Remote Sensing of Ecological Responses to Changes in the Hydrological Cycles of the Tonle Sap, Cambodia

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Abstract— **The Tonle Sap or Great Lake of Cambodia is the largest freshwater lake in Southeast Asia, exhibiting large changes in spatial extent between the wet and dry seasons. The extensive wetlands around the Tonle Sap support a high level of biodiversity of great importance not only to the Tonle Sap but to the entire Mekong river system. Time-series of MODIS 500m 8 Day Surface Reflectance product imagery covering the period 2000-2005 were used to establish seasonal flooding cycles and flooding extents, and ASTER surface reflectance product was used to map vegetation distributions. Water resource use on the Mekong upstream of the Tonle Sap is reducing and moderating the monsoonal flood pulse which sustains the lake and floodplain system. This can be linked to the timing of large dam construction within the Mekong River basin. There is an urgent need to develop more effective cross-border management plans and cooperation for the water resources of the Mekong system before the unique and economically important Tonle Sap region slips into further decline.**

Keywords-Tonle Sap, wetlands, Cambodia, MODIS

I. INTRODUCTION

The Tonle Sap or Great Lake of Cambodia is the largest freshwater lake in Southeast Asia, covering an area of 250-300,000 Ha during the dry season and up to 1.6 million Ha during the wet season [1]. It was listed as a UNESCO Biosphere reserve in 1997, and is designated as a Protected Area under Cambodian Royal decree and through numerous international agreements. By far the largest area of savannah swamp forest and inundated forest in Asia, it contains important Ramsar-listed wetlands, and supports extensive fisheries and agriculture of critical importance to the Cambodian economy [1]. Some 2.9 million people live in the five provinces surrounding the lake. With economic and political stability returning to the region in the past decade, the population around the margins of the lake is expanding rapidly, along with agricultural activity. Floodplain hydrology and wetland, flooded forest and riparian communities are being modified at a rapid rate and with major ecological impacts.

The Tonle Sap is characterized by a unique monsoon driven hydrological cycle. Besides drainage from the Mekong via the reversible Tonle Sap tributary during the monsoonal flood, 13 other catchments drain into the lake. The lake plays an important role in flood peak attenuation and flow control to the Mekong Delta, storing up to 40 km^3 of Mekong floodwater each year and releasing it slowly back into the system [2]. The flood pulse fills the lake and floods an extensive area of the floodplain, usually for several months from August through to January, creating a unique flooded forest plant community [3]. These temporary wetlands serve essential ecosystem processes in terms of nutrient exchange between the lake (and the Mekong system upstream) and the floodplain, and are essential for fish breeding [4]. Flooded forests are found mainly around the dry-season lake shoreline and comprise about 10% of the floodplain and are dominated by *Barringtonia acutangula, Baringtonia micratha* and *Diospyros cambodiana.* At higher elevations are extensive areas of short tree shrubland dominated by species of Euphorbiaceae, Fabaceae, and Combretaceae, together with *Barringtonia acutangula,* and seasonally flooded grasslands occupy the distal margins [5]. Large seasonal contrasts in lake levels affect the characteristics of the wetland vegetation, with some forest areas enduring fluctuations of up to 8m and complete canopy submergence for months at a time [6].

Development and water impoundment and extraction upstream on the Mekong, particularly in southern China, is thought to be affecting the size, timing and intensity of the monsoonal flood pulse that defines and sustains the Tonle Sap [7]. The two main dams built by China on the upper reaches of the Mekong are the Manwan dam, which was completed in 1993, and the larger Dachaosan dam, which was completed in 2003. Although catchments in China account for approximately one fifth of the flows in the Mekong overall, they can contribute 70-80% of flows during the dry season [2]. Of even greater concern is the disruption to the monsoonal flood peak, which must reach sufficient levels and be sustained long enough to maintain the seasonal reverse flow in the Tonle Sap river. This inflow from the Mekong accounts for approximately 70% of flow into the lake [6], with the remainder coming from local catchments.

Most management efforts on the Tonle Sap to date have focused on maintaining fisheries, which provide up to 70% of the protein intake for the entire Cambodian population [8], and protection of the Ramsar wetlands as bird nesting sites. Natural resource management is severely under-resourced and occurs in a piecemeal manner [9] in the face of poorly delineated jurisdictions and conflicting economic interests. Despite the importance of the Tonle Sap lake to the Cambodian economy, only in recent years have authorities and research agencies begun to characterise the flooding cycles of the lake or map floodplain vegetation distributions. Some modelling of lake hydrology was completed in 2003 [10] and an Asian Development Bank project is currently underway to produce GIS datasets of lake resources [1]. The Cambodian Mekong National River Commission (MNRC) in association with the multi-country Mekong River Commission (MRC) now monitor flood conditions in the Mekong and the Tonle Sap, but data is restricted to a limited number of gauging stations and is often not reliable. For example, the nearest MRC gauging station is located at Kampong Chhnang, on the Tonle Sap tributary.

II. Aims and Methods

The aims of this study were to utilise remote sensing methods to (a.) characterise the flood cycles of the lake; (b.) map the spatial distribution of water across the floodplain, and; (c.) determine vegetation distributions across the floodplain and their relationship to the flooding cycles of the lake. The current flood monitoring and mapping efforts of the MNRC and MRC rely on simple linear models of the relationship between river gauge height collected at only a few locations and maximum annual volume and flooded area. Few of the tributaries which drain the 13 catchments around the lake and make significant contributions to lake volume and flooded area have any gauging stations, and hydrological relationships between these tributaries and the lake are complex. In addition, modification of the floodplain and retention of floodwaters behind dykes and other structures restricts floodwater movement and distribution [11].

Time-series of MODIS 500m 8 Day Surface Reflectance imagery collected over the period 2000-2005 were used to establish seasonal flooding cycles and flooding extents, and ASTER surface reflectance product imagery was used to map vegetation distributions. An ASTER dry-season mosaic of the Tonle Sap floodplain was constructed with rectification carried out using WAAS corrected GCPs collected during fieldwork. The available ASTER coverage over the Tonle Sap is fragmented, both spatially and temporally, due to almost perpetual high levels of cloud cover, but it was possible to generate a complete mosaic. Wetland vegetation associated with the floodplain was categorised into community groupings and representative sites were mapped in using GPS. On the basis of training sites mapped during fieldwork, wetland vegetation across the floodplain was classified using maximum likelihood classification on the 9 visible/near-infrared and shortwave infrared bands of the ASTER imagery, which were resampled to 30m. This facilitated determination of the types and extent of wetland vegetation, although field validation of the classification was difficult due to the size and inaccessibility of much of the floodplain. Standard confusion matrices and Kappa statistics [12] were computed to ascertain classification accuracy on a subset of training sites not used in the original classifications. The ASTER mosaic, with its relatively high level of spatial precision, was also used as the basemap for rectification of the MODIS data.

A large time-series of MODIS 500m 8 Day Surface Reflectance imagery collected over the period 2000-2005 was used to characterize the flood cycles during the period June to March, usually at 2 week intervals, where the data was of sufficient quality. The MODIS imagery was subsetted to the area of the Tonle Sap and rectified to the ASTER basemap using 6 GCPs per image. Inundation mapping in floodplain environments can be problematic due to the presence of high levels of vegetative cover, shallow inundation over large areas and dark organic rich alluvial soils which can appear inundated when they are not [13]. The methods used to map inundation can have a marked effect on the observed patterns [14]. Usual inundation mapping methods involve use of a ratio of mid-infrared reflectance to a visible band reflectance [15] although this is generally only suitable for relatively deep water. Investigations of techniques for floodplains suggest a combination approach using this ratio and MIR change detection is necessary to deal effectively with the shallow water problem [16]. Due to the unique nature of the floodplain vegetation and shallow inundation over much of the wet season lake area, a specialised flood detection algorithm was developed using MODIS B6/B4 ratio combined with a B1 threshold, and this was verified using the higher resolution wet-season ASTER imagery. The MODIS time series was used to determine the extent of flooding and changes in flood amplitude and duration in conjunction with hydrological data from the MNRC and MRC.

III. Discussion

Like many ephemeral wetlands around the world, the distribution of the mosaic of flooded forest, scrub and grassland around the lake is determined largely by the duration and depth of flooding [9], and to a lesser degree substrate. The tropical climate, nutrient rich soils and abundant water present on the floodplain mean that vegetative growth occurs rapidly, and forests and wetlands quickly regenerate. It has been suggested that much of the present wetland vegetation is secondary regrowth [3], however this seems unlikely over the majority of the Tonle Sap wetlands, which are highly inaccessible. Only on the northwestern margins of the lake, where the ancient civilizations of Angkor flourished between A.D. 802 and 1431 [17] is large scale clearing likely to have occurred to facilitate extensive agricultural schemes. Many of these were re-established, often unsuccessfully, during the Khmer Rouge period [18]. While limited historical data exists on the distribution of plant communities across the floodplain, it is clear from the analyses that the majority of the floodplain vegetation is still intact and capable of near normal ecological functioning subject to floodwater availability.

The anthropogenic modification of the floodplain on its northern margins is, however, having a significant impact on the floodwater distribution and movement. Floodplain structures result in permanent inundation of large areas that were previously subject to a wetting and drying cycle; essential for the maintenance and survival of many plant and animal species, including many economically important fish species. In addition, retention and restriction of floodwater movement inhibits nutrient exchange between the floodplain and the lake, and movement of juvenile fish into the lake and the Mekong. The impoundments disrupt the moving littoral of the lake's flood pulse [19] where high turnover rates of organic matter and nutrients occur. The gradient of plant species adapted to seasonal degrees of inundation, nutrients and light no longer experiences the conditions under which it evolved. According to the flood cycle patterns revealed by the MODIS time series, most of the impoundment structures are built within the zone that would normally be inundated around the end of August in any given year, drying out by mid-December, giving a flood residence time of around 3-4 months. There is also an obvious interaction with floodplain soils. Significant waterlogging occurs around these structures for much of the year, which is a commonly observed phenomenon associated with water storages [20]. This is causing a number of changes to wetlands in these areas. Euphorbiaceae, Fabaceae, and Combretaceae species, which once colonised the mosaic of flooded savannah forest are being replaced by those which can tolerate saturated soils. In the areas behind the dyke walls, which now form permanent water storages, natural wetland species have disappeared completely, due either to blanket infestations of water hyacinth and fringing introduced scrub species.

The MODIS derived flood maps indicate a significant reduction in flooding extent of the Tonle Sap lake since 2000. While the 2000 flood was large by historical standards, and caused widespread damage and loss of life throughout the Mekong Basin [ref], every year since then has been characterised by a reduction in the spatial extent of flooding across the floodplain. This corresponds with MNRC and MRC observations that the flood peaks are now reduced in amplitude and have a much faster fill and drain cycle [21]. The very large Dachaosan dam in southern China began filling in 2003. The monsoons deliver large quantities of water very quickly into the dams where it can be released slowly throughout the year for hydroelectricity generation and for irrigation. The Chinese government currently has another three dams under construction in the upper reaches of the Mekong, with the Xiaowan dam now nearing completion, and another three are at the planning stage [22]. This will form an 8 dam cascading system capable of retaining very large volumes of water that would otherwise contribute to the monsoonal Mekong flood pulse. With limited fossil fuel reserves and exponential growth in energy demand, the Mekong and other Chinese rivers are seen as offering abundant cheap and clean power. The Chinese dams in the upper reaches of the Mekong are unlikely to be responsible for all reduced flow into the Tonle Sap, as the region may also be experiencing some ongoing effects of drought and climate change [2], and irrigation development is also occurring rapidly on other tributaries which feed the lake. Other proposed dams for Laos and Thailand are likely to further ameliorate the Mekong flood pulse in the future.

IV. Conclusion

Interference with the natural flood cycles and inundation patterns of the lake and surrounding floodplain are causing changes in vegetation and are affecting biological productivity not only on the Tonle Sap but throughout the Mekong system. Water resource use upstream of the Tonle Sap is reducing and moderating the monsoonal flood pulse which sustains the lake and floodplain system. This can be linked to the timing of large dam construction within the Mekong River basin, although Laos and Thailand are extracting increasing amounts of water from the Mekong as well for use in rapidly expanding rice irrigation schemes. While social benefits may arise from amelioration of floods which in some years can cause extensive property damage and loss of life, this must be balanced against the need to maintain flood cycles which can sustain the environment and economic activities of the Tonle Sap such as fishing and agriculture. There is an urgent need to develop new cross-border management plans and agreements for the water resources of the Mekong system before the unique and economically important Tonle Sap region slips into further decline.

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