vulnerability of regime shifts and ecosystem feedbacks of SES is not yet developed when the ecosystems are exposed to different levels of environmental stress. The positive and negative feedbacks, which operate as loops (figure 2), regulate the social-ecological system dynamics, and plays a significant role in social-ecological resilience (Biggs et al 2018). The positive feedbacks respond to sudden collapses of SES as a result of gradual changes in the climatic and other environmental factors including the sustained human exploitation of biotic resources, habitat losses and fragmentations (Suding et al 2004). In contrary, the negative feedbacks show the dampening of an initial rate of change and consequently slowing down the causes of effect (van de Leemput et al 2016). The positive and negative feedback loops when they are operating independently (figure 2), show linear responses to the change, and has a high degree of resistance with no or little impact on social-ecological system. Hence, the output for biodiversity or ecosystem regime shifts under the linear change of stressors (inputs) are less vulnerable (figure 2). However, presence of positive feedback loops in SES amplifies the output conditions such as the increased non-linearity followed by alternative stable state shifts of ecosystems and reduction in the social-ecological resilience (van de Leemput et al 2016). The existence of multiple positive feedback loops in SES inevitably leads to the significant loss of social-ecological resilience with an irreversible collapse of biodiversity and ecosystem goods and services (figure 2).

Given the unprecedented regional environmental changes and increased vulnerability of the ecosystem regime shifts in southeast Asia (Wallace et al 2003), a comprehensive understanding of the present time social-ecological resilience of the freshwater systems is essential. While assessing social-ecological resilience of the regional freshwater systems in southeast Asia, two critical points needs to be considered carefully: firstly, it is important to note that what drives social-ecological resilience of the freshwater systems, and secondly, how social-ecological resilience is maintained so that this can generate ecosystem goods and services to the society. Studies suggest that response diversity is thought to drive social-ecological resilience of the freshwater systems.

Figure 1. Map of southeast Asia including the two prominent freshwater systems studied in the lower Mekong Basin: Tonle Sap Lake (TSL) and the Vietnamese Mekong Delta (VMD).
Elmqvist et al. 2003, Nash et al. 2016), while the water governance in the ecological, political and financial spectra inclusively maintains the regional flow of freshwater goods and services (Green et al. 2013, Schulz 2018, Wei et al. 2018).

The lower Mekong Basin is one of the biodiversity hotspots for freshwater goods and services in southeast Asia (see figure 1). The area represents the important social-ecological systems with positive and negative feedback loops (Dent et al. 2002, Li and Bush 2015, Szabo et al. 2016). Disruptions in the environmental flows, natural flood pulses and eutrophication caused by nutrient enrichments in the Mekong river and associated river channels and wetland systems due to various drivers including the hydropower development, catchment land use and climate change, all have made considerable implications for regime shifts and social-ecological resilience (Kummu et al. 2008, Huu Nguyen et al. 2016). Hence, based on the frameworks of positive and negative feedbacks and presence of associated loops, this study aims to establish the relationships between the response diversity and social-ecological resilience and to examine the role of water governance in the maintenance of freshwater ecosystem goods and services in the lower Mekong basin. This study will then investigate two case studies on social-ecological system in the region: the Tonle Sap Lake and the Vietnamese Mekong Delta. Finally, as a conclusive remark, an innovative sustainability framework is developed to advise on how social-ecological resilience is maintained so that the regional freshwater goods and services will sustain in the future.

2. Biodiversity, social-ecological resilience and water governance

2.1. Relationship between biodiversity and social-ecological resilience

The interactions between biodiversity and ecosystem functioning are central to ecosystem goods and services (Loreau 2010). Biodiversity enhances social-ecological resilience by generating essential ecosystem goods and services to the society (McIntyre et al. 2016). Functional groups support ecosystem performance, and to increase goods and services. The loss of a functional group, such as the apex predators, consumers, or benthic filter-feeders, can result in drastic alteration in food webs thereby performance of ecosystems (Hooper et al. 2005). The species diversity within the functional groups, (also called as response diversity), strongly responds to the rapid environmental change, and plays a central role in maintaining social-ecological resilience and thus mediating

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**Figure 2.** Emergence of various feedback loops and subsequent ecological regimes over time at the gradients of lower to higher impacts. Presence of negative and positive feedback loops in an ecosystem is common and important as they connect output (services or state) and signals (responses) back to the inputs (predictor). (A) Independent presence of individual feedback loops (positive and negative) stabilizes the system dynamics in its basal state, and the response is usually a linear. (B) Presence of positive & negative feedback loops together reflects the ecosystem complexity and amplifies the state behaviour and increases the output signals (non-linearity) back to the inputs, this ultimately leads to the system oscillation (i.e. regime shifts/alternative equilibria). (C) Presence of multiple positive feedback loops destabilizes the system resilience further by disrupting the input-output connectivity, consequently leading to the emergence of ‘cut off feedback loop’ (or no feedback), a persistent and undesired (collapsed ecological state) with increased societal conflicts.

(Elmqvist et al. 2003, Nash et al. 2016), while the water governance in the ecological, political and financial spectra inclusively maintains the regional flow of freshwater goods and services (Green et al. 2013, Schulz 2018, Wei et al. 2018).
long term provision of goods and services to the society (Folke et al 2004). Despite the ongoing impacts of environmental change and habitat disintegration on diversity losses, the higher order species interactions of the functional feeding groups strongly maintain the response diversity by avoiding or minimizing the destabilizing effects on the species interactions (Bairey et al 2016, Bray et al 2018). The resulting outcome supports ecosystem renewal and reorganization and enhances adaptive capacity when the ecosystem is undergoing regime shifts (Mori 2016). At increased societal demands of ecosystem goods and services (e.g. crop yields), response diversity enhances connectivity among ecological, social, political and financial systems. For instance, in the lower Mekong basin, the irrigated cropping and natural freshwater systems can function only if both systems receive shared water supply to maintain crop and fish diversity and ecosystem functioning in a watershed. A trade-off, between the aquatic system, which provides irrigated and environmental waters, and the social-political system, which mobilizes resources including lands and fertilizers, maximize the crop yields in the basin (figure 3). The framework (figure 3) on freshwater social-ecological system provides the current state of ecosystem goods and services and vulnerability to regime shifts. Resource flows from the aquatic system support both irrigation and environmental waters and maintain response diversity of (crop and fish). For instance, the highly productive swamps and its historic capture fisheries are one of the major trading commodities in the basin and have become significant for regional sustainability and economic growth (Bhattarai and Navy 2009). However, the management including trades imposed by social and political system on capture fisheries also have negative impacts leading to a dramatic shift in the diversity, productivity and exports (Sodhi et al 2004, Blake and Friend 2009). Despite the use of commercial fertilizers to increase crop productivity in the region, there has been the ramification in the natural soil fertility (Rowcroft 2008). Similarly, logging and deforestation have altered natural flow regimes, sedimentation, water pollution and downstream salinization (Dudgeon 2010). Disruption in the natural flood pulses due to construction of hydropower dams has made dramatic effects on species diversity (Räsänen et al 2017) and ecological adaptation (Arias et al 2012). Climate change has intensified the conditions further. The cumulative impacts of drivers, both climatic and anthropogenic, have caused species redundancies and viability of genetic diversity (Hector and Bagchi 2007). The confounding effects of climatic-and-

human-mediated water shortages for irrigation in the basin over the recent decades have reduced crop yields and production stability constraining the regional network and supply of agri-ecosystem businesses (Postel 2000). The response diversity has an ability to reflect the viability of agri-ecosystems and manifests the

![Diagram](image-url)
changes in the crop yields as well as the linkages between natural and social systems thereby the basin-wide social-ecological resilience (Folke et al 2004).

2.2. Role of water governance in maintenance of ecosystem goods and services
Limited scientific knowledge on ecosystem functioning and associated goods and services can hinder water governance (Sim and Balamurugan 1991). Two areas of scientific knowledge are thought to be significant and needs to be aligned with water governance for better outcomes of the ecosystem goods and services in the lower Mekong basin. The use of indices to measure the riverine ecosystem health is widely adopted by resource managers for many years as a part of the Integrated Water Resources Management program worldwide. However, simplified indices of the complex ecosystems can appeal to policy makers and water resources managers that assist effective governance frameworks for ecosystems goods and services. The Australia’s National Framework for the Assessment of River and Wetland Health and the EU-Water Framework Directive 2000/60/EC are the examples where indices play significant roles in water governance framework and ultimate ecosystem goods and services (Liu et al 2019). Southeast Asia is projected to experience steep declines in the freshwater resources including the species diversity. In the absence of policy interventions, this could lose not only an important natural resource but also the associated wealth, jobs and culture. Unfortunately, none of the agreements on the river basin management among the regional nations explicitly addresses the importance of science i.e. the impact of climate change and latest human disturbances in the region. For instance, water governance in preventing the overharvesting of fisheries in the basin is not effective. The interannual or multidecadal climatic changes also have long lasting impacts on regional ecosystem and fisheries diversity. A strong multilateral negotiation among the transboundary nations to prevent the ecological collapse of the fish stock is urgently needed. A carefully designed international cooperative governance framework is also thought to protect water resources and sustain ecosystem goods and services in the lower Mekong basin (Oremus et al 2020).

3. Social-ecological resilience of freshwater systems

3.1. Case study I: Tonle Sap Lake
While Tonle Sap Lake remains an interesting and complex social-ecological system in southeast Asia (figure 1), the lake offers an excellent research platform for the assessment of social-ecological resilience. The large, 15 000 km² area containing 50–80 m³ water is a highly productive ecosystem providing economic benefits to 1.5 million people directly (Arias et al 2012, Seak et al 2012). This hotspot biodiversity containing 149 fish, 11 bird and 200 species of mammals and plants shows important nexus among water, energy and food over the millennia (Keskinen et al 2015). The network of reservoirs, channels, moats, and embankments extended over 1000 km² of the Angkor Wat temple built for provision of water for agriculture, ecology and humans is an impressive feature of the SES (Day et al 2012). The water management has profound implications for mitigating climate change and water balance. Flood hazards and ecosystem services have been strongly mediated by seasonal hydrodynamics of the Mekong River (Penny 2006, Lamberts 2006, Lamberts and Koponen 2008). The flood pulse events in TSL creates habitat for food resources (e.g. fish) to the local community. Fish production exceeds up to 65 000–75 000 tonnes per year during inundation and supports diversity and community during dry season (Lim 1999, Lamberts 2006). The flood pulse events go back to 5000 years BP when the course of the Mekong River was altered, this allowed the transport of salts, nutrients and sediments to TSL. The sediment plumes originated from the Mekong River during flooding are important part of ecosystem productivity of the TSL (Lamberts 2006). Functional groups of primary producers: periphyton, phytoplankton, rooted and floating macrophytes support food web, transfer nutrients to fish and crops then to the people via food chain (Lamberts and Koponen 2008) (figure 4).

However, reduction in the response diversity in TSL is strongly reflected by the loss of fish diversity over the recent past. About 120 species of fish, belonging to 26 families were recorded in 1995–1997, in which about 53% of the fish family declined within the past 5–6 decades. Over the past 50 years, the percentage shared water in the Tonle Sap River and the TSL has reduced to half due to low flows in the Tonle Sap river during the wet season. Climate change and water withdrawals (for irrigation) and poor governance have amplified the conditions (figure 4). The conditions of reduced

Water in the river system together with sustained land use changes have led to ecological regime shift followed by reduced social-ecological resilience with loss of response diversity and ecosystem goods and services. Human impacts such as overfishing during spawning and migration at low water level and deforestation are reported to be the key drivers (Lim 1999). Rapid development of hydropower dams in the upper reaches of the Mekong River, large irrigation schemes and urbanisation all have substantially altered response diversity. These activities have also caused high rates of downstream sedimentation (Kummu et al 2008). The cumulative impact
assessment by multilateral agencies have suggested substantial decline in the flood volume and areas during wet seasons in TSL (Kummu and Sarkkula 2008). Populations of fish species largely adapted to flood pulses have reduced. Low discharge in the river has imposed ecological stress and increased competition for water and food between nature and society (figure 4). However, the known threats to response diversity, regime shift and social-ecological resilience of the TSL are relatively limited. The upstream-downstream migration of the high value fish species has been interrupted by the construction of large scale irrigation and hydropower dams (Winemiller 2016). The natural share of water between ecology and society has been substantially altered due to low flows and variable flood pulses (Fischer et al 2015). The cumulative impacts of environmental drivers including climate change, river regulation, water withdrawals and poor governance together appear to have led to the regime shifts (figure 4).

Participatory engagement and dialogues among scientists and stakeholders has been suggested for the improvement of water resource governance in TSL (Ratner et al 2014). Despite the long history of human occupation in the catchment, the social-ecological system of TSL is found to transform only after the regulation of the Mekong River system six decades ago (Scholes et al 2013). The biological records extracted from the TSL sediments potentially offer a long term change in response diversity and ecosystem dynamics and provide broader understanding of flood-pulse induced ecosystem processes and SES in the lower Mekong basin (Willis et al 2010).

### 3.2. Case study II: Vietnamese Mekong Delta

Vietnamese Mekong Delta (figure 1) displays an important system for social-ecological resilience. Eighteen million people of VMD are dependent on more than 54% ecosystem goods and services derived from 47% of the nation’s cultivated areas (Drogoul et al 2016). These productive riparian ecosystems have been enhanced by recent agricultural reforms including the use of commercial fertilizers, and improved irrigation technologies (drainage system) consequently extending the export of paddy, shrimps, and fruits (Nguyen and Woodroffe 2015). However, the agribusinesses in VMD is threatened by rapid climate change, sea level rise, urbanization and salinization (Drogoul et al 2016). The widespread drainage and canal constructions have profoundly modified the hydrology of the VMD. The excessive drainage of surface water from wetlands has reduced natural flood periods (Nguyen and Woodroffe 2015). Some of the drainage in the upstream Mekong have been significantly altered leading to disruptions in the biological and hydrological connectivity with the VMD and consequently reducing response diversity and social-ecological resilience.

Widespread use of pesticides in VMD has also caused loss of floral and faunal diversity (Wilby et al 2006). Societal and political transformation in Vietnam over the past 50 years has altered social-ecological resilience of the VMD. For example, the governance to replace paddy culture by shrimp farming has led to elevation of tidal intrusion and subsequent salinization in the coastal areas (Renaud et al 2014). The capacity of waste and sediment recycling has been significantly reduced due to river regulation and aquaculture. River regulation has disrupted Predator–prey interactions, food webs and riparian productivity further (Trinh et al 2012). Alteration of flood-pulse induced ecosystem processes and SES in the lower Mekong basin (Willis et al 2010).

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**Figure 4.** Social-ecological resilience of the Tonle Sap Lake (TSL) in lower Mekong Basin (Cambodia) before and after of the yearly changes in the flood-pulse hydrology from Mekong River (thick blue curve) and Tonle Sap River (tributary of Mekong-light blue curve) (for map see figure 1). (A) Natural flood pulse system (before): shared water for the river and the society (shaded light blue area) in wet and dry seasons. (B) Reduction in the shared water (Today) in Tonle Sap River (half-shaded light blue area) due to low flows in the Mekong river during the wet season causing shift in ecosystem (vertical red dotted line). (C) Regime shift from resilient to less resilient TSL system (black curve) with reduced response diversity. T1, where the high response diversity plays a central role to stabilize the river ecosystem, after T1 with increased ecological stress, the response diversity begins decline, at T2, response diversity becomes critical to collapse. Passing of response diversity at T2.
Figure 5. Social-ecological resilience of the Vietnamese Mekong Delta (VMD), where response diversity comprises fisheries and crops (e.g. paddy, shrimp). Resilience of delta is largely dependent on vigour of response diversity (blue arrows connecting paddy-fish-ecosystem in the left) to contribute to ecosystem goods and services and to the society at through consumption and export (blue boxes in the right). However, different environmental drivers (climate change, land use activity, global economic recession), as well as water governance and decision-making processes can influence the social-ecological system (blue cure in the middle) thereby alter social-ecological resilience. When the vigour of response diversity is high, SES is resilient before $T_1$. As the vigour of response diversity reduces due to increased environmental stress, the SES crosses the $T_1$. The passing of response diversity at $T_2$ is highly critical to resilience of the VMD.

Figure 6. Social-ecological resilience of the lower Mekong basin over time (dotted curve): (A) Prior to anthropogenic impacts, response diversity generated high value (resilient) ecosystem goods and services (green ball). (B) Once the system began degrading due to disturbance (thick downward red arrow), it became less resilient (light green ball), but there was a self-recovery prior to $T_1$. (C) Passing of $T_1$ reduced social-ecological resilience further (current scenario) leading to conservation awareness among scientists and stakeholders (yellow ball). (D) The passing of $T_2$ could become disastrous (red ball) to the society due to natural and anthropogenic impacts including water shortages. Collapse of ecosystem goods and services and low-income socio-economic conditions increases societal conflicts (thick upward red arrow). Careful management prior to $T_1$ brings back the ecosystem to generate high-income goods and services to the society. However, after passing of $T_2$, the management could be extremely difficult.
of agriculture and fisheries biomass productivity have influenced local and international food trades (figure 5). The changing nature of ecological, social and political system due to climate change, land use change, urbanisation and poor government all have increased vulnerability to ecological regime shifts and social-ecological resilience of the VMD (figure 5).

4. Conclusions

River regulation, climate change, sea level rise and nutrient enrichment together have posed serious threats to social-ecological resilience of freshwater system in the lower Mekong basin. Shortages of water for environment and alteration of flood pulses over the recent past have threatened response diversity and ecosystem structure and functioning. Regime shifts and possible collapse of supply of essential freshwater goods and services in the region are likely to have disrupted regional trades and increased societal conflicts. The high-income agribusiness such as paddy and timber have faced challenges as ecological resilience has declined while the impacts on the river system have increased. Incomes generated by fisheries have become moderate as the actions needed for land and water conservation are insufficient. The socio-economic conditions have become critical to collapse due to the result of increasing cumulative impacts of stressors (figure 6). Water resource conservation using resilience management would be effective measure as such approach provides an integrated perspective for understanding and recognition of regime shifts. Recognizing social-ecological interactions is crucial in resilience management of freshwater ecosystems. Institutions working for social-ecological resilience in the lower Mekong basin should adopt resilience management approach including the effective water governance policies to avoid regime shifts. Collaboration among scientists and stakeholders across the transboundary nations of the lower Mekong basin improves dialogues and regional social-ecological resilience. The provision of ecosystem stewardship of ecosystem goods and services to the future generations in the region is a fundamental necessity.

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