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Impacts of hydropower and climate change on drivers of ecological productivity of Southeast Asia's most important wetland

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ABSTRACT

The Tonle Sap is the largest lake in Southeast Asia and its fishery supports the livelihood and nutrition of millions of people in Cambodia. However, the hydrological and ecological drivers of this ecosystem are changing as a result of hydropower development on the Mekong River and global climate change. The objective of this study was to quantify the impacts of the Mekong's future hydrological alterations on aquatic net primary production (NPP) of the Tonle Sap. A three-dimensional (3D) hydrodynamic model was used to evaluate eleven scenarios of hydropower development and climate change, with respect to water flows, suspended sediments, and floodplain habitat cover, which were identified as the key drivers of productivity change. We found that hydropower development would cause the most distinct changes in seasonality by reducing wet season water levels and increasing dry season water levels. Combined scenarios of hydropower and climate change revealed that areas of open water and rainfed/irrigated rice would expand by 35 ± 3% and 16 ± 5%, respectively, while optimal area for gallery forest would decrease by 40 ± 27%. The estimated annual net sedimentation was projected to decrease by 56 ± 3% from the 3.28 ± 0.93 million tons baseline values. Annual average NPP in the open water and in the floodplain was 1.07 ± 0.06 and 3.67 ± 0.61 million tons C, respectively, and a reduction of 34 ± 4% is expected. Our study concludes that Tonle Sap's drivers of ecological productivity – habitat cover, sedimentation, and NPP – will face a significant change, and a decline of its ecosystem's services should be expected if mitigation and adaptation strategies are not implemented.

1. Introduction

Floodplain wetlands are among the most productive and valuable ecosystems on earth; they provide critical ecosystem services to society, including flood regulation, food production, water treatment, nutrient storage, and wildlife habitat (Constanza et al., 1997). Nearly half of the world's wetlands, however, have been lost to hydrological alterations and land reclamation (Junk et al., 2013), especially those in fertile floodplains. The majority of the remaining unregulated floodplains occur in the (sub-) tropics, where wetlands are under threat by fast growing economies with expanding agriculture and hydropower capacity. In addition to those pressures, global climate change is increasing the frequency and magnitude of floods and droughts (Dai, 2011; Hirabayashi et al., 2013), augmenting the vulnerability of these ecosystems. In light of the critical condition of floodplain wetlands worldwide, it is crucial to quantify the impacts that hydrological alterations could have on the crucial services provided by these ecosystems.

The Tonle Sap is a unique ecosystem with an enormous hydrological, biological, nutritional, and cultural value to Cambodia and the lower Mekong region. The Tonle Sap is composed of a 2600 km^2 permanent shallow lake, a 120 km long river that connects the lake to the Mekong River, and a 12,876 km^2 floodplain covered with a mosaic of natural and agricultural habitats that the Mekong replenishes with water and sediments annually (Fig. 1). These habitats are home to important populations of threatened animal species (Campbell et al., 2006; Davidson, 2006), and the ecosystem provides critical spawning and rearing habitat for one of the largest freshwater capture fisheries on the planet (Baran and Myschowoda, 2009; Cooperman et al., 2012), which is reported to provide up to 80% of the protein consumed by millions of people in the surrounding provinces of Cambodia and beyond (Hortle, 2007).

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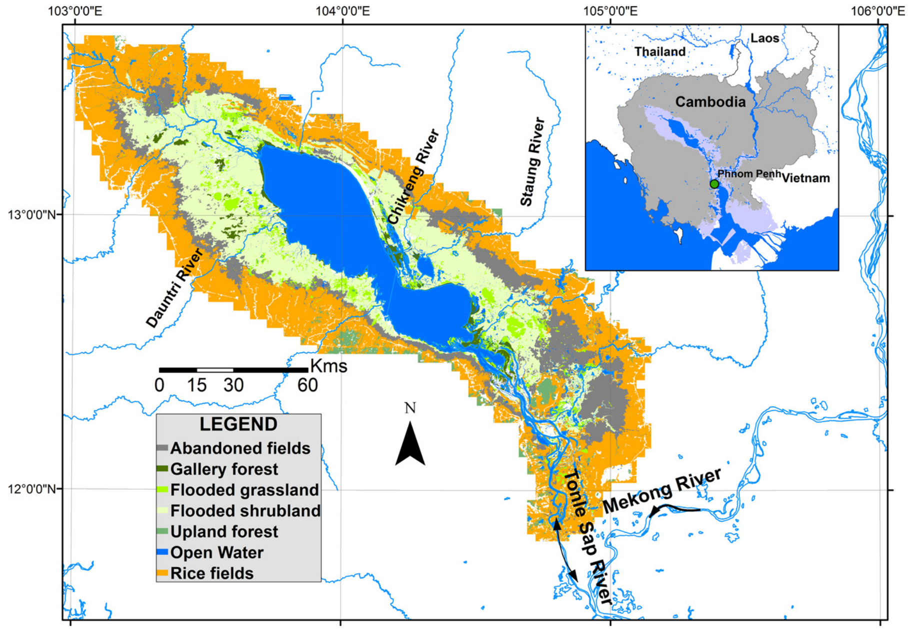

Fig. 1. Overview map of the Tonle Sap.

The surface hydrology and flood-pulse in the Tonle Sap is driven by the Asian Monsoon regime, which brings approximately 65% of the total annual rainfall to the Mekong Basin between July and October (MRC, 2005). More than half of the annual flow into the Tonle Sap comes directly from the Mekong via the Tonle Sap River (53.5%), 34% from 11 tributaries in the Tonle Sap catchment, and 12.5% from rainfall precipitation (Kummu et al., 2013). The Mekong is also the source of 72% of the suspended sediments entering the Tonle Sap (Kummu et al., 2008). During the dry season (October through May) the Tonle Sap River discharges up to 8000 $m^3 s^{-1}$ out from the lake toward the Mekong (Fig. S1). At the end of this period of "normal" flow, in May, the lake reaches a minimum depth of less than 1.5 m and a surface water area less than 2600 km^2. When the monsoon reaches the basin, the level of the Mekong River rises to a higher level than the Tonle Sap, forcing the Tonle Sap River to reverse its flow toward the lake. This phenomenon causes the lake's water depth to increase by 5.6–9.0 m and its surface area by 7517–12,876 km^2. At the peak of the flood (between the end of September and the beginning of October), the total flood extends over 9637–15,278 km^2. Flood duration varies proportionally to flood level throughout the floodplain, from a few days at the outer edge to 9–11 months in the gallery forest. The average flood duration over the entire floodplain is 3.9–6.7 months per year.

Nonetheless, the hydrology that drives the Tonle Sap system is changing. The Mekong basin is undergoing rapid hydropower development; reservoir active storage has increased three-fold in recent decades (from 7.9 km^3 in 1990 to 29.9 km^3 in 2010) and another three-fold increase is expected in the foreseeable future (Lauri et al., 2012; MRC, 2009; Piman et al., 2013). Moreover, there is evidence of an increase in the frequency of extreme floods and droughts in the basin associated with changes to the El Niño-Southern Oscillation (Delgado et al., 2012; Räsänen and Kummu, 2013), but whether these observations are caused by climate change or not has not been proven yet. There is much uncertainty in the simulations of future climate change in this monsoon-driven region and there is no agreement as to what the general direction of impacts could be (Kingston et al., 2011; Lauri et al., 2012; Thompson et al., 2013). Large tropical floodplains with unimodal and predictable hydrology are typically described following the flood-pulse concept (Junk et al., 1989), which states that geochemical and biological processes are dictated by the seasonal pulse of water. Recent studies on the water chemistry, vegetation, soils and fauna all suggest that the Tonle Sap acts like a classic flood-pulse ecosystem (Arias et al., 2013; Brooks et al., 2009; Irvine et al., 2011). From this we therefore expect that changes in the flood-pulse should have a direct impact on physical and chemical properties of the lake, which subsequently would impact primary and secondary productivity (including fisheries). These connections have not been comprehensively measured for the Tonle Sap, but given the imminent transformations that the drivers of productivity are undergoing, it is crucial to use available empirical evidence in conjunction with numerical models to examine resulting changes in productivity.

Multiple modeling approaches have been used to simulate the interaction between ecological and hydrological properties of large tropical wetlands. When data are limited, one approach is to simulate responses at high trophic levels as a direct function of hydrology, disregarding interactions with primary producers (e.g., Linhoss et al., 2012). In contrast to the data limited approach above, detail information on multiple trophic levels has been used to simulate the energy exchange within foodwebs (e.g., Angelini and Agostinho, 2005; Brown et al., 2006). Another approach consists in simulating the interaction among compartments of water, sediments, and primary producers; models of this kind can represent wetlands as single geographic units with multiple compartments (e.g., Weber et al., 1996), as spatially-explicit systems of links and nodes (e.g., Kuper et al., 2003), or as spatially-distributed models where variables are represented by layers of pixel-based information covering the spatial extend of each ecosystem (e.g., Reyes et al., 2000; Fitz and Trimble, 2006). A further step in hydro-ecological models is to explicitly integrate hydrology and primary production with multiple trophic levels. This last type of models requires detailed ecological data that is unavailable for most large tropical wetlands, hence these models have been primarily developed only for the Everglades (DeAngelis et al., 1998; Gaff et al., 2000).

The development of ecological models of the Tonle Sap has been minimal compared to other large tropical wetlands. Hydrodynamic models have been applied to the Tonle Sap (Fujii et al., 2003; Sarkkula et al., 2003; WB, 2004), but their applicability and linkage to ecological models remains limited because of inadequate information relating the hydrology to the ecology. Among the few numerical models applied to the Tonle Sap, the 3D EIA is the only