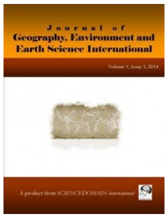

Journal of Geography, Environment and Earth Science International
5(3): 1-13, 2016; Article no.JGEESI.23531
ISSN: 2454-7352

SCIENCEDOMAIN ***international***
www.sciencedomain.org

An Exploratory Application of Remote Sensing Technologies and Statistical Analysis to Provide Rapid and Cost Effective Inundation Predictions for the Tonle Sap Lake Floodplain System

Elydia Binte Azman[1], Grace Eu Yi Ying[1], Lim Yean Yue Gladys[1], Seah Yiting[1], B. S. Wu[1*] and K. N. Irvine[1]

[1]National Institute of Education, Nanyang Technological University, 1 Nanyang Walk, Singapore 637616, Singapore.

Authors' contributions

This work was carried out in collaboration between all authors. All authors read and approved the final manuscript.

Article Information

DOI: 10.9734/JGEESI/2016/23531
Editor(s):
(1) Dr. Chew Hung Chang, National Institute of Education, 1 Nanyang Walk, Singapore.
(2) Dr. Diganta Das, National Institute of Education, 1 Nanyang Walk, Singapore.
Reviewers:
(1) Heng Chinda.
(2) Chew Hung Chang.
Complete Peer review History: http://sciencedomain.org/review-history/13396

Conference Proceeding

Received 5th August 2015
Accepted 17th September 2015
Published 23rd February 2016

ABSTRACT

Aims: The objective of this study is twofold: i) explore a simple, empirical relationship based on freely available, remotely sensed data and the water levels recorded at Prek Kdam (one week prior) to predict total inundated area of the Tonle Sap flood plain; and ii) use the relationship to provide a preliminary demarcation of flood risk zones around the Tonle Sap Lake.

Study Design: This study is designed to predict inundation in the Tonle Sap Lake, Cambodia.

Place and Duration of Study: Tonle Sap Lake, with data and satellite images for the period between June 2008 and November 2013.

**Corresponding author: E-mail: bingsheng.wu@nie.edu.sg;*
Note: This paper was presented in SEAGA (Southeast Asian Geographers Association) International Conference 2014, Siem Reap, Cambodia (at Royal University of Phnom Penh), 25 - 28 November 2014.

Methodology: Three approaches were adopted in this study: 1) Classification: to examine flooded regions during wet seasons by Landsat images. 2) Regression model: to explore the relationship between the flooded areas and water level at Prek Kdam, near the mouth of the Tonle Sap Lake. 3) Visualization and estimation: To observe dynamics of inundation and predict the potential flooded areas based on the regression.

Results: The adoption of GIS and remote sensing helps the delineation of flood zones. The results of the statistical analysis demonstrated a strong linear relationship between water levels at Prek Kdam and flooded areas at the Tonle Sap Lake. Together with the adoption of GIS and remote sensing technologies, the regression model can be further used to support flood prediction, management and regional planning.

Conclusion: This research develops a flood warning tool for the government and the public to intuitively evaluate the potential flooding areas in the Tonle Sap Lake during monsoon seasons. It can further help the government prepare for flood risk management and develop a sustainable environment.

Keywords: Tonle Sap Lake; floodplain; remote sensing; GIS; regression model.

1. INTRODUCTION

The Tonle Sap Lake, Cambodia, is the largest inland freshwater lake in Southeast Asia and one that has both a remarkable natural and cultural history (Fig. 1). Sometimes called the “Heart of the Mekong” because of its important role in the biodiversity and aquatic life of the great river, it also is home to floating villages, riparian communities (with more than 1.2 million people living on the lake and immediate floodplain between National Roads 5 and 6), accounts for around 60% of Cambodia’s total annual inland fish catch, and is the primary reason why provinces bordering the lake have amongst the highest fish and other aquatic organism consumption in the Lower Mekong Basin [1-3]. The highly biodiverse and productive fishery of the lake is maintained by what is known as the “flood pulse” phenomenon [4,5] generated by the monsoon rains and snowmelt from the Himalayas. As flow rate and water levels rise on the mainstem of the Mekong River in May/June, eventually there is not sufficient capacity for all water to discharge to the ocean via the Mekong Delta. At this point, the flood pulse travels up the Tonle Sap River, expanding the size of the lake. When the dry season commences and flow on the Mekong River declines, water will begin to drain from the lake, reversing the direction of flow on the Tonle Sap River. Because of this ‘pulsing’ characteristic, the surface area of the Tonle Sap Lake varies from about 2,500 km^2 during the dry season to about 15,000 km^2 in the rainy season (roughly the size of Lake Ontario in North America). Water depth increases from around 1 m in the dry season to approximately 7–9 m in the rainy season [6,7]. Water quality of the lake is impacted by the pulsing characteristic (e.g. [8-10]) and there is a positive correlation between annual fish catch (tons) and peak water level during the rainy season [8,11]. Given the growing pressure from development within the Mekong Basin countries and the increase in constructed and planned dams for hydropower (e.g. [12-15]), it is understandable there have been a number of recent studies trying to assess impacts of such development on the lake’s ecosystem, fisheries, food security, and society (e.g. [16-23]).

Besides the benefit of highflows and water levels in the rainy season to fisheries, as in all river basins there is a risk of societal impact due to flooding. Most recently, between the end of October and end November, 2011, there were 331,765 households (over 1.5 million people) affected by flooding with 247 people losing their life; 46,403 households being evacuated; and 232,377 hectares of rice fields, representing 9.4 per cent of the total rice crop area in Cambodia, reported as damaged [24]. The flow magnitude at the Kratie gauge on the mainstem of the Mekong River upstream of the Tonle Sap during this period was slightly greater than a 10 year return period. Theoretically, the large cascading system of dams being planned and constructed in China will reduce such flood impacts by shaving off peak flows through prudent storage, although analysis of flow data to date suggest discharge alterations during the rainy season so far were relatively small at the Mekong River Commission’s Chiang Saen (northern Thailand) gauge [25].

Fig. 1. Physiographic characteristics of the Tonle Sap/Mekong system in Cambodia and Vietnam

A variety of approaches have been developed to forecast flooding on the Mekong River over the past 15 years. These have included different levels of deterministic modeling, such as non-linear reservoir or tank type approaches to represent different components of the rainfall-runoff cycle; semi-distributed, grid based, macroscale models that represent the interaction between land cover, climate, and runoff generation; one, two, and three-dimensional hydrodynamic modeling; as well as more probabilistic-oriented modeling [16,26-30]. Johnston and Kummu [31] provided a thorough review of historical modeling efforts for the Mekong River, with Johnston and Smakhtin [32] further noting "Repeated modeling using different algorithms with the same data has limited value. A case in point is hydrodynamic modeling of the Lower Mekong floodplain and delta. No fewer than seven hydrodynamic models have been built for this region, but all are constrained by the quality of the existing DEM and availability of reliable, up-to-date information on floodplain infrastructure." Others have used satellite imagery or a combination of satellite imagery and modeling to assess flooding (e.g. [33-39]). Although different satellites and software systems have been used, most often the focus of these studies has been the remote sensing methodology and the applications tend to be at a broader temporal (i.e. tracking changes in floods) and spatial scale (i.e. whole basin). When the satellite imagery assessment was linked to the hydrologic/hydraulic modeling, it tended to be a fairly sophisticated model application.

The objective of this study is twofold: i) at the risk of seeming to perpetuate modeling studies, we explore a simple, empirical relationship based on freely available, remotely sensed data and the water levels recorded at Prek Kdam (one week prior) to predict total inundated area of the Tonle Sap flood plain; and ii) use the relationship to provide a preliminary demarcation of flood risk zones around the Tonle Sap Lake.

2. MATERIALS AND METHODS

2.1 The Tonle Sap – Physiography and Hydrometeorology

The Tonle Sap Lake and basin form the central area of Cambodia and are rimmed by the Cardamom Mountains and Elephant Mountains to the southwest and the Dangrek Mountains to the north (Fig. 1). The total contributing area of the basin to the lake is 67,000 m^2. There is some debate regarding the formation of the Tonle Sap Lake and the development of the flood pulse phenomenon. Penny [40] noted that a Japanese team examined the stratigraphy and mineralogy of sediment cores from the lake and concluded the lake started as a series of smaller lakes connected by extensive wetlands but by the mid-Holocene (approximately 5,500-5,000 B.P.) the interconnected pulsing between the Mekong River and Tonle Sap began. However, Penny [40] examined the stratigraphy and pollen record from three cores that he collected and concluded the lake was influenced by tidal and saline water in the early-Holocene, roughly >7,000-5,500 B.P. More recently, Day et al. [41] used Sr, Nd, and Pb isotopes and elemental levels in sediment cores from the lake and they suggested the current pulsing-type system developed between 5,600 and 3,600 BP. Regardless of the exact time when the pulsing system was initiated, it can be concluded that the system has been in place for thousands of years.

2.2 Regression Modelling and Flood Maps

The Mekong River Commission (MRC) has a flood management and early warning program in place (http://ffw.mrcmekong.org/) and Plate [42] provided a review of the three components of such a system: a) flood forecasting and prediction; b) transmission of the forecast into a warning for local communities; and c) conversion of the flood warning into remedial action. The water level gauge at Prek Kdam is one of 23 monitoring stations on the Mekong River system and is located approximately 100 km south of the Tonle Sap Lake (Fig. 2.). Kummu et al. [43] calculated the water balance for the lake at a daily time step over an eight-year period (May 1997 to April 2005) and concluded 53.5% of the lake's water originates from the Mekong River, 34% comes from the lake's direct tributaries, and 12.5% comes from precipitation. Clearly, then, the Mekong River flow has a dominant role in the lake's water balance. A representative range of water levels, as measured at the MRC's Prek Kdam gauge, is shown in Fig. 3. This graph reveals water levels can be quite different under various wet and dry conditions and suggests the inundation of the Tonle Sap Lake floodplain may be forecast by changes of water levels. As a result, remote sensing images were used to extract the flooded areas for the examination of a potential relation with water level data at the Prek Kdam site. The MRC has made available water level data for 23 stations since 2008 (http://ffw.mrcmekong.org/historical_rec.htm).
Landsat images of the Tonle Sap Lake were selected for the period 2008 to 2013 (Table 1) for an exploratory test of the feasibility to forecast floodplain inundation most simply using freely available remotely sensed data. Images were selected during start and peak of wet seasons. Four main categories – water body (blue), flooded areas (red), land (earth) and cloud (white), were classified in Erdas Imagine software (Fig. 4.). The classification results were also used to draw boundaries of flooded regions and Tonle Sap Lake in monsoon seasons. The areas of inundated regions in different years were further computed and used for regression modeling and flood maps.

Table 1. Landsat images of the Tonle Sap Lake during 2008 and 2013

	Wet season – Start		Wet season – Peak	
Year	**Date**	**Image type**	**Date**	**Image type**
2013	1 & 10 June	Landsat 7 SLC Off	23 Oct & 1 Nov	Landsat 7 SLC Off
2011	28 June & 7 July	Landsat 4/5	18 & 27 Oct	Landsat 4/5
2010	12 & 19 June	Landsat 4/5	16 & 23 Oct	Landsat 4/5
2009	29 May & 7 June	Landsat 4/5	29 Oct & 5 Nov	Landsat 4/5
2008	20 & 27 June	Landsat 4/5	30 Aug & 8 Sept	Landsat 4/5

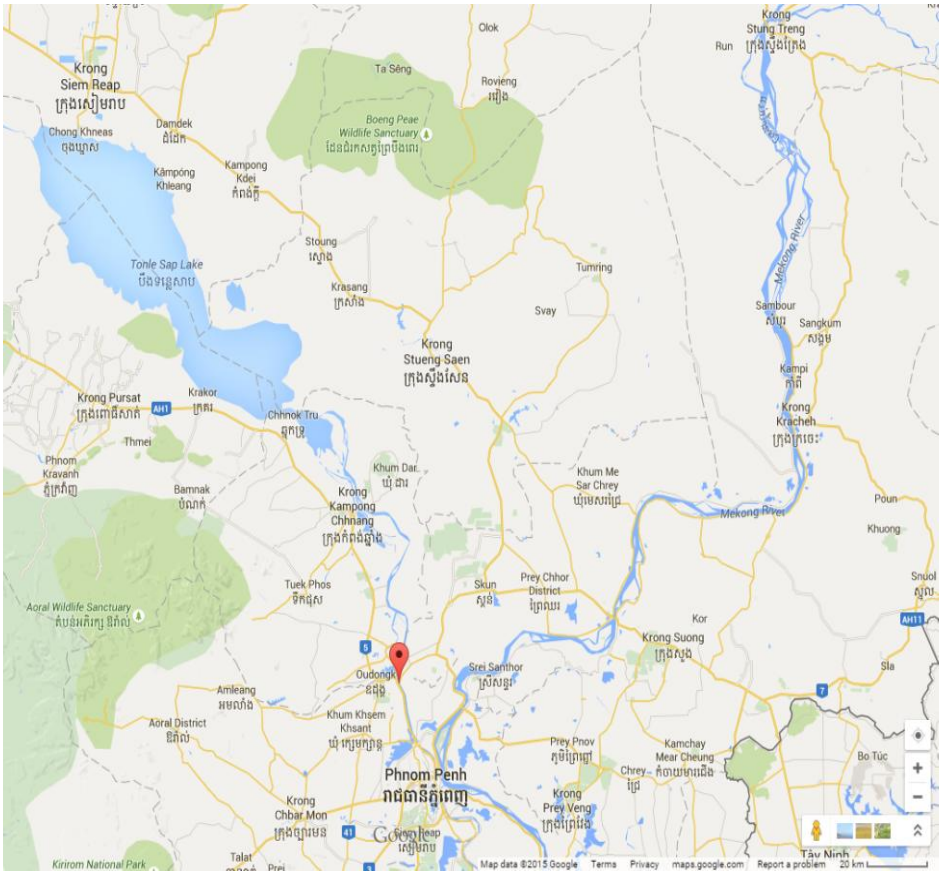

Fig. 2. Prek Kdam (the red symbol) and the Tonle Sap
Source: Google Maps

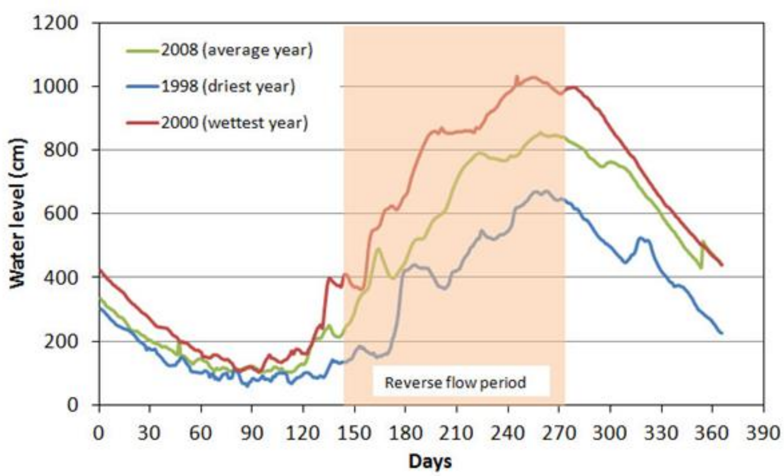

Fig. 3. Historical water levels as measured at Prek Kdam
(from http://mekongriver.info/historic-flows)

To explore the relationship between water levels and inundated regions of the Tonle Sap, a linear regression model was built through data analysis in Microsoft Excel. Taking into consideration the lag time between Prek Kdam and the lake, as well as the different dates of each image, a simple approach was used to identify the dates of water level data at Prek Kdam that should be included in the analysis (Fig. 5.). To further visualize the inundated areas under different water levels, boundaries of flooded regions in classified images were digitized and overlaid in ArcGIS10.

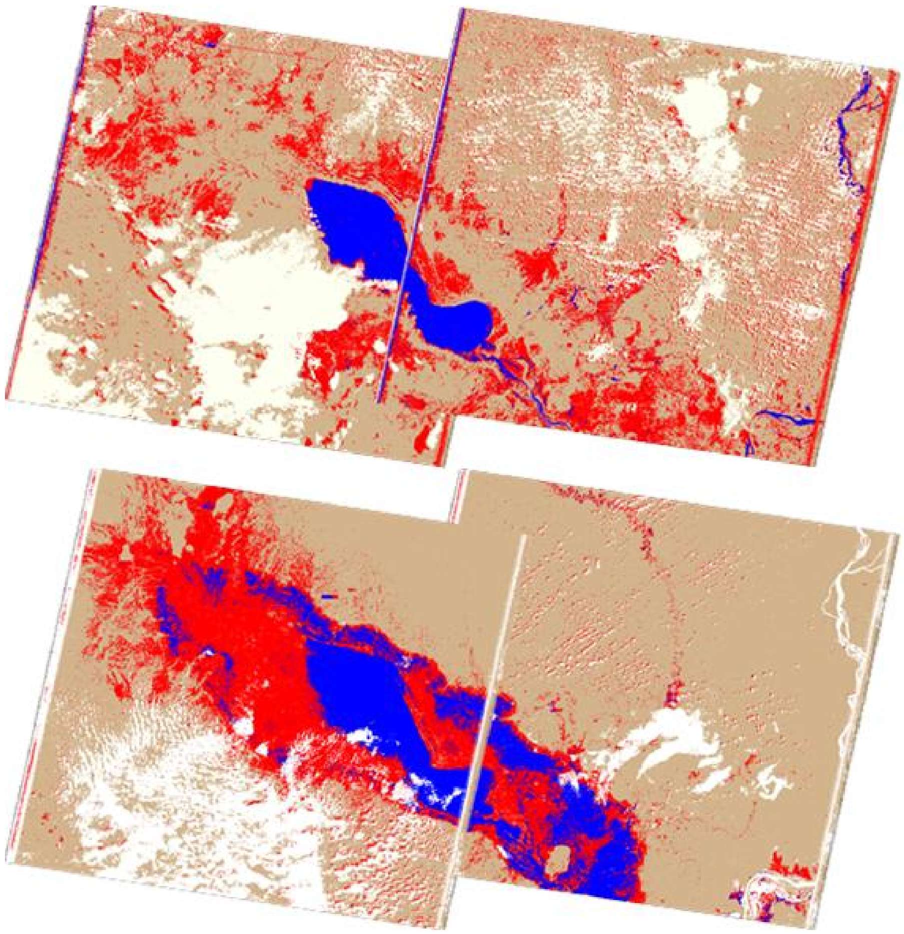

Fig. 4. Start (above) and peak (below) of the wet season at the Tonle Sap Lake (Oct 2011)

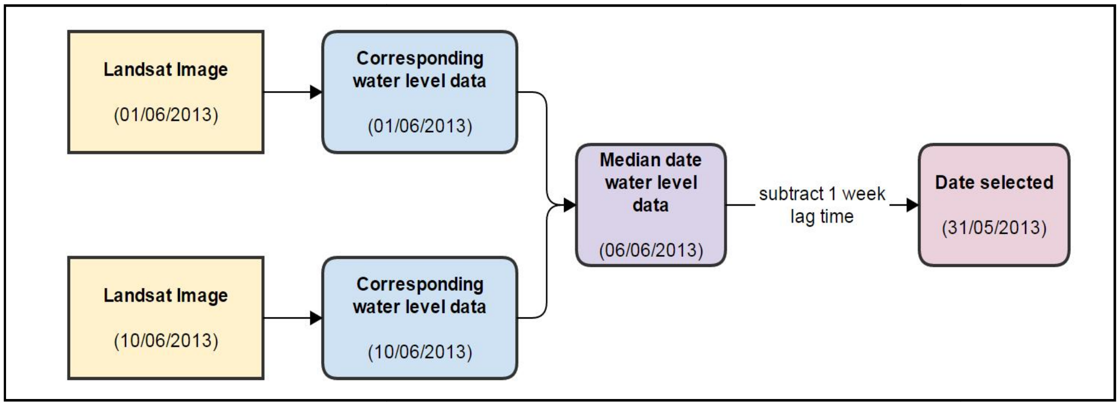

Fig. 5. The approach to specify the date of water level data used in the inundation analysis

3. RESULTS AND DISCUSSION

The results of the statistical analysis demonstrated a strong linear relationship between water levels at Prek Kdam and flooded areas at the Tonle Sap Lake (Fig. 6.). Together with the adoption of GIS and remote sensing technologies, the regression model can be used to estimate the range of potentially flooded areas. According to the results of digitizing and overlay processes, Fig. 7(a) visualizes the inundated regions under different water levels at Prek Kdam for the 2008-2013 period. Fig. 7(b) identifies 4 zones as prone to annual flooding based on common trends of inundated regions across the six years. Zone 1 is the area around the mouth of the Tonle Sap Lake. If water level at Prek Kdam is higher than 7 meter, this zone likely will be inundated. Zone 3, the furthest from the Mekong River source, has a lower chance to be inundated if water level at Prek Kdam is not high enough. Since a large extent of these two regions will be affected during the flooding season, it is essential to evaluate the effectiveness of the flood mitigation approaches [44] and adopt better flood preparation and response plans in these two zones. Due to the restriction of terrain, the inundation areas in Zone 2, the region at the northeast side of the Tonle Sap Lake, and Zone 4, the region at the southwest side of the Tonle Sap Lake, are not as large as Zone 1 and Zone 3. However, there are two main roads along the Tonle Sap Lake, National Roads 5 and 6. When the water level at Prek Kdam is higher, these two roads will be likely inundated and affect the traffic between south and north parts of the Tonle Sap Lake. It may influence the evacuation and emergency responses of Zone 3.

The adoption of GIS and remote sensing helps the delineation of flood zones to support flood management planning. Doch et al. [45] observed that there are numerous government agencies (and NGOs) in Cambodia that deal with flood management, but several issues limit the effectiveness of this management. First, there appears to be an overlap of mandates in a number of cases, with no clear coordination of planning or on-the-ground efforts. Resources to support water management planning efforts are limited and agencies often see each other competing for these limited funds, which also hampers coordination. These challenges are not uncommon in Cambodia's water resource sector [46]. Finally, Doch et al. [45] noted that the Ministry of Water Resources and Meteorology (MOWRAM) have responsibility for pre-flood intervention measures, including early warning systems, while the National Committee for Disaster Management (NCDM), an inter-ministerial, multi-level group has responsibility to reduce disaster risk from floods that includes early warning, evacuation, and recovery plans. Despite these mandates, Doch et al. [45] concluded that the provincial departments of MOWRAM had no reliable tools to study and predict a flood event. The approach outlined in this study can provide a simple, easily understood, and quickly applied flood inundation tool to warn communities on the lake up to one week in advance. GIS also has the potential for other applications in flood management. For example, Dewan [44] used GIS to evaluate the effectiveness of the flood mitigation approaches like the construction of embankments in India, while Tran et al. [47] applied GIS to assist with the development of emergency evacuation plans. Doch et al. [45] used GIS and mapping at watershed, commune, and household scales to assess the vulnerability of agricultural communities to flooding in the Sangke River watershed, a tributary to the northwest end of the lake that is adjacent to Siem Reap Province and flows through the city of Battambang. As a result, the simulation of inundation of the Tonle Sap Lake through the measurement of water level at Prek Kdam can be further adopted in two main areas: (a) regional and urban planning, and (b) flood disaster management, and helps mitigation of negative impacts under extreme floods in the Tonle Sap Lake.

3.1 Regional and Urban Planning

Much of the floodplain area around the lake is rural land use but there are numerous villages that line the national roads, rural roads, and major tributaries in this area (Fig. 8.). Traditional rural Cambodian houses generally are built on stilts, in part as a form of adaptation to frequent flooding conditions (Fig. 9.). However, as observed during the 2011 flood, often groups of houses were isolated in pockets of higher ground, requiring inhabitants to be evacuated by boat. Early warning can increase evacuation times and movement of valuable assets to higher ground, or provides time for sand bag and temporary dike construction. However, early warning will not provide protection to crop loss. As an alternative, community preparation, to the household level, needs to be considered. Doch et al. [45] in their household survey for the Sangke River watershed noted that adaptive capacity to floods depended on food security and income, but often depended on access to credit, external aid, and sale of household assets. They reported that agricultural innovation and structural adaptation measures were relatively scarce and that there was a need for improved dialog between government agencies (national and provincial), NGOs, and local communities.

The principal urban areas in the Tonle Sap floodplain that were impacted by the 2011 flood include Kampong Channang, Kampong Thom, Siem Reap, and Battambong. Although Molyvann [48] noted that Cambodian cities have a long history of water management using combinations of dikes, wetlands, and "prek and bong" (prek is a canal cut through river bank levees to allow silt-rich flood waters to enter agricultural lands behind the levee and to fill bongs, or ponds, also in the agricultural area), such systems were not capable of holding back the 2011 flood waters. Similarly, national and

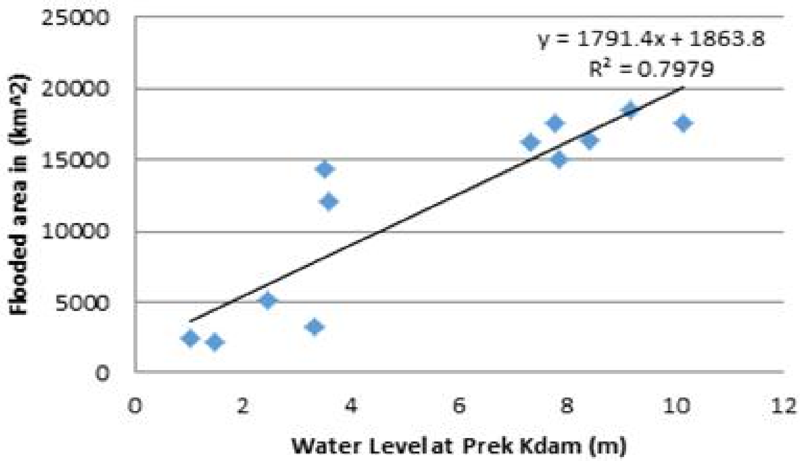

Fig. 6. Relationship between the flooded area in the Tonle Sap and the water level at Prek Kdam

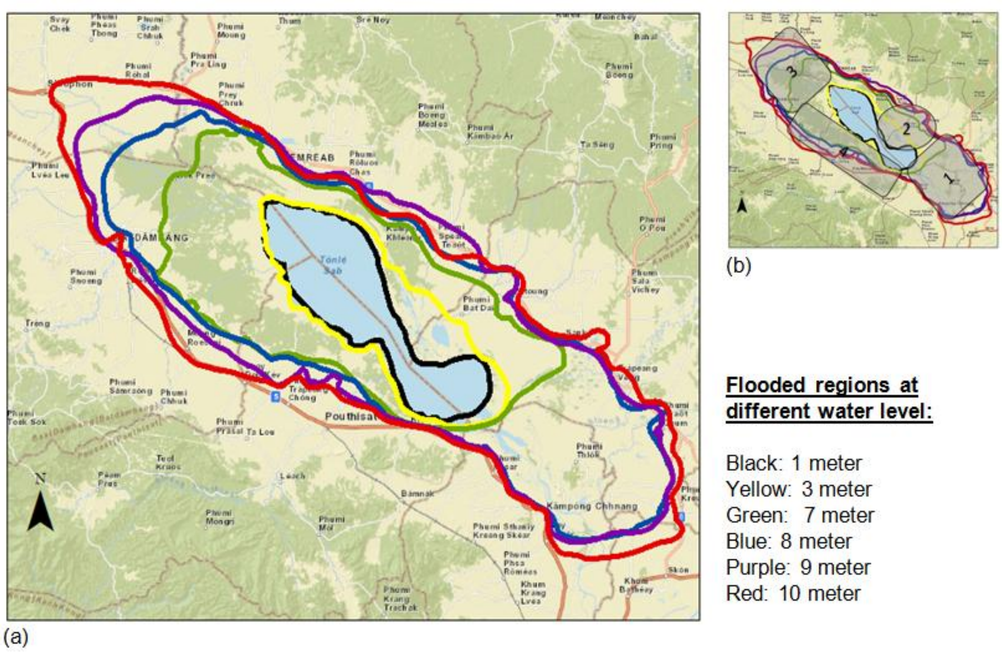

Fig. 7. (a) The flooded regions under various water levels at Prek Kdam and (b) 4 flood zones

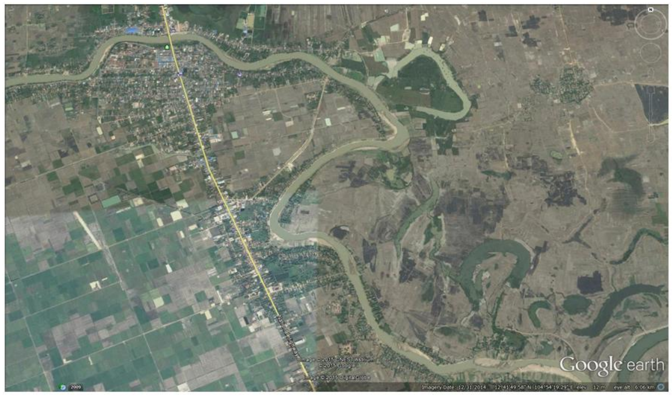

Fig. 8. Villages (and the provincial capital of Kampong Thom to the north) stretch along elevated areas bordering National Road 5 and the Sen River

Fig. 9. Traditional rural Cambodian house constructed on stilts, Kampong Thom region

local roads were extensively damaged during this flood. Even in developed countries using state-of-the-art water engineering technologies, damage due to extreme weather conditions occurs [49]. For instance, Hurricane Katrina hit New Orleans in 2005 and more than half of the levees were destroyed, resulting in many people losing their lives and homes [50]. However, given the lead time of up to a week, it may be cost-effective to implement temporary flood control measures (e.g. regular sand bagging and “big bag techniques) in urban areas with great structural and commodity assets as was done with some level of success for downtown Bangkok during the same 2011 flood [51].

3.2 Flood Disaster Management

Due to the regular frequency of flooding in the Tonle Sap Lake, prediction constitutes one of the crucial disaster management strategies because it helps ample evacuation time to reduce damages to property, livestock and human lives [52]. The integration of the flood zone map and the regression model of water level dynamics at Prek Kdam provide a simple yet intuitive disaster management tool. First, the spatial extent of flooded areas can be used to identify the risks and vulnerability. Second, real time water levels data at Prek Kdam can be immediately used to predict the spatial extent of flooding at the lake. If there is a drastic change of water level at Prek Kdam, in terms of the lag time, flood risk areas with a proper size of the buffer zone will be highlighted, so the government (provincial MOWRAM offices and NCDM) can indicate the possibility of an extreme flood in the Tonle Sap Lake several day earlier and warn people living in the flood risk areas to take proper actions. Residents living within the flood risk areas would be provided sufficient time to take the necessary precautions. The development of the buffer zone is to alert residents who are not in the flood risk areas but might be affected. These warnings would be especially helpful for residents at Zone 2 and 4. In 2011, for instance, 54,414 households in Kampong Khleang and Kampong Thom (Zone 2) were affected [24]. If the local authorities can prepare by putting in place emergency evacuation plans and relocating people before the arrival of floods, damage and lose of life will be reduced.

The government also needs to be aware of the efficiency of evacuation. If water level at Prek Kdam is higher than 10 meters, it is likely that main roads in Zone 2 and 4 and around the Tonle Sap Lake will be inundated, which will increase the difficulty of land-based evacuation of residents in Zone 3. The government should prioritize these areas when providing updated and real-time information on water levels and assistance available for swift evacuation.

4. CONCLUSION

This research develops a flood warning tool for the government and the public to intuitively evaluate the potential flooding areas in the Tonle Sap Lake during monsoon seasons. Unlike sophisticated approaches using hydrological modeling or geo-spatial analyses for flooding simulation, this research integrates GIS, remote sensing, and statistical analysis to generate a linear regression model of water level and establish visualization of inundated regions in the Tonle Sap Lake. Through spatial representation and changes of water level, this research reveals a simple yet feasible approach to predict the spatial extent of flooding in the Tonle Sap Lake. This approach can be further adopted into urban planning and flood disaster management. The government will then be able to focus on specific flood prone areas when issuing warnings or evacuating residents.

This study was meant as an exploratory assessment to combine freely available satellite imagery with simple statistical analysis of water levels from the MRC gauge station at Prek Kdam to predict inundation areas around the Tonle Sap. While this approach is promising, additional years of data should be analyzed to strengthen forecast certainty. High-resolution remote sensing images such as Quickbird or IKONOS could be adopted to better delineate the exact locations of the villages and flooded areas. Field-truthing, that includes village surveys to confirm inundation areas for given years, also should be conducted. Finally, the analytical approach can be further extended as a dynamic model to evaluate real-time flooding areas via the changes of water level data. In addition, although precipitation does not significantly contribute to the source of the lake's water, it certainly plays a role in the fluctuation of water level. The numerical data of precipitation and rainfall patterns will be considered in this model. To implement the dynamic model and simulate the expansion of inundated regions, Cellular automata (CA) can be introduced as a key part of the methodological framework. The rationale of CA is to develop rules based on statistical analyses and reveal how various driving factors play different roles in land-use changes [53]. The CA-based modeling will be able to link the linear regression of water level data and simulate different scenarios. The scenarios can further help the government better prepare for flood risk management and develop a sustainable environment.

DISCLAIMER

SEAGA (Southeast Asian Geographers Association) International Conference 2014, Siem Reap, Cambodia (at Royal University of Phnom Penh), 25 - 28 November 2014.

ACKNOWLEDGEMENTS

We would like to thank reviewers whose perceptive comments have enriched this paper.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. Baran E. Cambodian inland fisheries: Facts, figures and context. WorldFish; 2005.
2. Keskinen M. The lake with floating villages: Socio-economic analysis of the Tonle Sap Lake. Water Resour Dev. 2006;22(3):463-480.
3. Hortle KG. Consumption and the yield of fish and other aquatic animals from the Lower Mekong Basin. MRC Technical Paper. 2007;16:1-88.
4. Lamberts D. Little impact, much damage: The consequences of Mekong River flow alterations for the Tonle Sap ecosystem. Modern Myths of the Mekong, Water & Development Publications - Helsinki University of Technology; 2008.

5. Lamberts D, Koponen J. Flood pulse alterations and productivity of the Tonle Sap ecosystem: A model for impact assessment. Ambio. 2008;37(3):178-184.
6. Fujii H, Garsdal H, Ward P, Ishii M, Morishita K, Boivin T. Hydrological roles of the Cambodian floodplain of the Mekong River. Int J River Basin Manag. 2003;1(3):253-266.
7. Koponen J, Kummu M, Sarkkula J. Modelling environmental change in Tonle Sap Lake, Cambodia. Internationale Vereinigung fur Theoretische und Angewandte Limnologie Verhandlungen. 2005;29(2):1083-1086.
8. Van Zalinge N, Loeung D, Pengbun N, Sarkkula J, Koponen J. Mekong flood levels and Tonle Sap fish catches. Second International Symposium on the Management of Large Rivers for Fisheries, at Phnom Penh, Cambodia; 2003.
9. Campbell IC, Poole C, Giesen W, Valbo-Jorgensen J. Species diversity and ecology of Tonle Sap Great Lake, Cambodia. Aquat Sci. 2006;68(3):355-373.
10. Irvine K, Richey J, Holtgrieve G, Sarkkula J, Sampson M. Spatial and temporal variability of turbidity, dissolved oxygen, conductivity, temperature, and fluorescence in the lower Mekong River–Tonle Sap system identified using continuous monitoring. Int J River Basin Manag. 2011;9(2):151-168.
11. Baran E, Van Zalinge N, Bun NP. Floods, floodplains and fish production in the Mekong basin: Present and past trends. Contribution to the Asian Wetlands Symposium; 2001.
12. Dore, J, Yu X, Li K. China's energy reforms and hydropower expansion in Yunnan. In: Lebel L, John Dore J, Danial R, Koma YS, editors. Democratizing Water Governance in the Mekong Region. Thailand: Mekong Press; 2007.
13. Greacen C, Palettu A. Electricity sector planning and hydropower. In: Lebel L, John Dore J, Danial R, Koma YS, editors. Democratizing Water Governance in the Mekong Region. Thailand: Mekong Press; 2007.
14. Stone R. Mayhem on the Mekong. Sci. 2011;333(6044):814-818.
15. Kuenzer C, Campbell I, Roch M, Leinenkugel P, Tuan VQ, Dech S. Understanding the impact of hydropower developments in the context of upstream–downstream relations in the Mekong river basin. Sustain Sci. 2013;8(4):565-584.
16. Kummu M, Koponen J, Sarkkula J. Assessing impacts of the Mekong development in the Tonle Sap Lake. Proceedings of the International Symposium on Role of Water Sciences in Transboundary River Basin Management; 2005.
17. Kummu M, Sarkkula J, Koponen J, Nikula J. Ecosystem management of the Tonle Sap Lake: An integrated modelling approach. Int J Water Resour Dev. 2006;22(3):497-519.
18. Baran E, Myschowoda C. Dams and fisheries in the Mekong Basin. Aquat Ecosyst Health Manag. 2009;12(3):227-234.
19. Friend R, Arthur R, Keskinen M. Songs of the doomed: the continuing neglect of capture fisheries in hydropower development in the Mekong. Contested waterscapes in the Mekong region: Hydropower, livelihoods and governance. 2009;307-332.
20. Arias ME, Cochrane TA, Piman T, Kummu M, Caruso BS, Killeen TJ. Quantifying changes in flooding and habitats in the Tonle Sap Lake (Cambodia) caused by water infrastructure development and climate change in the Mekong Basin. J Environ Manage. 2012;112:53-66.
21. Orr S, Pittock J, Chapagain A, Dumaresq D. Dams on the Mekong River: Lost fish protein and the implications for land and water resources. Glob Environ Change. 2012;22(4):925-932.
22. Arias M, Piman T, Lauri H, Cochrane T, Kummu M. Dams on Mekong tributaries as significant contributors of hydrological alterations to the Tonle Sap Floodplain in Cambodia. Hydrol and Earth Sys Sci. 2014;18(12):5303-5315.
23. Arias, ME, Cochrane TA, Kummu M, Lauri H, Holtgrieve GW, Koponen J, Piman T. Impacts of hydropower and climate change on drivers of ecological productivity of Southeast Asia's most important wetland. Ecol Modell. 2014;272:252-263.
24. United Nations. CAMBODIA – Flood Season Situation Report #5; 2011. Available:http://reliefweb.int/sites/reliefweb.int/files/resources/Document1_81.pdf (Accessed 06 August 2015)
25. Lu XX, Li S, Kummu M, Padawangi R, Wang JJ. Observed changes in the water flow at Chiang Saen in the lower Mekong:

Impacts of Chinese dams? Quat Int. 2014;336:145-157.
26. Kite G. Modelling the Mekong: hydrological simulation for environmental impact studies. J Hydrol (Amst). 2001;253(1):1-13.
27. Costa-Cabral MC, Richey JE, Goteti G, Lettenmaier DP, Feldkötter C, Snidvongs A. Landscape structure and use, climate, and water movement in the Mekong River basin. Hydrol Process. 2008;22(12):1731-1746.
28. Vastila, K, Kummu M, Sangmanee C, Chinvanno S. Modelling climate change impacts on the flood pulse in the Lower Mekong floodplains. J Water and Clim Change. 2010;1(1):67-86.
29. Keskinen M, Kummu M, Kakonen M, Varis O. Mekong at the crossroads: Next steps for impact assessment of large dams. Ambio. 2010;41(3):319-324.
30. Lacombe G, Douangsavanh S, Vogel RM, McCartney M, Chemin Y, Rebelo LM, Sotoukee T. Multivariate power-law models for streamflow prediction in the Mekong Basin. J Hydrol: Reg Stud. 2014;2:35-48.
31. Johnston R, Kummu M. Water resource models in the Mekong Basin: a review. Water Resour Manag. 2012;26(2):429-455.
32. Johnston R, Smakhtin V. Hydrological modeling of large river basins: How much is enough? Water Resour Manag. 2014;28(10):2695-2730.
33. Tanaka M, Sugimura T, Tanaka S, Tamai N. Flood–drought cycle of Tonle Sap and Mekong Delta area observed by DMSP-SSM/I. Int J Remote Sens. 2003;24(7):1487-1504.
34. Begkhuntod P. Application of satellite information for flood risk reduction in Mekong River Basin. Proceedings of Regional Workshop on Innovative Approaches to Flood Risk Reduction in the Mekong Basin; 2007.
35. Sakamoto T, Nguyen NV, Kotera A, Ohno H, Ishitsuka N, Yokozawa M. Detecting temporal changes in the extent of annual flooding within the Cambodia and the Vietnamese Mekong Delta from MODIS time-series imagery. Remote Sens Environ. 2007;109(3):295-313.
36. Ticehurst C, Dyce P, Guerschman J. Using passive microwave and optical remote sensing to monitor flood inundation in support of hydrologic modelling. Interfacing modelling and simulation with mathematical and computational sciences, 18th World IMACS/MODSIM Congress; 2009.
37. Westerhoff R, Huizinga J, Kleuskens M, Burren R, Casey S. Operational satellite-based flood mapping using the delft-FEWS system. Proceedings of the ESA living planet symposium, Bergen, Norway; 2010.
38. Dung NV, Merz B, Bárdossy A, Thang TD, Apel H. Multi-objective automatic calibration of hydrodynamic models utilizing inundation maps and gauge data. Hydrol and Earth Sys Sci. 2011;15(4):1339-1354.
39. Ricko M, Carton JA, Birkett C. Climatic effects on lake basins. Part I: modeling tropical lake levels. J Clim. 2011;24(12):2983-2999.
40. Penny D. The Holocene history and development of the Tonle Sap, Cambodia. Quat Sci Rev. 2006;25(3):310-322.
41. Day MB, Hodell DA, Brenner M, Curtis JH, Kamenov GD, Guilderson TP, Peterson LC, Kenney WF, Kolata AL. Middle to late Holocene initiation of the annual flood pulse in Tonle Sap Lake, Cambodia. J Paleolimnol. 2011;45(1):85-99.
42. Plate EJ. Early warning and flood forecasting for large rivers with the lower Mekong as example. Journal of Hydro-environ Res. 2007;1(2):80-94.
43. Kummu M, Tes S, Yin S, Adamson P, Józsa J, Koponen J, Richey J, Sarkkula J. Water balance analysis for the Tonle Sap Lake–floodplain system. Hydrol Process. 2014;28(4):1722-1733.
44. Dewan AM, Islam MM, Kumamoto T, Nishigaki M. Evaluating flood hazard for land-use planning in Greater Dhaka of Bangladesh using remote sensing and GIS techniques. Water Resour Manag. 2007;21(9):1601-1612.
45. Doch S, Diepart JC, Heng C. A multi-scale flood vulnerability assessment of agricultural production in the context of environmental change: The case of the Sangke River Watershed, Battambang Province. In: Diepart JC, editor. Learning for Resilience, Insights from Cambodia's Rural Communities. Phnom Penh: The Learning Institute; 2015.
46. Irvine K, Lakhena C, Phallin C, Sreyneang C, Saophuong N, Putheary N, Kunthy S, Sophearith Y. Integrated Water Resources Management – opportunities and challenges for Cambodia. Water Resources and Development in Southeast

Asia. In: Irvine K, Murphy T, Vanchan V, Vermette S, editors. Boston: Pearson Learning Solutions; 2010.

47. Tran P, Shaw R, Chantry G, Norton J. GIS and local knowledge in disaster management: A case study of flood risk mapping in Viet Nam. Disasters. 2009;33(1):152-169.
48. Molyvann V. Modern khmer cities, Phnom Penh: Reyum Publishing; 2003.
49. Lu P. Spatial planning and urban resilience in the context of flood risk: A comparative study of Kaohsiung, Tainan and Rotterdam: TU Delft: Delft University of Technology; 2014.
50. Van Heerden IL. The failure of the New Orleans levee system following hurricane Katrina and the pathway forward. Public Adm Rev. 2007;67(s1):24-35.
51. Chaosakul T, Koottatep T, Irvine KN. Low impact development modelling to assess localized flood reduction in Thailand. In: James W, Irvine KN, Joksimovic D, Li JY, McBean EA, Pitt RE, Vasconcelos JG, Wright SJ, Wu JS. editors. Pragmatic Modeling of Urban Water Systems, Monograph 21. Ontario: Computational Hydraulics International; 2013.
52. Ford D, McFadden D, Hilmes-Robinson M. Early warning. Civ Eng. 2002;72(8):62.
53. Wu BS, Sui DZ. Modeling impacts of globalization on desakota regions: A case study of Taipei Metropolitan Area. Environ Plann B Plann Des; 2015 (In press).

Peer-review history:
The peer review history for this paper can be accessed here:
http://sciencedomain.org/review-history/13396