LAND-COVER CHANGE INFLUENCED BY AN ALTERED FLOODING REGIME OF THE TONLE SAP LAKE IN THE FLOODPLAIN OF SIEM REAP AND BATTAMBANG PROVINCES, CAMBODIA

By

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To my Dad, Mom, Aunt Nancie, and Uncle Roger

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Cambodia’s Tonle Sap Lake (TSL) is one of the most biologically diverse and ecologically important systems within the Mekong River Basin in Southeast Asia. The lake provides specific ecosystem services (ES) such as rice crop production and fisheries capture that local populations depend on for their livelihoods. Hydropower development of the mainstream Mekong and tributaries, along with other environmental factors such as climate change will alter the naturally occurring, annual flooding regime that the TSL experiences. The purpose of this thesis is to describe how the land-cover (LC) associated with the TSL change with the influence of multi-year increasing and decreasing flood trends to provide forecasts as to how the ecosystem services associated with the lake may be affected.

Remote sensing techniques were used to develop a land-use and land-cover classification for areas in the Tonle Sap floodplain in Siem Reap and Battambang provinces. ESs were inferred by their respective LC classes. Periods of decreasing and increasing flooding were analyzed with the decreasing floods being representative of the change that may occur with hydropower development. The results show that rice

production may not be at risk to ES loss and the fisheries, although less clear, may also not be at risk with a declining flood trend. Although the shrubland LC increased during this time period, fish may not be able to inhabit these areas for foraging unless they are submerged; therefore, the shrubland habitat that supports fisheries production may still be at risk to changes in the flooding regime.

CHAPTER 1
INTRODUCTION

One of the most difficult and compelling tasks facing geography and the environmental sciences is accurately quantifying and assessing human-environment interactions (Phillips 2013). Although this phenomenon is mostly under-recognized in economic and political systems throughout the world, human interactions within the natural environment are arguably the most important issues that affect all life in today's world (Simon 1980). As the human population has drastically increased and the power of technology has become accessible throughout the world, the scope and nature of human-environment interactions has changed drastically (Simon 1980). Historically, human-environment interactions were analyzed only on a small scale with localized urbanization and agricultural production; however, now it is understood that human-driven interactions affect the environment throughout the entire global ecosystem (Grimm et. al. 2000). Overall, there is a global need for understanding human-environment interactions as human activities increase throughout the world.

Coupled human-environment systems throughout the world have different communities and stakeholders that determine the vulnerability of people, places, and ecosystems to environmental change (Turner et. al. 2003). Although over 50% of the global population lives in urban areas, a large part of the world's population is still located near freshwater sources due to our dependency on freshwater (Kummu et. al. 2011). Interestingly, Kummu et. al. (2011) showed that over 50% of the world's population lives closer than 3 km to a surface freshwater body and only 10% of the population lives farther than 10 km away from freshwater bodies. Therefore, in part because a large majority of the world's populations live near water, it is crucial to understand human-environment interactions that are occurring in these coastal systems.

For some riparian systems, an annual flood pulse is the main driving force that influences productivity and major biotic interactions (Junk et. al. 1989). These systems respond to the rate of rise and fall and to the amplitude, duration, frequency, and regularity of these pulses; therefore, unpredictable pulses or a reduction in pulses can cause a disruption to these systems, which can lead to impeding the natural adaptation the organisms have developed around the flood pulse (Junk et. al. 1989).

The impacts of human activity reach all aspects of the planetary ecosystem, but are most closely associated with air, water, and soil degradation (Fraser et al 2003). Over the last few decades, global electricity production has more than doubled and electricity demand is rising rapidly around the world as economic development spreads to emerging economies (Yuksel 2007). Due to population growth in locations such as China, governments are looking for increases in sustainable mechanisms such as hydropower dams to create large amounts of power (Chang 2010). For systems such as the Mekong River Basin (MRB) located in Southeast Asia, the flood pulse is important in sustaining the fisheries production and rice harvesting. Hydropower development in the Upper Mekong River Basin (UMRB) would provide substantial power but it would likely reduce the amplitude of the flood pulse and therefore affect biodiversity and ecosystem service values associated in the Lower Mekong River Basin (LMRB) while also decreasing the sources of livelihoods and food security in these riparian communities (Grumbine and Xu 2011).

As stated previously, hydropower development can provide certain advantages and disadvantages in different locations around the world. For instance, the Tennessee Valley Authority (TVA) in the southeastern U.S. is one example that defines the advantages and disadvantages of hydroelectric development. The intentions of the TVA were to modernize the economy of the Tennessee Valley region by a series of large-scale infrastructure investments including hydroelectric dams as well as new roads, canals, and flood control systems (Klein and Moretti 2013). The TVA used large public investments in a severely underdeveloped region to generate economic growth and welfare (Klein and Moretti 2013). Dams and other technologies would control flooding as well as produce electricity that would be used to support other sectors associated with the Tennessee River (Ekbladh 2002). The industrialization of the Tennessee Valley provided lasting benefits to the region by creating high-paying manufacturing jobs in the region; however, the agriculture sector did not return as much growth and expansion as was expected when this program was first implemented (Klein and Moretti 2013). The small agricultural return from the implementation of the TVA was caused by the events of the Great Depression since demands were high but supplies for expanding were low ("About TVA: Our History").

Throughout the 1950s and 1960s, the TVA built nuclear power plants to expand our nation's capacity for economic growth and influence innovation ("About TVA: Our History"). Throughout the 1970s, the US was forced to create new models for energy conservation since fuel costs were on the rise. During the Vietnam War in the 1960's and early 1970's, the United States sought to prove that its involvement in Southeast Asia was positive due to the United States' support of the development of the Mekong

River (Ekbladh 2002). The benefits of the TVA were used to show how the Mekong region could have positive economic and social impacts with hydroelectric development. Unfortunately, the program was not implemented since the TVA could not be used to model a system such as the Mekong River Basin (MRB) due to the geographical, political, and economic differences in each system.

The Mekong River is under intense pressure to develop with upstream dams under construction and proposed dams downstream to produce economic prosperity (Grumbine et. al. 2012). The hydropower dams throughout the basin would dramatically alter ecosystems and human livelihoods. Recent studies have concluded that these developments will lead to flow alterations of the Mekong River that would alter the ecosystems downstream such as the Tonle Sap River, the Tonle Sap Lake (TSL), and its floodplain (Kummu and Sarkkula 2008, Arias et. al. 2012). This changing environment is expected to intensify the challenges that people are facing in rural areas, particularly Cambodian populations dependent on the flood pulse for providing their livelihoods (Nuorteva et. al. 2010). Nuorteva et. al. (2010) found that despite people's tradition to adapting to the seasonal variation of water, their capacity to adapt to unusual environmental changes is weak, with the poorest communities being the most vulnerable. This research addresses this theory of human-environment adaptations as seen in the floodplain of the TSL.

This research will examine two short periods of increasing and decreasing flooding regimes to understand the human-environment interactions that are taking place in the floodplain of the TSL. These periods were selected to understand how populations associated with the TSL floodplain may react to hydropower development.

Riparian communities within Siem Reap and Battambang Provinces were classified according to specific land cover (LC) types that are common to the floodplain such as shrublands and rice fields. Additionally, the land cover types were defined by the services they provide to the riparian communities. For example, changes in the shrubland LC were used to represent the changes the fisheries sector of the TSL and rice fields were used to represent rice crop harvesting. The land-cover change in these areas is then interpreted alongside these periods of increasing and decreasing floods to forecast how people may adapt as hydropower development increases throughout the MRB. This research will contribute to developing the human-environment interactions existing in the floodplain of the TSL to understand the effects of hydropower development on these riparian communities.

CHAPTER 2
RESEARCH AND DEVELOPMENT

Introductory Remarks

The Tonle Sap Lake (TSL) is the largest lake within the Mekong River Basin (MRB) in Southeast Asia, and is influenced by the annual flooding regime of the Mekong River (Arias et al. 2013, Bayley 1995, Johnston and Kummu 2012, Sakamoto et al. 2007). The TSL has an average surface area seasonally fluctuating between approximately 2,500 km^2 at the end of the dry season to over 15,000 km^2 during the wet season (Frappart et al. 2006, Kummu 2003). Maximum water level of the lake has been recorded as less than 2m above sea level (asl) in the dry season and up to 14m asl at the peak in the wet season (Rainboth 1996, MRC 1992). The lake's basin is also characterized by very low and shallow land-surface slopes and by seasonal water level peaks that vary between seven to ten meters asl (Fujii et al. 2010; Sarkkula et al. 2004). Approximately 75% of the annual water transport throughout the Mekong River Basin in an average year occurs in the four months between July and October (Piman et al. 2013).

A river stage hydrograph was created from data provided by the Mekong River Commission can be seen in Figure 2-1 below. This graph shows the annual variation in the flooding regime from 1960 through 2006. The Prek Kdam gauging station was selected due to its proximity to the TSL. The geographical location of this hydrologic station would best represent the hydrologic regime of the TSL since this station is located at the outflow of the TSL. Figure 2-2 shows the locations of the hydrologic stations along the Mekong River and its tributaries.

This large variation of water storage and inundated and exposed land is influenced by the seasonal hydrologic cycle, which is important for supporting the ecosystem services (ESs) associated with the TSL. The annual flood pulse is the driving force that maintains ecosystem and fish life cycles that are associated with a low gradient hydrological system such as the TSL (Fujii et al. 2010, Gupta et al. 2002, Junk et al. 1989, Toth et al. 1995). The TSL is a highly productive ecosystem with an annual fish catch estimated between about 180,000-250,000 T during the wet season. Additionally, a fishery on the Tonle Sap River harvests about 12,000 T of migrating fish that move from the lake into the Mekong River early in the dry season (Campbell et al. 2006). Due to the outflow of water into the Mekong River, many fish species migrate into deeper water in the lake or its tributaries (van Zalinge et al. 2003).

The Mekong Secretariat (1992) described four categories of fish species in the MRB: species associated with the main streams and with the open lake; “white” fish which are associated with the main channels and streams but also migrate into the floodplain; “black” fish which includes species able to survive in less favorable water conditions; and “opportunists” which are small, fast-growing and prolific species capable of utilizing the flood period for reproduction and growth (Mekong Secretariat, 1992; van Zalinge, et al. 2003). Many species such as the “white” fish, undertake longer longitudinal migrations from the lake to the Mekong River, mainly moving upstream and staying in deep pools during the dry season. Approximately 63% of the total fisheries catch in the TSL are migrating fish species that spawn in the Mekong River at the onset of the rainy season and are carried downstream by the currents and swept into the floodplain of the TSL (van Zalinge et al. 2003, Campbell et al. 2006).

Many people claim that fisheries production has been declining in Cambodia, and the causes for this decline are believed to be from widespread illegal fishing, over-fishing caused by an increasing number of fishermen, and ineffective fishing management by the government (Baran and Myschowoda 2008). The Department of Fisheries of the Ministry of Agriculture, Forestry and Fisheries is the agency that holds the authority over the fishing domain (FAO 2005). The objectives of the Department of Fisheries are to maintain the resource for food security for all rural people, to use additional production for income generation from export, and to assure that fisheries provide substantial input for the national economy (FAO 2005). The issuance of licenses is the most important management tool used by the Department of Fisheries. However, due to the provincial institutional settings, the authority of the Department of Fisheries is weakened since people can purchase licenses without receiving approval from the Department. This causes a political environment with conflicting interests and policies between official guidelines and private companies (FAO 2005). The three types of saltwater designated fishing in Cambodia are described by the Marine Conservation Cambodia as illegal, unreported, and unregulated ("IUU and MCS in Cambodia"). Illegal fishing includes fishing by foreign or national vessels that do not have permission or use illegal fishing techniques such as trawling in waters shallower than 20 meters. Unreported fishing refers to mainly Thai and Vietnamese vessels that do not accurately report their fish catch; and finally, unregulated fishing includes fishing with a fake license or registration as well as the transfer of fish catch at sea ("IUU and MCS in Cambodia"). Additionally, due to the minimal regulations placed upon fraudulent and formal licensing agents, more licenses have been sold without regards to the consequences of overfishing. These licensing agents award the licenses based on profits from selling the licenses rather than the profits from the fisheries sector itself; therefore, the number of licenses sold are not monitored or recorded to prevent overfishing (FAO 2005).

According to the FAO's (2005) report, the usage of fishing lots is one of the most effective ways of implementing fisheries management; however, this method is generally short term with fishers neglecting the long-term goals of fish productivity. Fishing lots are parceled areas within the TSL that are managed by their respective owners and were for the usage of their respective communities (Lim et. al. 1999). Fishing lots were first introduced to fisheries management in the TSL about 150 years ago as a means to produce revenue for the owners and to produce jobs in neighboring towns (Sokhem and Sunada 2006). In 2000, there were many protests over these fishing lots due to the declining fish stocks and access issues. Fishing lots were typically auctioned every two years to maximize profits; but after much protest, the lots were released to the public to restore villagers' access to fishing areas (Sokhem and Sunada 2006). In 2012, the fishing lots were closed and it is unclear whether or not the fisheries sector has benefited from this management decision in the TSL (Hap et. al. 2016, Seak et. al. 2011). The fishing lot management system was one method the communities of the TSL used temporarily to manage fisheries production; however, this method proved to be unsustainable for the TSL. Therefore, it was decided that in order for the management of the inland fisheries to be effective and successful in the TSL, coordinated action would be required at regional, national, and local levels with the most urgent issues present at the local level (FAO 2005). Interestingly, this fishing lot methodology can be seen in present day management practices (2015) with the usage of community fish ponds that will be discussed later in this thesis.

Well over one million people rely on Cambodia's fisheries sector for their livelihoods, and the majority of the Cambodian population is located within the floodplain of the TSL and the Tonle Sap and Mekong Rivers (Bonheur and Lane 2002). The TSL is a contributing factor to the continued functionality of the fisheries sector of the Mekong River Basin (Holtgrieve et al. 2013, Kite 2001). Fish harvested from the Mekong River Basin account for 40-60% of the protein intake of rural Cambodians; some figures even suggest that the actual proportion being closer to 75% (Keskinen 2003). Additionally, rice production is also a large portion of local Cambodians' livelihoods. Asian countries contain over half of the world's population and they also attribute to the highest production of rice on a global scale ("10 Largest Rice Producing Countries"). The top ten rice-producing countries in order from highest production to lowest are the following: India, China, Indonesia, Bangladesh, Thailand, Vietnam, Burma, the Philippines, Cambodia and Pakistan. These countries are also considered the top rice consumers on a global scale since the account for about 90% of the world's rice consumption ("10 Largest Rice Producing Countries"). The villages around the TSL in Cambodia are some of the largest contributors to rice production in Southeast Asia. Cambodia has also recently gained prevalence in exporting rice with the development of automated rice mill facilities that make it possible to export milled rice to Europe, China, and the United States ("10 Largest Rice Producing Countries"). Therefore, rice production and export are important contributing factors that maintain the livelihoods of populations in Cambodia.

The Mekong River is one of the world's largest river systems that has remained fairly untouched by hydropower development (Grumbine and Xu 2011). However, countries located in the Upper Mekong River Basin (UMRB) such as China and Thailand in the Lower Mekong River Basin (LMRB) have built dams along the Mekong River and associated tributaries since the early 2000s and plan to continue to implement hydropower projects over the next few decades. The upstream and downstream locations of the MRB will be affected by hydropower development, but the most severe impacts will be seen in the human-environment interactions that occur downstream in the floodplain of the TSL (Kuenzer et al 2013). The LMRB has an expected hydropower potential of 30,000 megawatts, of which only 10% have been developed to date (MRC 2010). By 2030, the construction of 62 dams of which 6 are on the Mekong River and 56 on the LMRB tributaries are expected to be completed (MRC 2011, Wild and Loucks 2015). Additionally, there are plans for a total of 134 dams to be built eventually throughout the LMRB (MRC 2011). This development throughout the basin will greatly increase the availability of hydroelectricity; and although this increase in economic expansion may seem advantageous to populations throughout the basin, these projects will directly influence the seasonal hydrologic regime experienced in the TSL (Bakker 1999).

Although all parts of the MRB will be influenced by hydropower development, countries and provinces located downstream, such as the Cambodian provinces Siem Reap and Battambang, will experience the greatest detrimental effects to their populations' livelihoods (Kuenzer et al 2013). The lake is expected to have lower high flows during the wet season, which might cause farmers to develop new management practices to sustain their crop yields. Rice is generally cultivated in the higher elevations of the floodplain of the TSL and farmers use flooding a source of water to flood their fields. Thus, the floods provide an ES for rice production. If wet season high flows do not inundate these areas, the rice fields may not be able to sustain their crops due to the decrease in the availability of floodwater potentially causing a smaller rice yield. Fisheries catch is also a concern with an altered flooding regime since fisheries production is influenced by the available area for foraging during the wet season via submerged vegetation. Previously vegetated areas in the floodplain might shift to wet season rice fields or a different land cover under a diminished flooding extent causing a decrease in fish catch during the wet season. Overall, the flooding regime is expected to respond to hydropower development with less water availability during the wet season and more water availability during the dry seasons. These changes will have specific impacts on the fisheries and rice crop ESs that are maintained by the inundation and dry periods of the TSL.

Land cover change can be analyzed with specific flooding regimes to understand the influence of the flood pulse on respective LC and the ESs they support. For example, an increasing flooding regime over several years will show floods that reach habitats higher in the floodplain such as dry season rice. When this flooding regime remains consistently high, farmers may abandon rice fields due to the crops inability to adapt to the extended period of inundation thus causing the land to fallow and appear as shrublands. When this occurs, rice fields will diminish and the shrubland land cover class (LCC) will assume these areas that will ultimately support more fish-foraging habitats in the floodplain. On the other hand, with a decreasing flooding regime, flood height and magnitude would be smaller which might cause farmers to pursue new areas to harvest rice that could take away from the shrubland LCC. When this occurs, fisheries production will decline due to the conversion of shrubland habitats to rice fields and rice crop production will increase. Both trends will be analyzed in this study to understand how the ecosystem services are responding to increasing and decreasing flooding regimes.

The purpose of this research is to study the LC changes related to increasing and decreasing flooding extents in the floodplain of the TSL infer the ES consequences from LC change. The main research questions that will be addressed include the following:

1. How were LCs associated with the floodplain of the TSL in Siem Reap and Battambang provinces altered during a period of decreasing wet season high floods from 2006-2009? Furthermore, how might these LC changes be linked to the respective ESs they provide?

2. How were the habitats in the floodplain of the TSL in Siem Reap and Battambang provinces altered during a period of increasing wet season high floods from 2003-2005?

3. How might the ESs represented by the land-cover types be effected by an altered flooding regime in the TSL?

The TSL has high biodiversity and experiences seasonally alternating periods of wet and dry periods. It is hypothesized to see the LC change responses to an altered flooding regime quickly throughout the floodplain. This is because populations relying on the flooding regime manage their land based on a resilient management approach (Liao 2012).

Liao developed a theory of urban resilience that is defined as a “city’s capacity to tolerate flooding and to reorganize should physical damage and socioeconomic disruption occur, so as to prevent deaths and injuries and maintain current socioeconomic identity" (Liao 2012). The adaptive capacity of the livelihoods determines how people can cope with environmental changes whether caused by climate change or water resources development (Nuorteva et. al. 2010). Informal field observations suggest that the rice farmers are reacting quickly to the changes in the flooding regime experienced in the TSL. Therefore, two hypotheses were developed to understand how land use and respective LC changes occur during multi-year periods of peak flooding increase or decline. Additionally, a hypothesis including the location of LC change was also developed for testing in this study.

1. As stated previously, hydropower development will cause lower wet season high floods. If the flood peak is reduced, rice fields will develop closer to the lake due to the smaller flooding regime experienced by these habitats. These habitats closer to the lake will become managed and irrigated to permit rice cultivation and the shrubland areas will be converted to rice fields. Therefore, a declining flood trend during the wet season will allow increased rice cultivation in areas of the floodplain that are neighboring to the TSL. The conversion of land near the lake to wet season rice will decrease the area of the shrubland LC and therefore decrease the available area for fish foraging during the wet season. Therefore, periods of lower high flows will experience an increase in the ES that support rice agriculture and the ES that support fisheries will experience a decline due to the decrease in available shrubland area for fish foraging.

2. Larger wet season flooding events will cause wet season rice located closer to the lake to be too heavily inundated (Mak 2001) which could result in a large decline of these rice crops. To account for this decline in wet season rice, dry season rice fields will be developed to compensate for the losses from wet season rice fields. This conversion will be seen in areas where farmers have land suitable to produce both wet and dry season rice crops. Therefore, during periods of high flooding, wet season rice crops will decrease and more emphasis will be placed on dry season rice productivity. With this retreat of wet season rice farther away from the lake, the shrubland areas will increase causing more available areas for fish to forage and reproduce. Although the flooding extent is expected to decrease during the wet season as a consequence of hydropower development, the opposite scenario (increasing flooding) must also be explored to explain the LC interactions taking place within the floodplain. Therefore, during increasing peaks, it is expected to see more habitats convert from rice fields to shrublands due to the increased extent of the TSL; however, future high flooding events are predicted to be lower due to the storage of water in hydropower dams.

3. The majority of the LC change will occur along the outer boundary of the floodplain where the habitats are intermittently flooded on a seasonal scale. Therefore, I expect to find the majority of LC change to occur within the range of seven to ten meters above sea level (asl) in the floodplain due to the variable wet season high flooding events.

Prior Research

The expansion of hydropower development in such a short period of time requires impact evaluation of the dams on the temporal and spatial distribution of water and sediment that contribute to maintaining the productivity of the habitats associated with the Tonle Sap Lake (TSL) (Wild and Loucks, 2015). The expected change in the flood pulse due to hydropower development has been modeled in multiple studies (Arias et al. 2012, Tanaka et al. 2003, and Lamberts 2008). All models suggest that hydropower development will cause lower wet season floods and higher dry season water levels which will affect the availability of water to cultivate wet and dry season rice. Since the communities within the floodplain rely on the grasslands for grazing cattle and family-scale farming to support their livelihoods, any alterations to this regime would probably alter their way of life (WCS 2016). Anthropogenic flow alterations will also most likely cause a shift in the timing of the flood pulse, which will affect the migratory fish species that depend on the natural flood pulse for specific reproductive phases (Lamberts 2008). Other research has proposed the opposite effect stating that hydropower development might also increase floodplain productivity and enhance dry season water availability (Vastila et al. 2010); however, most research efforts have suggested that the effects of hydropower development will alter the sustainability of fish and rice crop production of the TSL (Bonheur and Lane 2002, Kirby and Mainuddin 2009).

There are also ambitious plans to increase irrigated land in the Lower Mekong River Basin (LMRB) to respond to the expected human population growth through 2050 (Pech and Sunada 2008; Piman et al. 2013). This increase in development would potentially increase dry season irrigation by 50% over the next twenty years (Piman et al 2013). However, this goal is highly dependent on the availability of suitable crop soils, high seasonal variation of rainfall, and other physical conditions that will influence the increase of irrigated areas (Piman et al. 2013).

Pearse-Smith (2012) observed that hydropower development will also change floodplain vegetation and suitable areas for agricultural development due to the altered periods of growth and senescence caused by the changing flooding regime. Multiple studies have used different techniques to understand the effects the changing flood pulse will have on ecosystems associated with the floodplain. For instance, researchers have developed an algorithm that interprets satellite imagery from the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor that is a part of the NASA EOS Terra satellite to understand rice harvesting in Southeastern Asia (Xiao et al. 2006). This algorithm generated a spatial distribution model of rice paddies throughout Southeast Asia to understand the initial period of flooding and transplanting of rice. They found that the MODIS data accurately showed the initial flooding of the lake and transplanting of the rice crops; additionally, the MODIS data also returned an accurate depiction of rice paddy area when compared with the national agricultural statistics (Huke and Huke, 1997, Xiao 2006). This research can be used as a tool to understand the timing of the wet season related to the growth of rice paddies with the seasonal flooding regime. Figure 2-3 provides a crop calendar published by the Ministry of Agriculture, Forestry, and Fisheries (NAFF) as cited in Shean (2013) as Figure 2-2.

Although caveats such as the usage of a large geographical scale might not accurately portray a system such as the floodplain of the TSL, the study conducted by Xiao 2006 contributes to understanding the effects of the flooding regime on rice paddies throughout the wet season. The methods I will use in my research will address the evident caveats from Xiao et. al. (2006) by interpreting rice field distribution with multiple satellite imagery sources (Landsat and MODIS) on a smaller geographical scale.

MODIS data have also been used to classify habitats in the Tonle Sap based on the individual periods of inundation from the flood pulse. Arias et al. (2012) determined five specific habitats that had different hydroperiods from the evaluation of MODIS time-series data with an unsupervised classification algorithm. These habitats include: 1) open water, flooded for 12 months in an average hydrological year; 2) gallery forest, with a hydroperiod of 9 months; 3) seasonally flooded habitats, flooded 5-8 months and dominated by shrub lands and grasslands; 4) transitional habitats, flooded 1-5 months and dominated by abandoned agricultural fields, receding rice/floating rice, and lowland grasslands; and 5) rain-fed habitats, flooded up to 1 month and consisting mainly of wet season rice fields and village crops (Arias et al. 2012). Their results found that accelerating water infrastructure development (including hydropower, irrigation, flood control, and water supply) would increase the open water area and the area of wet season rice and village crops while the area of seasonally flooded habitats would decrease (Arias et al. 2012). The results presented in Arias et al. (2012) are useful in understanding land-use change since the habitats in the Tonle Sap floodplain will experience land-cover transitions from one type to another due to the altered flood pulse. However, the land-cover classification developed by Arias et al. (2012) was not validated with field observations but rather shown to be plausible through model simulations. The methodological approach taken by Arias et. al. was applied in this research; however, instead of linking LC with flooding period, ecosystem services were inferred from the LC types developed in the field.

From the 8th century to the present, the history of agricultural change has been analyzed and it has been driven by economic, political, and climatic factors (Mak 2001). Mak (2001) interviewed farmers throughout eight provinces in Cambodia about rice cultivation. The farmers all reported different sources of water for their agricultural use, which were summarized as follows: "35% of interviewed farmers depended completely on rainfall to grow their early wet season crop, 37% used supplementary irrigation, 8% used a tube-well, 3% relied on a lake or river branch, and 18% (who were in the Mekong Delta, Kampong Cham Province, and Kandal Province) depended on river flooding" (Mak 2001: p 144).

In addition to water, fertilizer availability and soil suitability also plays a large role in determining the productivity of rice fields during the wet and dry seasons. A wide variety of techniques are used in the floodplain to maintain rice cultivation; and any disruption in the flooding regime or precipitation in these areas will cause farmers to adjust their management practices to permit a prosperous crop yield. Therefore, farmers could potentially adapt their techniques to maintain crop yields during an altered flooding regime caused by hydropower development. Rice farming in the TSL floodplain can be completed with a crop management method that will include both single and multi-crop yields or a seasonal method that depends on the wet and dry season (Nguyen et al. 2013, Xiao et al. 2006). The type of farming selected by the farmers is highly variable since farming is managed based on economic objectives and environmental constraints. Because of this relationship, any change in one component can affect the entire system (Mak 2001).

Farmers are challenged to maintain crop yields throughout a changing flooding regime as well as any changes in precipitation. For example, during the most recent 2011 flooding event, one of the highest in recent history, farmers lost most of their wet-season rice crops to flooding. Farmers compensated by increasing the dry season rice acreage which offset the wet season rice losses and in turn increased irrigated crop yields (Shean 2013). A study conducted in the Chi River Basin, Thailand showed how the seasonal monsoon conditions occasionally produced larger flooding regimes which would potentially destroy the rice crops (Waisurasingha et al. 2008). Therefore, they developed an algorithm that would select the specific types of rice crops that should be harvested during the wet season to minimize crop loss and maximize farmer's incomes (Waisurasingha et al. 2008). Additionally, Landsat 8 OLI imagery has been used to map rice paddies in the Mekong River and TSL to understand how severe flooding events damage crops annually (Dao and Liou 2015). The rice classification from Dao and Liou (2015) estimated the area of rice paddies affected by wet season flooding which are useful to local governments for mitigation and post-flood compensation and restoration. Farmers are expecting increased losses to rice crop production due to combined influences of El Niño events with hydropower development. Therefore, farmers are demanding that the government compensate for the losses they expect to experience during the wet season (Savyouth 2015). These measures could also explain the possibility of farmers adapting their management techniques to the seasonal variations in the flooding regime to sustain their crop yields.

This Study

The purpose of this study is to describe land-cover change that occurred during periods of declining annual flood peaks and increasing annual flood peaks, the former of which may mimic the conditions during a period of hydropower development. I use a combination of techniques for field data collection as well as interpretation from satellite imagery. This research develop a present-day classification of the LC in the floodplain of the TSL. The respective changes of the ESs that support the fisheries and rice production will be interpreted based on LC change in the floodplain. Furthermore, this research will test the hypothesis that a changing flood pulse will influence LC change, by analyzing multi-year periods of rising and declining wet season peak floods. As discussed above, the fisheries and rice crop yields are highly dependent on the flood pulse in the TSL. Therefore, the relationship between flooding regime and land-use and land-cover change will be interpreted based on the respective fisheries or rice production that these habitats provide.

Flooding extent and water level were extracted from the analysis of MODIS imagery and a digital elevation model that interpreted the periods of high and low lake level during the wet season. The dates selected for analysis included periods of an increasing trend of peak floods over 3 years and a declining trend of peak floods over 4 years. By analyzing LC change from these selected time periods, the farmer’s and respective vegetation responses associated with the LC change will be developed.

Projections about ESs will be discussed according to the respective LC transitions occurring in the floodplain, as influenced by wet season flooding events. For instance, declining peak flooding events might cause the conversion of shrublands to paddy fields therefore decreasing the available area for fish foraging causing the fisheries ES to become less productive. Although fish have the ability to forage in paddy fields, the abundance of food in the paddy fields is typically low causing fish to forage in other areas of the floodplain (Katano et. al. 2003). In order for the coexistence if rice production and fish populations in rice areas, new irrigation systems need to be developed; therefore, for purposes of this research, shrublands will be classified as the primary source for fisheries production in the floodplain. Paddy fields may persist or expand during a declining peak flood event thus providing the ES supported by rice production. Although some fish species can invade and forage in the inundated rice fields during the wet season, there are factors such as canal irrigation and food availability that decide on whether the fish will be able to thrive in the rice fields (Katano et. al. 2003). In fact, the changes in rice fields and irrigation ditches to allow for increased production have probably led to a decrease in fish diversity; so although fish can forage in these habitats, rice fields are not the primary source for their foraging (Katano et. al. 2003). The concluding projections about the fisheries and rice crop production will be determined from the results of the three tested hypotheses of this thesis explained in the introduction of this thesis.

Study Area

The Tonle Sap Lake (TSL) is the major lake within the Mekong River Basin (MRB). The MRB begins in the eastern watershed of the Tibetan Plateau and extends throughout China, Myanmar, Laos PDR, Thailand, Cambodia, and ends at its discharge location of the Mekong Delta in Vietnam (Figure 2-4). The Mekong River is the main conveyor of water throughout the MRB by transporting snow melt and rainfall in the upper parts of basin to the lower areas located in places such as the TSL (Sakamoto et al. 2007). The annual variation of flooding can be substantial with alternating seasons of wet periods and dry periods. The extent of flooding can be linked to climatic events such as El Niño and La Niña. In general, strong El Niño periods have corresponded to years of lower than normal wet season floods, whereas La Niña periods have corresponded to years of higher than normal floods (Cochrane et al 2014). During the rainy season, the Mekong River floods heavily, forcing water to flow northward into the Tonle Sap River and eventually into the TSL. As the Mekong River flow recedes near the beginning of the dry season, the flood waters drain from the lake into the Tonle Sap River which flows into the Mekong River that discharges through the Mekong River Delta. The sediment and water flows occurring upstream of the Mekong River have a direct impact on the water availability downstream such as in the TSL (MRC 2010).

The floodplain of the TSL is composed of different zones that respond to the period of inundation during the wet season and exposure during the dry season (Arias et al. 2012, Bayley 1995, MRC 2010, van Zalinge et al. 2003). During the dry season, the aquatic/terrestrial transition zone is exposed, allowing terrestrial vegetation to exist and regrow while the during the wet season the flood pulse inundates the area, creating foraging and nursery grounds for fish (Hogan et al. 2011). During the inundation period, many fish species reproduce and spawn in the submerged terrestrial zone, which is highly productive for fish foraging (Dudgeon 2000, Irvine et al. 2011). Once the floodwaters recede, the vegetation in the floodplain becomes exposed and some fish species respond by migrating upstream via the Mekong River or by staying in the permanently flooded areas of the lake to forage (Baran 2006). During this period of exposure, this aquatic/terrestrial transition zone begins the regrowth phase during the dry season and the vegetation in maintained until the hydrological cycle inundates the area during the next wet season (Delgado et al. 2010, Gasith and Resh 1999, Junk et al. 1989).

The Mekong River is located in a region that is affected by a mixed Indian and Western North-Pacific monsoon (Delgado et. al. 2012). The average annual rainfall from 1990-2012 is shown in Figure 2-5. Typically, the wet season occurs from May through October and the dry season is from November through April. This trend is related to the timing of the Southwestern monsoon since 80 to 90% of the discharge in the LMRB occurs from May to October (Delgado et al. 2012). Other sources of annual precipitation can be accounted for by snow melt from the Tibetan Plateau and localized tropical storms which are also related to the periodicity of the Southwestern monsoon circulation (Delgado et al. 2012).

Siem Reap and Battambang provinces together cover an area approximately 22,000 km^2; however, the study area for this research was narrowed to include only areas of the provinces that are part of the TSL floodplain. A digital elevation model from the Shuttle Radar Topography Mission (SRTM) was used to select the area that is within 15 meters above sea level (asl). This elevation was chosen based on the maximum flood heights recorded from the Prek Kdam gauge station (Figure 2-2). Therefore, the 15-meter asl contour was extracted from the DEM to include the highest flood (approximately 11 m asl) as well as any outlier flood measurements that might exceed the seasonal maxima that occur between 8m asl and 10m asl in the floodplain. The horizontal reference datum for the DEM used is the WGS84 (World Geodetic System 1984) and the vertical datum for the DEM from the SRTM is mean sea level as determined by the WGS1984 Earth Gravitational Model (EGM96) geoid.

Field Work

Field work was conducted in May and June of 2015 at the end of the dry season. Training samples were collected according to the CIPEC protocol (Green et al. 2005) for land-cover classification and accuracy assessment. Additionally, a combination of field training samples (Figure 2-6) and Google Earth training samples were collected to create the image classification and accuracy assessment. Random and convenience sampling methods were used in the field for determining the different LC types that were present in the field (Teddlie and Yu 2007). Informal conversations with the villagers were also conducted with a convenience collection method to understand how the changing flood pulse is affecting fishing communities and rice cultivation (Appendix A) (Bernard 2011, Teddlie and Yu 2007).

The LC classes recorded in the field included shrubland, grassland, flooded forest, flooded shrubland, and rice field. Wet and dry season rice were differentiated by analyzing the spectral signatures of the classes from Landsat imagery (Appendix B); additionally, the seasonal growth periods as well as the inundation for wet and dry season rice were determining factors as to what type of rice was classified. This was then compared with knowledge obtained in the field from local villagers about the seasonal periods of inundation within the floodplain. The other LCs such as the flooded forests, grasslands and shrublands were combined to create the shrubland LC. These aggregated LC classes were appropriate for this study since the respective LCs in each class were directly related to the ES that they provide (i.e. shrubland being an aggregate of flooded forests and shrubs to represent the fisheries-related ES). Two classes for water and clouds were are classified to eliminate non-terrestrial land covers. The assumption for areas classified as the shrubland LC class includes the area of fish foraging habitat during the flooded period, and rice was split into wet and dry season rice based on the spectral signatures of each class as well as location of the rice in the floodplain. Finally, elevation within the floodplain for each training sample was recorded with a Garmin eTrex 12-Channel Global Positioning System.

Data Sources and Pre-Processing

Various resources and geographical datasets were used throughout this research (Table 2-1). By analyzing the hydrograph provided in Figure 2-1, I selected one period where the flooding regime had increasing peak wet season water levels and a period where the flooding regime had decreasing peak wet season water levels. The hydrograph provided by the Mekong River Commission contains the high and low water level for each year from 1960-2006. This dataset was extracted from the Mekong River Commission's Data Portal (mrcmekong.org). After comparing the flood levels from the hydrograph provided from the MRC and the extracted water levels from the MODIS data (see Flood Elevation and Extent Analysis), I concluded that the MODIS imagery provided an accurate depiction of the water levels from 2006-2013. Therefore, a period of an increasing flooding regime trend was selected from 2003-2005 and the period for a declining flooding regime was selected for 2006-2009.

Landsat images from specific dates were acquired through the USGS Global Visualization Viewer (glovis.usgs.gov). All Landsat images were acquired during the dry season (early February to early April). Since the dry season has the lowest water availability in the floodplain, the vegetation and rice fields were exposed. Therefore, the images were selected from the end of the dry season to create the most accurate classification of the land-cover (LC) in the floodplain. Six images were acquired by Landsat 5 Thematic Mapper (April 13, 2004, January 10, 2005, February 14, 2006, February 1, 2007, March 23, 2008, and February 6, 2009). Landsat 7 ETM+ was used for January 29, 2003 image analysis. The final image for analysis was acquired from the Landsat 8 Operational Land Imager and Thermal Infrared Sensor on February 7, 2015. All images were calibrated and corrected for geometric and atmospheric errors (Green et al. 2005).

The delineation of the study area was created by a combination of multiple resources. Geospatial shapefiles and topographic maps were provided by the Mekong River Commission. A 30 by 30-meter spatial resolution digital elevation model from the Shuttle Radar Topography Mission (SRTM) was used to interpret results with an elevation reference to the floodplain (Farr et al 2007). This digital elevation product meets the Interferometric Terrain Height data specifications that includes a $\leq$10m relative vertical height accuracy for the 30m x 30m spatial sampling (Table 2-1). This spatial resolution was appropriate because of the floodplain’s shallow elevational gradient from the lake to upland areas. Additionally, data that include data for roads, topography, political boundaries, and protected areas were provided by the Food and Agriculture Administration of the Royal Government of Cambodia. All datasets were referenced to WGS84 UTM 48N projection. A list of the organizations, that provided spatial data for this research, the URLs and dates accessed, and a very brief description of the data are included in Table 2-1.

Hydropower development is expected to be the largest contributing factor to a changing flood pulse in the TSL. A dataset from the Open Development Mekong provided the most up-to-date state of the current and potential hydropower development throughout the MRB (Figure 2-7). This dataset listed the status of each dam as: cancelled, no data, operational, planned, suspended, under construction, or unknown.

Flood Elevation and Extent Analysis

The SRTM DEM was used to interpret water surface area within the study area. The product used defines an ocean elevation at 0m. Lakes of 600m or more in length are flattened and set to a constant height. This digital elevation model was most acceptable due to the low gradient transitions between the elevations throughout the floodplain. This study is limited to the range of 0-15 m asl in the TSL. Since the lowest extent of the TSL generally is at 4m, the elevations from 4-15m will include the areas of changing inundation between the wet seasons. Each meter within this range was converted to a separate zone and the area of overlap of each LC was calculated using a spatial zonal analysis tool.

LC change trajectories were also analyzed with the DEM to understand the location each trajectory occurred in the floodplain. The same trajectory periods discussed previously (2003-2005 for an increasing flood trend and 2006-2009 for a decreasing flood trend) were interpreted for the coverage of each trajectory within the 0-15m boundary created from the digital elevation model. Multiple trajectories were analyzed to understand the conversion of shrubland to wet or dry season rice as well as the habitat transitions from rice fields to shrublands.

The flood extent was analyzed by image interpretation of the MODIS Terra sensor product MOD13Q1 (250 m resolution, 16-day composite). This sensor records a spectral signature from vegetation and uses an algorithm to compute the enhanced vegetation index (EVI). The Enhanced Vegetation Index is a modified normalized difference vegetation index:

$$EVI = G\frac{\rho^{*}{}_{nir} - \rho^{*}{}_{red}}{\rho^{*}{}_{nir} + C_1\rho^{*}{}_{red} - C_2\rho^{*}{}_{blue} + L}(1 + L) \tag{2-1}$$

with ρ^* being the band reflectance, a soil adjustment factor, *L,* and two coefficients, C_1 *and* C_2, which describe the usage of the blue band in correction of the red band for atmospheric aerosol scattering. The coefficients C_1, C_2, and *L*, are determined as 6.0, 7.5, and 1.0 respectively and *G* is a gain factor set to 2.5 (Jenson and Lulla 1987).

The 16-day composite represents 16 days of measured EVI and records 23 images per year. The dates analyzed included February 2000 through December 2013. Each image was interpreted by using an EVI threshold value of 2000 for water or flooded land and then the area for each date was recorded. The EVI value is a 16-bit signed integer with values from -2000 to 10,000. These values are then multiplied by a scale factor of 0.0001 to create values between -0.2 and 1.0 from Equation 2-1. Therefore, a selected EVI value of -2000 indicates a value of -0.2 EVI and was chosen to represent the Tonle Sap Lake. The flooding regime was interpreted for trends in the variability of the wet season highs.

Wet season maxima were extracted from the MODIS imagery by selecting the elevation where the maximum flood extent was present. Dry season lows were extracted with this same method but the values remained nearly constant at 4 m asl throughout the time period.

Land-Cover Classification

Training samples were collected by field work conducted in May and June of 2015. A hybrid approach to image classification was created to include both field samples as well as training samples taken using Google Earth. Training samples collected in the field were used to establish appropriate LC classes to classify the 2015 satellite image accurately. A maximum likelihood supervised classification method was used throughout the image dates. Fifteen LC classes were developed: 5 types of shrubland (shrubland, grassland, forests, flooded grasslands, and flooded shrublands), 5 types of rice fields were divided into wet and dry season rice, and 5 types of water (rivers, open lake, small tributaries, etc.). The other images (2003-2005 and 2006-2009) were classified based on the spectral signature interpretation of the 2015 LC classification (see description of spectral signatures below). For example, shrubland vegetation was mostly present closer to the lake and rice fields were characterized by distinct patterns in landscape structure on the outer boundary of the floodplain. Google Earth (Google Earth v.7.1, 2013) along with field experience was used to identify the LCs associated with this study and to further help with classification of the 2003, 2004, 2005, 2006, 2007, 2008, and 2009 images.

Each image was classified with 15 LCs, and then in post-classification the classes were combined to form the four main LCs: shrubland, wet season rice, dry season rice, and open water. Further definitions of these LC types are summarized in Table 2-2. These three LCs were selected because they represent the dominant habitats associated with two main ESs supplied from the lake: fisheries and rice cultivation. Knowledge of the study area and visual interpretation was incorporated into this study and helped to classify the image further to ensure a high accuracy for the classified image.

Reflectance Spectral Signatures

The reflectance spectral signatures for each LC class were created to understand the characteristics of the vegetation classes. Fifteen spectral signatures were created for the 2015 classified image and training samples were selected for the other images based on similar spectral signatures. For example, the spectral signature for the shrub LC class in the 2015's classification was used to select the training sample points for the 2003-2005 and 2006-2009 LC classification of shrublands. Samples that had similar if not identical spectral profiles were considered to be a part of the same class for the other time periods in this study. Also, each training sample for the specific LC class was selected according to location, spectral signature, and to the satellite images from Google Earth (Appendix B).

Change Trajectory Analysis

A change trajectory was created to analyze LC transitions. The three-date trajectory from 2003-2005 was calculated for an increasingly higher flooding season regime and a second four-date trajectory from 2006-2009 was interpreted around a declining flooding regime. A change trajectory is a post-classification method that compares an image pixel by pixel to determine spatial and temporal patterns of change of each LC type (Cassidy et al. 2013, Lu et al. 2004, Patarasuk and Binford 2012). Multiple trajectories were created for each time period; but for purposes of this research, the only trajectories that were analyzed were the conversion from wet season rice to either dry season rice or shrublands, the conversion from shrublands to wet season or dry season rice, and the conversion from dry season rice to wet season rice or shrublands. Cloud cover was included in the classifications and percent overlap of cloud cover for each LC was analyzed; however, the changes that included the water class or the cloud cover were combined with the “other trajectory” category to emphasize the changes occurring with the LC’s associated with ecosystem services.

Locations of LC-Change for the Increasing and Decreasing Peak Flooding Regime

A zonal analysis was implemented to understand where the land-cover change occurred in the floodplain. A digital elevation model was used to overlay with the change trajectories to determine where the change was occurring within the floodplain. The results show only the trajectories that are associated with ecosystem services as previously listed. This analysis determined whether the change occurred in the same locations at the peak flooding events. For example, if the trajectory occurred predominantly within the 10-meter elevation and the flood heights for the peak wet season were 10 meters from the hydrograph, the relationship between land-cover change and flood peak elevation was explained. Therefore, the LC change in the floodplain was directly influenced by the changing flooding regime.

LC Accuracy Assessment

An accuracy assessment was performed on the 2015 classified image (Table 2-3). The accuracy assessment used field verified training samples along with reference samples that were selected due to their similarity to each respective LC class. Accuracy assessments for earlier dates can be seen in Appendix E of this thesis.

Field Conversations

Anonymous and randomly encountered informants provided information concerning the flooding regime as well as the impacts it has on their livelihoods. This information was then used to classify each village as primarily fishing or rice farming.

Table 2-4 below provides a brief overview of the livelihoods for each of the samples (fishing, rice harvesting, or both). Areas located near Siem Reap represented families that had access to rice fields and were also located near small tributaries that connected to the Tonle Sap Lake (TSL) which allow for fishing. These communities also developed monitored "community fish ponds" where fish would be maintained during the dry season to provide food for the village when the flood recedes (Figure 2-8). A picture taken from the field of the fish catch in May 2015 is shown in Figure 2-10.

One informant near Siem Reap mentioned that they were primarily a rice farming community but since they had access to a boat, they were also able to fish. This informant also commented that the floods have been decreasing in height over the last 10 years; but according to the hydrograph in Figure 2-11, this is not true. Therefore, the comments provided by the informants could be inaccurate and biased; however, their insights were valuable in understanding community livelihoods within the floodplain. Informants also commented on any recent urban development such as roadways, new condominiums for tourists, or were barren lands in the process of being developed due to the increase in tourism around Siem Reap (Figure 2-9). Another informant also commented on the availability of soils in their town stating that urbanization has caused a high demand for sands and gravels for concrete aggregate to create and build roads. Interestingly, the informant commented also that sand and gravel used to support road construction manage to be replaced every year with the floods thus maintaining the system. This is another environmental service that the flooding regime provides, but it was not analyzed in this research. In Prasat Bakong, one informant noted that there were “large flooding events in 2000, 2010, and 2011.” These dates correspond with two of the three flooding peak flooding events according to the hydrograph in Figure 2-11. Additionally, I visited three villages near Kompong Pluok and Sot Nikum that were recorded as flooded forests for the shrubland land-cover (LC) classification. These villages were all located on one of the tributaries associated with the TSL so villagers were capable of accessing the lake to fish. The informants in this village also stated how areas farther away from the tributary were capable of growing rice during the wet season; therefore I classified the livelihood of this village to be agricultural and the LC classification to be wet season rice. The informants also discussed the new regulations that private companies (China and Thailand were mentioned) are enforcing throughout the TSL such as “check points” that require licensed fishermen to pay fees to proceed to fish beyond the check point. In other words, the fees that private companies are forcing onto the fishermen provides indication of “land grabbing” or in this case “water grabbing” for their benefit. Although water grabbing is a new concept to the MRB, owners of these areas of water are the primary beneficiaries while the poorer communities and the ecosystems in these areas are negatively impacted (Matthews 2012). Multiple villagers stated that these dams threaten their livelihoods; therefore, the villagers regularly travel to Phnom Penh to protest these dam closures only to have the dams opened for a short period of time and then close again, denying water to downstream areas.

Villages in Battambang Province were mostly rice-producing communities. Only a few families owned a boat to fish in flooded areas during the wet season; furthermore, depending on the location of the homestead during the dry season, the boats would become useless unless the tributaries were inundated enough to allow access to the lake. Some locations (Samples 4, 7, 21, 26, and 33) were capable of harvesting wet season rice two times a year and harvesting dry season rice one time per year. The period of inundation throughout villages in Battambang Province was variable and some villages were capable of maintaining other crops such as watermelon, beans and corn. The high crop yield in these areas is most likely due to the geographic tolerance the crops have developed within the specific elevation of the floodplain where the fields are located (Elevation data given in Appendix A). Canals and privately owned dams have been built throughout the province to control water availability and flow patterns within certain villages. The dams are small and have the ability to open regularly but private companies (China and Thailand were mentioned) keep them closed to maintain water in areas that are conducive to their crop yield. Therefore, water grabbing can also be seen in Battambang Province.

Flood Extent and Elevation

A flood hydrograph from the Mekong River Commission included a time series from 1960-2006 (Figure 2-11). These hydrographs were then compared to determine the accuracy of the MODIS derived flood height data. Since five out of the six years were consistent with the confirmed flood height from the MRC (Figure 2-12), the flood heights derived from the MODIS imagery were an accurate depiction of the flooding regime (Figure 2-13). Therefore, the data provided by the MODIS analysis can be used to interpret the years where the MRC did not have data available.

The wet season of 2011 was the largest peak flood extent seen throughout the time series and it also recorded the highest flood elevation (Figure 2-12). The lowest peak flood height was observed in 2010 (although an informant said that this was a high flood year) with a height of 6 meters and an extent less than 8000 km^2. The MODIS imagery showed the lowest flood height during the dry season to be at 4 m which is the elevation of the TSL within a digital elevation model. Therefore, the MODIS imagery analysis was capable of determining changes accurately over larger areas of water such as the floodplain of the TSL. Throughout the MODIS time series, the timing of the wet and dry seasons remained fairly consistent. For instance, large flooding events typically started in mid-September to early November and the waters would begin to recede in Late-January to early February. The lowest extent was typically measured in May or June from 2000-2013.

Decreasing and increasing flooding years were classified as flooded/not flooded for each pixel. The classifications for individual flood years can be seen in Figures C-2 to C-8. A change trajectory was also created from the MODIS imagery for the increasing and decreasing floods to visualize the changing flooding regime throughout the study area. The increasing flooding regime trajectory can be seen in Figure 2-14 and the area cover for each trajectory is shown in Table 2-5. Table 2-5 shows that the largest trajectory (not including the permanently flooded area of the lake) was the areas that were not flooded throughout this time period (37.9%, 2011.2 km^2). The second largest trajectory were the areas that remained flooded from 2003-2005 which also included the area of the lake (30.0% or 1592.0 km^2). The third largest trajectory that was seen during the increasing flooding event was when the floodplain was not flooded in 2003 and then remain flooded for 2004 and 2005. This trajectory accounted for 19.9% of the study area (1,056.0 km^2). Overall, more areas within the floodplain converted to flooded areas with an increasing flooding regime, as expected.

Change trajectories were analyzed with the decreasing flooding regime to determine whether the areas within the floodplain were experiencing smaller flooding extent from 2006-2009. The largest trajectory in the floodplain during this time series analysis were the areas that remained non-flooded throughout this time period (50.2% or 2,663.69 km^2) (Figure 2-15). The overall conversion from flooded or not-flooded areas to non-flooded areas (61.2% or 3,247.6 km^2) was larger than the conversion of either classes to flooded areas (38.8% or 2,058.9 km^2). Therefore, this trajectory shows an overall trend of the floodplain experiencing a decreasing flooding regime from 2006-2009.

LC Classification of 2015

A LC classification was developed from training samples taken in the field in 2015 (Fig 16.) This classification was used to interpret the other images where field validation data were not available. The classification includes the following distributions for the LC classes: dry season rice (682.3 km^2, 8.7%), wet season rice (2,203.7 km^2, 28.1%), shrubland (3,513.4 km^2, 44.8%), and water (1,442.9 km^2, 18.4%). Wet season rice is generally found closer to the lake and its associated tributaries and dry season rice is generally found in the higher elevations farther from the lake. Dry season rice fields were easier to classify due to the time of image acquisition near the harvesting period; on the other hand, wet season rice was distinctly present in fields along the outer boundary of the shrublands since these areas were maintained by irrigating with flood water from the previous season. Wet season rice was also classified in the Landsat imagery from the field conversations with villagers willing to discuss the inundation periods for their rice fields. The overall LC classification accuracy of 81.0% this image is noted in Table 2-3.

LC Distribution 2003-2004-2005

The results for the LC distribution in 2003, 2004, and 2005 (increasing flooding regime) is shown in Figures 17 and 18. The area occupied by wet and dry season rice varied throughout these dates. For example, the dry season rice was first classified with an area of 23.3% of the floodplain in 2003, then decreased to 15% of the floodplain in 2004, and finally in 2005 increased to 20.3% of the total area of the floodplain (Figure 2-18). Wet season rice experienced the opposite behavior with increasing rice area in the floodplain between 2003 and 2004 (15.9% to 24.4% respectively). The shrubland LC consistently expanded throughout the floodplain from 2003 to 2005. The shrubland LC class was also the largest LC present in the floodplain of the TSL. The water LC distribution remained fairly consistent throughout this time period.

The larger increase in wet season rice was seen from 2003-2004 and the larger increase in dry season rice was seen from 2004-2005. Rice cultivation can occur during the wet and the dry season typically at the higher elevations within the 15 m asl boundary. The location of the rice paddy fields varied throughout the dates analyzed mostly due to the availability of suitable land capable of maintaining rice production during the wet or dry seasons. The shrub LC class was mostly located in areas closer to the TSL (Figure 2-17), and in lower elevations. The flooding regime associated with the lake causes certain vegetation types such as shrublands and flood-adapted forests to thrive in these areas.

The water LC class remained constant throughout this study because the images were acquired during the dry season when the lake was at its lowest. Some cloud cover was seen in the 2004 and 2005 LC distributions, but was not in the 2003 image. The largest obscurity was seen in the overlap of clouds with dry season rice at 12.8% of the 2004 and 2005 classified images. These results show that there is a large area of LC that is obscured between the 2004 and 2005 LC distributions. The cloud distribution in 2005 accounted for 5.2 % of the total area classified. Although the cloud distribution in 2005 was small at 5.2%, all of the LCs in the 2004/2005 distributions were affected by their overlap. Therefore, the trajectories that include this cloud LC class were listed as “other trajectory” in the analysis to separate the trajectories with cloud cover from the trajectories that relate to the changes in ecosystem services.

The change in LC area distribution was determined for the three dates (Table 2-7). Overall dry rice showed a decrease in area from 2003-2005 with approximately 12.9% of the total area been lost to other LCs. The wet rice LC experienced this same trend but at a larger loss of area for the 2003-2005-time series (-38.4%). The shrubland LC class experienced the largest growth between these three LCs with a total increase of distribution of 21.2% from 2003-2005 (Table 2-7). These changes in LC distribution will be linked by the LC change trajectories to determine the relationship between losses/gains of habitats and the conversion between the LCs.

LC Distribution 2006-2007-2008-2009

The same patterns of location of each LC class was seen in the 2006-2009 classifications (Figure 2-19) as the 2003-2005 classifications (Figure 2-17). Shrublands were found closer to the lake due to their reliance on water supply whereas rice fields were located farther from the lake due to their ability to thrive on tributary flows or precipitation events. Wet season rice was located closer to the lake and other water sources due to the water supply. Dry season rice was generally found within the higher elevations of the floodplain, and wet season rice was typically found within the boundary between the shrublands and the dry season rice LC. The TSL was classified throughout these dates; however, the 2006 image shows some cloud coverage over the water as well as classification of rice fields. This is an error in the classification method and these areas are listed as “other trajectory” in the LC change analysis.

The LC distribution for the 2006-2009 period is shown in Figure 2-19. Due to the limited availability of quality Landsat images, two years had extensive cloud cover (2006 and 2008). Approximately 14.3% of the study area (1121.4 km2) of 2006 and 16.1% (1262.6 km2) of 2008 were classified as clouds. The clouds obscured 9.7% of the dry season rice between the 2006 and 2007 classification and also obscured 13.9% of the wet season rice between the 2008 and 2009 classification. The largest LC distribution was the shrubland LC class with at least 35% of each year’s area being classified as this LC (Figure 2-20). The wet season rice was the smallest LC distributed throughout the study area with the lowest area in 2006 at 12.3% and the largest area seen in 2008 at 18.9%. The dry season rice LC experienced an overall increase in distribution throughout the study period with 17.2% of the total area being this LC to 23.3% of the total area. The water LC class altered between increasing and decreasing trends due to the cloud coverage that was present in 2006 and 2008. Cloud trajectories were placed in the “other trajectory” category in later analyses.

The percent change in LC distribution is seen in Table 2-8. All LC’s from this table indicate an overall increasing trend in distribution throughout the time period. There was a decrease in dry season rice from 2007-2008 (-8.6%) and a decrease in the shrubland cover from 2007-2008 (-11.8%). Throughout the time period for the decreasing flooding regime, dry season rice increased in distribution by 35.6%, wet season rice increased in distribution by 35.0% and shrubland cover increased by 3.5%.

Spectral Signatures (Appendix B)

The spectral signatures were used to determine differences in land-cover (LC) classes to separate the different types of rice fields as well as shrublands, forests, and grasslands. The spectral signatures for the LC classes that were developed for this research can be seen in Appendix B of this thesis.

LC Change Trajectory for 2003-2005: Increasing Peak Flooding Event

Land cover change trajectories of the years 2003, 2004, and 2005 were compared on a pixel-by-pixel basis to examine the possible LC changes. A three-date change trajectory was analyzed and can be seen in Figure 2-21 and Table 2-9 below. For this flooding regime, only 11 trajectories that each represent >1% of the landscape are described. The two-date trajectories for 2003-2004 and 2004-2005 are listed as supplemental information in Appendix D.

Table 2-9 shows that more than 50% of the floodplain remained unchanged (this percentage excludes the water category); however at least 40% of the floodplain did undergo a change from 2003-2005. The permanently shrubland category remained the largest percentage of unchanged trajectory with 36.1% from 2003-2005. Areas that remained classified as water throughout this period of increasing flooding regime were the second largest unchanged trajectory within the study area at 18.0.% of the total area. Permanently dry season rice had the third highest percentage of unchanged trajectory at 15.9% total area cover. The ‘other trajectory’ category accounted for 9.0% of the total area of LC change. Since this category includes the change to or from cloud cover, it will not be interpreted further in this analysis.

The conversion of wet season rice to shrubland accounted for 5.1% of the total LC change in the study area. The conversion from wet or dry season rice to shrubland was the largest LC change seen from 2003-2005 existing in 7.9% of the study area. The second largest LC change trajectory was seen in the conversion from wet season rice to dry season rice at 2.9% of the study area. When combined with the trajectory of shrublands to dry season rice, the total LC conversion from either shrublands or wet season rice to dry season rice accounts for 3.8% of the study area. The conversion of dry season rice to wet season rice existed in 2.0% of the total area, and the conversion of shrubland to wet season rice existed in 0.8% of the total area. Therefore, the conversion of land from either dry season rice or shrublands to wet season rice accounted for the smallest percentage at 2.8% of the study area.

LC Change Trajectory for 2006-2009: Decreasing Flooding Regime

The same interpretation discussed above was applied to the results for the 2006-2009 decreasing flooding regime. Eleven trajectories were analyzed according to the land cover type that relates with their respective ecosystem service. These included the following LC changes: permanently water, permanently shrubland, permanently wet season rice, permanently dry season rice, shrubland to dry season rice, shrubland to wet season rice, wet season rice to shrubland, wet season rice to dry season rice, dry season rice to shrubland, and dry season rice to wet season rice. Additionally, trajectories that were less than 1% of the total area cover were not considered. Figure 2-22 and Table 2-10 illustrate the four-date LC trajectories results.

Similar to the results found from the 2003-2005-time period, more than 50% of the floodplain remained unchanged throughout the analysis from 2006-2009. On the other hand, at least 45% of the floodplain did undergo a change. The three largest LC trajectories over the entire time period (2006-2009) were the conversion from wet season rice to shrublands at 5.7%, the conversion from dry season rice to wet season rice at 4.7% and finally the conversion from shrublands to wet season rice at 2.7%. Areas that were permanently shrubland remained consistent throughout the time period with 35.3% of the floodplain classified as this trajectory from 2006-2009. The 'other trajectory' category represented 12.5% of the total area throughout this time period. The overall conversion from dry season rice or shrublands to wet season rice was the largest trajectory in the floodplain accounting for 7.4% total area. The second largest conversion of land was the transition of wet season rice or dry season rice to shrublands at 6.4% of the total area. Finally, after combining the conversion of shrubland or wet season rice to dry season rice, this trajectory accounted for the smallest area in the study area at 3.6%.

Locations of LC Changes Relative to An Increasing Peak Flooding Event

The data show that there is a clear relationship between the LC change and the flooding regime existing in the floodplain. The relationship between LC change and elevation in the floodplain for 2003-2005 is shown in Figure 2-23. The data that support Figure 2-23 can be found in Table D-2 in Appendix D.

These data were used to distinguish the locations where the largest area cover value was observed for each trajectory. The six main trajectories showing the LC change between wet season rice, dry season rice, and shrubland were selected to determine where LC change is occurring within the floodplain to relate it with the flooding regime shown in the flood hydrograph in Figure 2-12. As shown from Figure 2-12, the peak flooding occurred at approximately 8 meters in 2003, and 9 meters in 2004 and 2005.

From the results, there is a clear trend in increasing and decreasing patterns of LC change throughout the floodplain. For example, all LC trajectories peaked within high elevations of the floodplain (shrubland to wet season rice at 10 meters; wet season rice to shrubland, dry season rice to shrubland, and dry season rice to wet season rice at 11 meters; wet season rice to dry season rice at 12 meters; and shrubland to dry season rice at 12 and 13 meters). Although LC change occurred throughout the floodplain, the largest percent cover for the trajectories from 2003-2005 were within the areas of the floodplain that experience an altered flooding regime (between 9-13 meters of the floodplain according to Figure 2-23).

Locations of LC Changes Relative to a Decreasing Peak Flooding Event

For the decreasing flooding regime existing from 2006-2009, the flood heights recorded from Figure 2-11 were 9 meters in 2006, 7 meters in 2007, and 7 meters in 2008. After overlaying the LC trajectories with the digital elevation model, a relationship was determined between the trajectories and flooding regime. Figure 2-24 shows this relationship for an increasing regime. The conversion from shrubland or wet season rice to dry season rice existed primarily within the 11 and 12 meter elevations. There are clear increasing and decreasing trends of the locations of LC trajectories throughout the floodplain elevations. These trends were similar to the trends shown in the 2003-2005 trajectory analysis with elevation. The largest percent cover change from shrublands to dry season rice was highest at 12 meters and the trajectory for wet season rice to dry season rice was highest in 11 meters of the floodplain. Both conversions from wet season rice or dry season rice to shrublands occurred largest within the 10-meter elevation. Finally, the conversion from dry season rice to wet season rice was at its highest area cover at 11 meters and the conversion from shrubland to wet rice was largest at 12 meters. Therefore, a similar trend developed from the 2003-2005 elevation analysis is apparent in the 2006-2009 elevation analysis (majority of trajectory cover is within 9-13 meters of the floodplain).

Discussion

Three hypotheses were tested in this research (refer to hypotheses 1 through 3 in the introduction of this thesis). Hypothesis 1 stated that during a decreasing flooding event, from 2006-2009 we would see a decrease in the shrubland LC and an increase in the wet season rice and dry season rice LC. The hypothesis was rejected. The conversion from wet season rice to shrubland was the largest trajectory throughout the study area (5.7%). The next two largest trajectories were the conversion from dry season rice to wet season rice (4.7%) and the conversion from shrubland to wet season rice (2.7%). These two LC trajectories from the 2006-2009 time series support the hypothesis since it was stated wet season rice would increase due to the conversion of the land to rice fields to maintain crop yields. Although these two trajectories confirm the conversion of land to wet season rice fields, the hypothesis cannot be supported since the largest LC trajectory was seen in the conversion from wet season rice to shrublands.

Hypothesis 2 stated the following: in the case of an increasing flooding regime, it was expected to see an increase in shrubland LC, a decrease in wet rice LC, and an increase in dry season rice LC. This hypothesis was supported. From 2003-2005, the largest LC change was seen in the conversion from wet season rice to shrublands (5.1%). The second and third largest LC change seen from 2003-2005 was the conversion from wet season rice to dry season rice (2.9%) and the conversion of dry season rice to shrubland (2.8%). Therefore, with an increase in shrublands, the wet season rice fields were expected to decrease in total areas throughout the study area within the floodplain. Additionally, the hypothesis stated that as the wet season rice fields decreased, the dry season rice fields would increase due to the flood height being pushed into higher elevations in the floodplain. Since both the conversion from dry season and wet season rice to shrublands accounted for the largest trajectory for 2003-2005, the first part of the hypothesis concerning shrubland LC was supported. Since the second largest LC conversion existing in 2.9% of the study area was the creation of dry season rice fields from wet season rice fields, the second and third parts of this hypothesis can also be supported.

Finally, an elevation analysis was performed on the LC change trajectories to determine where within the floodplain the change was occurring. Hypothesis 3 stated the following: the majority of the LC change is expected to occur within the range of 7 to 10m asl due to the variable wet season high flooding events. For the increasing flooding regime period (2003-2005), most of the LC change trajectories occurred between 9 and 13 meters within the floodplain. The conversion from shrublands or wet season rice to dry season rice was primarily found in higher elevations within the floodplain due to its ability to persist further away from direct water sources such as the Tonle Sap Lake (TSL). For a decreasing flooding regime (2006-2009), the LC change trajectories were mostly seen within the 9 to 13-meter elevation.

The results from this study show how riparian communities respond to short-term influences of changes in the flooding regime in the floodplain of the Tonle Sap Lake (TSL). The field conversations also help explain the short-term response mechanism that the populations in the floodplain have adapted to maintain their crop yields. Most of the LC change occurs in the locations where the peak flood reaches 9-13 meters asl;

therefore, LC change is influenced by the flooding regime. My study also found that with decreasing flood peaks (hypothesis 1), the shrubland LC that supports the fisheries production in the TSL will increase in area thus providing areas where fish can continue to forage. This is only possible if the areas that contain these shrublands are inundated during the wet season for fish foraging. If the wet season high floods do not reach these areas that changed to shrubland, fish productivity may be at risk. Additionally, wet season and dry season rice fields remained persistent within the floodplain with a decreasing flooding regime. As mentioned previously, it is expected to see a decrease in wet season flood peaks due to hydropower development that is occurring in the Mekong River Basin (MRB). Furthermore, this altered flooding regime might cause habitats associated with the floodplain such as shrublands and rice fields to decline thus decreasing the overall productivity of fisheries and rice production from the floodplain of the TSL (Arias et al 2013). Nuorteva et al 2010 also stated that the populations that will be most affected by the changing flooding regime were the poorest communities because of their inability to adapt. However, after analyzing the human-environment interactions that occurred with a changing flooding regime in my research, I conclude that riparian communities will adapt quickly to an altered flooding regime. Therefore, since my results show that habitats persisted and even grew through the decreasing flooding regime, proposed hydropower development might not have the adverse effects mentioned in Arias et al 2013 and Nuorteva et al 2010. Instead, the communities will adapt on a year-to-year basis in order to produce the most crop yield to sustain their livelihoods.

Future Research

The classification method used in this study was robust but some improvements can be made. For instance, the classification for the Landsat images was based on the knowledge developed from field samples taken in 2015. Due to the lack of training samples available for this study area, the classifications were created from prior knowledge of floodplain dynamics as well as accurate image interpretation. Future research should include more training samples to be taken in the floodplain of the TSL. Additionally, the field data collection should also be conducted during the wet season. It would be interesting to return to the training sample locations that were recorded in 2015 during the wet season to understand the LC interactions between the two seasons. Also, the classification was made from the knowledge based on the villagers' personal insights; therefore, it would be interesting to return to the training sample sites and validate their interpretation of what occurs during the wet season.

This research analyzed only flooding trends during the wet season highs; additionally, the temporal scale was only from 2000-2013. Future research will include a longer term analysis of flooding to understand the decadal oscillations of the flooding regime with climate change as well as altered Western Pacific monsoons. Future research will also include the analysis of the changing flooding extent during the wet season. This can be accomplished by analyzing LC change only during the dry season to understand how water availability is changing from an altered flooding regime.

Table 2-1. Description of Datasets used in this study.

Organization	Ancillary Data Description	URL and Date of Access
Mekong River Commission	The Mekong River Commission provided the location of hydropower dams harmful to migratory fish species, future and present dam locations, and political and environmental boundaries including rivers and provinces.	(www.mrcmekong.org) & (portal.mrcmekong.org/flood) October 2, 2015
Food and Agriculture Adiminstration of the United Nations (FAO)	The FAO provided spatial datasets that were used for political boundaries such as provinces, roads, and topography of the country of Cambodia.	(www.fao.org/cambodia/fao-in-cambodia) October 2, 2015
United States Geological Survey	The National Aeronautics and Space Administration and the National Geospatial-Intellegence Agency created the Shuttle Radar Topography Mission that provided the digital elevation model that was used in this study.	(earthexplorer.ugsg.gov) October 2, 2015
United States Geological Survey	The USGS provided scenes from Landsat satellites for the times selected via the usage of the Global Visualization Viewer (GloVis).	Scenes selected: 2003: February 29, L7 ETM+ 2004: April 13, L5 TM 2005: January 10, L5 TM 2006: February 14, L5TM 2007: February 1, L5 TM 2008: March 23, L5 TM 2009: February 6, L5 TM 2015: February 7, L8 OLI & TIRS (glovis.usgs.gov)

Table 2-1. Continued

Organization	Ancillary Data Description	URL and Date of Access
Open Development Mekong	This website provided shapefiles for the state of hydropower development throughout the MRB.	(http://opendevelopmentmekong.net/) April 11, 2016
The Land Processes Distributed Active Archive Center (LP DAAC)	LP DAAC is one of several discipline specific data centers that was created through the partnership of NASA and USGS. Specifically, the MOD13Q1 product was analyzed which provided 250 meter resolution 16-day EVI composites for the study area.	(https://lpdaac.usgs.gov/) January 25, 2016
NASA Jet Propulsion Laboratory at California Institute of Technology	This website provided the statistics used for the digital elevation model created from the Shuttle Radar Topography Mission.	https://www2.jpl.nasa.gov/srtm/statistics.html May 22, 2017

Table 2-2. Description of LC Classes.

LC	Description
Shrub (S)	includes flooded habitats that could potentially be used as fish foraging sites to the fish species associated with the TSL. This class includes flooded forests, flooded shrublands, and flooded grasslands.
Dry Season Rice	includes rice harvesting fields that are higher in elevation and generally are located farther away from water sources than wet season rice. These fields are harvested throughout the dry season (February-June) and are most sustainable in rain-fed habitats.
Wet Season Rice (W)	includes the lowland and irrigated areas of the floodplain that can support rice cultivation during the monsoon season. Wet season rice is typically found closer to areas in close proximity to the TSL as well as noticeable ponds throughout the imagery. These qualities permit wet season rice to ensure growth and allow harvesting.
Water (Water)	includes all areas of permanent innundation. This class represents the extent of the TSL as well as the permanently flooded tributaries associated with the lake.
Cloud (C)	includes any cloud cover that was present in the selected image date.

Table 2-3. Accuracy Assessment for LC Classification in 2015.

	Ground Reference Test					
Class	Water	Shrub	Wet Rice	Dry Rice	Total	Users Accuracy
Water	51	6	4	2	63	81.0%
Shrub	6	53	11	0	70	75.7%
Wet Rice	3	7	62	2	74	83.8%
Dry Rice	0	3	4	38	45	84.4%
Total	60	69	81	42	252	Overall Accuracy
Producers Accuracy	85.0%	76.8%	76.5%	90.5%		81.0%

Table 2-4. List of the community type for the training samples collected in the study area.

Sample #	Primary Fishing Community	Primary Agriculture Community	Both Fishing and Agriculture Community	No Data
1		X		
2			X	
3			X	
4			X	
5	X			
6			X	
7			X	
8			X	
9	X			
10	X			
11	X			
12	X			
13			X	
14	X			
15	X			
16	X			
17	X			
18	X			
19	X			
20			X	
21		X		
22			X	
23		X		
24			X	
25	X			
26			X	
27			X	
28		X		
29			X	
30			X	
31				X
32		X		
33		X		
34				X
35			X	
36			X	
37				X
38			X	

Table 2-5. Percent Cover Analysis of the Increasing Flooding Regime from 2003-2005. F means flooded, NF means not flooded.

Flooding Trajectory 2003, 2004, 2005	% Area
NF-NF-NF	37.9
NF-NF-F	12.2
NF-F-F	19.9
F-F-F	30.0

Table 2-6. Percent Cover Analysis of the Decreasing Flooding Regime from 2006-2009. F means flooded, NF means not flooded.

Flooding Trajectory, 2006, 2007, 2008, 2009	% Area
NF-NF-NF-NF	50.2
F-NF-NF-NF	11.0
F-NF-NF-F	8.9
F-F-F-F	29.9

Table 2-7. Percent Change that each LC experienced between the time periods. (-) indicates a decrease in area and (+) indicated an increase in area.

LC	2003-2004	2004-2005	2003-2005
DR	-35.6%	+35.3%	-12.9%
WR	+53.5%	-59.8%	-38.4%
S	+7.1%	+13.2%	+21.2%

Table 2-8. LC Distribution Change from 2006-2009.

LC	2006-2007	2007-2008	2008-2009	2006-2009
DR	+8.7%	-8.6%	+36.3%	+35.6%
WR	+42.3%	+8.0%	+12.2%	+35.0%
S	+0.8%	-11.8%	+16.5%	+3.5%

Table 2-9. Land-cover trajectories and percent change from 2003-2005.

Land cover change	2003-2005 % Cover
Permanently shrubland	36.1
Dry rice - shrubland	2.8
Wet rice - shrubland	5.1
Permanently dry rice	15.9
Shrubland - dry rice	0.9
Wet rice - dry rice	2.9
Permanently wet rice	6.5
Dry rice - wet rice	2
Shrubland - wet rice	0.8
Water	18.1
Other trajectory	9
TOTAL	100

Table 2-10. LC trajectories and percent change during the three periods and the entire study time.

Land cover change	2006-2009 % Cover
Permanently shrubland	35.3
Dry rice - shrubland	0.7
Wet rice - shrubland	5.7
Permanently dry rice	14
Shrubland - dry rice	1.9
Wet rice - dry rice	1.7
Permanently wet rice	4.9
Dry rice - wet rice	4.7
Shrubland - wet rice	2.7
Water	15.7
Other trajectory	12.5
TOTAL	100

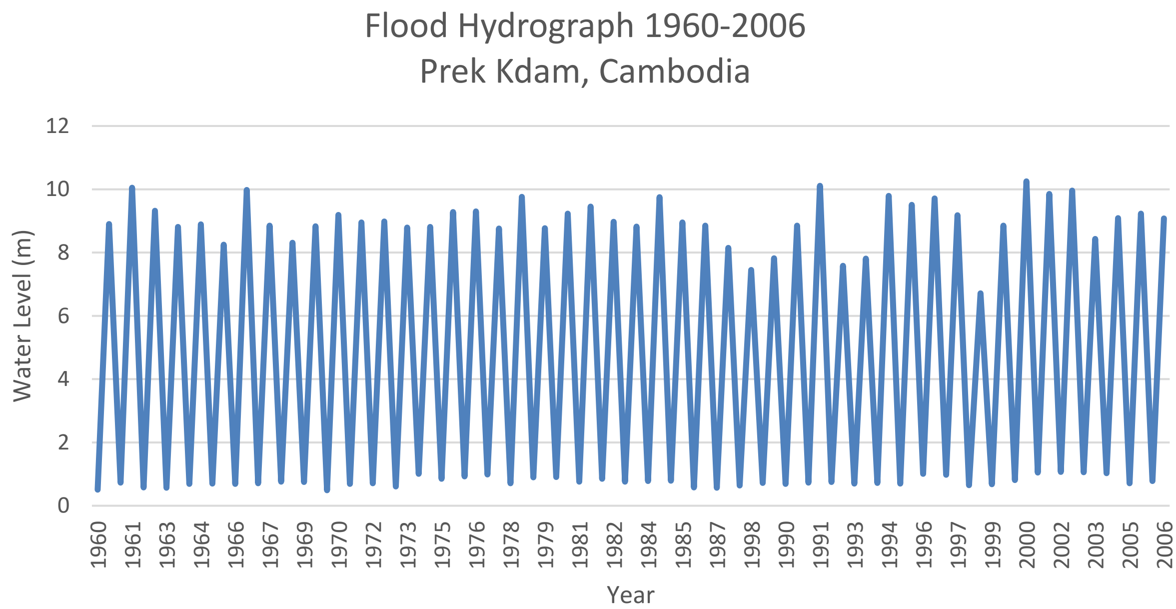

Figure 2-1. Mekong River Commission Hydrograph for Prek Kdam, Cambodia from 1960-2006 (Source: Mekong River Commission Data Portal, www.mrcmekong.org). The zero gauge elevation of Prek Kdam is 0.08m above mean sea level (MSL).

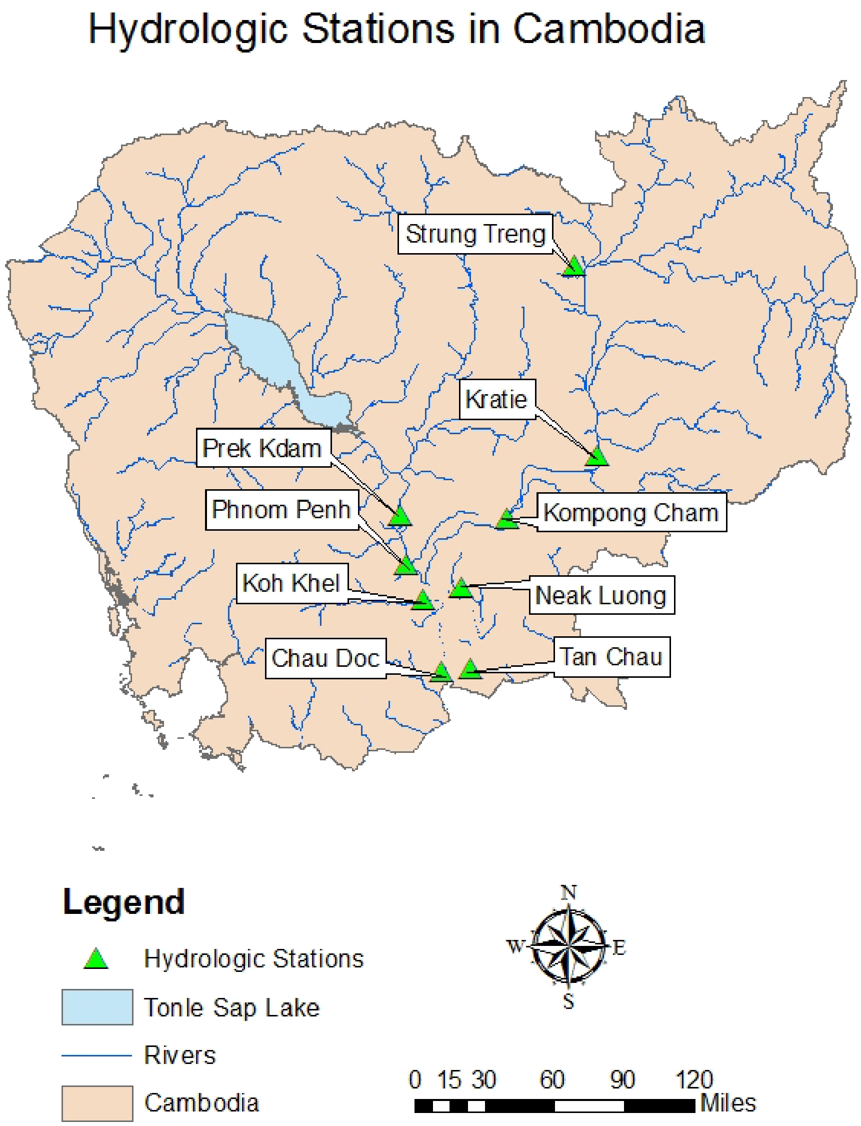

Figure 2-2. Hydrologic Stations in Cambodia. (Data from MRCMekong.org).

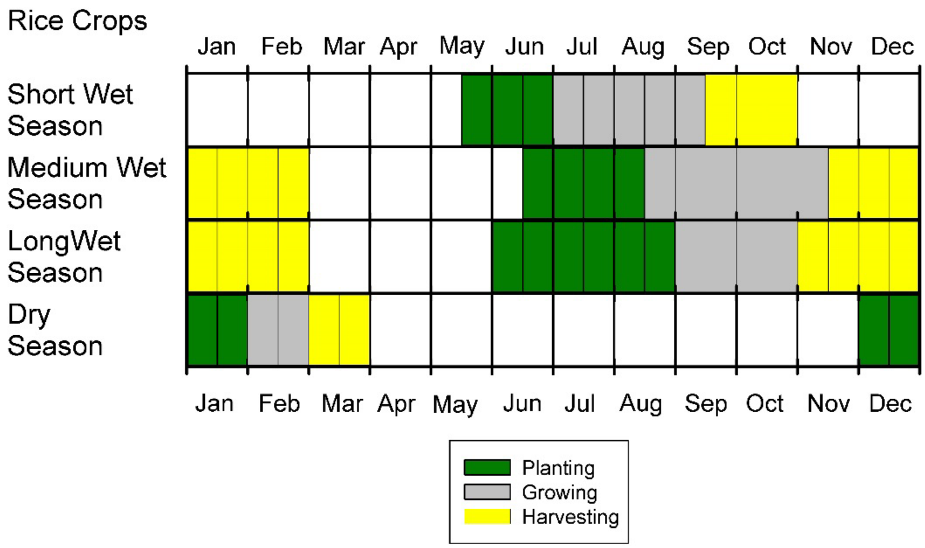

Figure 2-3. Annual Crop Calendar developed from the Ministry of Agriculture, Forestry, and Fisheries (NAFF), Cambodia 2012 (cited in Shean 2013 as Figure 2).

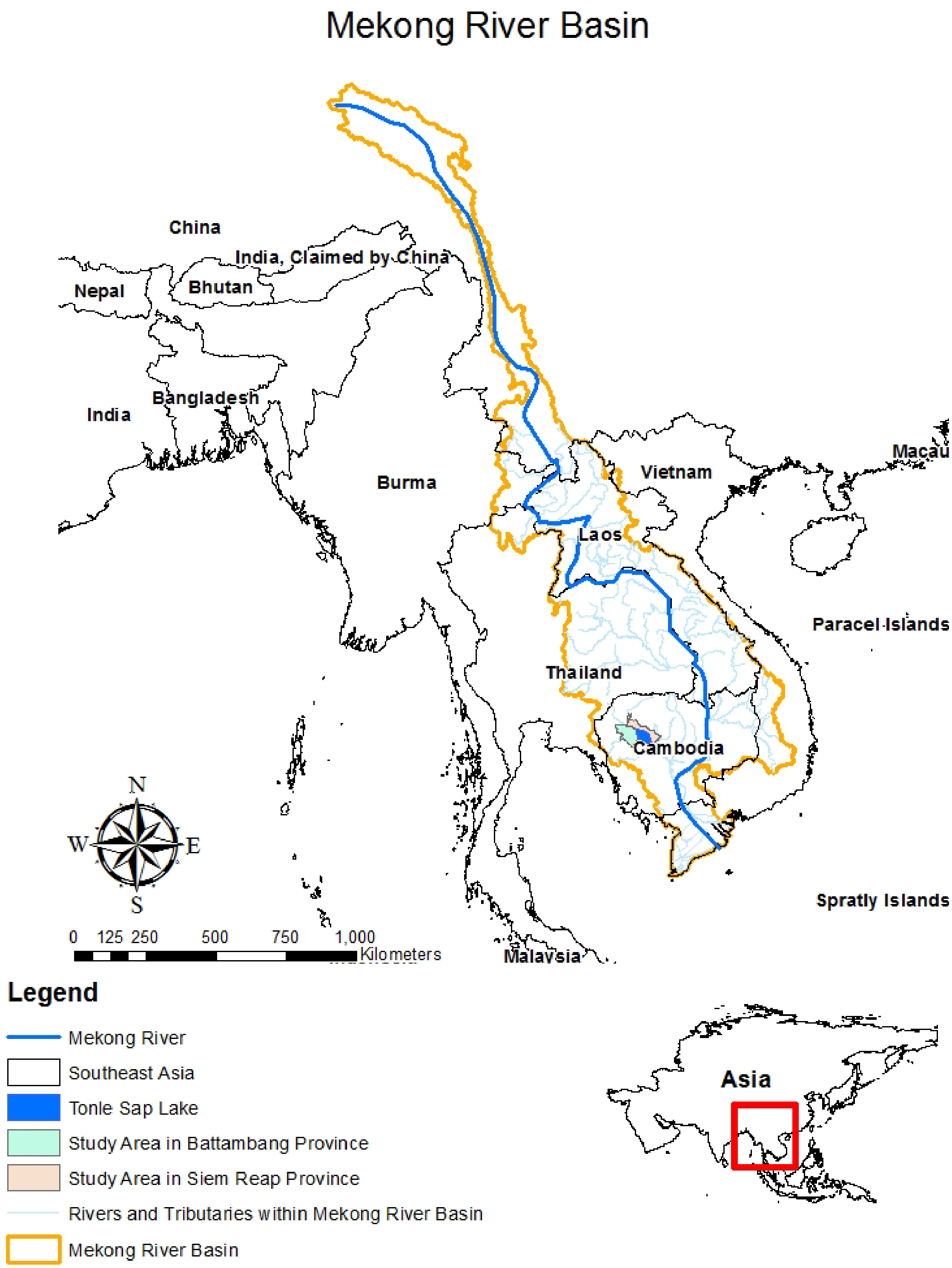

Figure 2-4. Flow of Mekong River from Tibetan Plateau in China throughout the Mekong River Basin to its discharge point in Vietnam at the Mekong River Delta.

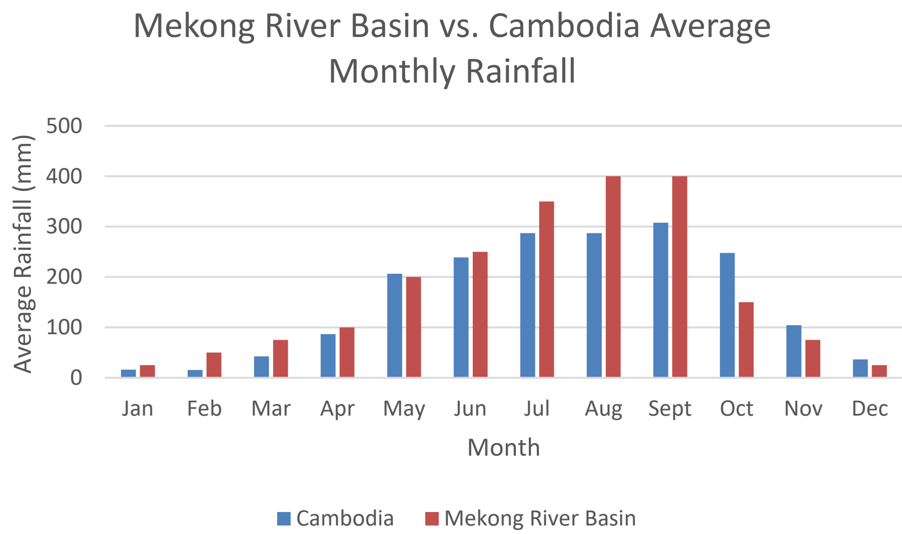

Figure 2-5. Average Monthly Rainfall for the Kingdom of Cambodia (data provided from the University of East Anglia, Climate Research Unit, www.cru.uea.ac.uk/data).

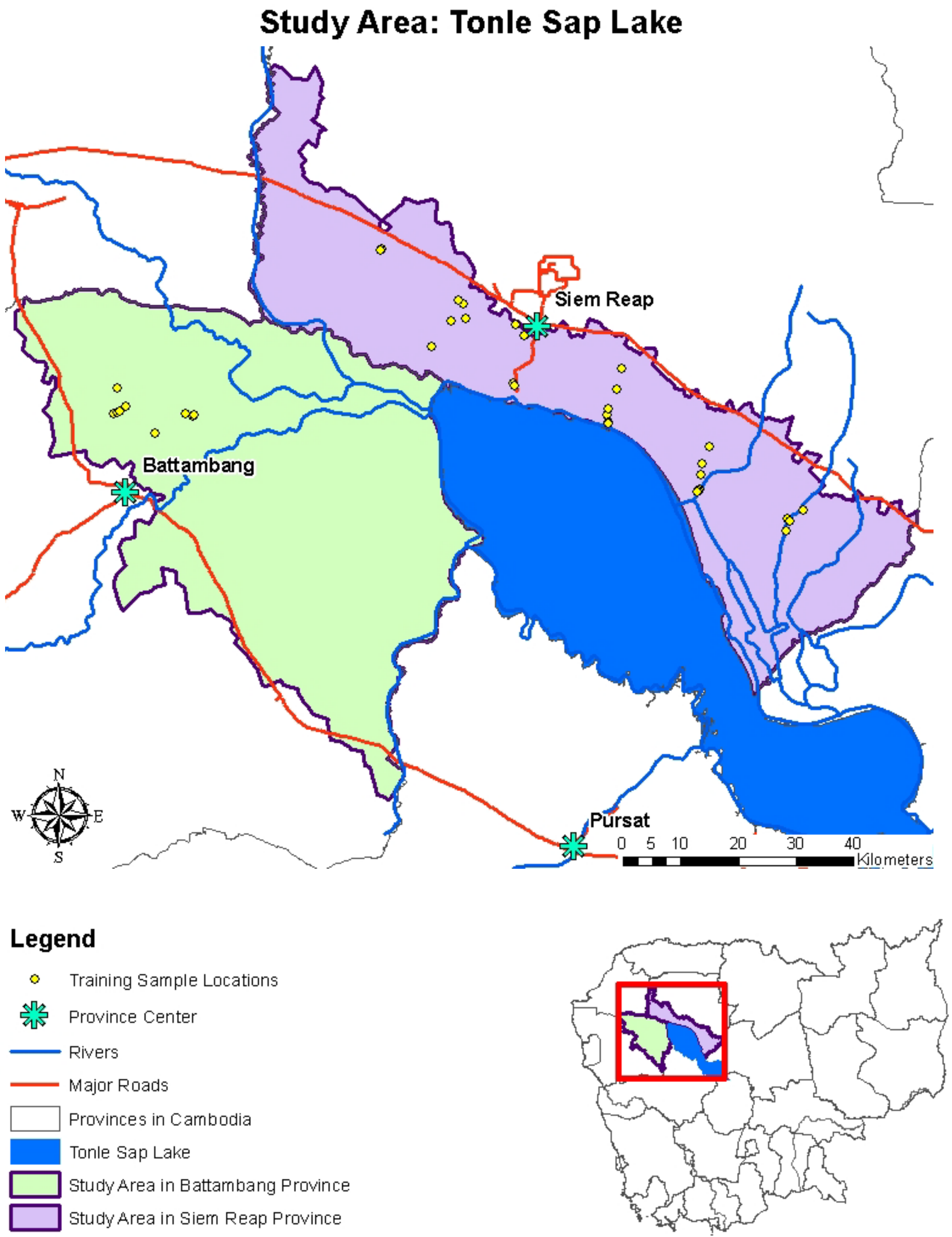

Figure 2-6. Study Area with TSL floodplain areas in Siem Reap and Battambang Provinces including Training Sample Locations. The boundary of the study area was defined by the 15-m a.s.l. elevation contour.

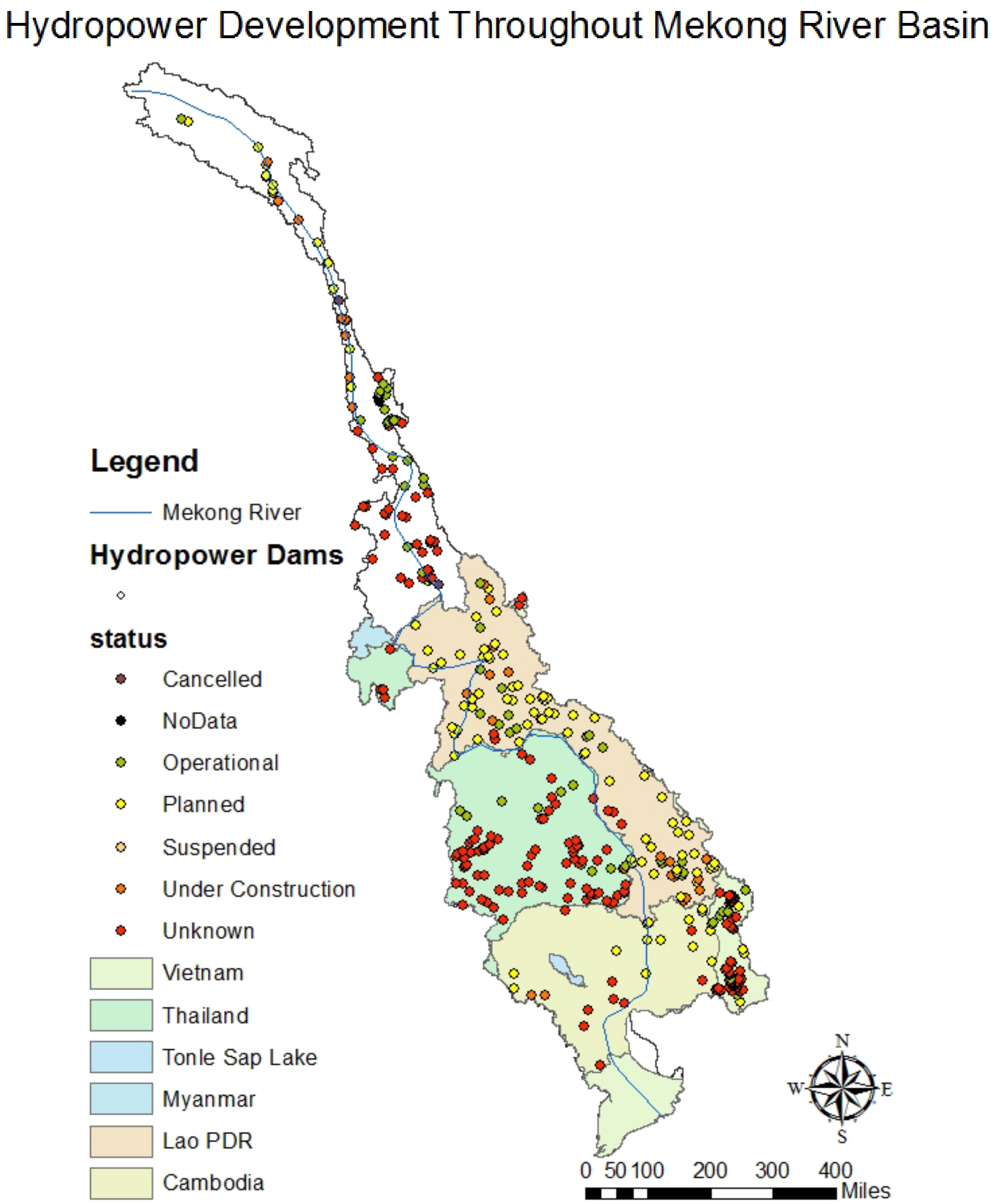

Figure 2-7. Status of hydropower dams throughout the Mekong River Basin in 2014 (www.opendevelopmentmekong.net).

Figure 2-8. Morgan L. Ridler. Community fish ponds outside of Siem Reap Province. May 30, 2015.

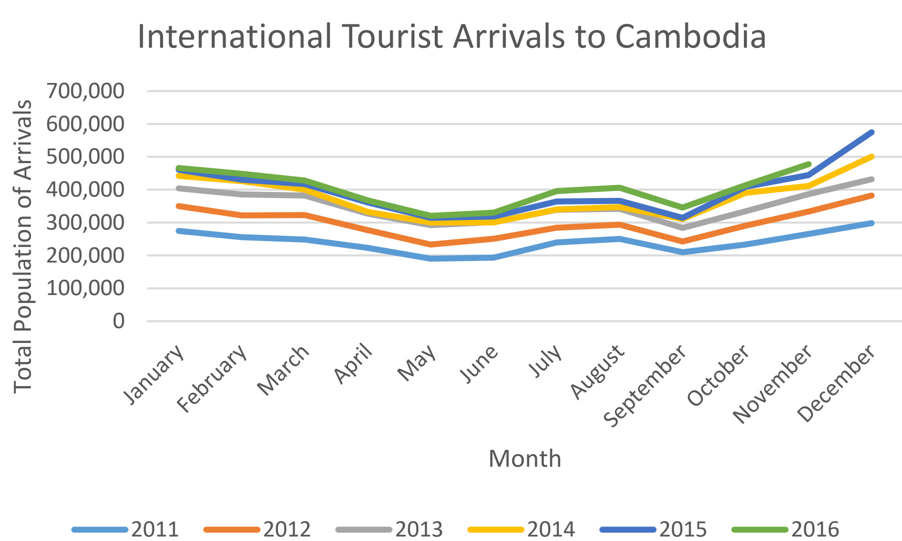

Figure 2-9. International tourist arrivals to Cambodia. Data provided from the Statistics and Tourism Information Department from the Ministry of Tourism, Kingdom of Cambodia ("Tourism Statistics Report 2016").

Figure 2-10. Morgan L. Ridler. Fish Catch outside of Siem Reap near Tonle Sap Lake. May 31, 2015.

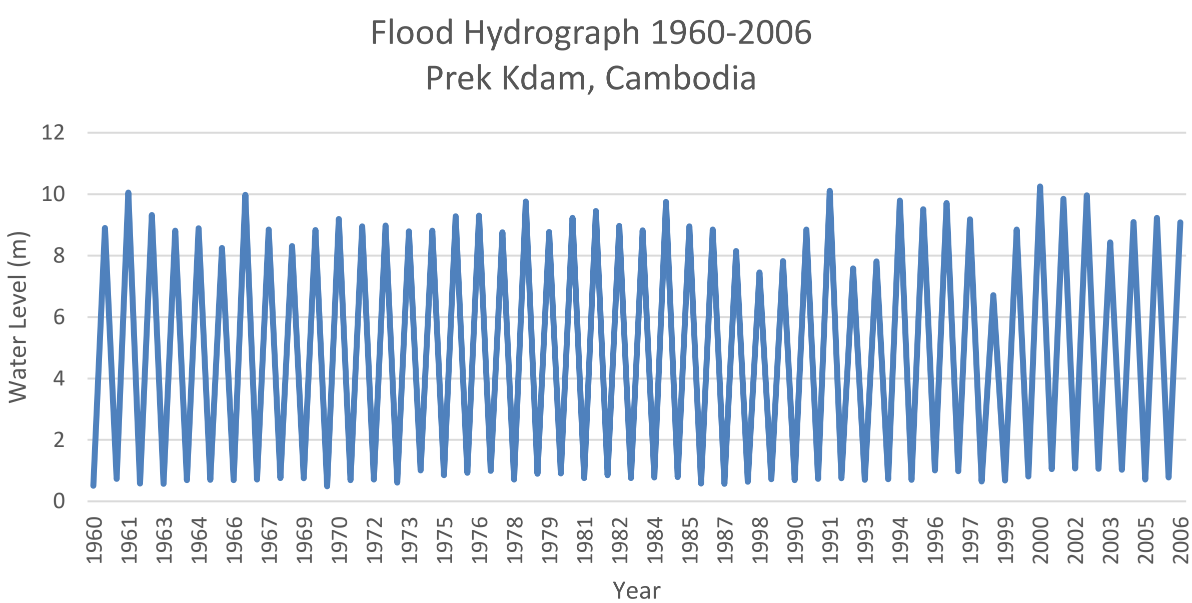

Figure 2-11. Flood Hydrograph from the Mekong River Commission for 1960-2006.

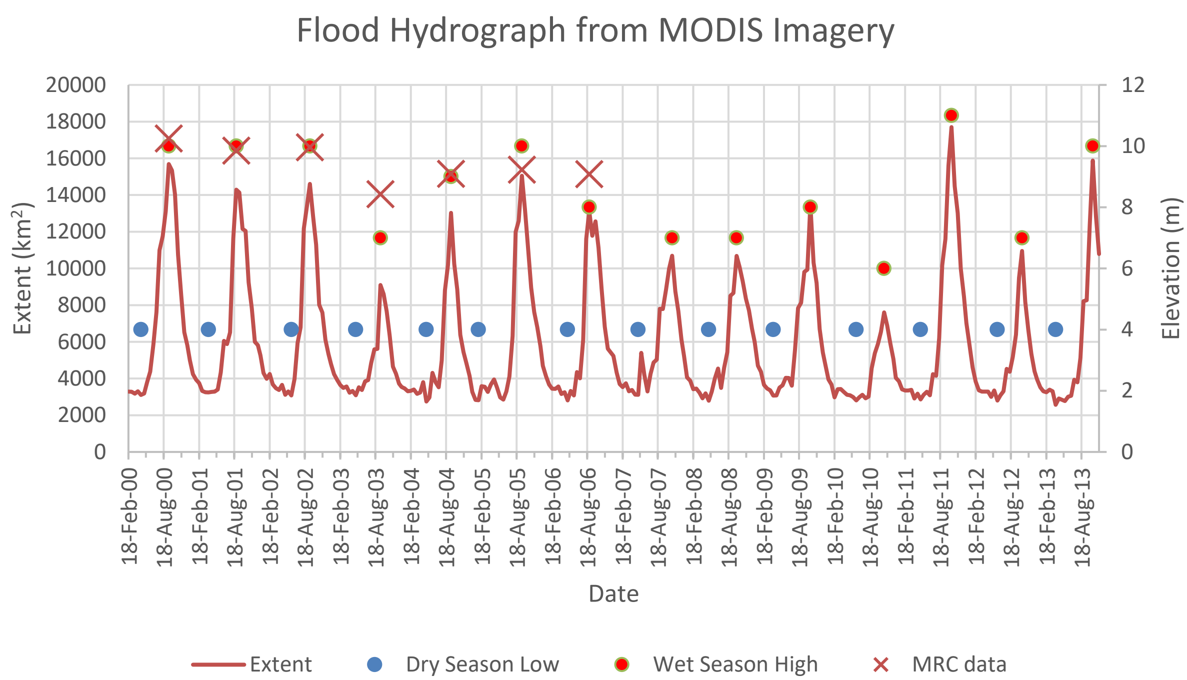

Figure 2-12. Flood Hydrograph with derived extent and flood height interpreted from MODIS Imagery for 2000-2013.

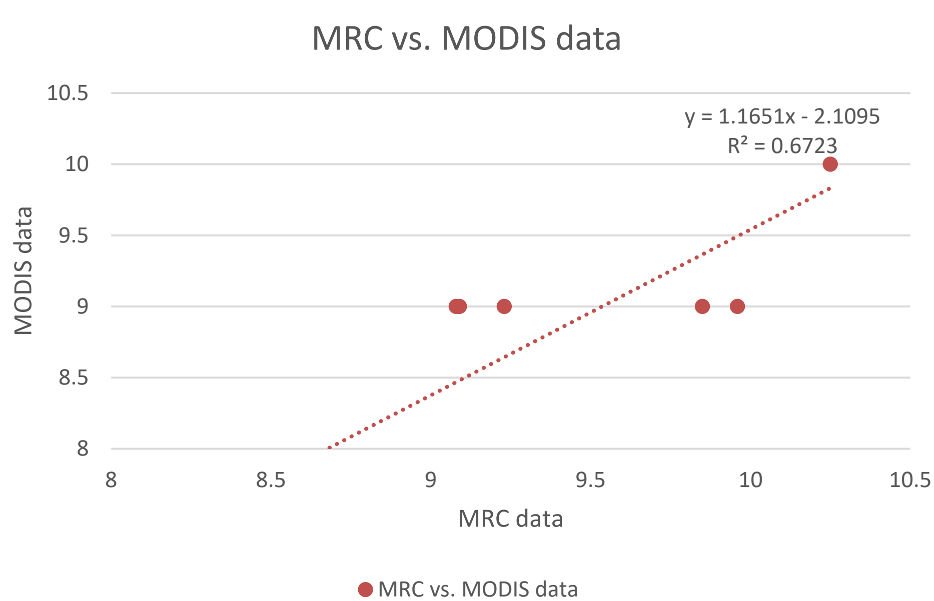

Figure 2-13. Comparison of MRC and MODIS data to determine similarities. The p-values for this regression were 0.044 and 0.024 (MRC and MODIS respectively) which indicate that the result is statistically significant.

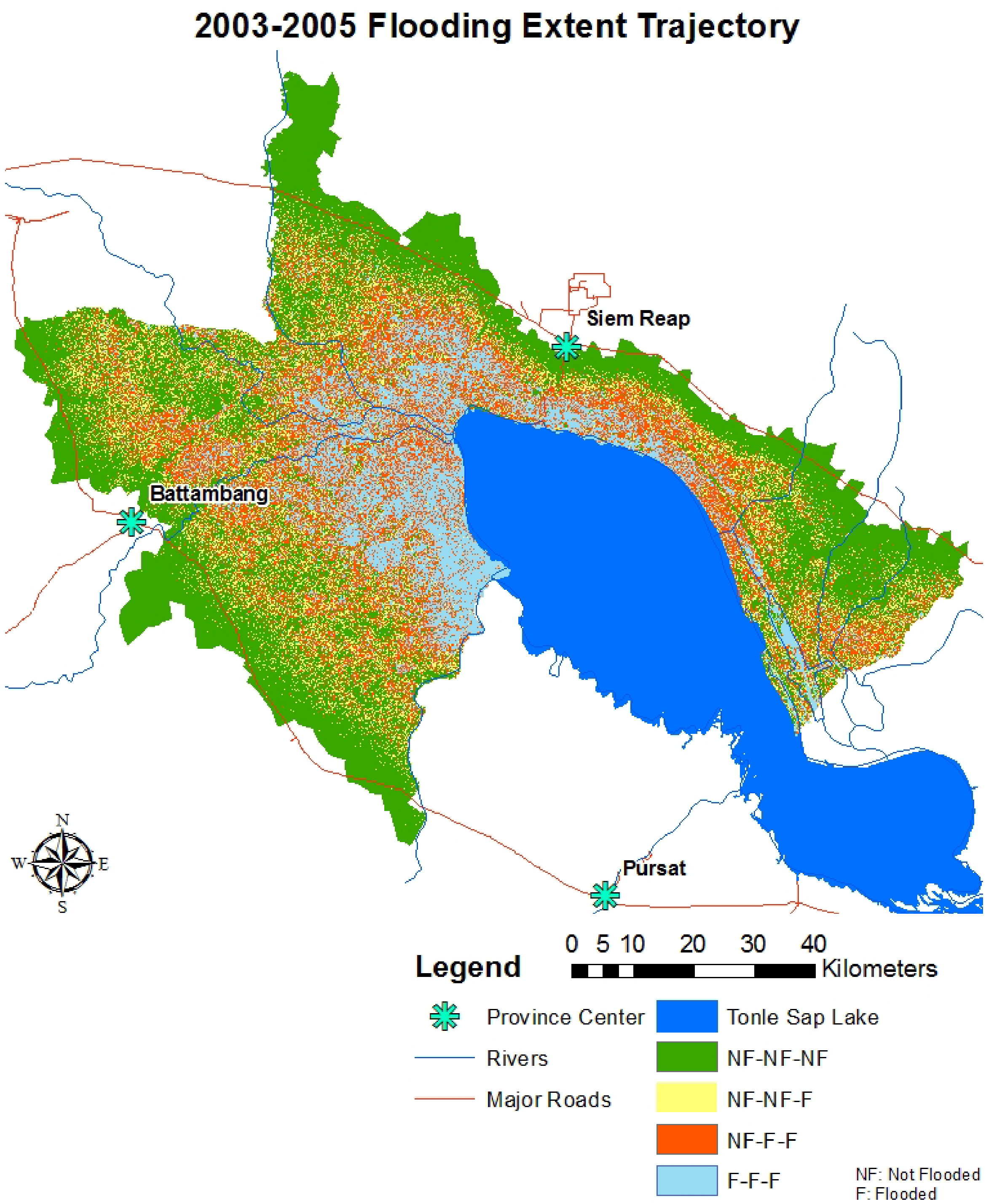

Figure 2-14. Increasing Flooding Regime Trajectory for 2003-2005. F means flooded, NF means not flooded.

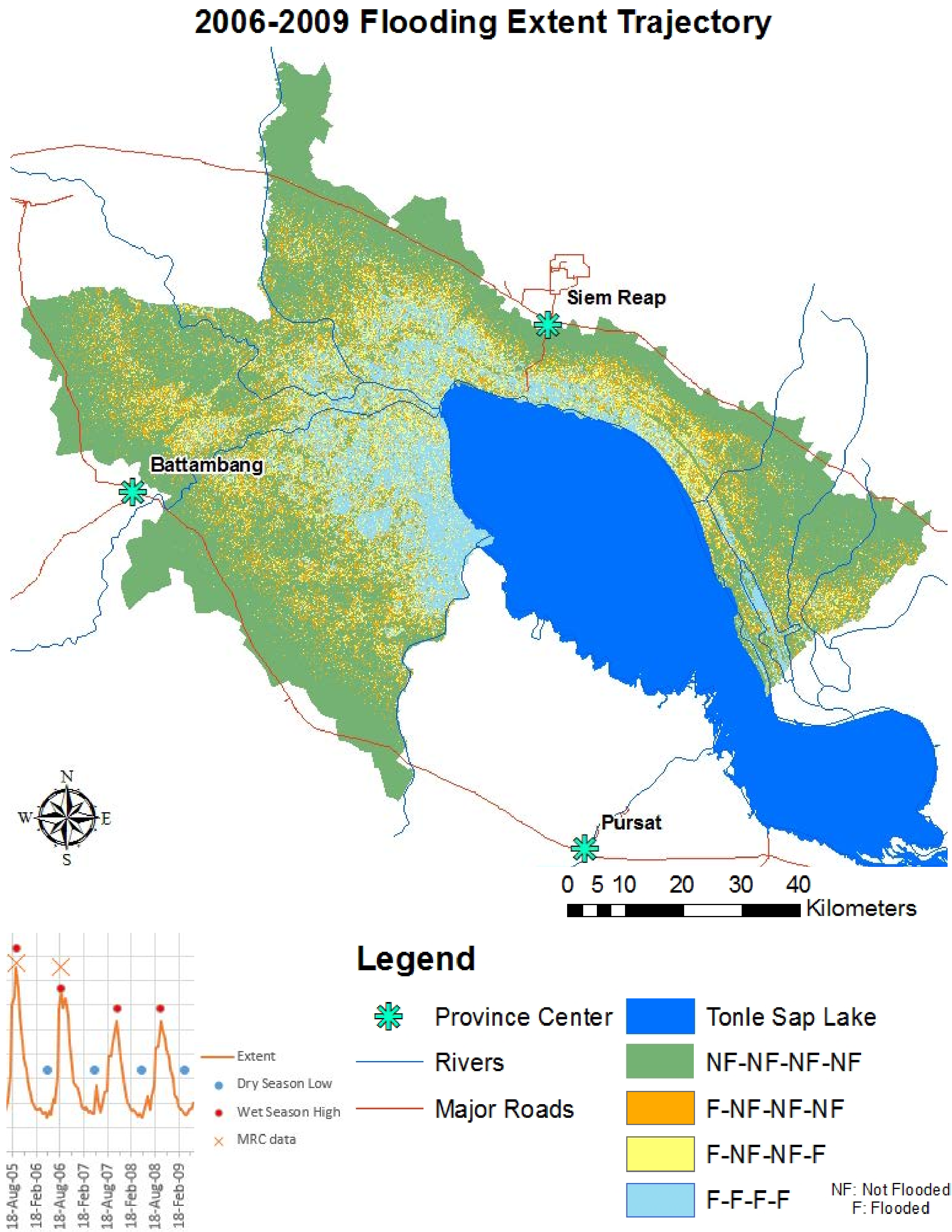

Figure 2-15. Decreasing Flooding Regime Trajectory from 2006-2009.

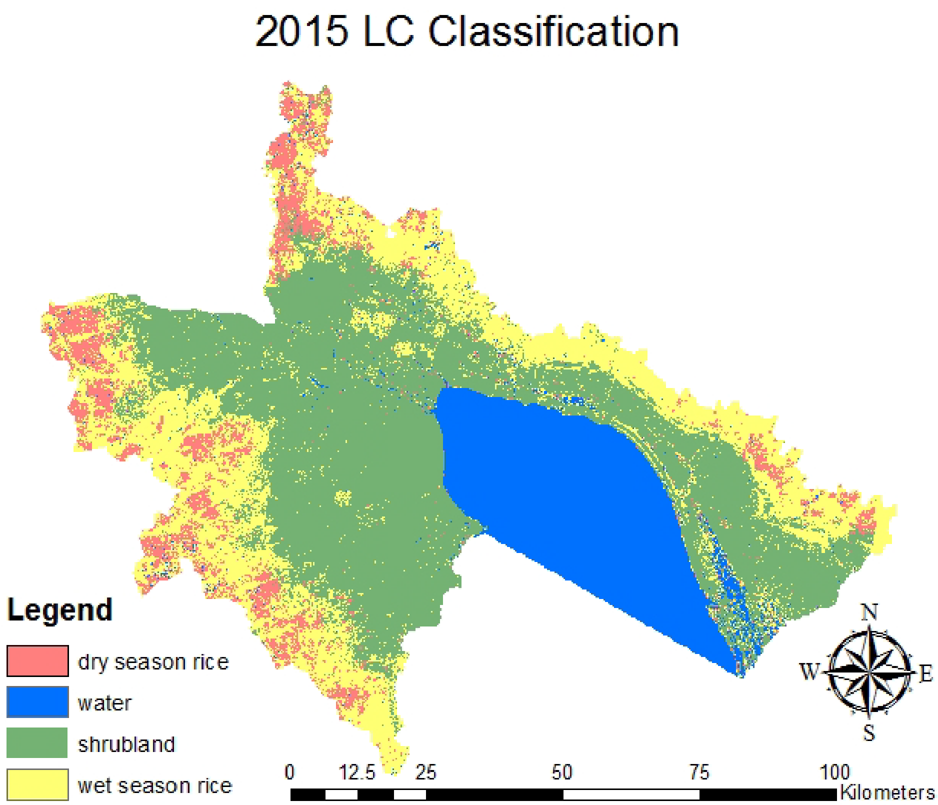

Figure 2-16. Land Cover Classification of 2015 Landsat image.

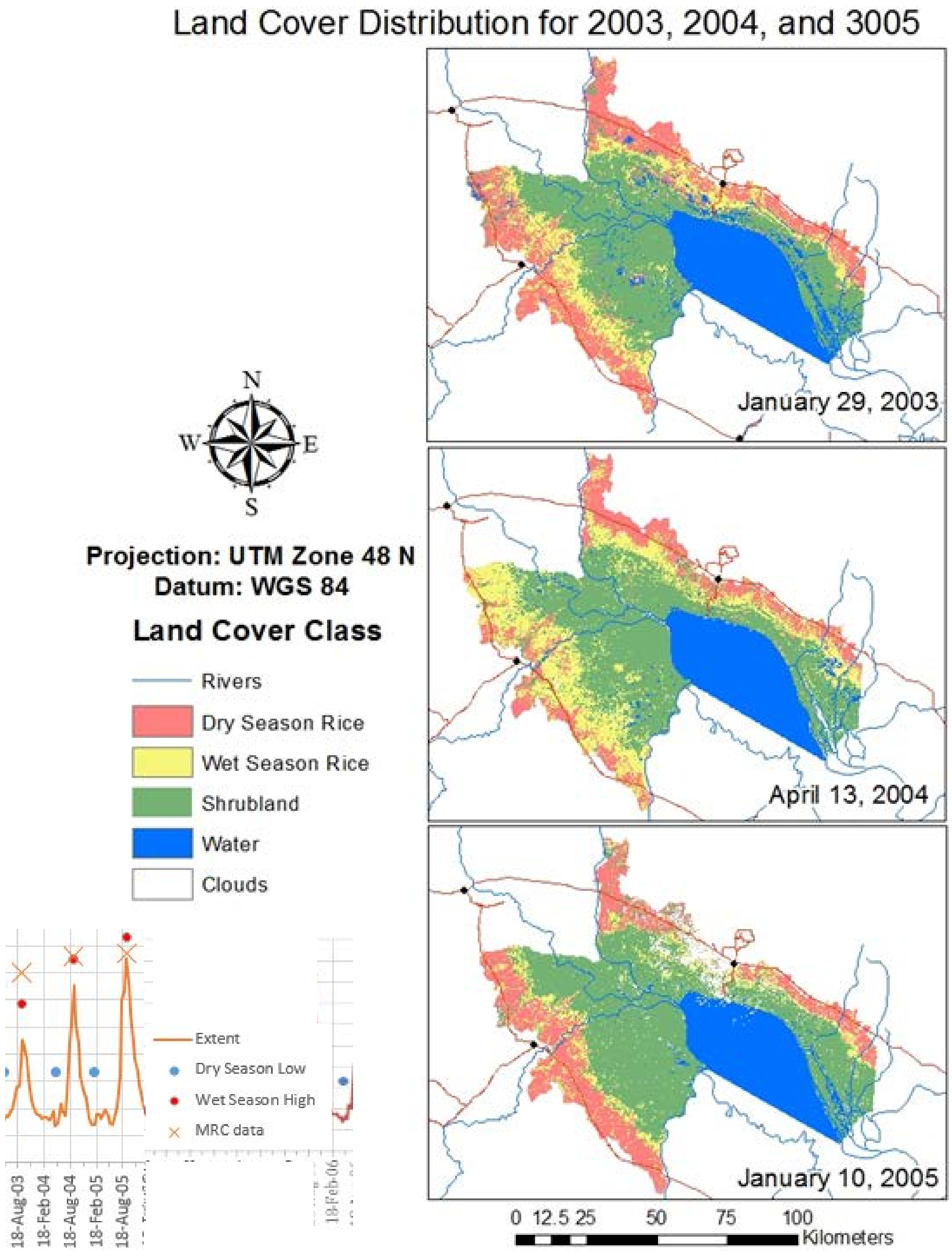

Figure 2-17. Land-Cover Classification for the study area within Siem Reap and Battambang Provinces for 2003, 2004, and 2005.

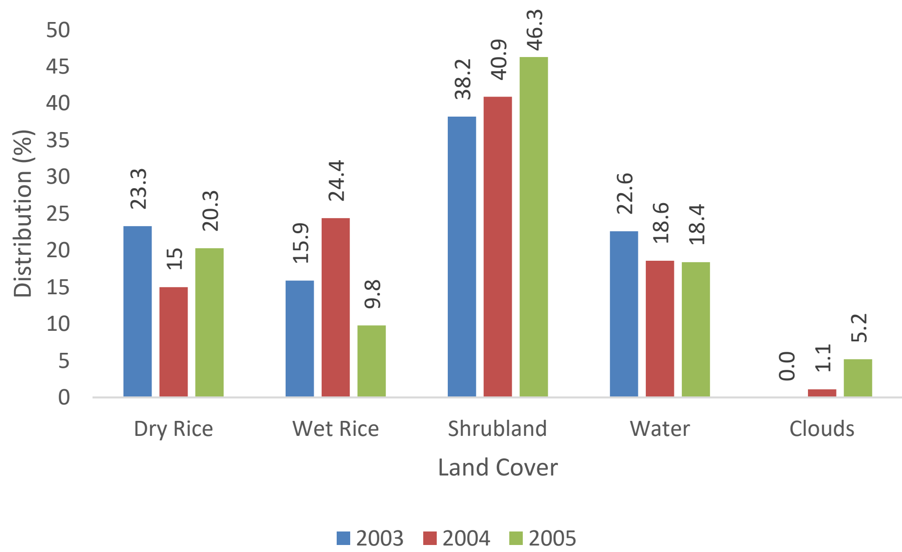

Figure 2-18. Land Cover Distribution in study area of Siem Reap and Battambang Provinces from 2003, 2004, and 2005.

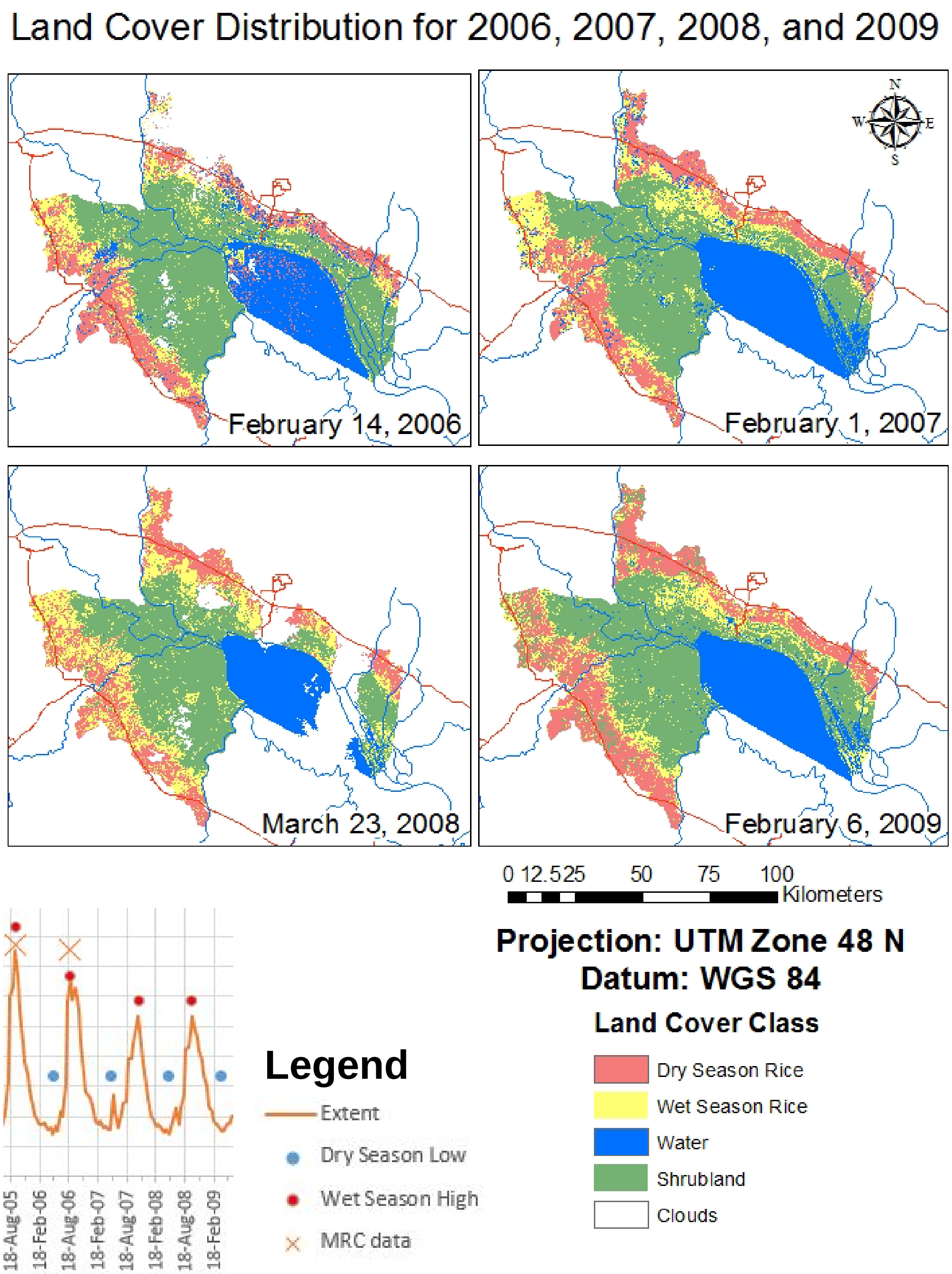

Figure 2-19. LC Distribution for 2006, 2007, 2008, and 2009.

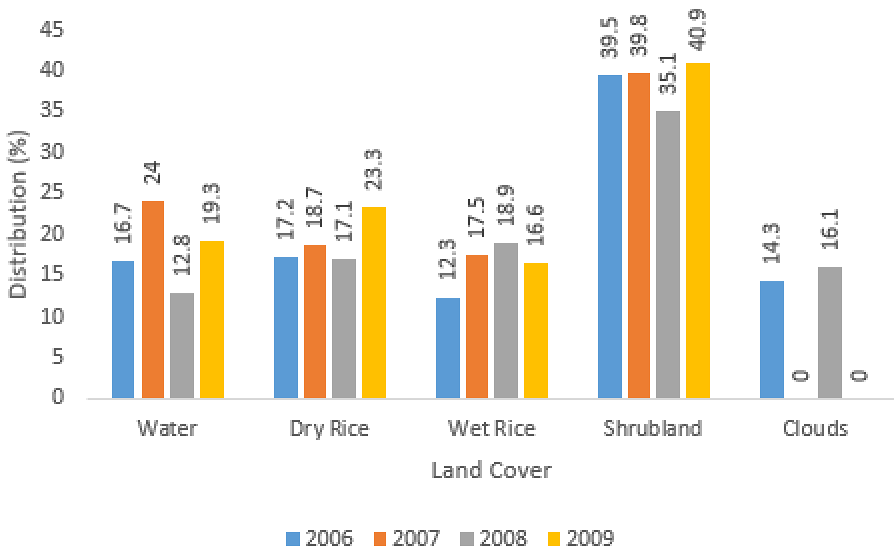

Figure 2-20. Percent LC Distribution from 2006-2009.

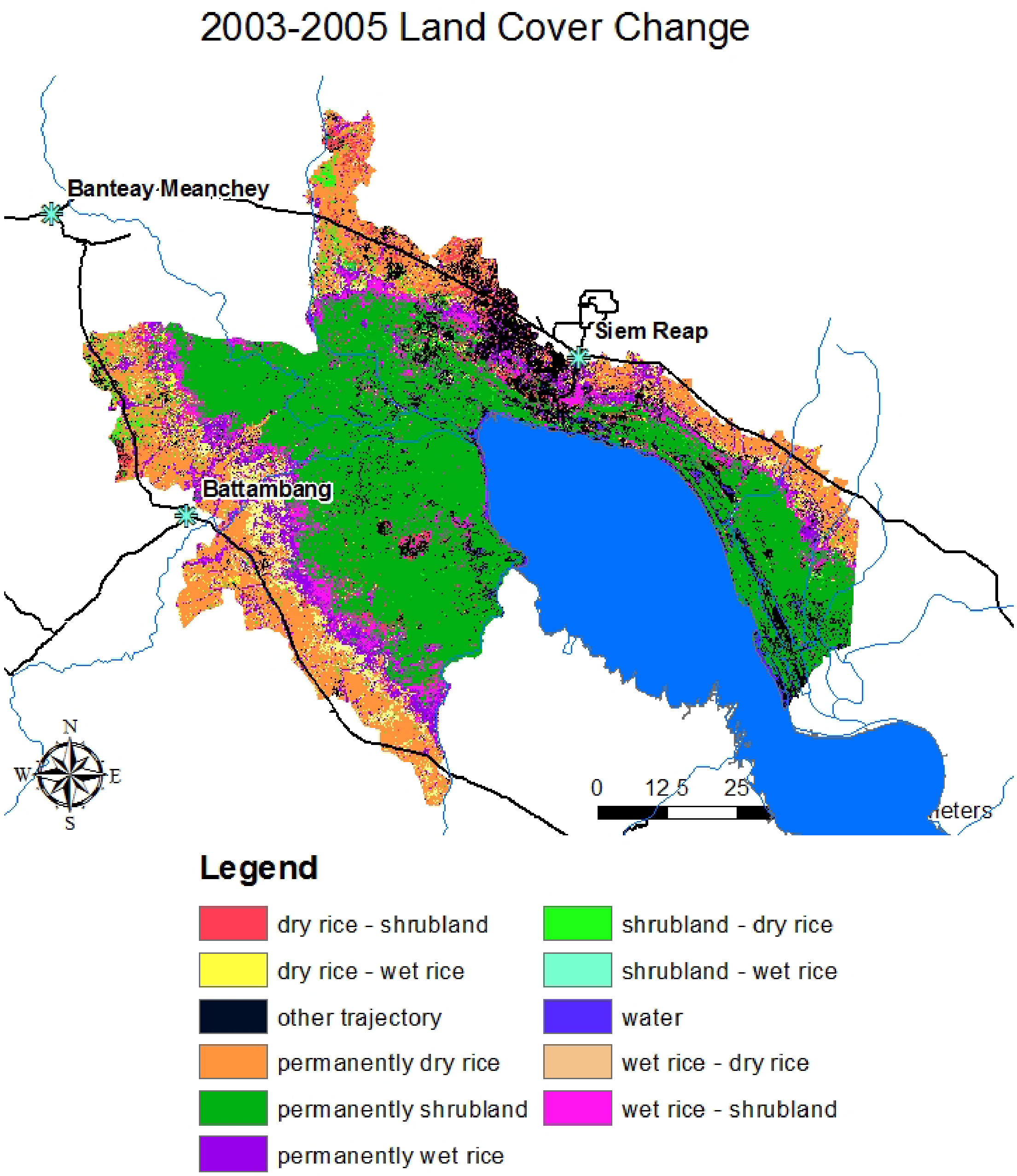

Figure 2-21. Three-date land-cover change trajectories for Siem Reap and Battambang Provinces.

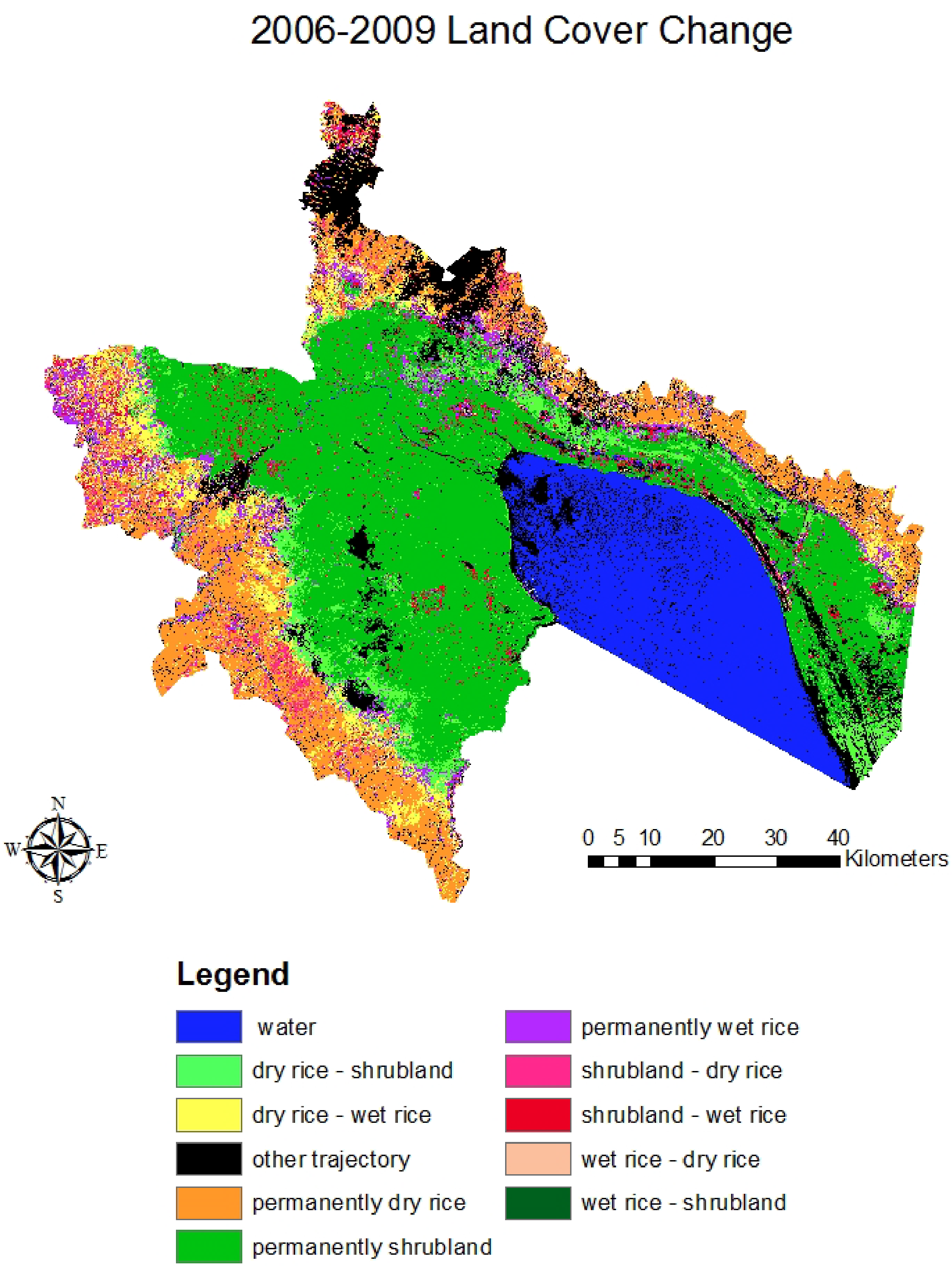

Figure 2-22. Four-date LC change trajectories for Siem Reap and Battambang Provinces from 2006-2009.

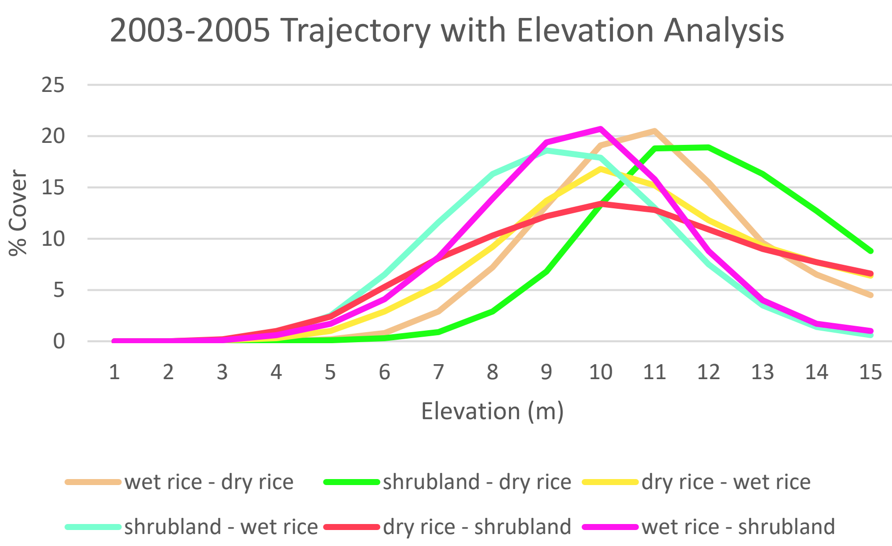

Figure 2-23. LC Trajectory Elevation Analysis for the period from 2003-2005.

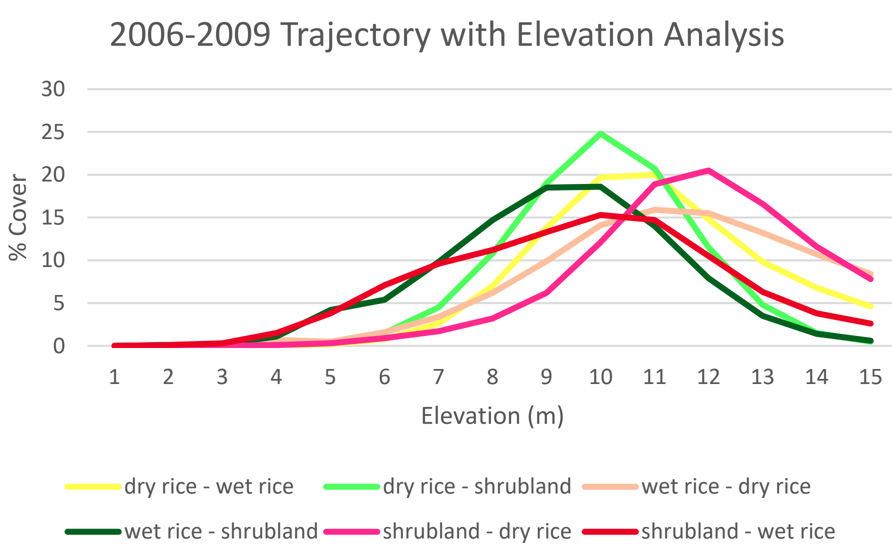

Figure 2-24. LC Trajectory Elevation Analysis for the period from 2006-2009.

CHAPTER 3
CONCLUSION

The results from this study describe the LC changes that occurred within the floodplain of the Tonle Sap Lake (TSL) during periods of increasing and decreasing peak floods. Most of the LC change occurred between 9m and 12 m asl in the floodplain. The flooding regime is related to the LC transitions that occurred around the land covers associated with this lake system. Hypothesis 1 was rejected due to the overall increase in the shrubland LC. Wet season rice also increased during the decreasing flood peaks, which also supported the first hypothesis. The period decreasing flood peaks was selected due to its ability to represent the interactions that are occurring due to hydropower development in the floodplain. Since there was an increase in the shrubland LC during a decreasing flooding regime, fisheries production will be maintained since the available area for foraging increased. Wet season and dry season rice fields also increased during a decreasing flooding regime.

My study showed that riparian communities respond quickly to changing flooding regimes by adapting their rice farming practices to take advantage of the seasonal floods despite their magnitude. This human-environment interaction was confirmed by the fluctuations of rice field LC both in periods of increasing and decreasing flooding regimes. My results disagree with previously accepted research in the floodplain of the TSL. Therefore, I recommend that additional research be conducted to confirm whether the riparian communities are responding on a year-by-year basis to the peak flooding events. By understanding the short-term responses of the riparian communities to the altered flooding regime caused by hydropower development, a more definitive conclusion can be made on whether the communities will adapt to the decreased flooding regime that is expected with development throughout the Mekong River Basin.

APPENDIX A
COMMENTS FROM FIELD INFORMANTS

Table A-1. Comments from field informants.

Elevation (m a.s.l)	Comments
10	During the dry season the land is barren but is possible to irrigate during the wet season.
9	Family member discussed their wet season rice productivity for their rice fields and also their ownership of a boat for fishing during the rainy season. The member mentioned experiencing lower high floods for the last 2 years with water only reaching her waist instead of it being above her head during the wet season.
9	No Data
9	This area maintains fish throughout the year with the usage of community fishing ponds. Icreased irrigation is noted to force water away from the crops during the rainy season to prevent crop devastation. This location is flooded 2-3 times per year. The community is also implementing more techniques to increase their fish catch, such as using nets instead of baskets.
11	It is noted that this area used to be rice fields but due to the demands of urbanization, the fields were filled to provide roadways and houses were built for increasing population.
11	This sample represents what the previous sample used to be like before urbanization. This sample includes wet season rice fields that are productive during the floods and abandoned the rest of the year. It is noted that soil from this site is taken every year to build roads but the sediments from the flood waters replenish what was taken annually; therefore providing an inexpensive alternative to building roads.
14	This location does experience seasonal effects from flooding but increased irrigation has caused the path of water to be away from these areas. It is noted that this location used to harvest village crops three times a year but the land owners are changing the land to only produce crops one time a year.
10	This location is 3-5 months flooded and flooding begins in September. This location also has a river located that is connected with the TSL. This area is only suitable for wet season rice crops and it is noted that 2000, 2010, and 2011 experienced higher floods than normal.

Table A-1. Continued.

Elevation (m a.s.l)	Comments
8	This location is flooded 5-6 months of the year.
7	This was noted as a primary fishing community. It is noted that the fish catch has been smaller and less productive over the last ten years. This location experiences flooding 5-6 months of the year.
7	This location is noted to have increased tourism during the wet season. Location is 5-6 months flooded during the year.
8	No Data
9	This location sustains wet season rice for 6 months out of the year and is barren during the dry season and can not produce village crops.
8	This village is a strictly fishing village and is flooded 5-6 months of the year.
8	Location is flooded 5 months during the wet season.
8	This is a fishing village. During the wet season the villagers are only allowed to fish in certain areas and there are "check points" throughout the lake where companies implement a fine for fishing past the desginated areas. Villagers are forced to pay these fines in order to sustain their livelihoods. Additionally, some months villagers are not allowed to fish and they pay fines to fish during the off-season.
8	This location is flooded 5 months during the rainy season.
8	This location is flooded 6 months out of the year.
9	This location is experiencing deforestation due to the conversion of forested areas to irrigated rice fields. This area is 4-5 months flooded during the year.
9	It is noted that deforestation occurred 2-3 years ago and the land was converted to rice fields. This location is flooded 5 months during the year. Also, villagers created fish ponds in order to maintain fish populations during the dry season.
9	This location is flooded 4-5 months out of the year. This area is cultivated two times per year during the wet season and once during the dry season.
8	This location is 3-4 months flooded out of the year. Rice is only culitvated once near the end of the wet season when the water receeds.

Table A-1. Continued.

Elevation (m a.s.l)	Comments
8	This location is 3-4 months flooded and rice crops are cultivated one time per year when the floods receed.
8	This location is flooded 4-5 months of the year.
10	No Data
9	This location is flooded 1-2 months and the rice fields are cultivated two times per year during the rainy season. It is also noted that fisherman use electric shock to kill fish to sell in the markets.
9	This location is 3 months flooded and sustains village crops but no rice fields. This is a fishing and farming community.
9	It was noted that this location has village crops such as watermelon, beans, and corn.
10	This location showed areas of cable of fishing as well as rice cultivation.
11	Villagers from this community travel to Phnom Penh 3-4 times per year to protest the construction of small dams that block water flow to their crops. These habitats are flooded 4-5 months of the year and private companies built dams in order to maintain water on their land rather than others. Rice cultivation and fish harvesting occurs here, but the private companies control where water flows throughout the year.
11	No Data
11	This location is flooded 3 months of the year from August through October.
11	This location floods 3-4 months of the year. This area have the same issue with water availability since the dams are only opened during specific times of the year and usually they are only opened when the villagers complain to open them.
11	No Data
11	This location is flooded two months out of the year. Village crops and rice crops are present.
13	This location is only flooded for 1.5 months of the year.
13	No Data

Table A-1. Continued.

Elevation (m a.s.l)	Comments
8	It is noted that this location is seasonal and experiences wet season flooding but the period of inundation was not recorded.
8	This location is flooded 2-3 months out of the year.

APPENDIX B
SPECTRAL SIGNATURES

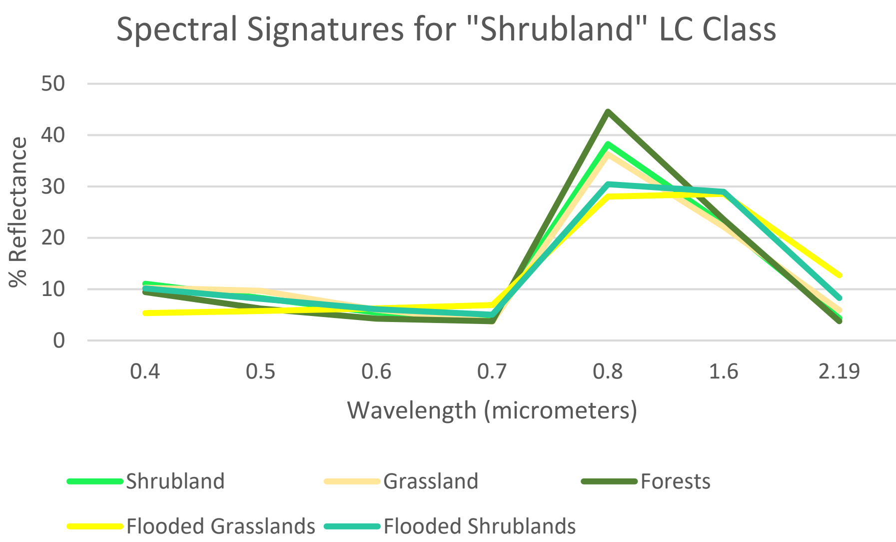

Figure B-1. Spectral Signatures for the shrubland land-cover class. This class consists of a combination of training samples that included shrubland, grassland, forests, flooded grasslands, and flooded shrublands.

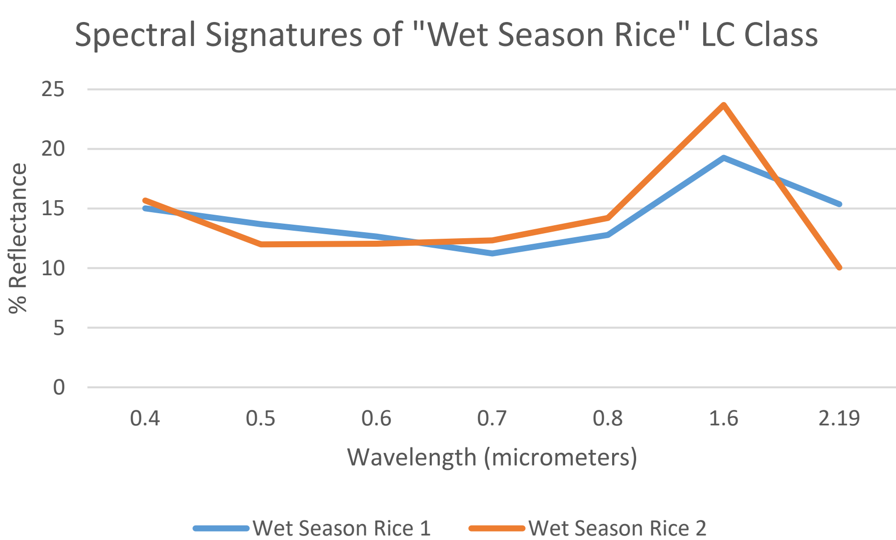

Figure B-2. Spectral Signatures for the Wet Season Rice land-cover class. This class consists of a combination of training samples that included two separate samples of areas classified as wet season rice.

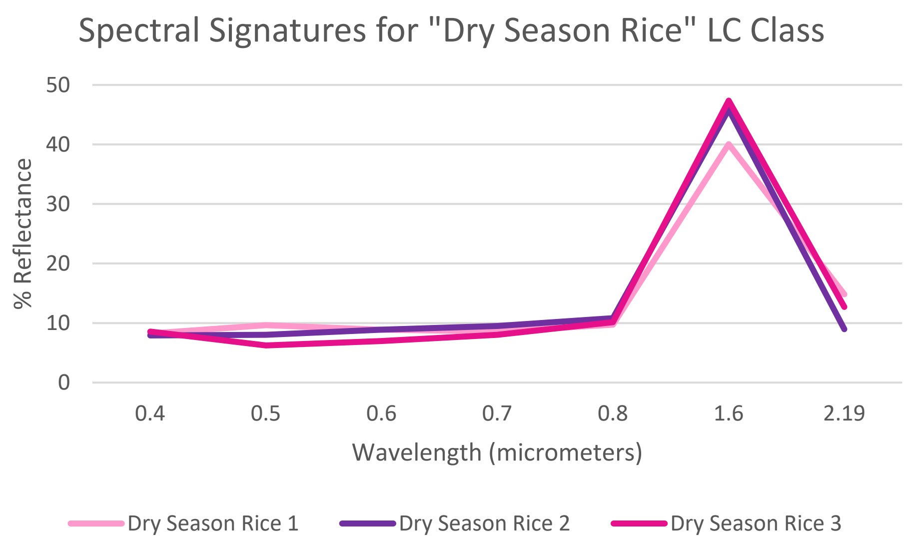

Figure B-3. Spectral Signatures for the Dry Season Rice land-cover class. This class consists of a combination of training samples that included three separate samples of areas classified as dry season rice.

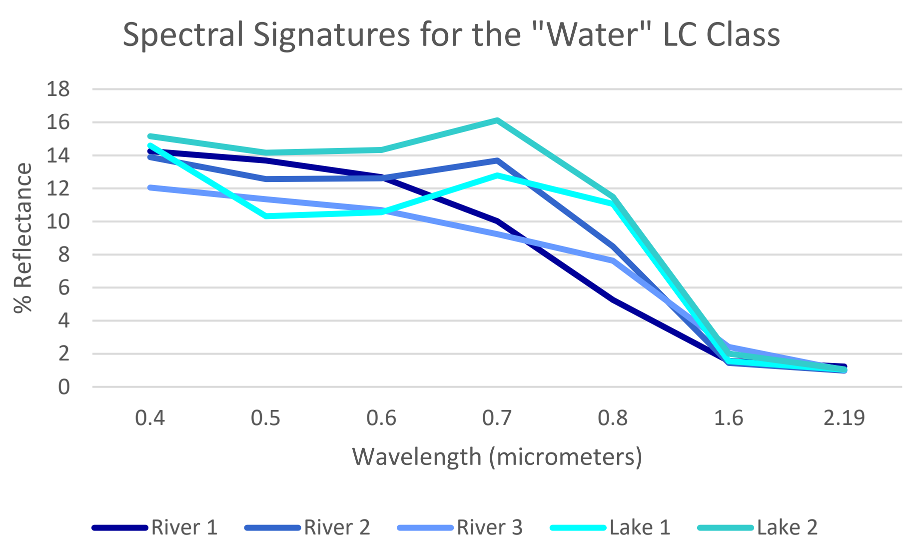

Figure B-4. Spectral Signatures for the Water land-cover class. This class consists of a combination of training samples that included the following: river 1, river 2, river 3, lake 1, and lake 2.

APPENDIX C
SUPPLEMENTAL INFORMATION FOR FLOODING TRAJECTORIES

Table C-1. Percent Cover of Flooded and Not-Flooded Area for the Period of Increasing Flooding Regime.

Year	% Area Flooded	% Area Not Flooded
2003	29.9	70.1
2004	49.8	50.2
2005	62.1	37.9

Table C-2. Percent Cover of Flooded and Not-Flooded Area for the Period of Decreasing Flooding Regime.

Year	% Area Flooded	% Area Not Flooded
2006	49.8	50.2
2007	29.9	70.1
2008	29.9	70.1
2009	38.8	61.2

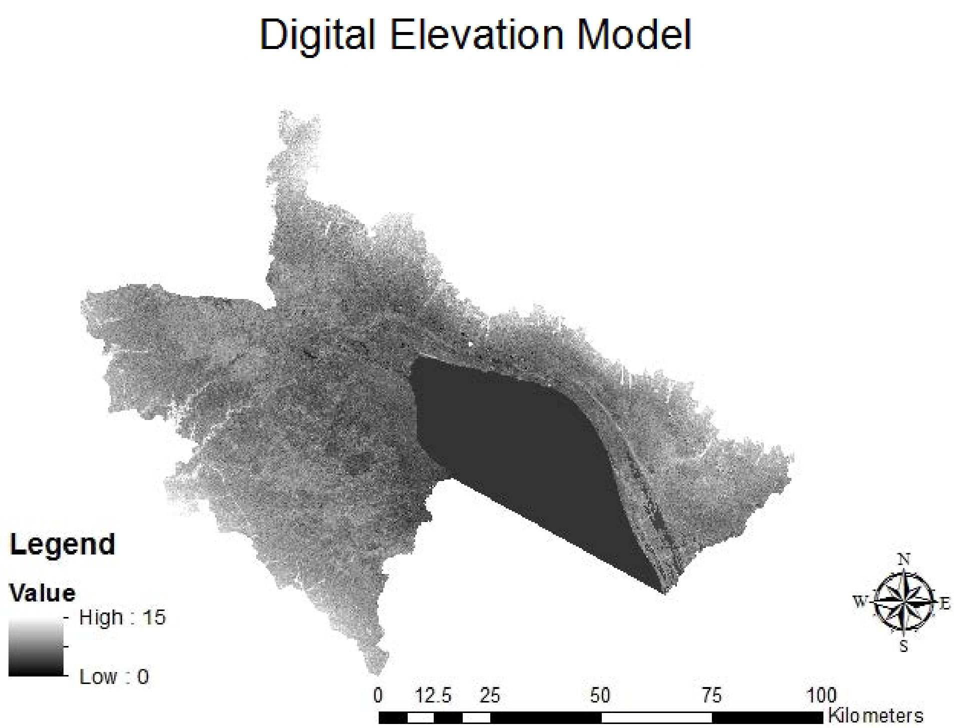

Figure C-1. Digital Elevation Model used to select the study area for this analysis.

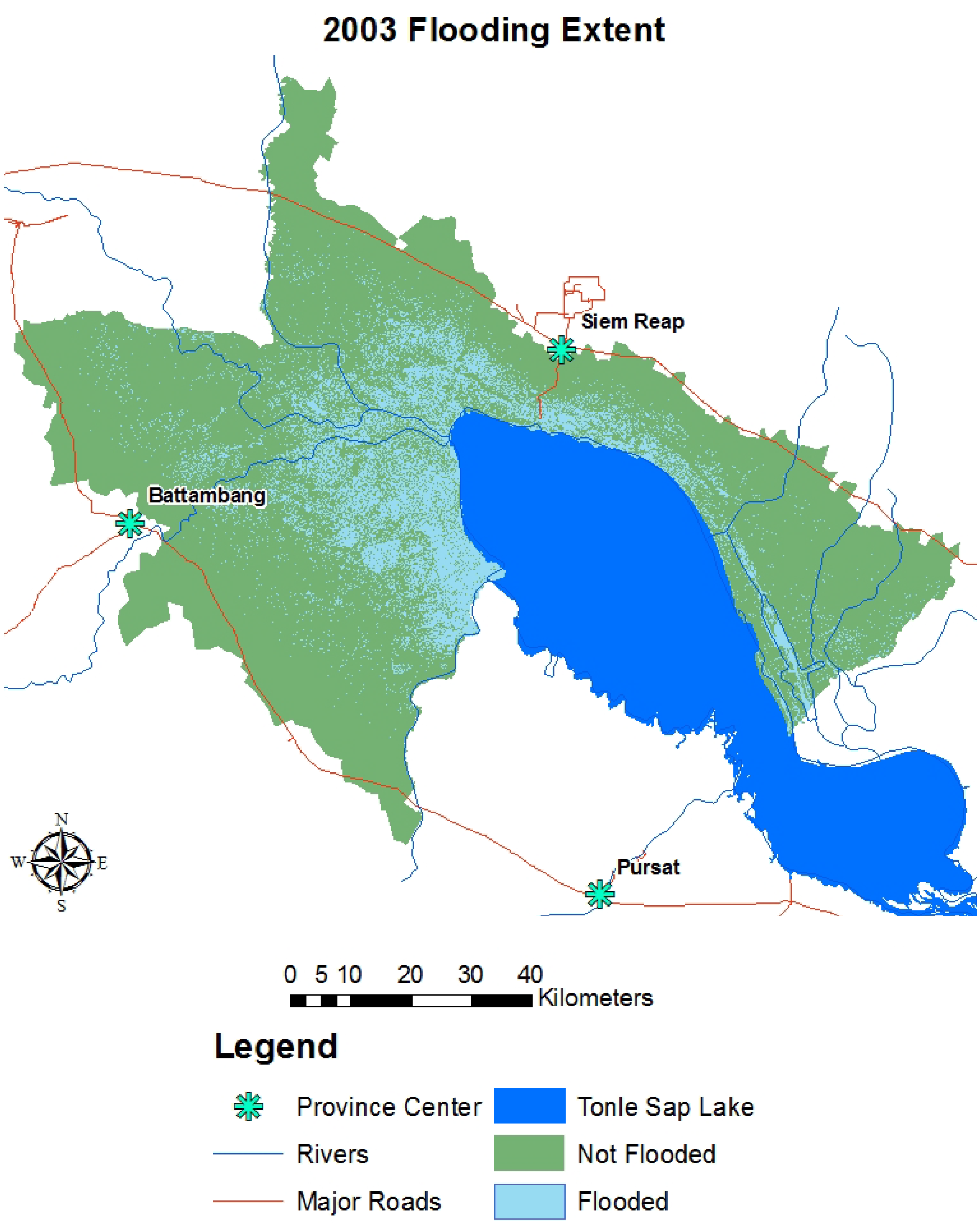

Figure C-2. 2003 Flood Classification for Siem Reap and Battambang Provinces.

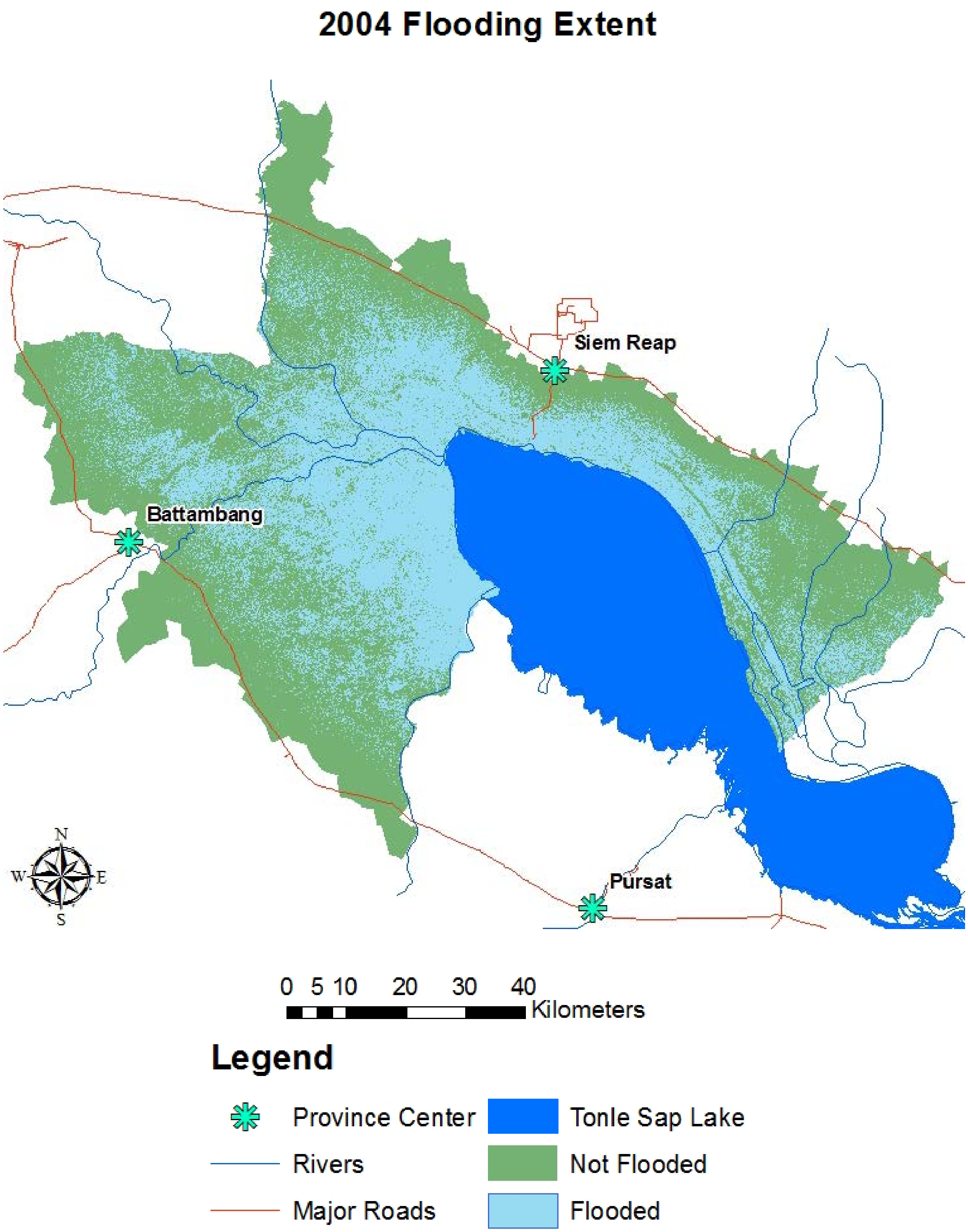

Figure C-3. 2004 Flooding Classification for Siem Reap and Battambang Provinces.

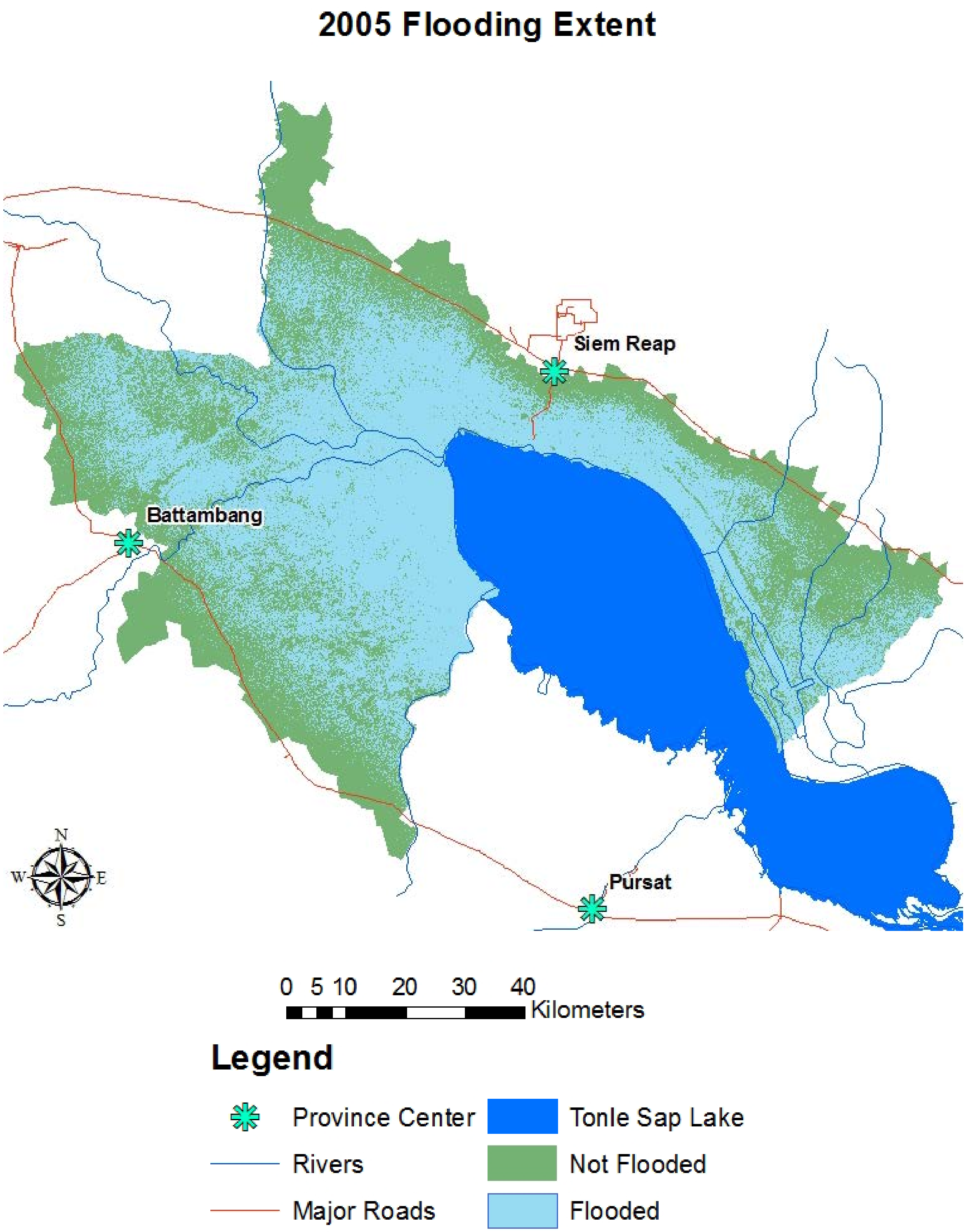

Figure C-4. 2005 Flooding Classification for Siem Reap and Battambang Provinces.

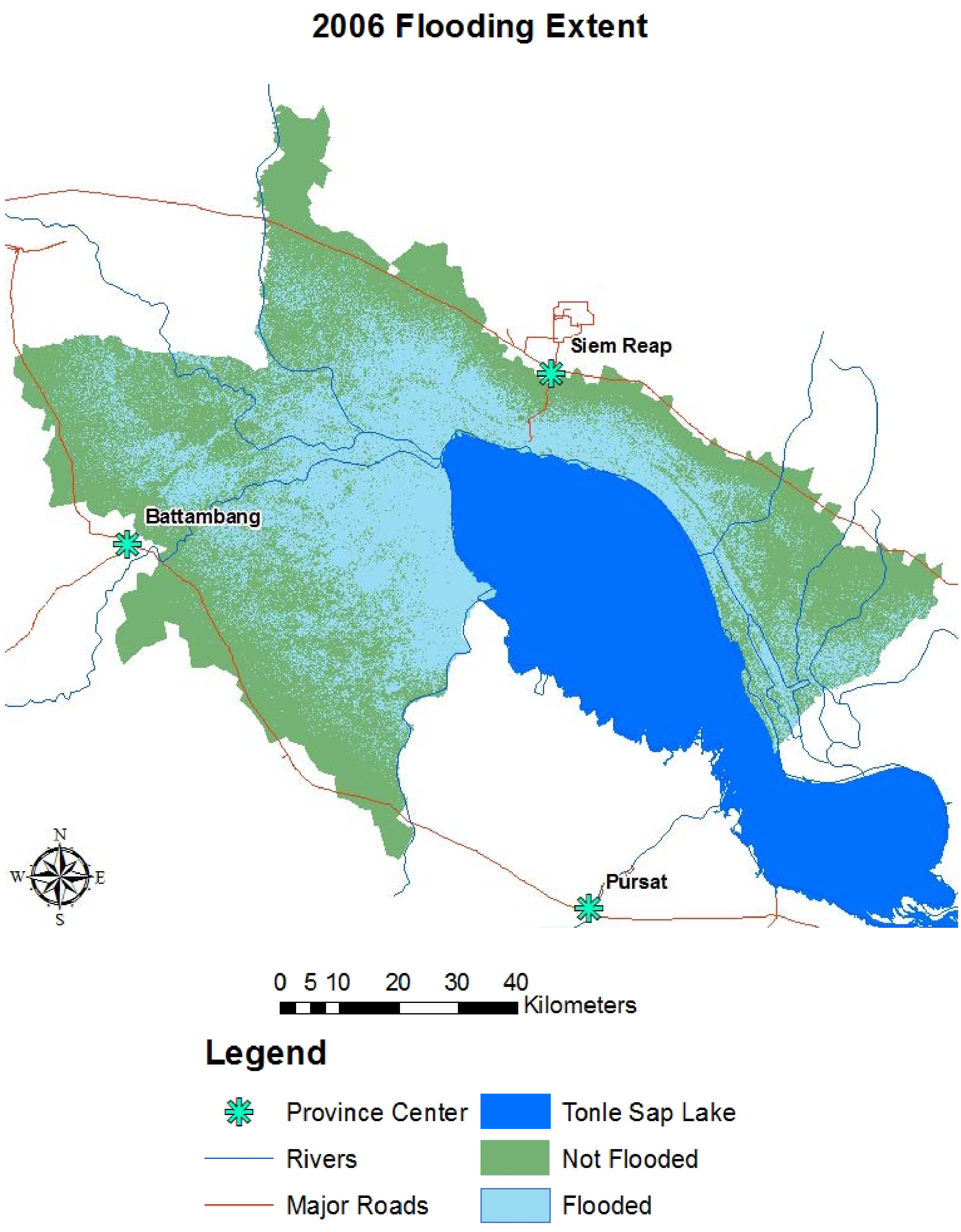

Figure C-5. 2006 Flooding Classification for Siem Reap and Battambang Provinces.

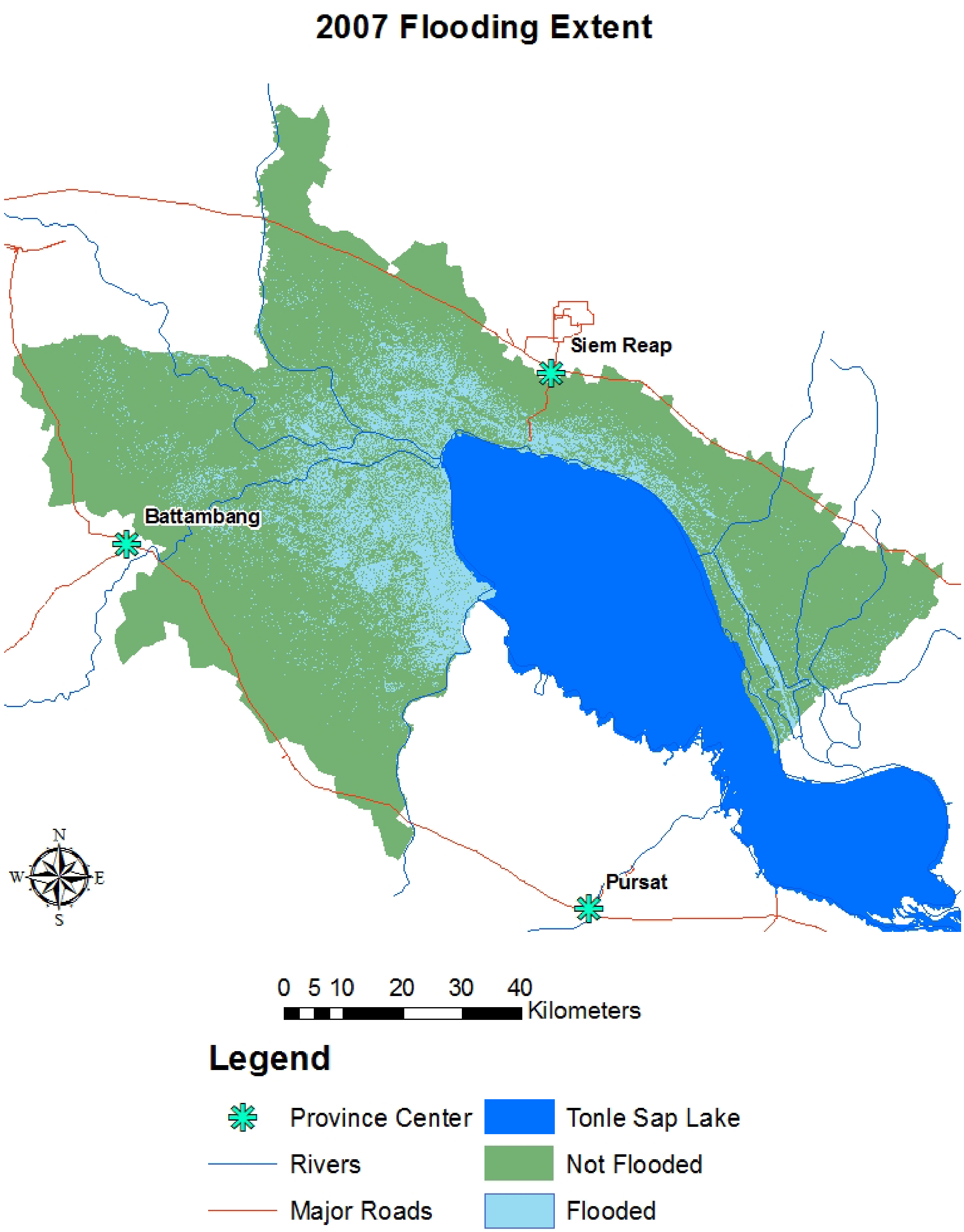

Figure C-6. 2007 Flooding Classification for Siem Reap and Battambang Provinces.

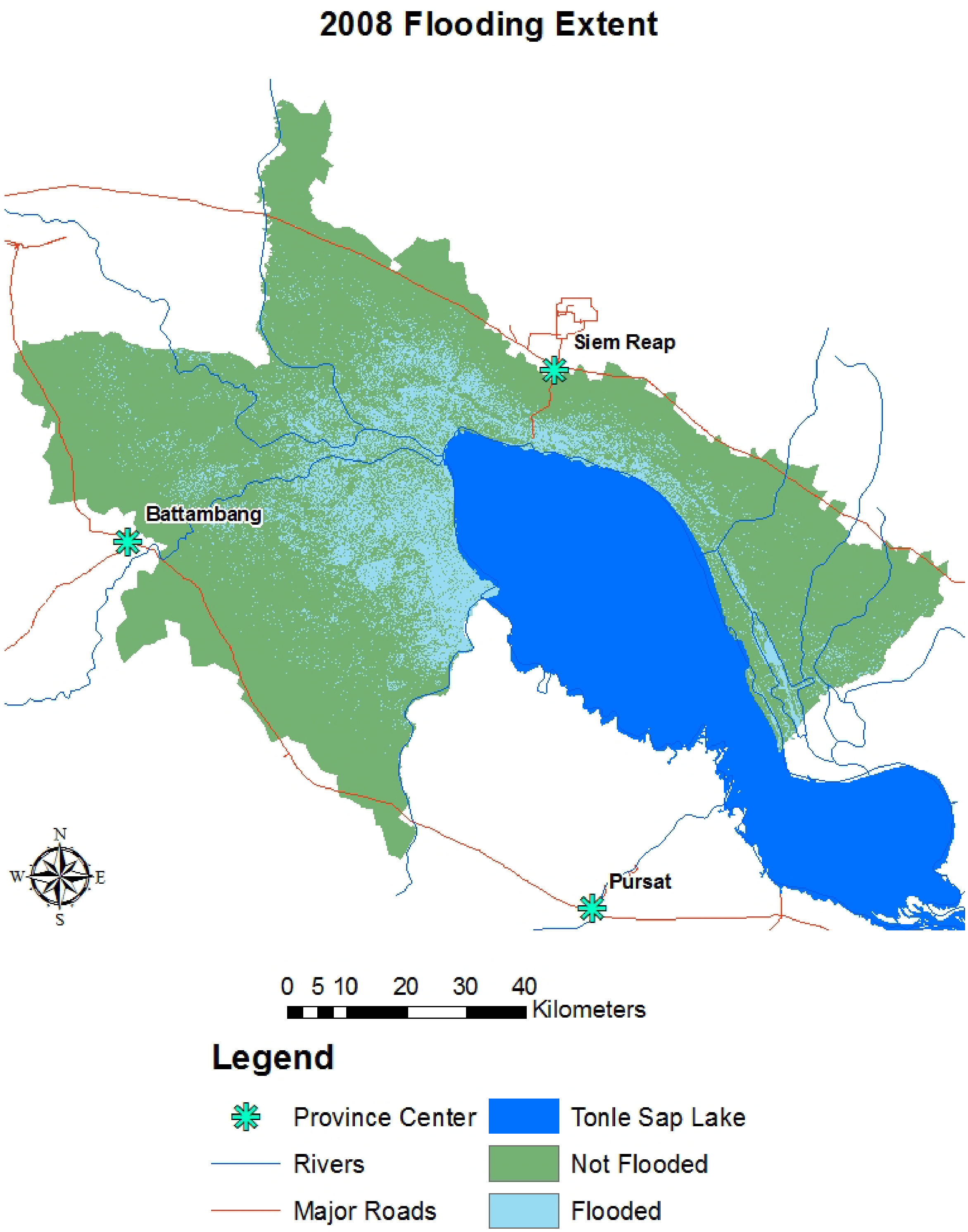

Figure C-7. 2008 Flooding Classification in Siem Reap and Battambang Provinces.

2009 Flooding Extent

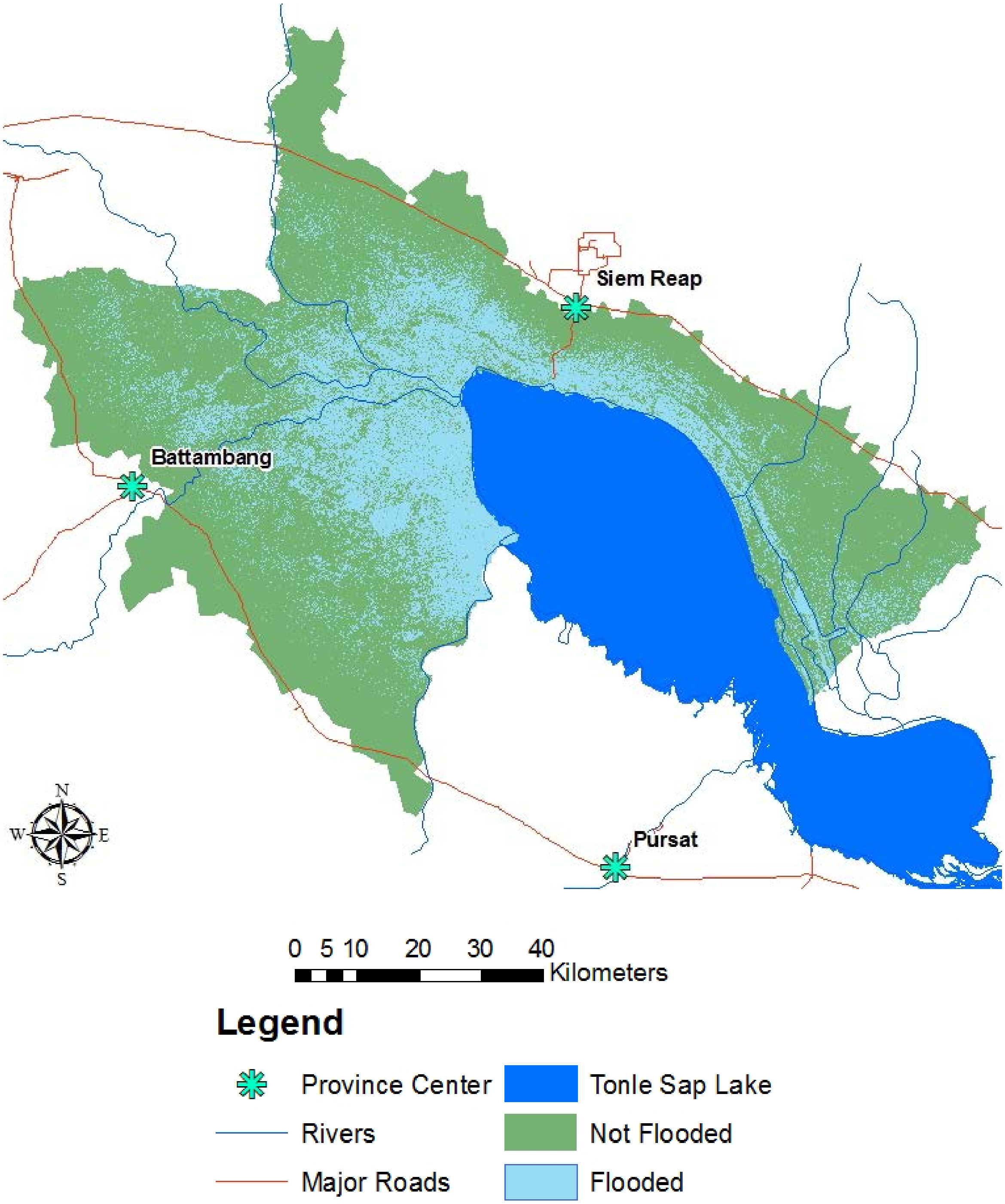

Figure C-8. 2009 Flood Classification for Siem Reap and Battambang Provinces.

APPENDIX D
LAND-COVER TRAJECTORIES: SUPPLEMENTAL INFORMATION

Table D-1. Land-cover trajectories and percent cover change during 2003-2004 time-period.

Landcover change	2003-2004 % Cover
Dry rice - shrubland	1.2
Dry rice - wet rice	10.0
Other trajectory	6.3
Permanently dry rice	11.7
Permanently shrubland	32.2
Permanently wet rice	8.4
Shrubland - dry rice	0.6
Shrubland - wet rice	4.8
Water	17.7
Wet rice - dry rice	2.4
Wet rice - shrubland	4.7
TOTAL	100.0

Table D-2. Land-Cover Trajectories and percent cover change during the 2004-2005 time-period.

Landcover change	2004-2005 % Cover
Dry rice - shrubland	1.5
Dry rice - wet rice	1.7
Other trajectory	7.0
Permanently dry rice	9.8
Permanently shrubland	35.6
Permanently wet rice	4.8
Shrubland - dry rice	0.3
Shrubland - wet rice	2.9
Water	17.3
Wet rice - dry rice	9.9
Wet rice - shrubland	9.2
TOTAL	100.0

Table D-3. Land-Cover Trajectories and percent cover change during the 2006-2007 time-period.

Land cover change	2006-2007 % Cover
Water	16.1
Dry rice - shrubland	0.2
Dry rice - wet rice	2.9
Other trajectory	14.7
Permanently dry rice	13.0
Permanently shrubland	36.7
Permanently wet rice	7.7
Shrubland - dry rice	0.0
Shrubland - wet rice	1.3
Wet rice - dry rice	3.5
Wet rice - shrubland	3.8
Total	100.0

Table D-4. Land-Cover Trajectories and percent cover change during the 2007-2008 time-period.

Land cover change	2007-2008 % Cover
Water	13.8
Dry rice - shrubland	0.1
Dry rice - wet rice	5.7
Other trajectory	17.4
Permanently dry rice	12.8
Permanently shrubland	32.9
Permanently wet rice	9.0
Shrubland - dry rice	0.1
Shrubland - wet rice	2.3
Wet rice - dry rice	3.2
Wet rice - shrubland	2.6
TOTAL	100.0

Table D-5. Land-Cover Trajectories and percent cover change during the 2008-2009 time-period.

Land Cover Change	2008-2009 % Cover
Water	13.8
Dry rice - shrubland	0.2
Dry rice - wet rice	7.9
Other trajectory	14.5
Permanently dry rice	13.8
Permanently shrubland	31.7
Permanently wet rice	6.4
Shrubland - dry rice	2.1
Shrubland - wet rice	3.8
Wet rice - dry rice	1.5
Wet rice - shrubland	4.3
TOTAL	100.0

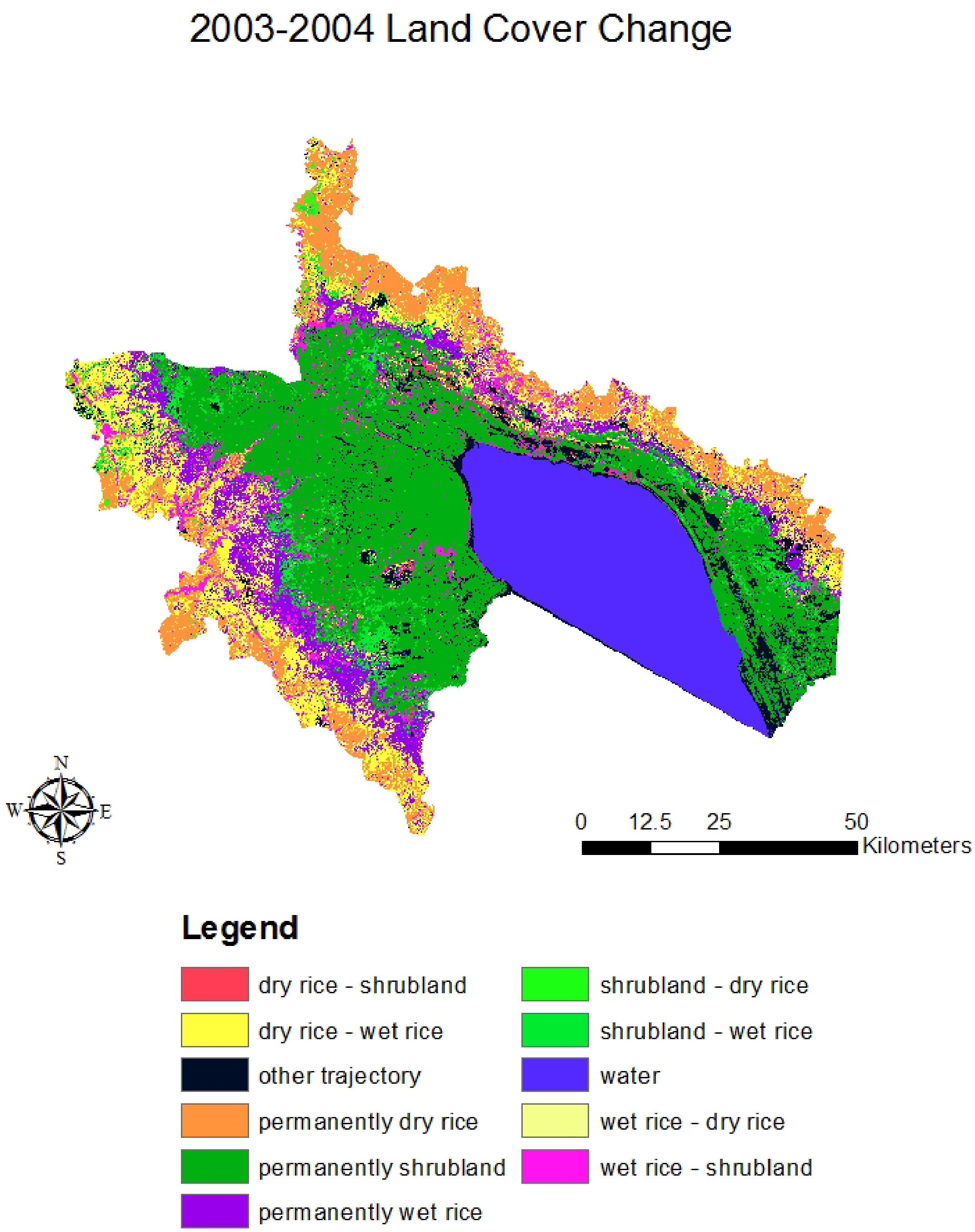

Figure D-1. Land Cover Change Trajectory for 2003-2004 time-period.

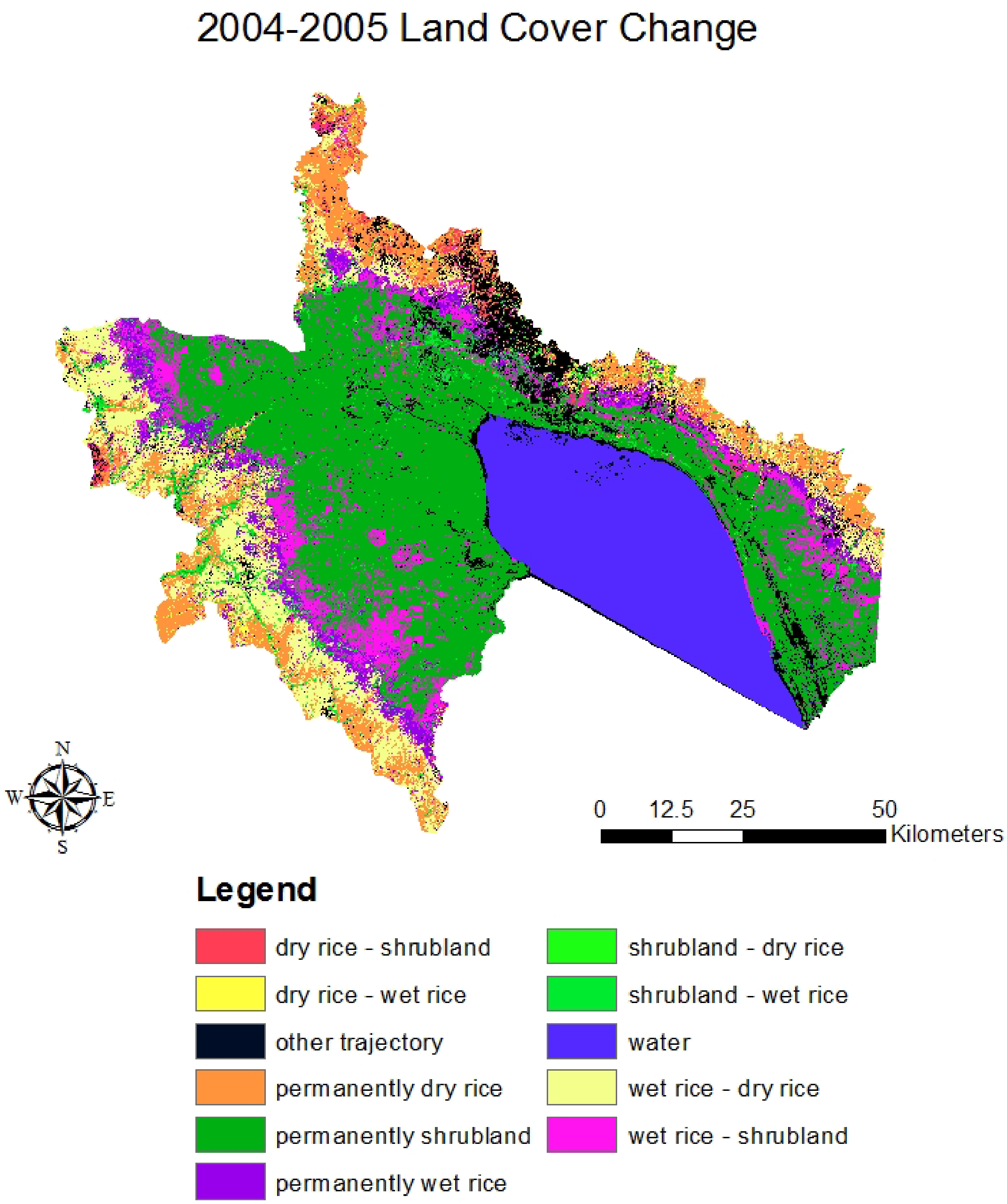

Figure D-2. Land Cover Change Trajectory for 2004-2005 time-period.

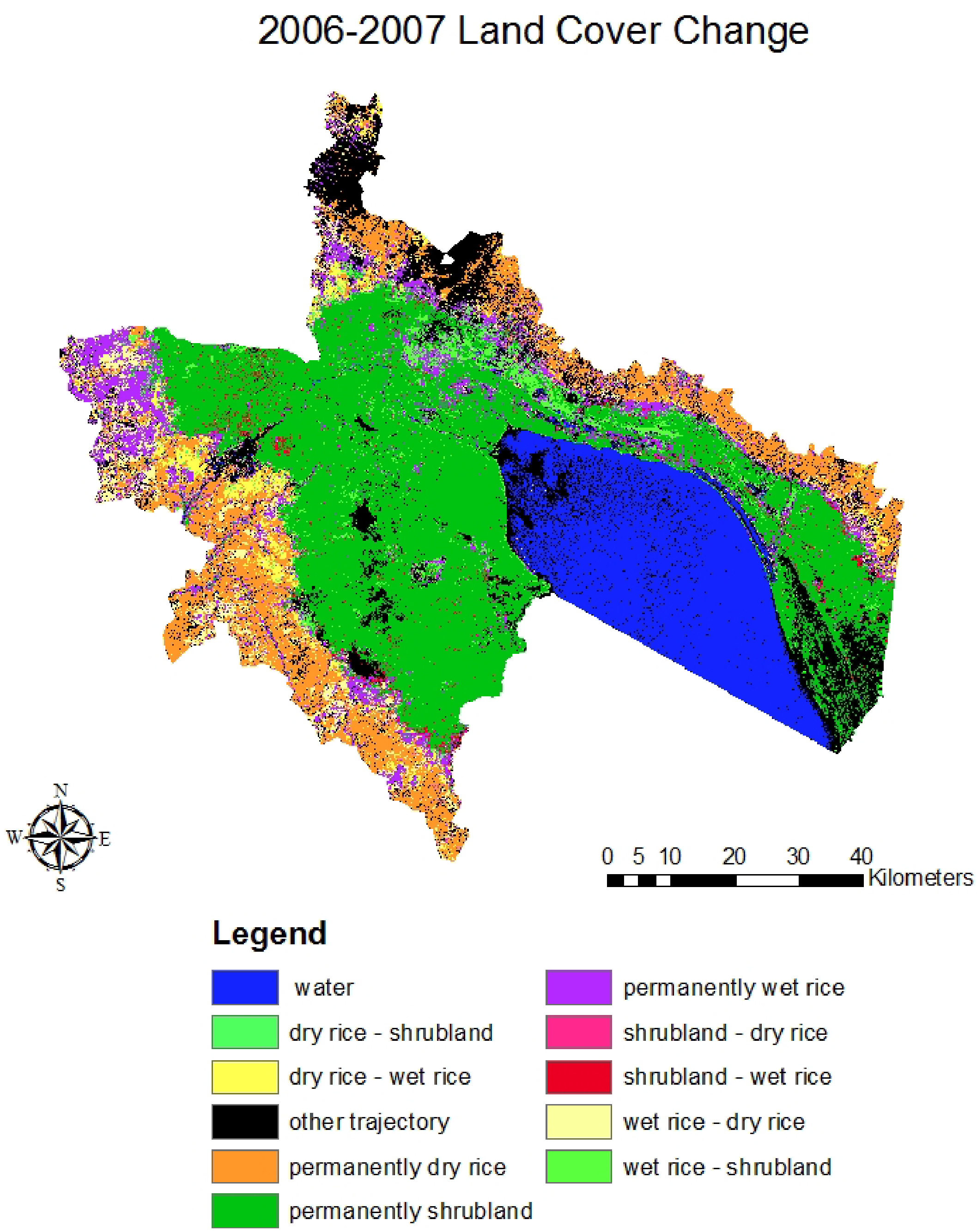

Figure D-3. Land-Cover change Trajectory for the 2006-2007 time-period.

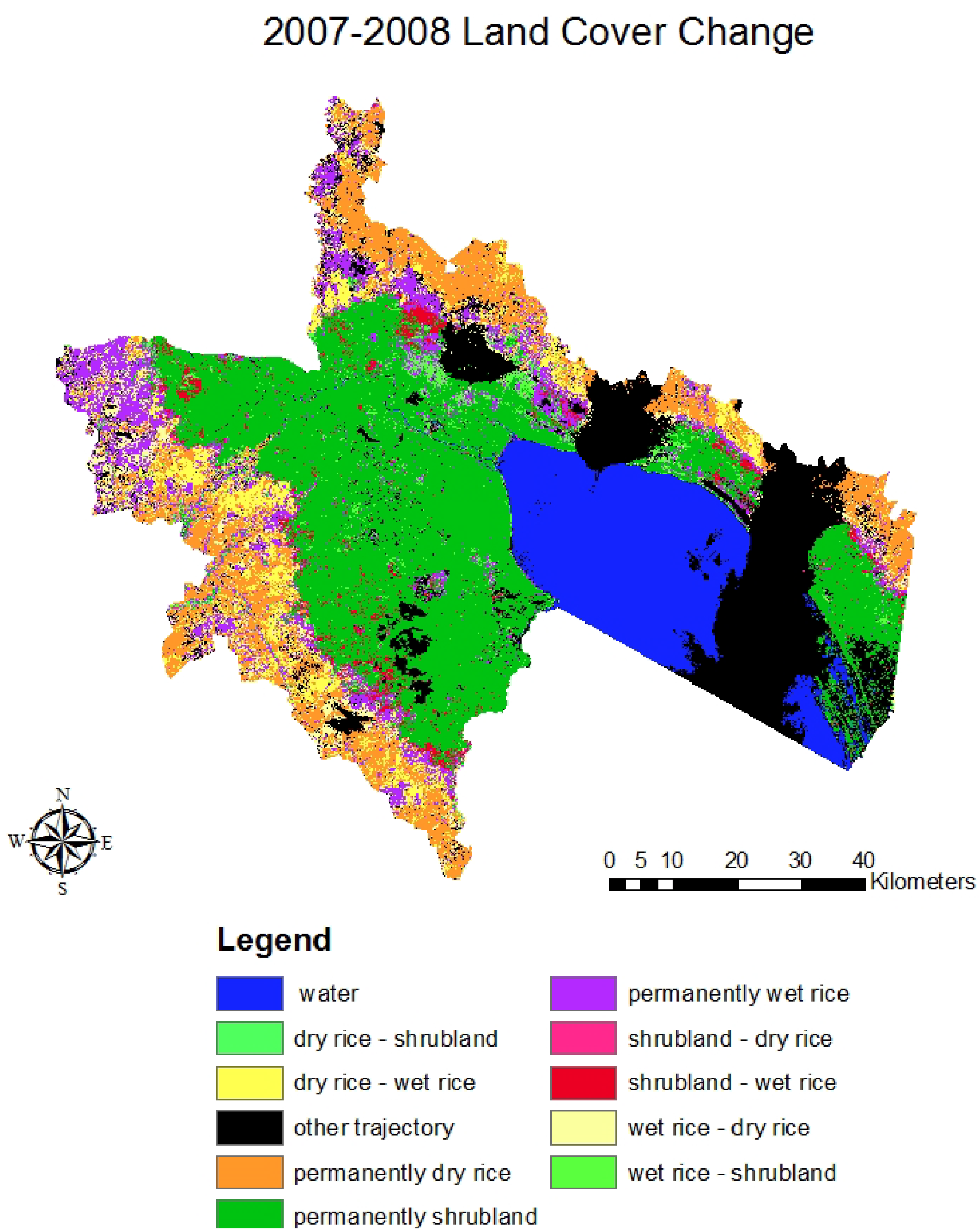

Figure D-4. Land-Cover Change Trajectory for the 2007-2008 time-period.

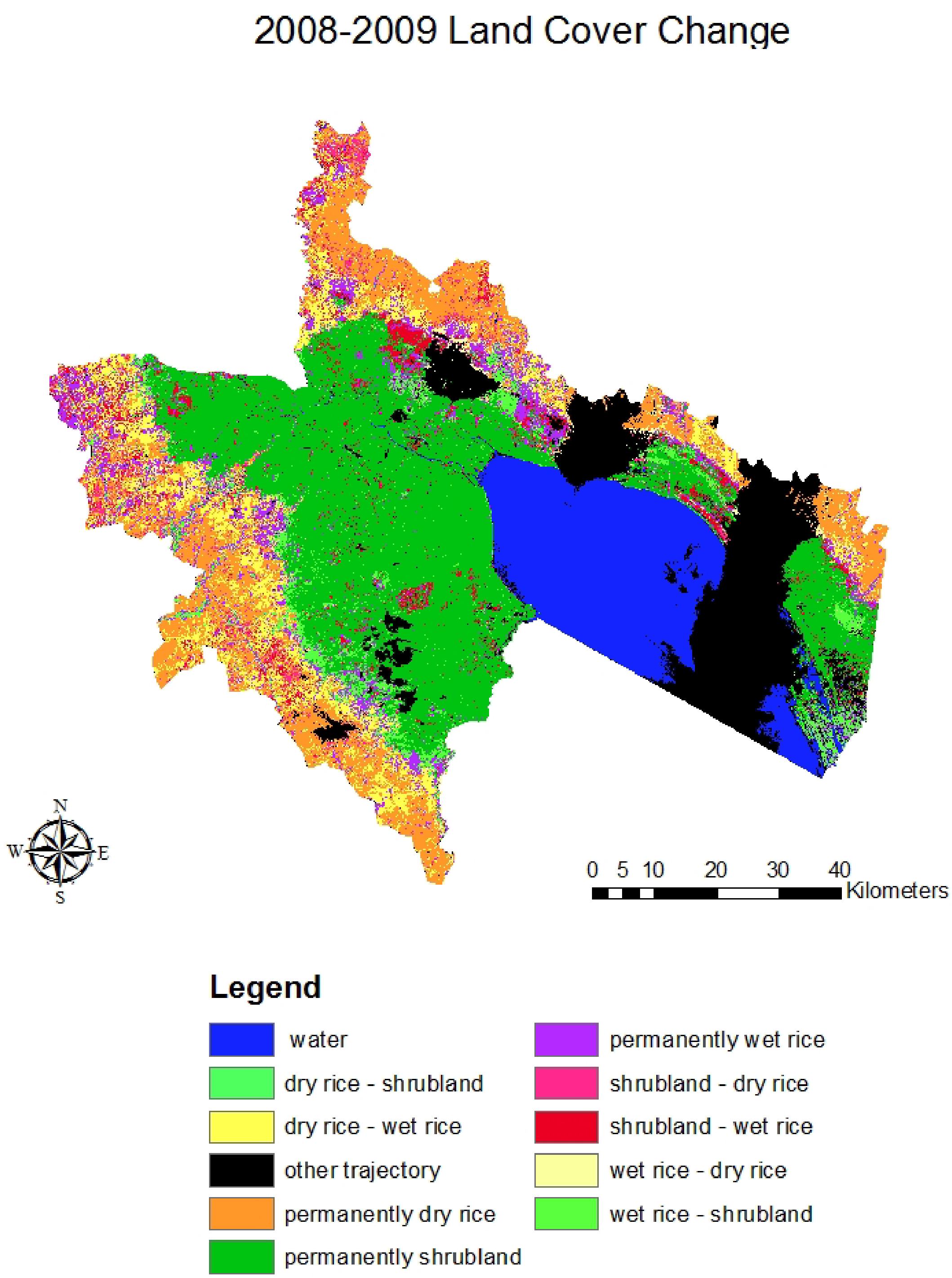

Figure D-5. Land-Cover Change Trajectory for the 2008-2009 time-period.

APPENDIX E
ACCURACY ASSESSMENTS

Table E-1. Accuracy Assessment for LC Classification in 2003.

Class	Ground Reference Test Water	Shrub	Wet Rice	Dry Rice	Total	Users Accuracy
Water	47	4	3	3	57	82.5%
Shrub	2	55	5	0	62	88.7%
Wet Rice	1	3	70	4	78	89.7%
Dry Rice	4	2	3	46	55	83.6%
Total	62	65	75	50	252	
Producers Accuracy	75.8%	84.6%	93.3%	92.0%		Overall Accuracy 86.5%

Table E-2. Accuracy Assessment for LC Classification in 2004.

Class	Ground Reference Test Water	Shrub	Wet Rice	Dry Rice	Total	Users Accuracy
Water	40	2	2	3	47	85.1%
Shrub	5	43	6	3	57	75.4%
Wet Rice	4	5	69	4	82	84.1%
Dry Rice	4	7	8	47	66	71.2%
Total	53	57	85	57	252	
Producers Accuracy	75.5%	75.4%	81.2%	82.5%		Overall Accuracy 79.0%

Table E-3. Accuracy Assessment for LC Classification in 2005.

	Ground Reference Test					
Class	Water	Shrub	Wet Rice	Dry Rice	Total	Users Accuracy
Water	33	5	4	5	47	70.2%
Shrub	3	47	5	2	57	82.5%
Wet Rice	5	6	65	6	82	79.3%
Dry Rice	3	8	6	49	66	74.2%
Total	44	66	80	62	252	
Producers Accuracy	75.0%	71.2%	81.3%	79.0%		Overall Accuracy 77.0%

Table E-4. Accuracy Assessment for LC Classification in 2006.

	Ground Reference Test					
Class	Water	Shrub	Wet Rice	Dry Rice	Total	Users Accuracy
Water	40	2	4	3	49	81.6%
Shrub	0	47	3	5	55	85.5%
Wet Rice	2	4	66	10	82	80.5%
Dry Rice	3	2	7	54	66	81.8%
Total	45	55	80	72	252	
Producers Accuracy	88.9%	85.5%	82.5%	75.0%		Overall Accuracy 82.1%

Table E-5. Accuracy Assessment for LC Classification in 2007.

	Ground Reference Test					
Class	Water	Shrub	Wet Rice	Dry Rice	Total	Users Accuracy
Water	40	5	2	2	49	81.6%
Shrub	3	40	5	7	55	72.7%
Wet Rice	6	4	62	10	82	75.6%
Dry Rice	5	4	5	52	66	78.8%
Total	54	53	74	71	252	
Producers Accuracy	74.1%	75.5%	83.8%	73.2%		Overall Accuracy 77.0%

Table E-6. Accuracy Assessment for LC Classification in 2008.

	Ground Reference Test					
Class	Water	Shrub	Wet Rice	Dry Rice	Total	Users Accuracy
Water	35	6	5	3	49	71.4%
Shrub	1	42	5	7	55	76.4%
Wet Rice	3	9	59	11	82	72.0%
Dry Rice	6	2	3	55	66	83.3%
Total	45	59	72	76	252	
Producers Accuracy	77.8%	71.2%	81.9%	72.4%		Overall Accuracy 75.8%

Table E-7. Accuracy Assessment for LC Classification in 2009.

	Ground Reference Test					
Class	Water	Shrub	Wet Rice	Dry Rice	Total	Users Accuracy
Water	43	2	3	3	57	82.5%
Shrub	5	38	5	0	62	88.7%
Wet Rice	5	3	70	4	78	89.7%
Dry Rice	3	2	3	46	55	83.6%
Total	56	65	75	50	252	
Producers Accuracy	76.8%	84.6%	93.3%	92.0%		Overall Accuracy 86.5%

LIST OF REFERENCES

"10 Largest Rice Producing Countries." *WorldAtlas*. N.p., 27 Jan. 2016. Web. 30 Mar. 2017.

Arias, M. E., Cochrane, T. A., Piman, T., Kummu, M., Caruso, B., Killeen, T.J. 2012. *Quantifying changes in flooding and habitats in the TSL (Cambodia) caused by water infrastructure development and climate change in the Mekong Basin.* Journal of Environmental Management, 112: 53-66.

Arias, M. E., Cochrane, T. A., Norton, D., Killeen, T.J., and Khon, P. 2013. *The Flood pulse as the Underlying Driver of Vegetation in the Largest Wetland and Fishery of the Mekong Basin.* AMBIO, 13 pages.

Bakker, K. *The politics of hydropower: developing the Mekong."* Political Geography 18.2 (1999): 209-232.

Baran, E. 2006. *Fish migration triggers in the Lower Mekong Basin and other tropical freshwater systems.* MRC Technical Paper No. 14, Mekong River Commission, Vientiane. 56 pp.

Baran, E., and Myschowoda, C. 2008. *Dams and fisheries in the Mekong Basin.* Aquatic Ecosystem Health and Management (12): 227-234.

Bayley, P. 1995. *Understanding Large River Floodplain Ecosystems.* BioScience, Vol. 45:3, pages 153-158.

Bonheur, N., and Lane, B. D. 2002. *Natural Resources management for human security in Cambodia's Tonle sap Biosphere Reserve.* Environmental Science and Policy 51, pp 33-42, ISSN: 1462-9011.

Cassidy, L., Southworth, J., Gibbes, C., and Binford, M. 2013. *Beyond classifications: Combining continuous and discrete approaches to better understand land-cover change within the lower Mekong River region.* Applied Geography. 39, pp 26-45.

Campbell, I.C., Poole, C., Gisen, W., and Valbo-Jorgensen, J. 2006. *Species diversity and ecology of Tonle Sap Great Lake, Cambodia.* Aquatic sciences (68): 355-373.

Cochrane, T.A., Arias, M.E., and Piman, T. 2014. *Historical impact of water infrastructure on water levels of the Mekong River and the Tonle Sap system.* Hydrology and Earth System Sciences (18): pp 4529-4541.

Chang, C. 2010. *A multivariate causality test of carbon dioxide emissions, energy consumption and economic growth in China.* Applied Energy 87(11): 3533-3537.

Dao, P. D., and Liou, Y. 2015. *Object-based flood mapping and affected rice field estimation with Landsat 8 OLI and MODIS Data.* Remote Sensing 7(5): 5077-5097.

Delgado, J. M., Apel, H., and Merz, B. 2010. *Flood trends and variability in the Mekong River.* Hydrology and Earth System Sciences (14): pp 407-418.

Delgado, J.M., Mertz, B., and Apel, H. 2012. *A climate-flood link for the lower Mekong River.* Hydrology and Earth System Sciences (16): pp 1533-1541.

Dudgeon, David. 2000. *The Ecology of Tropical Asian Rivers and Streams in Relation to Biodiversity Conservation.* Annual Review of Ecological Systems,31:239-263.

Ekbladh, D. 2002. *'Mr. TVA': Grass-Roots Development, David Lilienthal, and the Rise and Fall of the Tennessee River Valley Authority as a symbol for US Overseas Development, 1933-1973.* Diplomatic History 26(3): 335-374.

Food and Agricultural Organization of the United Nations. 2005. *Tonle Sap Fisheries.* Pp 51-101.

Farr, T.G., Rosen, P.A., Caro, E., Crippen, R., Duren, R., Hensley, S., Kobrick, M., Paller, M., Rodriguez, E., Roth, L., Seal, D., Shaffer, S., Shimada, J., Umland, J., Werner, M., Oskin, M., Burbank, D., and Alsdorf, D. 2007. *The Shuttle Radar Topography Mission.* Reviews of Geophysics (45).

Fraser, E.D.G., Mabee, W., and Slaymaker, O. 2003. *Mutual vulnerability, mutual dependence: the reflexive relation between human society and the environment.* Global Environmental Change. Vol. 13, Is. 2. Pp. 137-144.

Frappart, F., Do Minh, K., Hermitte, J. L., Cazenave, A., Ramillien, G., Le Toan, T., and Mognard-Campbell, N. 2006. *Water volume change in the lower Mekong from satellite altimetry and imagery data.* Geophysical Journal International. Pp. 570-584.

Fujii, H, Garsdal, H, Ward, P, Ishii, M, Morishita, K, Boivin, T. 2010. *Hydrological roles of the Cambodian floodplain of the Mekong River*. International Journal of River Basin Management, 1:3, 253-266.

Gasith, A. and Resh, V. H. 1992. *Streams in Mediterranean Climate Regions: Abiotic Influences and Biotic Responses to Predictable Seasonal Events.* Annu. Rev. Ecol. Syst. (30): 51-81.

Green, G. M., Schweik, C. M., and Randolf, J.C. *Retrieving land-cover change information from Landsat satellite images by minimizing other sources of reflectance variability.* E.F. Moran, E. Ostrom (Eds.), Seeing the forest and the trees: Human-environment interactions in forest ecosystems, MIT Press, Cambridge, MA (2005), p.p. 131-160.

Grimm, N. B., Grove, J. M., Pickett, S. T. A., and Redman, C. L. 2000. *Integrated Approaches to Long-term studies of urban ecological systems.* BioScience 50(7): 571-584.

Grumbine, R. E., Dore, J., and Xu, J. 2012. *Mekong hydropower: drivers of change and governance challenges.* The Ecology Society of America: Frontiers in Ecology and the Environment 10(2): 91-98.

Grumbine, E.R., and Xu, J. *Mekong hydropower development.* Science 332.6026 (2011): 178-179.

Gupta, A., Hock, L., Xiajing, H., and Ping, C. 2002. *Evaluation of part of the Mekong River using satellite imagery.* Geomorphology (44): pp. 221-239.

Hap, N., Un, S., and Nasielski, J. 2016. *A review of socioeconomic studies in the fisheries sector in Cambodia.* Inland Fisheries Research and Development Institute (Fisheries Administration) and World Fish. Phnom Pehn, Cambodia. 14 pp.

Hogan, Z. S., Moyle, P. B., May, B., Vander Zanden, M. J., and Baird, I. G. 2004. *The Imperiled Giants of the Mekong: Ecologists struggle to understand- and protect- Southeast Asia's large migratory catfish.* American Scientist (92) 3: pp 228-237.

Holtgrieve, G. W., Arias, M. E., Irvine, K. N., Lamberts, D., Ward, E. J., Kummu, M., Koponen, J., Sakkula, J., and Richey, J. E. 2013. *Patterns of Ecosystem Metabolism in the TSL, Cambodia with Links to Capture Fisheries.* PLoS ONE 8(8): e71395.

Huke, R. E., and Huke, E.H. 1997. *Rice area by type of culture: South, Southeast, and East Asia.* Manila (Philippines): International Rice Research Institute, 59 p.

"IUU and MCS in Cambodia." 2016. Marine Conservation Cambodia. http://www.marineconservationcambodia.org/what-we-do/iuu-and-mcs.

Irvine, K. N., Richey, J. E., and Hotgrieve, G. W. 2011. *Spatial and temporal variability of turbidity, dissolved oxygen, conductivity, temperature, and fluorescence in the lower Mekong River-Tonle Sap system identified using continuous monitoring.* International Journal of River Basin Management. Vol. 9, Iss. 2. Pp. 151-168.

Jenson, J. R. and Lulla, K. *Introductory digital image processing: A remote sensing perspective*. Geocarto International. 2.1 (1987).

Johnston, R. and Kummu, M. 2012. *Water Resource Models in the Mekong Basin: A Review.* Water Resource Management (26): pp. 429-455.

Junk, W. J., Bayley, P. B., Sparks, R. E. 1989. *The flood pulse concept in river-floodplain systems.* P. 110-127. In D. P. Dodge Proceedings of the International Large River Symposium. Can. Spec. Publ. Fish. Aquat. Sci.106.

Katano, O., Hosoya, K., Iguchi, K., Yamaguchi, M., Aonuma, Y., and Kitano, S. 2003. *Species diversity and abundance of freshwater fishes in irrigation ditches around rice fields.* Environmental Biology of Fishes. Vol. 66, Is. 2. Pp. 107-121.

Keskinen, M. 2003. *The great diversity of livelihoods: Socio-economic survey of the TSL.* Water Utilization Program-Modelling of the Flow Regime and Water Quality of the Tonle Sap MRCS/WUP-FIN Project. MRC Finnish Environmental Institute, Phnom Penh.

Kingston, D.G., Thompson, J.R., and Kite, G. 2011. *Uncertainty in climate change projections of discharge for the Mekong River Basin.* Hydrology and Earth System Sciences (15): pp 1459-1471.

Kirby, M. and Mainuddin, M. 2009. *Water and agricultural productivity in the Lower Mekong Basin: trends and future prospects.* Water International (34.1): 134-143.

Kite, Geoff. 2001. *Modelling the Mekong: hydrological simulation for environmental impact studies.* Journal of Hydrology. Vol 253 (1-4): pp. 1-13.

Klein, P., and Moretti, E. 2013. *Local Economic Development, Agglomeration Economics, and the Big Push: 100 years of evidence from the Tennessee Valley Authority.* The Quarterly Journal of Economics 129(1): 275-331.

Kripalani, R.H., and Kulkarni, A. 1997. *Rainfall variability over South-East Asia-Connections with Indian Monsoon and ENSO Extremes: New Perspectives.* International Journal of Climatology (17): pp 1155-1168.

Kuenzer, C., Campbell, I., Roch, M., Leinenkugel, P., Tuan, V. Q., and Dech, S. *Understanding the impact of hydropower developments in the context of upstream-downstream relations in the Mekong river basin.* Sustainability Science 8.4 (2013): 565-584.

Kummu, Matti. 2003. *The Natural Environment and Historical Water Management of Angkor, Cambodia.* WAC, 28 pages.

Kummu, M. and Sarkkula, J. 2008. *Impact of the Mekong River Flow Alteration on the Tonle Sap Flood Pulse.* AMBIO: A Journal of the Human Environment 37 (3): pp. 185-192.

Kummu, M., de Moel, H., Ward, P.J., and Varis, O. 2011. *How Close Do we Live to Water? A Global Analysis of Population Distance to Freshwater Bodies.* PLoS One. Vol.6, Is. 6.

Lamberts, D. 2008. *Little impact, Much Damage: The Consequences of Mekong River flow Alterations for the Tonle Sap Ecosystem.* Modern Myths of the Mekong: pp.3-18.

Liao, K. 2012. *A theory on Urban Resilience to Floods- A Basis for Alternative Planning Practices.* Ecology and Society. Vol. 17, Is. 4. 48pp.

Lim, P, Lek, S., Touch, S. T., Mao, S., and Chhouk, B. 1999. *Diversity and spatial distribution of freshwater fish in Great Lake and Tonle Sap river (Cambodia, Southeast Asia).* Aquatic Living Resources 12 (6): 379-386.

Lu, D., Mausel, P., Brond zio, E., and Moran, E. 2004. *Change Detection Techniques.* International Journal of Remote Sensing (25) 12: pp.2365-2401.

Mak, S. 2001. *Continued innovation in a Cambodian rice-based farming system: farmer testing and recombination of new elements.* Agricultural Systems (69.1-2): pp. 137-149.

Matthews, N. 2012. *Water grabbing in the Mekong basin- An analysis of the winners and losers of Thailand's hydropower development in Lao PDR.* Water Alternatives. Vol. 5, Is. 2. Pp. 392-411.

Mekong Secretariat, 1992. Fisheries in the lower Mekong basin. *Main Report.* Interim Mekong Committee. Bangkok, Thailand.

MRC (2011) *Annual Mekong Flood Report 2010*, Mekong River Commission, 76 pages.

Muller, E.K. 1977. *Regional urbanization and the selective growth of towns in North American regions.* Journal of Historical Geography 3(1): 21-39.

Nguyen, Y. T.B., Kamoshita, A., Araki, Y., and Ouk, M. 2013. *Water availability, management practices and grain yield for deepwater rice in Northwest Cambodia.* Field Crops Research (152): 44-56.

Nuorteva, P., Keskinen, M., and Varis, O. 2010. *Water, livelihoods and climate change adaptation in the Tonle Sap Lake area, Cambodia: learning from the past to understand the future.* Journal of Water and Climate change. Vol. 1, Is. 1. Pp. 87-101.

Patarasuk, R and Binford, M. 2012. *Longitudinal analysis of the road network development and land-cover change in Lop Buri province, Thailand, 1989e2006.* Applied Geography (32): 228-239.

Pearse-Smith, S.W.D. 2012. *The Impact of Continued Mekong Basin Hydropower Development on Local Livelihoods.* Consilience: The Journal of Sustainable Development (7.1): 73-86.

Pech, S. and Sunada, K. 2008. *Population Growth and Natural-Resources Pressures in the Mekong River Basin.* ABIO: A Journal of the Human Environment (37.3): 219-224.

Phillips, Leslie. 2013. *Human adaptation and its failures.* Academic Press.

Piman, T., Lennaerts, T., Southalack, P. 2013. *Assessment of Hydrological Changes in the Lower Mekong Basin from Basin-Wide Development Scenarios.* Mekong River Commission Secretariat, Vietiane, Lao PDR.

Rainboth, W. J. 1996. *FAO species identification field guide for fishery purposes.* Fishes of the Cambodian Mekong. FAO, Rome.

Sakamoto, T., Nguyen, N. V., Kotera, A., Ohno, H., Ishitsuka, N., Yokozawa, M. 2007. *Detecting temporal changes in the extent of annual flooding within the Cambodia and the Vietnamese Mekong Delta from MODIS time-series imagery.* Remote Sensing of Environment (109.3): 295-313.

Sarkkula, J., Baran, E., Chheng, P., Keskinen, M., Koponen, J., Kummu, M. 2004. *Tonle Sap Pulsing System and Fisheries Productivity.* Contribution to the XXIX International Congress of Limnology (SIL 2004), Lahti, Finland, 8-14 August 2004.

Savyouth, Hang. "Cambodian Villagers Demand Compensation for Expected Impact of China-Backed Dam." Radio Free Asia (Phnom Penh) 20-10-2015.

Seak, S., Schmidt-Vogt, D., and Thapa, G.B. 2011. *A comparison between biodiversity monitoring systems to improve natural resource management in Tonle Sap Biosphere Reserve, Cambodia.* International Journal of Biodiversity Science, Ecosystem Services & Management. Vol. 7, Is. 4. Pp. 258-272.

Shean, M. 2013. *CAMBODIA: Seasonal Flooding Impacts Wet Season Rice Production in 2013.* United States Department of Agriculture: Foreign Agricultural Service Commodity Intelligence Report.

Simon, J.L. 1980. *Resources, Population, Environment: An Oversupply for False Bad News.* Science. Vol. 208, Is. 4451. Pp. 1431-1437.

Sokhem, P. and Sunada, K. 2006. *The Governance of the Tonle Sap Lake, Cambodia: Integration of Local, National and Internation Levels.* Interantional Journal of Water Resources Development. Vol. 22, Is. 3. Pp. 399-416.

Tanaka, M., Sugimura, T., Tanaka, S., and Tamai, N. 2003. *Flood-drought cycle of Tonle Sap and Mekong Delta area observed by DMSP-SSM/I.* International Journal of Remote Sensing. Vol 24, Is. 7. Pp. 1487-1504.

Teddlie, C. and Yu, F. 2007. *Mixed Methods Sampling: A Typology with Examples.* Journal of Mixed Methods. Vol. 1, Is. 77. Pp. 77-100.

"About TVA: Our History." Web. https://www.tva.com/About-TVA/Our-History 4/23/2017.

Toth, L. A., Arrington, D. A., Brady, M. A., and Muszick, D. A. 1995. *Conceptual evaluation of factors potentially afftecting restoration of habitat within the Channelized Kissimmee River ecosystem.* Restoration Ecology (3): pp. 160-180.

"Tourism Statistics Report2016." 2016. *Kingdom of Cambodia: Statistics and Tourism Information Department, MOT.*

Turner, B.L., Matson, P.A., McCarthy, J.J., Corell, R.W., Christensen, L., Eckley, N., Hovelsrub-Broda, G.K., Kasperson, J.X., Kasperson, R.E., Luers, A., Martello, M.L., Mathiesen, S., Naylor, R., Polsky, C., Pulsipher, A., Schiller, A., Selin, H., and Tyler, N. 2003. *Illustrating the coupled human-environment system for vulnerability analysis: Three case studies.* Proceedings of the National Academy of Sciences of the United States of America. Vol. 100, Is. 14. Pp. 8080-8085.

Van Zalinge, N., Loeung, D, and Pengbun, N. 2003. *Mekong flood levels and Tonle Sap fish catches.* Contributed to the Second International Symposium on the Management of Large Rivers for Fisheries, Phnom Penh. Pp. 1-13.

Vastila, K., Kummu, M., Sangmanee, C., Chinvanno, S. 2010. *Modelling climate change impacts on the flood pulse in the Lower Mekong floodplains.* Journal of Water and Climate Change: 1,1.

Waisurasingha, C., Aniya, M., Hirano, A., Sommut, W. 2008. *Use of RADARSAT-1 data and a digital elevation model to assess flood damage and improve rice production in the lower part of the Chi River Basin, Thailand.* International Journal of Remote Sensing (29.20): 5837-5850.

Wild, T. B., and Loucks, D. P. 2015. *Mitigating Dam Conflicts in the Mekong River Basin.* Conflict Resolution in Water Resources and Environmental Management: 25-48.

Xiao, X., Boles, S., Frolking, S., Li, C., Babu, J. Y., Salas, W., and Moore, B III.2006. *Mapping paddy rice agriculture in South and Southeast Asia using multi-temporal MODIS images.* Remote Sensing of Environment 100.1: pp. 95-113.

Yuksel, I. 2007. *Development of Hydropower: A case study in Developing countries*. Energy Sources, Part B: Economics, Planning and Policy 2(2): 113-121.

Zalinge, N.V., Degen, P., Pongsri, C., Nuov, S., Jensen, J.G., Nguyen, V.H. 2003. *The Mekong River system.* Proceedings of the Second international Symposium on the Management of Large Rivers for Fisheries. Phnom Penh, Cambodia: 335-357.

BIOGRAPHICAL SKETCH

Morgan received her Bachelor of Science in oceanography from the Florida Institute of Technology in 2013. She was always passionate about environmental sciences and greatly enjoyed her coursework in geographic information systems (GIS). In 2014, she decided to pursue a graduate degree that would allow her to continue her academic career that involved GIS and remote sensing. She received her Master of Science in geography from the University of Florida in December.