Remote Sensing of the Ecology and Functioning of the Mekong River Basin with Special Reference to the Tonle Sap

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1. Introduction

The management of large transnational river basins is subject to a range of challenges stemming from differing national priorities, governance of land use activities and resource use, and differences in institutional capacity, data gathering and data sharing. Over vast, often inaccessible areas, remote sensing allows for rapid assessment of ecological resources and hydrological processes. This includes quantification of the extent and ecological functioning of vegetation communities, defining the distribution, duration and timing of flooding, measurement of water quality parameters, groundwater assessment, habitat assessment, and predictive modelling of the ecological impacts of landuse activities and changes to hydrological cycles. Remote Sensing technologies currently allow unparalleled capability for environmental monitoring and management. Data recording and delivery systems, sensor platforms, and sensor technology are constantly improving and each year deliver better remote sensing products for a wide array of applications. Largely independent of geopolitical constraints and boundaries, remote sensing systems allow investigation and analysis of water resources and ecosystem functioning and processes at a range of scales. Large transnational river basins such as the Mekong River basin, can be studied in their entirety or in part.

This chapter examines the use of remote sensing techniques in various investigations in the Mekong River Basin, with particular reference to work on the Tonle Sap (Great Lake) of Cambodia.

1.1 The Mekong River basin

The Mekong is the 10th largest river basin in the world in terms of mean annual outflow, with an annual discharge of 475 billion m^3 (Daming, 1997). From its source on the Tibetan Plateau, it flows some 4,800 km south to the Mekong Delta in Vietnam, draining a total catchment area of 795,000 km^2 (MRC, 2005). The Mekong River Basin spans the six countries of China, Myanmar, Lao PDR, Thailand, Cambodia and Vietnam and forms the major hydrological resource for Southeast Asian. The basin has always faced the challenges of widespread poverty, increasing demands on water and environmental resources, and conflict throughout the region (Jacobs, 2002). There is lack of coordinated management of the basin, although the Mekong River Commission (MRC), and its predecessors the Mekong Committee and the Mekong Interim Committee have sought to foster dialogue between the member countries since the late 1950s. The main achievement of the MRC, however, has been the development in recent decades of an extensive data gathering and dissemination system, flood forecasting and warning systems, and advancing the understanding of the ecological and physical attributes of the basin (Jacobs, 2002).

Flow and runoff in the Mekong is strongly seasonal, reflecting the influence of the annual monsoon in the lower reaches of the basin. The wet season peaks in September-October with flows in the lower basin of 20,000-30,000 m^3s^{-1}, compared to dry season flows of approximately 2,000 m^3s^{-1}, which are derived mainly from snow melt in the upper basin (Mekong Secretariat, 1989). The Mekong is subject to natural annual variability which affects the size of the flood peak in any given year and is driven primarily by El Nino Southern Oscillation (ENSO) events (Kiem et al. 2004). Future flood pulse activity may be threatened, however, with significant water resources development occurring throughout the Mekong basin, along with the uncertain effects of climate change on precipitation and river flows. Development and water impoundment and extraction upstream on the Mekong, particularly in southern China but also in Laos, Thailand and Vietnam, is thought to be affecting the size, timing and intensity of the monsoonal flood pulse (Blake, 2001; Osbourne, 2006). 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 (MRC, 2005). 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. Campbell et al. (2006) show a reduction in average flood height and flooded area over the past decade. One of the most significant hydrological features of the lower reaches of the Mekong basin is the Tonle Sap lake in Cambodia, which fills annually and plays an important role in flood attenuation and sediment and nutrient exchange from the Mekong (MRC, 2005). Events occurring in the upper reaches of the Mekong that systematically alter the flood hydrograph or change its timing are likely to have significant effects on the sustainability of the Tonle Sap (Kummu et al. 2004).

1.2 The Tonle Sap

The Tonle Sap or Great Lake of Cambodia (Figure 1) forms part of a unique and ecologically significant sub-system within the Mekong basin. It is the largest freshwater lake in Southeast Asia, covering an area of 250,000-300,000 Ha during the dry season and up to 1.6 million Ha during the wet season (ADB, 2002). Expansion of the lake during the wet season is due primarily to the annual monsoonal flood pulse moving down the Mekong and entering the lake through the Tonle Sap River, which reverses its course as the water level in the Mekong rises above that of the lake. Besides drainage from the Mekong 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 (MRC, 2005). 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. Some 2.9 million people live in the five provinces surrounding the lake (ADB, 2002). 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.

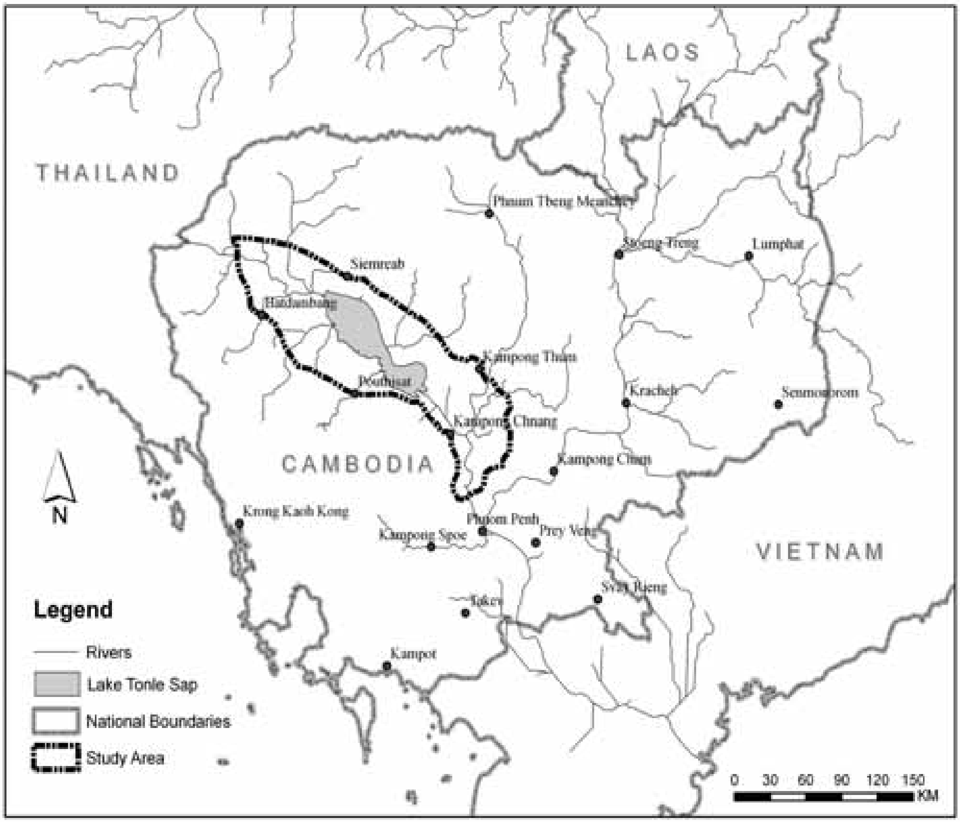

Fig. 1. The Tonle Sap Floodplain Study Area

Several ancient Ankorean capitals flourished on the northern margins of the Tonle Sap floodplain between A.D. 802 and 1431 (Chandler, 1996) and the floodplain has been modified in the past. Structures were built to control the movement of water across the floodplain and harvest it for agricultural purposes or to provide sites for aquaculture activities. This resulted in an extensive hydraulic network estimated to cover more than 1000 km² (Evans et al. 2007). Centralised control under the Ankorean court and highly organised agricultural production across the lowlands around Angkor produced economic surpluses for the state. Construction of reservoirs and channels occurred on a large scale through controlled use of labour, including slaves (Higham 2001). Although much of this original irrigation and agricultural infrastructure has probably been subsumed into more recent schemes, or obliterated by the flooding cycles of the lake, several examples of the largest ancient structures remain. These include the Domdek channel: a 200m wide channel extending approximately 80km through the floodplain with 10-15 m high walls; and the Western Baray at Angkor; a water storage covering 17.5 km^2.

The inflow from the Mekong accounts for approximately 70 % of flow into the Tonle Sap lake (Penny, 2006), with the remainder coming from local catchments. Some 80 % of the sediments and nutrients entering the lake from the Mekong are retained (MRC, 2005) and this annual process supports floodplain and fisheries productivity. The Tonle Sap lake is therefore highly susceptible to changes in the size, timing and duration of the annual monsoonal flood pulse, whether that occurs as a result of climate change or upstream water resources development. The past decade has seen reductions in flood height and flooded area of the lake (Campbell et al. 2006), although 2008 saw larger than normal floods throughout the Mekong. Kiem et al. (2008) in their latest modelling, suggest that precipitation will increase by 4.2% on average throughout the Mekong basin, concentrated in the upper sections of the basin in China. Chinvanno (2003) suggests that while there will be some shift in the timing of the flood peak, flooding durations will still be adequate for the survival of significant wetland areas on the Tonle Sap.

Most management efforts on the Tonle Sap to date have focussed on maintaining the lake's fisheries, which provide up to 70% of the protein intake for the entire Cambodian population (van Zalinge et al. 2000), and protection of the Ramsar wetlands as bird nesting sites. Natural resource management is severely under-resourced and occurs in a piecemeal manner (Bonhuer and Lane, 2002) 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 (Koponen et al. 2003) and an Asian Development Bank project is currently underway to produce GIS datasets of lake resources (ABD, 2002). 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 (Figure 1).

2. Remote Sensing of Floodplain Structures

Many extensive water impoundment structures as part of irrigation schemes have been built throughout the Tonle Sap floodplain to retain flood waters and support dry season rice cropping. Such anthropogenic modification of the floodplain occurs primarily on the northern margins of the lake in closer proximity to larger settlements. It is likely that these structures have a significant impact on floodwater distribution and movement and will simply serve as flood barriers if peak lake levels are diminished. 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 (Junk et al. 1989) 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.

An aim of the current study was to use remote sensing to determine the extent of floodplain structures around the Tonle Sap and where they lay in relation to flooding extent and duration. Major structures associated with irrigation schemes located within the annually flooded zone of the floodplain were mapped using WAAS corrected GPS to an accuracy of 2-3 m during fieldwork in 2006. High resolution Japanese/NASA ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) imagery was obtained over the floodplain for a range of wet and dry-season dates. ASTER senses in 14 spectral bands in the visible, shortwave and thermal infrared, at 15 m, 30 m and 90 m resolutions respectively (Lillesand et al. 2008). From the 37 ASTER multi-spectral surface reflectance product images obtained for the study, a mosaic of 11 dry-season images covering the Tonle Sap floodplain was constructed with rectification carried out using GCPs (Ground Control Points) 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 near-complete mosaic (Figure 2). As most of the structures occurred on the northern shore of the lake, generally they tended to have an east-west orientation. Horizontal spatial filtering was carried out on the imagery to identify and map the extent of major structures. Spatial filters operate on an image to emphasise or deemphasize image data of varying spatial frequencies. Directional first differencing is a simple directional image enhancement technique which improves the delineation of linear features (Lillesand et al. 2008).

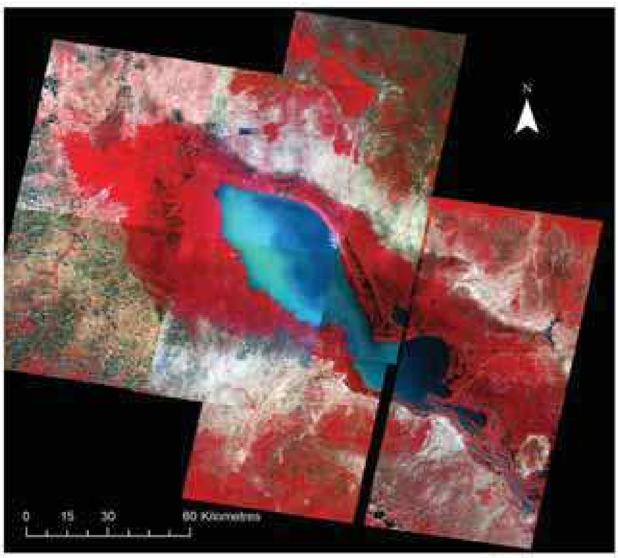

Fig. 2. ASTER Dry Season Image Mosaic of the Tonle Sap Floodplain

Using the filtered images it was possible to identify and map approximately 321 km of major impoundment structures which directly affect water movement across the floodplain (Figure 2). These were generally constructed parallel to the lake shoreline and serve to retain large volumes of water behind them as the lake waters recede after October in any given year. Major structures are defined as being greater than approximately 2m in height, although there are large networks of smaller formal and informal dykes, weirs and regulators which are also used or have been used to modify water movement. Most were built by hand during the Khmer Rouge years using forced labour, and in the absence of any hydrological or engineering knowledge (Kiernan, 1996). Extensive colonisation of these structures with floodplain vegetation has meant that they now form permanent features on the floodplain. According to the flood cycle patterns revealed by the time series analysis described later in this chapter, 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 (Figure 3). 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 (Ramireddygari et al. 2000). 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.

A secondary impact can also be observed. Irrigated rice fields are present on the lake shore side of most water impoundment structures. Increased nutrient levels associated with the application of fertilisers to the rice fields are likely to be affecting the surrounding wetlands through mobilisation during flooding in the wet season and affecting groundwater quality. Leaching of nutrients into the groundwater from these areas, along with increased utilisation of the groundwater by wetland plants due to higher groundwater levels has created succession towards more nutrient tolerant weeds such as *Mimosa pigra* (Campbell et al. 2006). Similarly, pesticides leaching into groundwater which lies close to the surface are affecting the wetland soils which contain the eggs of hundreds of fish species deposited when the lake is in flood. Changes in predator prey relationships that are important for the ecology of the lake (Scheffer, 1998) and its fisheries are likely to be occurring due to floodwater containment. The impoundments would restrict movement of larger fish into shallow areas of lake for predation during flooding and also form barriers to movement of juveniles out from hatchery zones to the lake and the Mekong system. This undoubtedly contributes to the well-documented reduction in the number of fish species and changes in size of individuals (Puy et al. 1999; Bonheur & Lane, 2002). However, the impoundments are also an important source of protein for the occupants of the floodplain, as they effectively operate as large unmanaged aquaculture sites for much of the year, possibly reducing pressure on lake fish stocks.

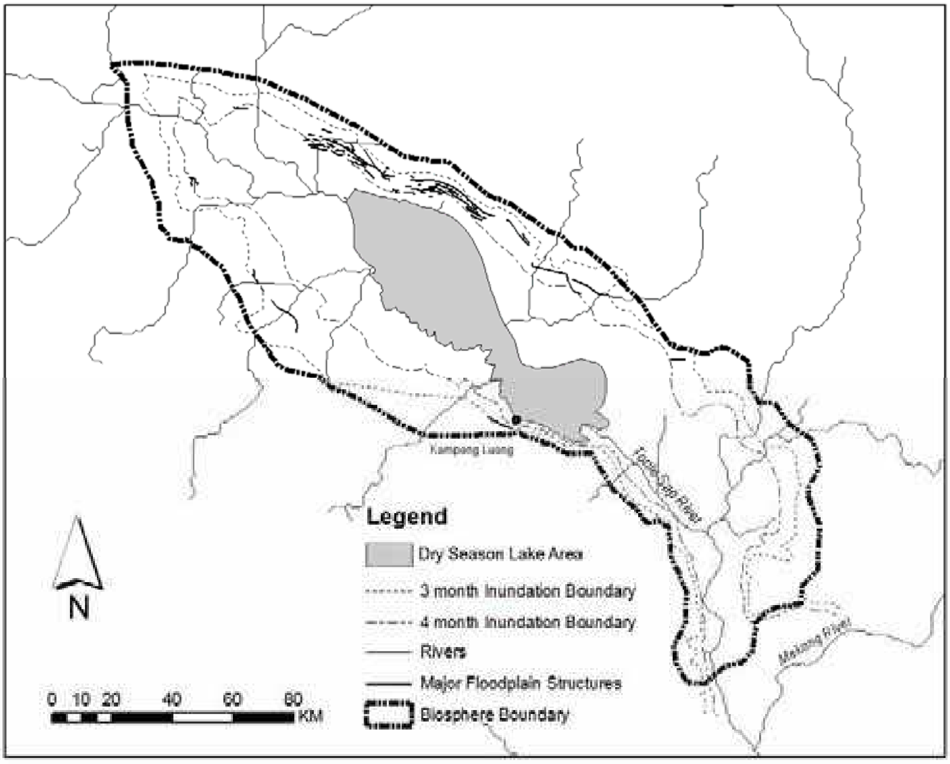

Fig. 3. Major Water Impoundment and Barrier Structures on the Tonle Sap Floodplain

The Khmer Rouge under Pol Pot sought to dramatically increase the areas of land under cultivation on the floodplain, and emptied the cities to provide forced labour for the extensive irrigation schemes that were established (Kiernan, 1996). These structures form by far the largest spatial extent of modifications to the present day floodplain, although many have now been abandoned or are in partial use. Of those surveyed during fieldwork, approximately 40% are now in disuse and others partially used on a seasonally varying basis depending on flooding extent, land availability and population pressures (Bonheur & Lane, 2002). Many of the areas originally modified for rice cultivation have failed to be maintained by the present population because of their inaccessible locations within the floodplain, poor siting, lack of centralised management and maintenance of the schemes, and destruction of infrastructure by flooding. Many of these areas have now reverted to permanent wetlands in areas that would previously have dried out when the floodwaters receded each year. Wright et al. (2004) report on some 570 irrigation schemes existing within the Tonle Sap basin, with only 195 being fully operational today. It is not know how many of these schemes fall within the area of the floodplain, although it is likely that a proportion are located in non-flooded areas. A recent phenomenon on the floodplain is the development of large scale privately owned irrigation schemes which seek to harvest floodwaters for rice production. Substantial areas of floodplain previously utilised by village communes for lower impact agricultural activities are being modified in this way. The use of ring-dyke structures to harvest flood waters for rice production are seen as the ideal new model for agricultural development of the Tonle Sap floodplain (Someth et al. 2009).

3. Remote Sensing of Groundwater Resources

Remote sensing has been widely used to measure the moisture content of soils (Jensen, 2007), although this often depends on the soil grain size and mineralogy, which will affect the ability of a soil mass to store water. Recently, a number of studies have begun to examine the use of remote sensing for inferring the nature of groundwater resources. Brunner et al. (2007) provide an overview of the potential use of remote sensing in the provision of data to support groundwater modelling in a number of large river basins. Other examples of recent studies include Mutiti et al. (2008), who examined groundwater resource development potential using Landsat imagery, Hendricks Franssen et al. (2008) who inferred groundwater patterning from remotely sensed data, and Milzow et al. (2009) who examined groundwater and hydrology of the large river/wetland system of the Okavango Delta using remote sensing. A range of remote sensing technologies are available to assist in the study of groundwater resources. These include technologies such as radar, LIDAR and digital photogrammetry to derive elevation products, airborne EM (electromagnetics) to examine changes in electrical conductivity in the shallow subsurface, and the remote sensing of vegetation, salt crusts and other surface features as a proxy for subsurface groundwater conditions (Brunner et al. 2007).

Groundwater resources are particularly important for the region in and around the Tonle Sap floodplain, as they form the major water supply for human use (Wright et al. 2004). The sedimentary depression of the Tonle Sap is surrounded by low-lying alluvium, with older coarser ferruginous silts, sands and grits around the perimeter overlain by red-clayey and silty sediments (Stanger et al. 2005). The alluvial deposits of the Tonle Sap floodplain are believed to be very good shallow aquifers, with high recharge rates (5-20 m^3/h) and a groundwater table generally within 4-6m of the surface. Groundwater quality is generally good apart from high iron content reducing palatability in some areas, and dangerous levels of arsenic contamination in others (Wright et al. 2004). In response to the large amplitude floods that characterise the hydrological cycle of the Tonle Sap, there is an annual cycle in groundwater levels from depths of around 6 m in riparian areas to a few centimetres in some parts of the floodplain (Stanger et al. 2005).

Loss of vegetation, particularly deep rooted tree species, reduces uptake of water from the soil profile and exacerbates waterlogging problems in the wetlands. A large seasonal population usually migrates from upland areas and the non-flooded areas of the Tonle Sap basin to the floodplain as the floodwaters recede, building temporary settlements on and around the water impoundment structures (Bonheur & Lane, 2002). The temporary settlements facilitate activities such as dry season rice cropping and fishing and informal aquaculture. Human settlement compounds the loss of larger wetland tree species in these areas as they form the primary source of fuelwood and building materials. This occurs on a wide scale despite a complete ban on all forms of timber extraction from the flooded forest areas. As well as the loss of deep rooted tree species, groundwater levels are also likely to be affected by the permanent and semi-permanent water impoundments, which would have a subsurface connection to the local water table (Ramireddygari et al. 2000). An aim of the current study was to investigate whether these effects existed and were detectable using available optical remotely sensed imagery. Soil moisture absorbs incident radiant energy in the 1.4, 1.9 and 2.7 μm regions, although the spectral response can be complex depending on soil type and soil characteristics (Jensen, 2007).

In three fieldsite locations on the Tonle sap floodplain, the relationship between groundwater and water storages was examined. During fieldwork elevated soil waterlogging adjacent to water storages could be observed through the presence of dark saturated soils along with consequent changes in vegetation type. Trenches were dug adjacent to the structures to ascertain depth to water table, and these confirmed water tables lying at or near the surface. Remotely sensed analysis of Landsat imagery over these areas made it possible to map the extent of waterlogging extending out from these structures. This involved the generation of wetness index maps, using the Kauth-Thomas (KT) transformation (Kauth & Thomas, 1976; Collins & Woodcock, 1996). A wetness index map derived from the KT transformation will indicate not only the level of surface soil moisture, but also the wetness of associated vegetation (Mutiti et al. 2008). A wetness index map for the fieldsite locations examined is presented in Figure 3. While the results do indicate a relationship between the size of the water storage and the area detected, such results are difficult to interpret without further information on the quantity of water stored, the duration of storage, the soil types and localised topography, all of which are unavailable for the Tonle Sap Floodplain. However, they did indicate the potential of remote sensing to detect and quantify these effects, and demonstrate the effects of waterlogging of soils adjacent to water impoundment structures – an important consideration given the rapid agricultural development occurring in some areas of the floodplain utilising water impoundments.

4. Remote Sensing of Floodplain Vegetation

The monsoonal driven 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 (McDonald et al. 1997). 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 (Puy et al. 1999). 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* (Wikramanayake & Dinerstein 2001) and seasonally flooded sedgelands and grasslands occupy the distal margins. Large seasonal contrasts in lake levels affect the characteristics of the wetland vegetation (Penny, 2006), with some forest areas enduring fluctuations of up to 8m and complete canopy submergence for months at a time (McDonald et al. 1997).

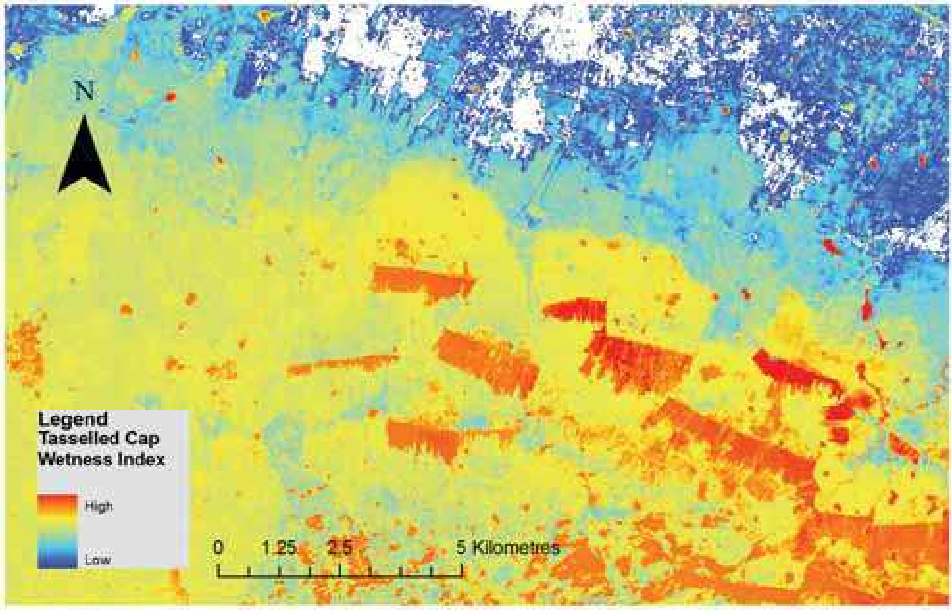

Fig. 4. KT Wetness Index Map of an area of the Tonle Sap Floodplain

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 (Bonheur & Lane, 2002), 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 (McDonald et al. 1997), although 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 (Chandler, 1996) 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 (Kiernan, 1996). While limited historical data exists on the distribution of plant communities across the floodplain, the majority of the floodplain vegetation is still intact, although often modified in areas closer to settlements, and capable of near normal ecological functioning subject to floodwater availability.

One aim of the current study was to use remotely sensed data to map the current distribution of wetland and floodplain vegetation around the Tonle Sap, so that these could be examined in relation to where they occur spatially on the floodplain in relation to flooding extent and duration. Previous efforts to map wetland vegetation distribution and its relationships to flooding (e.g. Kite 2001) utilised generalised USGS landcover classifications not particularly suited to the Tonle Sap floodplain. The ADB has generated landuse maps and metrics for all of the Tonle Sap catchments (ADB, 2009), although the landuse categories used are generalised and non-species specific.

Image classification procedures can be used to identify, map and quantify vegetation units of interest in remotely sensed imagery. The overall objective of image classification procedures is to automatically categorise all pixels in an image into land cover classes or themes (Lillesand et al. 2008). Image classification attempts to use the spectral information available in the data for each pixel as the numerical basis for categorisation. Different feature types will manifest different combinations of spectral response in each band (depending on sensor type) based on their inherent spectral reflectance and emittance properties which may also be variant in space and time. Spectral pattern recognition refers to the family of classification procedures that utilise this pixel-by-pixel spectral information as the basis for automated land classification (Lillesand et al. 2008).

Supervised classification is the procedure most often used for quantitative analysis of remote sensing image data. It rests upon using suitable algorithms to label the pixels in an image as representing particular ground cover types or classes (Richards & Jia, 2006). The multidimensional normal distribution of a spectral class is specified completely by its mean vector and its covariance matrix. Consequently, if the mean vectors and the covariance matrices are known for each spectral class then it is possible to compute the set of probabilities that describe the relative likelihoods of a pattern at a particular location belonging to each of those classes (Lillesand et al. 2008). It can then be considered as belonging to the class which indicates the highest probability. Therefore, if the mean vectors and the covariance matrix are known for every spectral class in an image, every pixel in the image can be examined and labelled corresponding to the most likely class on the basis of the probabilities computed for the particular location for a pixel. Before that classification can be performed however, the mean vectors and covariance matrix are estimated for each class from a representative set of pixels, called a training set. These are pixels which the analyst knows as coming from a particular spectral class.

Supervised classification consists therefore of three broad steps. First a set of training pixels is selected for each spectral class using the reference data available in the form of digital vegetation maps. The second step is to determine the mean vectors and covariance matrices for each class from the training data. This completes the learning phase. The third step is the classification stage, in which the relative likelihoods for each pixel in the image are computed and the pixel labelled according to the highest likelihood (Richards & Jia, 2006). Numerous mathematical approaches have been developed for spectral pattern recognition and it is beyond the scope and relevance of this chapter to review them all. Some commonly used classifiers are the Minimum-Distance-to-Means, parallelepiped, Gaussian Maximum Likelihood Classifier (MLC) and the Piecewise Linear Classifier. In the current study, MLC was used for the supervised classification of the ASTER optical imagery. MLC has a demonstrated reliability in achieving accurate classification of land cover types across a range of different environments (Bolstad & Lillesand, 1991; San Miguel-Ayanz & Biging, 1997).

MLC is one of the most commonly used supervised classification methods and it has been demonstrated to be extremely powerful and efficient in a great number of investigations (Maselli et al. 1990). It works most effectively when dealing with normal distribution in the spectral data, although it has also been shown to be relatively resistant to class distribution anomalies (Hixson et al. 1980; Yool et al. 1986). This classifier quantitatively evaluates both the variance and the covariance of the category spectral response patterns. It assumes a Gaussian distribution in the category training data, which is generally a reasonable assumption. Using this assumption the distribution of a category response pattern can be completely described by the mean vector and covariance matrix, it is possible to compute the statistical probability of an unknown pixel belonging to particular land cover class. In essence the maximum likelihood classifier delineates ellipsoidal "equiprobability contours" in the scatter diagram of spectral values which act as the decision regions (Lillesand et al. 2008).

The main limitation of maximum likelihood classification is the large number of computations required to classify each pixel. This is particularly true when either a large number of spectral channels are involved or a large number of spectral classes must be differentiated. Numerous extensions and refinements of the maximum likelihood classifier have been developed (Lillesand et al. 2008). These include the use of lookup tables in which the category identity of all possible combinations of digital numbers is determined prior to classifying the image and each unknown pixel is classified simply by reference to these lookup tables. This avoids the need to carry out complex statistical calculations for each pixel as they have already been determined for each category. Another means of optimizing maximum likelihood classifiers is to use some method to reduce the dimensionality of the dataset used to perform the classification. Procedures such as the principal components, canonical components (Jensen and Waltz, 1979) and tassled cap (Kauth and Thomas, 1976) transformations achieve this reduction of the dataset by making use only of the significant sections of the data.

Floodplain vegetation type and distribution were observed and mapped in the field in and around the Tonle Sap through a number of fieldwork surveys conducted in 2005 and 2006, in accessible locations. Remote sensing offers the ability to map landcover types over large areas, based on spectral information collected from representative vegetation communities and other landuse and landcovers (Lillesand et al. 2008). On the basis of training sites mapped throughout the floodplain during fieldwork, wetland vegetation and landcover across the floodplain was classified into 20 classes using maximum likelihood classification on the 9 visible/near-infrared and shortwave infrared bands of the ASTER imagery, which were resampled to 30 m. This facilitated determination of the types and extent of wetland vegetation directly affected by the water impoundment structures and their relationship to flooding patterns. Classification accuracy was assessed using standard confusion matrices to generate overall accuracy and Kappa statistics (Congalton & Green, 2008), using one training site for each landcover type not used in the original classification. As a result of the classification carried out over the floodplain using the imagery, it was possible to generate floodplain metrics for the various vegetation and landuse classes, and these are presented in Table 1.

Vegetation/Landuse Class	Area (ha)	Percentage
Barringtonia acutangula dom. Flooded Forest	107928	7.75
Barringtonia acutangula dom. Savannah	765737	55.01
Diospyros cambodiana dom. Savannah	184344	13.24
Euphorbiaceae Shrubland	53794	3.86
Tiliaceae Shrubland	61062	4.39
Mimosa pigra	7551	0.54
Sedge	17810	1.28
Phragmites Reeds	36928	2.65
Thornbush	3380	0.24
Water storage, unvegetated	19257	1.38
Water storage, vegetated	11345	0.81
Agricultural - rice	34972	2.51
Agricultural - fallow	11839	0.85
Legume cropping	250	0.02
Grasslands	67410	4.84
Mudbanks saturated soil	2722	0.20
Bare dry soil	2344	0.17
Firescar	1569	0.11
Rock outcrop	183	0.01
Human settlement	1664	0.12
Total (excluding Lake Area)	1392089	100.00

Kappa = 0.83

Table 1. Landcover classification results for the Tonle Sap floodplain

5. Relationships between Elevation and Floodplain Vegetation

High quality digital elevation data are essential for the assessment of floodplains and spatial arrangement of vegetation communities. Numerous studies of wetland vegetation have suggested that elevation is a primary determinant of vegetation type and location within wetland systems (Scoones, 1981; Hughes, 1990), and substrate to a lesser degree. Analysis of elevation data can yield important information on the spatial arrangement of vegetation in wetland and floodplain environments as it determines the extent and duration of flooding of these areas. In many of the developing countries which comprise the Mekong River basin high quality survey data is simply not available, and over large inaccessible areas such as the Tonle Sap floodplain, ground based survey is logistically impossible. Therefore remote sensing offers the primary means of gathering such data.

There are a range of remote sensing techniques available for the generation of elevation data or digital elevation models (dems). In general, higher precision in these products is accompanied by higher cost of acquisition and processing. Techniques include digital stereo photogrammetry, radar interfereometry and LIDAR. For the Mekong basin the primary dataset that has been utilised is the United States Geological Survey (USGS) GTOPO 30 dem, which is a 30 arc-second resolution product. The Shuttle Radar Topography Mission (SRTM) global product can also be used which has a 3 arc-second (approximately 90 m) resolution with 5 m vertical accuracy (Slater et al. 2006), and more recently, the ASTER GDEM global dem became available in 2009 with 30 m resolution and 15 m vertical accuracy. Of these datasets, only the latter is suitable for use in a low relief environment such as the Tonle Sap floodplain. In the GTOPO 30 and SRTM data, variations in floodplain relief are dominated by data anomalies. In all cases where remotely sensed elevation data are available, finer resolution dem data can be interpolated, but these may lead to a false representation of precision as they will normally retain the errors present in the original data (Longley et al. 2007). Kite (2001) used the USGS GTOPO 30 product for hydrological modelling of the Mekong Basin, and the ADB (2009) show flooded area maps and metrics for the Tonle Sap catchments interpolated from contour maps. In the current study, remotely sensed elevation data was utilised to investigate the relationship between the primary wetland and floodplain vegetation types and elevation, and hence relationship to flooding. For this purpose the ASTER GDEM product was used after processing to remove anomalies, most of which occur over areas of open water and along tile edges, and extracting only elevations below 30m in height. The resultant 30m dem for the Tonle Sap floodplain is shown in 3D in Fig 5.

Fig. 5. 3D dem of Tonle Sap floodplain, derived from ASTER GDEM

A simple GIS-based analysis of the location of vegetation communities in relation to elevation yields information on the elevation ranges they occupy within the floodplain. While elevation alone is not the sole determinant of flooding effects on vegetation, in a floodplain such as the Tonle Sap, where overbank flooding from the lake is the primary source of floodwater, it does indicate the sensitivities of various ecological communities to water level ranges. The depth and duration of flooding for these communities is a primary determinant of their evolution in a given location and their ecological functioning (Campbell et al. 2006). The main vegetation classes and their elevation ranges derived from this analysis are shown in Table 2.

Vegetation Class	Minimum Elevation (m)	Maximum Elevation (m)	Elevation Range (m)
Barringtonia acutangula dom. Flooded Forest	0.6	1.8	1.2
Barringtonia acutangula dom. Savannah	1.9	8.2	6.3
Diospyros cambodiana dom. Savannah	2.4	8.7	6.3
Euphorbiaceae Shrubland	5.3	10.4	5.1
Tiliaceae Shrubland	6.2	12.6	6.4
Sedge	8.2	11.3	3.1
Phragmites Reeds	1.0	2.6	1.6
Grassland	9.1	18.4	9.3

Table 2. Elevation ranges for primary vegetation classes

The elevation ranges of the primary vegetation classes of the Tonle Sap confirm that the flooded forest and reed communities occupy lower elevations on the floodplain, with Savannah woodland communities at higher elevations followed by shrubland, sedge and grasslands. Flooded forest, reed and sedge communities occupy the narrowest elevation ranges on the floodplain, while those communities at higher elevations are most likely to be affected by reductions in flood height. This information can then be used with the information on temporal flood extent patterns described below to characterise the horizontal and vertical arrangement of species on the floodplain. This landscape ecology approach to the understanding of floodplain structure provides important information on ecological functioning. Landscape ecology is based on the hypothesis that the interactions among biotic and abiotic components of the landscape are spatially mediated. Not only are the flows of energy material or species from place to place affected by the locations of the places in the landscape, but these flows then determine the interactions among energy, material and species (Malanson, 1993). A central theme of landscape ecology is that spatial structure controls the processes that continuously reproduce the structure. Landscape ecology is an approach to the study of the environment that emphasizes complex spatial relations. The relative locations of phenomena, their overall arrangement in a mosaic and the types of boundaries between them, become the priorities of study (Forman & Godran, 1986; Ingegnoli, 2002).

6. Flood Detection and Mapping

The monsoonal flood pulse is the primary mechanism affecting productivity in the Tonle Sap lake, wetlands and floodplain. The economically important fisheries of the Tonle Sap are strongly influenced by the maximum flooded area and resultant area of fish feeding and breeding habitat (Webby et al. 2005). Remote sensing of the inundation patterns across the study area therefore formed an important part of the current study. Knowledge of the extent and residence time of floodwaters on the floodplains of major rivers is essential for hydrological and biological studies of these systems, and yet for most areas of the Mekong, this remains largely unknown beyond simple maps of flood extent. For the Tonle Sap, the ADB has compiled maps showing minimum and maximum flood extents for the catchments around the lake as derived from satellite image interpretation (ADB, 2009). For the areas examined in this study, information on flow rates and stream heights may be available, but because of the low relief and complex hydrology of many wetland areas, these data do not correlate well with inundation patterns. Rates of organic matter production, decomposition and export to the river channel are closely linked to floodplain inundation patterns. Primary production rates in inland wetlands are very high and these communities may cover hundreds of thousands of square kilometres (Matthews and Fung, 1987). In many large river systems with associated extensive wetland areas, the difficulty in determining the extent of flooding makes it difficult to accurately estimate wetland area and characterise vegetation relationships. Ground measurement of flooding in forested wetlands is severely limited by the inaccessibility typical of these areas, where mobility is often hampered by flooding and boggy conditions. Remote sensing offers the ability to detect flooded over such areas, and this is typically done using optical or radar imagery.

With regard to optical remote sensing of inundation and the spectral reflectance of water, probably the most distinctive characteristic is the absorption of energy at near-infrared (NIR) wavelengths. Locating and delineating water bodies with remote sensing data is done most easily at NIR wavelengths because of this property (Lillesand et al. 2008). However, various conditions of water bodies manifest themselves primarily in visible wavelengths. Landsat TM imagery has been used to map floodwater distribution and characteristics (e.g Imhoff et al. 1987; Pope et al. 1992; Mertes et al. 1993, 1995; Johnston and Barson 1993), and optical SPOT data has also been used for floodwater mapping (Blasco et al. 1992).

Remote sensing of flooding may also be hampered by forest canopies that render the land/water boundary invisible to infrared and visible wavelength sensors and by frequent cloud cover during periods of rainfall. These limitations are largely overcome by SAR radar sensors which are unaffected by clouds and can significantly penetrate relatively dense forest canopies (Hess et al. 1990). Passive microwave remote sensing has also proved useful for revealing large-scale inundation patterns, even in the presence of cloud cover and dense vegetation (Choudery 1991, Sippel et al. 1994). The bright appearance of flooded forests on radar images results from double-bounce reflections between smooth water surfaces and tree trunks or branches. Enhanced back scattering at L-band has been shown to occur in a wide variety of forest types and is a function of both stand density and branching structure (Hess et al. 1990). Steep incidence angles (20-30^{o}) are optimal for detection of flooding, since some forests exhibit bright returns only at steeper angles. Backscattering from flooded forests is enhanced by underlying water. For forests of moderate density, L-band returns are dominated by corner reflections between trunks and surface and between branches and surface (Richards et al. 1987a). Scattering from a smooth water surface is specular, whereas that from soil includes a significant diffuse component and therefore the amplitude of returns will be higher for standing water beneath forests.

There is a high degree of structural diversity associated with flooded forests, as they occur on numerous substrates, in both saline and fresh water and at a wide range of latitudes (Matthews and Fung 1987). Most frequently studied have been the swamp forests of the coastal plains of the southeastern United States. Relatively bright L-band returns from semi-permanently to permanently flooded stands have been reported in several studies (e.g. Hoffer et al. 1986, Evans et al. 1986, Wu and Sader 1987). Detection of underlying water in mangrove swamps was demonstrated by Imhoff et al. (1987) in the Sundarbans region of Bangladesh and by Ford and Casey (1988) in East Kalimantan. Bright returns for seasonally inundated temperate forests are described by Richards et al. (1987b) for Eucalyptus camaldulensis forests in Australia. Ford et al. (1986) distinguished flooded varzea forest from non-flooded forest using SIR-B scenes of the Rio Japura in the Amazon Basin.

The forest stands cited above have very diverse structures: canopy depth relative to total tree height, dominant branching angle, and crown shape are quite variable. They also encompass a wide range of leaf type and tree heights. It is clear that stands with low stem densities may appear bright at L-band (Hess et al. 1990). Enhancement has also been shown for stands described as dense or thick (Hoffer et al. 1986, Ford and Casey 1988). Enhanced backscattering from flooded forests thus occurs over a broad range of tree species, canopy structures and stand densities. Richards et al. (1987b) demonstrated that brighter returns from flooded forests are not simply a function of vegetation differences between upland and lowland sites. They were able to clearly distinguish between flooded and non-flooded portions of a single forest type.

The accuracy of flood detection using radar imagery is difficult to determine since most studies of flooded forests focus only on those areas which do yield bright L-band returns. Near or complete absence of backscatter from flooded Maryland swamps with dense canopies has been noted by Krohn et al. (1983). It appears that dense undergrowth may significantly affect double-bounce returns. Ford and Casey (1988) found the opposite to be true, however, in flooded mangrove forests of Kalimantan. They found that open stands of low slender trees did not yield bright returns on SIR-B imagery while adjacent denser mangrove stands did. The above examples suggest that for certain forest types, the extent of flooding beneath the canopy would be underestimated using L-band radar. Overestimation would occur if other targets yielding bright returns were mistaken for flooded forests. Other sources of bright returns would normally be able to be visually distinguished from flooded forest based on shape, pattern, associated features and minimal site knowledge. A more serious source of confusion is non-forest vegetation naturally occurring adjacent to flooded forest. Flooded marshes (emergent herbaceous vegetation) typically appear dark at L-band (Krohn et al. 1983, Ormsby et al. 1985). However, marsh vegetation sometimes yields bright returns very similar to those from flooded forests (Krohn et al. 1983).

The magnitude of enhancement associated with double bounce beneath flooded forests can vary significantly. In many studies, variations in magnitude appear to be the result of differences in stand composition as well as flooding (Hess et al. 1990). The problem of separating backscatter variation caused by differences in vegetation from that caused by flooding was minimised in the study by Richards et al. (1987b), because of the virtually monospecifc stands of eucalyptus examined. Backscattering from flooded and non-flooded sites within the forest was estimated to vary by 10.8 dB: a substantial difference. Treating the canopy as a uniform layer of small particles, Engheta and Elachi (1982) estimate the enhancement resulting from the presence of a perfectly reflecting surface beneath the canopy to be 3 to 6 dB. It appears from the literature that L-band radar imagery used in the current study should enable accurate delineation of floodwater boundaries.