A landscape approach to assess impacts of hydrological changes to vegetation communities of the Tonle Sap Floodplain

M.E. Arias[1], T.A. Cochrane[1], B. Caruso[1], T. Killeen[2], and M. Kummu[3]
[1]Department of Civil and Natural Resources Engineering, University of Canterbury
Private Bag 4800, Christchurch 8140
NEW ZEALAND
[2]Conservation International
1919 M Street, NW Suite 600, Washington DC 20036
USA
[3]Water & Development Research Group, Aalto University
P.O. Box 15200, FIN-00076, Aalto
FINLAND
E-mail: mauricio.arias@pg.canterbury.ac.nz

Abstract: *The Tonle Sap is South East Asia's largest lake and Cambodia's most important fishery. The hydrology of the Tonle Sap is directly linked to water levels of the Mekong River, which will experience major alterations as a response to hydropower development, irrigation, and climate change. This paper proposes a landscape approach to understand the impacts of hydrological alteration on the floodplain's terrestrial vegetation. A land cover map, a digital elevation map and historical water records were used to create histograms of water depth for key vegetation communities. These histograms were used to create maps of vegetation coverage probability for future scenarios of hydrological changes. Selected scenarios of water resources development and climate change were used to demonstrate how vegetation could shift within the floodplain. This approach generated satisfactory results for land cover classes that extend over large portions of the floodplain such as wet season rice, abandoned fields, flooded shrubland and open lake.*

Keywords: *Hydroecology, Cambodia, Mekong River Basin, geographical information system*

1. INTRODUCTION

The Tonle Sap is the largest lake in Southeast Asia and forms one of the most diverse ecosystems in Cambodia and the Mekong River Basin (MRB). More than 1 million people live in the Tonle Sap Lake Floodplain (TSLF), and although only 6-16% of the population depends on fishing for their direct livelihood (Keskinen 2006), the intensive fishing effort makes the TSLF the most important fishery in Cambodia. The TSLF is also a habitat to a large diversity of unique terrestrial and aquatic organisms, and key areas of the floodplain have been designated as an UNESCO Biosphere Reserve (UNESCO 2010). The TSLF system covers an area of approximately 14,000 km^2, composed of an open water lake, a seasonally inundated floodplain, and a 120 km river that connects the TSLF with the Mekong River (MRC 2005). During the dry season (November-May) water flows from the Tonle Sap River into the Mekong, but during the wet season (June-October) monsoonal rains flood the Mekong River, making the Tonle Sap River to reverse into the lake. This causes the TSLF to annually fluctuate 8 m in water depth, 11,000 km^2 in areal extent, and 60 km^3 in water volume (Kummu & Sarkkula 2008).

Considerable changes to the flood pulse of the TSLF could occur as a result of alterations to the MRB hydrology (Kummu & Sarkkula 2008). Changes in the foreseeable future (20-50 years) are expected to occur in the MRB both as a result of water resources development (hydropower and irrigation) and climate change. Numerical models capable of quantifying changes in the hydrology of the MRB and the TSLF have been developed (e.g., Kite 2001; Fujii et al. 2003; Sarkkula et al. 2003; Eastham et al. 2008; Västilä et al. 2010). Nonetheless, how to connect and interpret the results of these hydrological models into a model of the TSLF ecosystem is still a subject that requires further research. Kummu & Sarkkula (2008) used results from two hydrological models to assess the impact of development on the gallery forest and concluded that a small increase in the dry season water levels of the TSLF would expand the open lake by 17-40%, change that would permanently inundate a disproportionate fraction of this important and symbolic vegetation community. The Mekong River Commission (MRC) assessed how the results from their basin-wide modelling scenarios would impact the TSLF ecosystem. MRC estimated that the flooded area could be reduced by 7.3% (900 km^2) under a very high development scenario, but could be increased by 8% (960 km^2) under a 2030 climate change scenario (MRC 2010). Their assessment did not consider how floodplain vegetation types could redistribute within the floodplain to adapt to a changing flood pulse.

The objective of this paper is to propose and describe a landscape approach to model vegetation cover shifts in the TSLF as a response to flood pulse changes. We used a land use/land cover (LULC) map in combination with water depth maps to link major vegetation groups to hydrological flood regimes. Histograms of water depth associated with each LULC class during a baseline scenario were first determined. This historical relationship was then used to predict future vegetation cover in the floodplain as a function of water level changes from hydrologic model scenarios.

2. METHODS

The proposed landscape approach consists of four steps in which basic geographical and hydrological datasets are gathered and processed within a geographical information system (GIS) interface (Figure 1). All analyses were carried using ArcMap™ 9.3 with ArcInfo license and spatial analyst extension except for editing the probability tables which was done with Microsoft Excel.

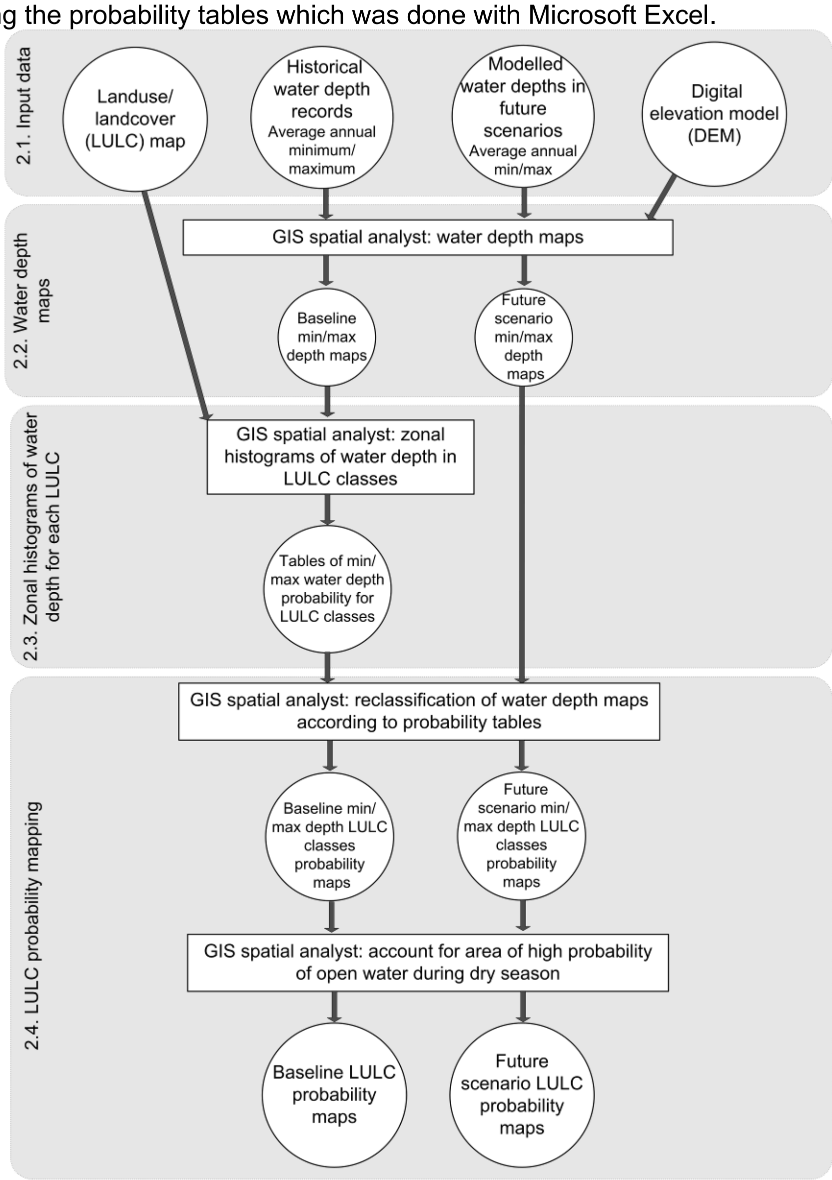

Figure 1 Schematic of the landscape approach to assess impacts of hydrological changes to vegetation communities of the Tonle Sap Floodplain. Circles indicate data and rectangles indicate processes.

2.1. Input data

The required input datasets include: 1) a LULC map, 2) a digital elevation model (DEM), 3) Historical daily water depth records, and 4) water depth results from modelled future scenarios. The LULC classes used for our analysis were extracted from the Japanese International Cooperation Agency (JICA) LULC map for Cambodia based on Landsat satellite images and aerial photography from the mid 1990s (Aruna Technology Ltd 2006). Only classes covering more than 1% of the total area, which spans from the open lake to an elevation of 15 m above mean sea level (amsl), were used. This resulted in seven unique LULC classes that cover 96% of the entire TSLF (Figure 2):

(i) Wet season rice: classified as *rice fields* in the original LULC map, consists mainly of rain-fed rice paddies grown during the wet season.
(ii) Abandoned fields: this class covers a large area between wet season rice fields and flooded vegetation, where deep water rice was traditionally grown at a large scale before the late 1970s. This area is covered with a mosaic of disturbance-indicating species (ie. *Mimosa pigra)*, farmed land vegetation, and natural vegetation found in the seasonally flooded classes (Hellsten et al. 2003).
(iii) Other agriculture: this class covers a large portion of the riparian zone along the Tonle Sap River where floating rice, receding rice, and a variety of other crops are planted.
(iv) (Seasonally) flooded shrubland: this class covers the largest area within the study boundaries and consists primarily of 3-6 m tall shrubs dominated by species such as *Vitex holoadenon*, *Combretum trifoliatum*, and young *Barringtonia acutangula* (McDonald et al. 1997). This area remains flooded for an average of 5 months every year.
(v) (Seasonally) flooded grassland: this class occurs in large stands surrounded by flooded shrubland. Flooded grasslands remain inundated on average 5-6 months every year.
(vi) Gallery forest: this class is classified as *flooded forest* in the JICA LULC map and it is dominated by tall *Barringtonia acutangula.* It borders most of the open lake and remains flooded an average of 8 months every year.
(vii) Open lake: this area represents the lake area that does not have rooted vegetation and remains flooded all year long.

The DEM used was a 20 m grid map created by JICA from stereo SPOT images (Milne & Tapley 2004). All maps were projected using UTM Indian 1960 Zone 48N coordinate system. Changes in lake water level were obtained from MRC for a monitoring station in Kampong Loung (12.575N 104.2144E).

2.2. Water depth maps

Average daily water level records at Kampong Loung were assumed to represent the water level throughout the inundated floodplain. These records were combined with the DEM to create maps representing the depth of water for every cell of the DEM at selected dates. The average annual maximum (8.88 m) and minimum water elevation (1.42 m) at Kampong Loung during the period between 1997 and 2000 were used to create depth maps of historical flooding (Figure 2c-d). This period of time represents our *baseline scenario*, because it matches closely the time when the JICA LULC map was developed and because it is a good representation of the recent hydrological history of the floodplain (Västilä et al. 2010).

Depth maps representing future scenarios were subsequently created. For demonstration purposes, two scenarios from predicted lake water level changes were used. Impacts from hydropower development and irrigation (*Development scenario*) was represented with results from ADB (2004), which predicted an increase of 0.60 m in water level during the dry season and an decrease of 0.54 m during the wet season after 20 years of water resources development in the MRB (ADB 2004 in Kummu & Sarkkula 2008). Impact of climate change (*climate change scenario*) was extracted from Västilä et al. (2010), who predicted a lake level increase of 0.16 m and 0.24 m during dry and wet seasons, respectively, as a cumulative impact of sea level rise and basin-wide climatic changes in the next 39 years.

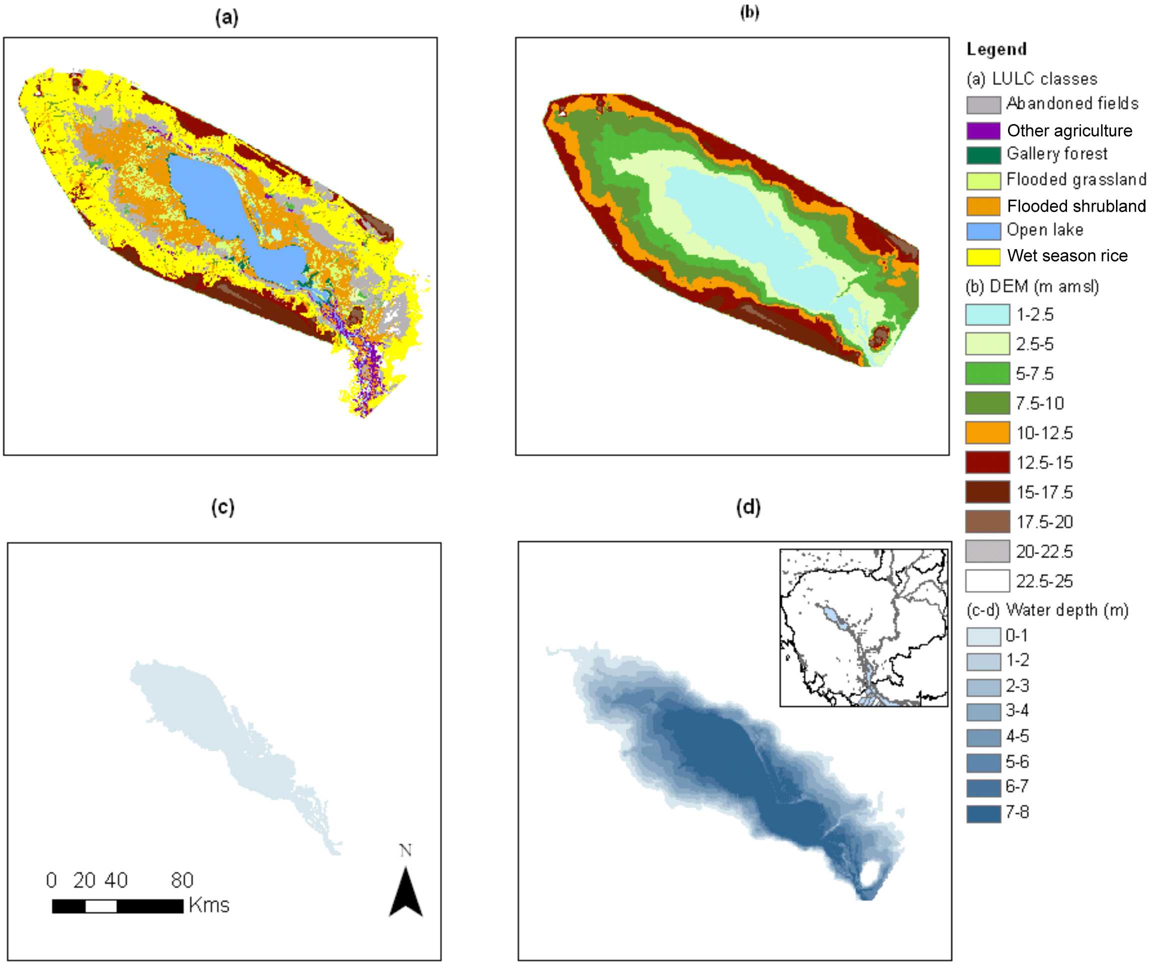

Figure 2 (a) Selected classes from JICA land use/land cover map (Aruna Technology Ltd 2006); (b) Digital elevation model (Milne & Tapley 2004); (c) Inundated extent and water depth at average yearly minimum water levels between 1997 and 2000; (d) Inundated extent and water depth at average yearly maximum water levels between 1997 and 2000. Insert shows the location of the Tonle Sap Lake and Mekong River in Cambodia.

2.3. Zonal histograms of water depth for each LULC

The baseline scenario water depth maps were used to create histograms of water depth for each LULC class. This was done using the zonal histogram function in the spatial analyst extension in ArcMap. The resulting tables showed how much area was flooded at different depth ranges within each LULC class. These tables were edited in Excel to normalize areal coverage at different depths relative to the total area covered by each LULC class, and in this way the likelihood of finding each LULC within a certain depth range was determined. Similarly, the area covered by different LULC was normalized based on the total area of floodplain covered at specific ranges of water depth. For instance, a total of 1347 km^2 throughout the floodplain experienced an average maximum water depth less than 1m in 1997-2000. We determined that this area was covered by 886 km^2 of wet season rice, 340 km^2 of abandoned fields and 20 km^2 of flooded shrubland, which represented 66%, 25%, and 2% of the total area with minimum flood depth. Since these percentages corresponded to the fraction of area covered by the LULC classes for the given water depth range, it was assumed that they are equivalent to the probability of each LULC class occurring as a response to maximum water depth below 1m.

2.4. LULC probability mapping

The tables of probability of LULC occurrence as a function of water depth were then converted into maps. Using the reclassification function in spatial analyst, maps of LULC occurrence probability were created for each LULC class for all three scenarios (total of 42 maps). Each probability map was created by reclassifying values in the water depth map with the value corresponding to the percentage of area covered by each LULC class for the specific range of water depth. Since only the open lake remains flooded throughout the year, maps of high probability of open water at minimum water depth were excluded from all the other probability maps to account for changes in the dry season water levels.

3. RESULTS AND DISCUSSION

3.1. LULC patterns during baseline period

Preliminary results of this study show that major LULC classes throughout the TSLF landscape are correlated to average minimum and maximum annual water levels. During the dry season, water depth throughout the floodplain is about 1 m, and most of the TSLF becomes dry except for the open lake (Table 1). The area covered with water during this time of the year was 3204 km^2, 80% of which was classified as Open lake. The remaining 20% corresponded primarily to Flooded shrubland, Flooded grassland, and Gallery forest. Although these vegetation types must become dry periodically in order to germinate, the analysis seems to indicate that it is not necessary for drying to occur every year. Alternatively, this could also be an artificial result of errors from the coarse LULC classification or DEM maps (e.g., detailed bathymetry was not included in the DEM).

During the wet season, there is a clear pattern of maximum depth of inundation that LULC classes are subject to (Table 1; Figure 3). Four clusters of coverage were found: 1) Wet season rice and Abandoned fields that dominate the areas with maximum water depth of 0-3m; 2) Other agriculture, Flooded shrubland, and Flooded grassland that covered most of the area with water depths 4-6m; 3) Gallery forest which mainly occurs in areas with maximum water depth of 6-8m; and 4) Open lake, which dominates the area with maximum water depths greater than 7m. However, there is some overlap between these clusters, mainly caused by Other agriculture and Gallery forest. Both of these LULC classes are relatively small and are located in particular transitional locations (i.e., Other agriculture on the Tonle Sap River and Gallery forest on the open lake edge) where other physical factors like availability of sediments and nutrients, or anthropogenic factors like accessibility, may play an important role. These external factors were not considered in this assessment.

Table 1 Areal coverage (km^2 and %, in parenthesis) of LULC classes as a function of annual average maximum and minimum water level in 1997-2000.

	Annual average maximum area coverage (km^2)									**Annual ave. min. area (km^2)**
Depth (m)	<1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	LULC total	≥1
Wet season rice	886 (66)	391 (32)	151 (12)	51 (4)	15 (1)	4 (0)	1 (0)	1 (0)	1500	1 (0)
Abandoned fields	340 (25)	648 (52)	634 (51)	329 (24)	102 (7)	17 (1)	9 (1)	3 (0)	2080	2 (0)
Other agriculture	13 (1)	17 (1)	27 (2)	37 (3)	33 (2)	41 (3)	13 (1)	31 (1)	212	27 (1)
Flooded shrubland	20 (2)	103 (8)	333 (27)	738 (53)	931 (65)	801 (65)	562 (63)	560 (16)	4049	429 (13)
Flooded grassland	13 (1)	21 (2)	39 (3)	100 (7)	262 (18)	289 (23)	205 (23)	124 (4)	1054	93 (3)
Gallery forest	0 (0)	2 (0)	5 (0)	16 (1)	14 (1)	17 (1)	45 (5)	98 (3)	197	80 (3)
Open lake	8 (1)	5 (0)	5 (0)	9 (1)	16 (1)	26 (2)	41 (5)	2591 (75)	2701	2572 (80)
Total flooded	1347	1242	1242	1384	1439	1234	894	3467	12250	3204

area											

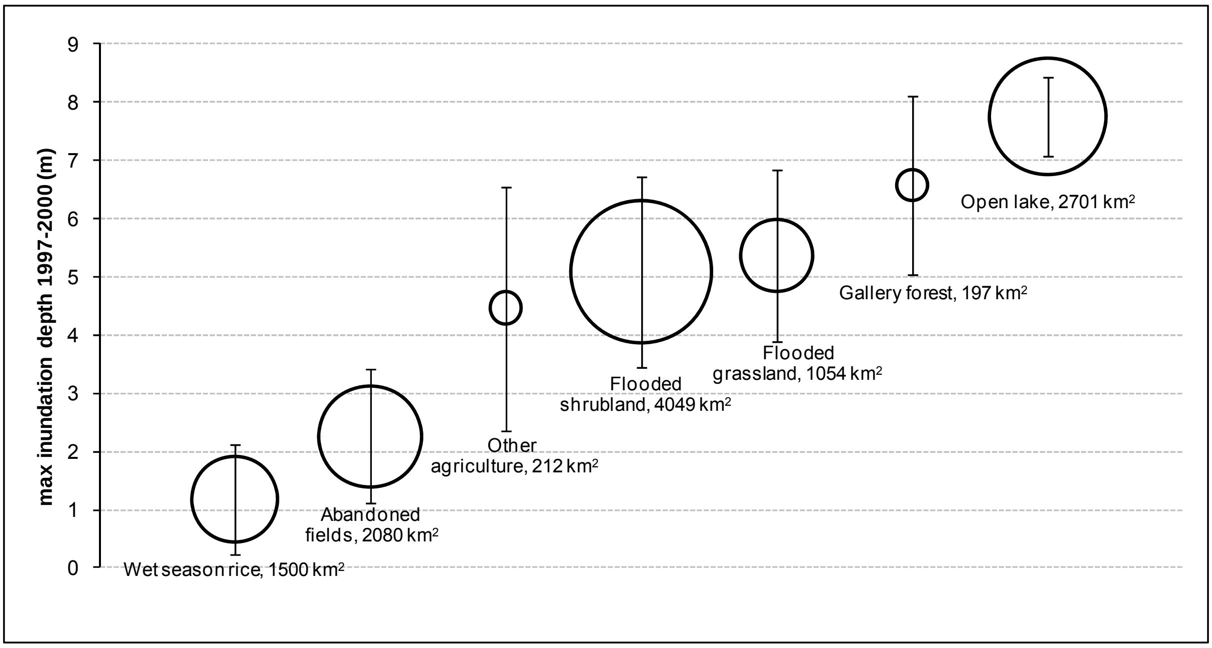

Figure 3 Mean distribution of maximum water depths in major land cover types during the period between 1997 and 2000. Bubble size and number next to LULC name represents area covered. Error bars set at 1 standard deviation.

The landscape patterns observed in this study are in good agreement with field observations throughout the floodplain. Wet season rice only withstands deep flooding for short periods of time (Hellsten et al. 2003), hence it is found in the outer perimeter of the floodplain where surface water is accessible part of the year but where maximum water depth is shallow. Traditional types of deep water rice can tolerate deeper waters much better than conventional rice (Sarkkula et al. 2003), and that is why this section of the floodplain with maximum inundation depth of 1-2m was traditionally used for this purpose before becoming abandoned. Flooded vegetation classes (shrubland, grassland, and gallery forest) have been documented to flood up to 7 m and to exhibit distinct patterns of structure and diversity of plant species, but as to what extent this is a result of flooding, human disturbance, or ecological factors remains unknown (McDonald et al. 1997). Despite these other disturbance factors that are possibly important –yet poorly studied and documented – it is quite remarkable that the historical land cover of the TSLF shows a strong association with flooding patterns. This provides a good baseline to study and model how the TSLF landscape might change in the future.

3.2. LULC change with future water resources scenarios

The relationship between water depth and LULC classes (Table 1) was used to create maps of coverage probability under the baseline, development, and climate change scenario (Figure 4). As a result of a development scenario, water level is expected to increase during the dry season and to decrease during the wet season. This could have different implications for the major LULC classes. Areas covered predominately with wet season rice would be reduced and move further into the floodplain. Areas with abandoned fields would be affected in a similar way as wet season rice, but to a much lesser extent. The area dominated by flooded shrubland and grassland would be considerably diminished as a result of both the reduction of water depth during the wet season in the outer part of the floodplain and the increase of the open lake during the dry season. In the climate change scenario, water level is expected to increase both during the dry and the wet seasons. This could lead to an expansion of wet season rice fields in the potentially extended outer boundary of the floodplain. Areas feasible for deep water rice would expand both inwards and outwards from the current abandoned fields. Areas covered with flooded shrubland and grasslands could expand upland from their current location throughout the entire floodplain.

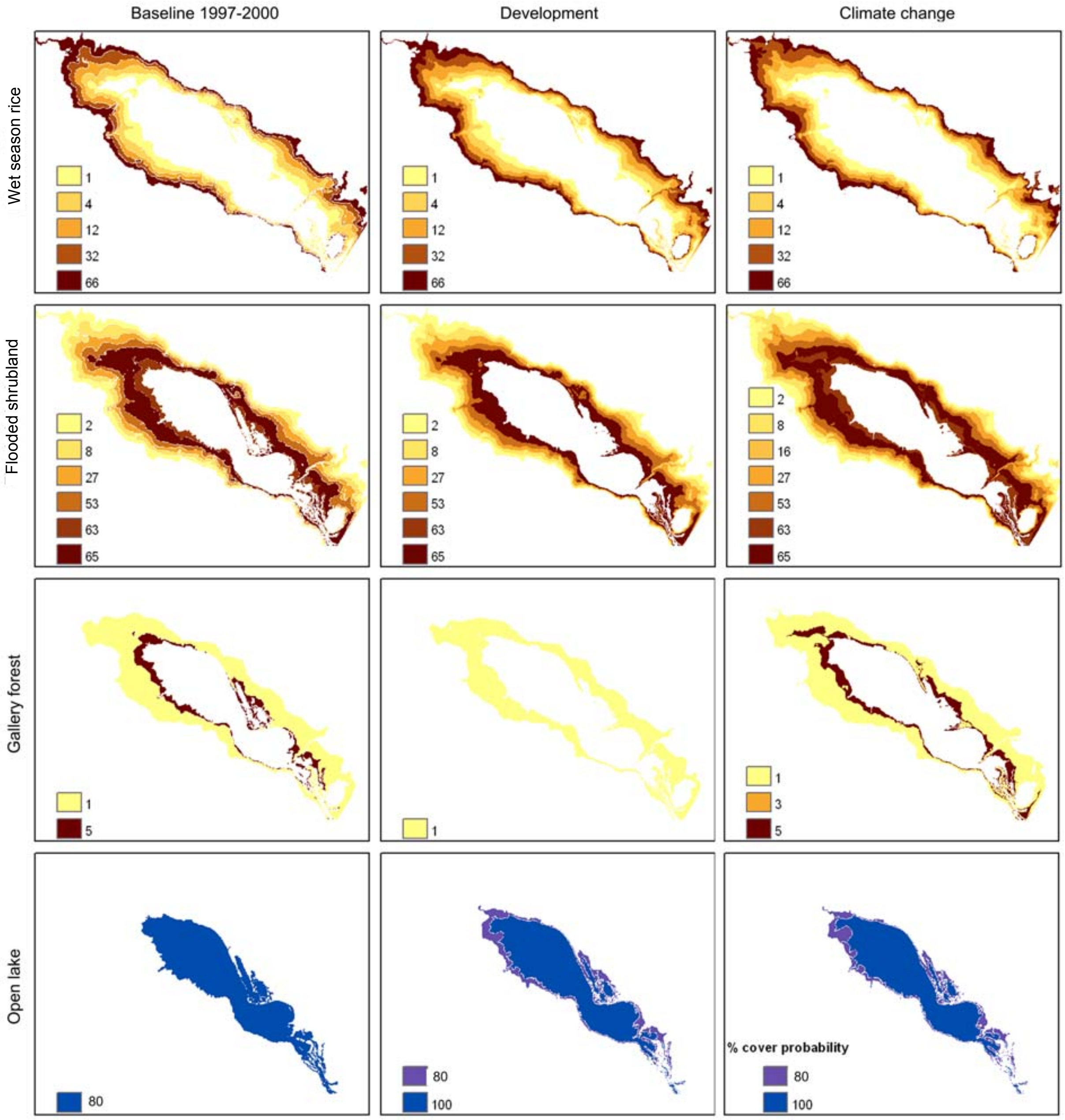

Figure 4 Maps of coverage probability of sample LULC classes as a function of average annual maximum and minimum water depth. Legend represents percent likelihood of coverage.

The probability maps presented in Figure 4 provide scenarios of potential shifts of the major LULC classes due to hydrologic changes. Based on these maps, it is possible to determine the most likely vegetation cover in the future. The best approach would be to use a maximum likelihood classification scheme to assign a vegetation cover to each grid cell using the highest LULC occurrence probability. Once the most probably vegetation cover as a response to flooding is mapped, other factors that also impact the LULC of the floodplain such as population pressure, irrigation reservoirs, and fisheries can be assessed.

In summary, this paper proposes a simple landscape approach to interpret the impacts that hydrological changes could have on vegetation cover of the TSLF. This approach generated satisfactory results for the LULC classes that covered large portions of the floodplain (Wet season rice, Abandoned fields, Flooded shrubland and Open lake). However, smaller and narrowly localized classes like Gallery forest and Other agriculture are not properly modelled because there are several other factors that may also determine the presence of these LULC classes. Future work will focus on extending the analysis to more results of hydrological models (including cumulative impacts of development and climate change combined), performing field surveys of floodplain vegetation to clarify some of the limitations and uncertainties of this landscape model, establishing monthly hydroperiods of the different vegetation classes to further refine the modelling relationships, and creating maps of future vegetation cover that can be used to quantify impacts on the ecological productivity of the TSLF.

4. ACKNOWLEDGMENTS

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