Received: 22 July 2019 | Revised: 15 March 2020 | Accepted: 22 March 2020

DOI: 10.1111/lre.12317

ORIGINAL ARTICLE

Lakes & Reservoirs: Science, Policy and Management for Sustainable Use | WILEY

Recent warming of Tonle Sap Lake, Cambodia: Implications for one of the world's most productive inland fisheries

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Funding information
National Science Foundation, Grant/Award Number: EAR 1740042 titled INFEWS/T1: Linking Current and

Abstract

Tonle Sap Lake in Cambodia is arguably the world's most productive freshwater ecosystems, as well as the dominant source of animal protein for the country. The rapid rise of hydropower schemes, deforestation, land development and climate change impacts in the Mekong River Basin, however, now represent serious concerns in regard to Tonle Sap Lake's ecological health and its role in future food security. To this end, the present study identifies significant recent warming of lake temperature and discusses how each of these anthropogenic perturbations in Tonle Sap's floodplain and the Mekong River Basin may be influencing this trend. The lake's dry-season monthly average temperature increased by 0.03°C/year between 1988 and 2018, being largely in synchrony with warming trends of the local air temperature and upstream rivers. The impacts of deforestation and agriculture development in the lake's floodplain also exhibited a high correlation with an increased number of warm days observed in the lake, particularly in its southeast region (agriculture R^2 = .61; deforestation R^2 = .39). A total of 79 dams, resulting in 72 km^3 of volumetric water capacity, were constructed between 2003 and 2018 in the Mekong River Basin. This dam development coincided with a decreasing trend in the number of dry-season warm days per year in the lower Mekong River, while Tonle Sap Lake's number of dry-season warm days continued to increase during this same period. The present study revealed that Tonle Sap Lake's temperature trends are highly influenced by temperature trends in the local climate, agriculture development and deforestation of the lake's watershed. Although there were no noticeable impacts observed from upstream dam development in the Mekong River Basin, local-to-regional agricultural and land management of the lake's watershed appear to be effective strategies for maintaining a stable thermal regime in the lake in order to facilitate maximum ecosystem health.

KEYWORDS

management, remote sensing, Tonle Sap, warming, water temperature

1 | INTRODUCTION

The rapid increase of hydropower development, deforestation, land development and climate change impacts in the Mekong River Basin are concerns for downstream ecosystems such as Tonle Sap Lake, one of the world's most productive freshwater fisheries (Baran & Myschowoda, 2009). Each factor is changing and interacting in the Tonle Sap watershed, degrading its water quality, of which at least 150 fish species, more than 200 plant species and 4.2 million human residents are dependent (Campbell, Poole, Giesen, & Valbo-
5 Jorgensen, 2006; MRC, 2003). Anthropogenic perturbations such as those noted above have been found to disrupt surface water thermal regimes, which can result in disruption of phenological, geographical and species size distribution (Janzen, 1967). Tropical vertebrate species, including fish, are believed to be particularly at risk under warming climate conditions because they already exist at the upper end of known thermal maxima, have evolved with narrower thermal windows and have limited adaptive capacity to temperature increases (Ficke, Myrick, & Hansen, 2007;Janzen, 1967;Stillman, 2003). Thus, a better understanding of Tonle Sap Lake's temperature characteristics can help inform water resource managers to plan and operate infrastructure and natural resources throughout the region in a manner that ecosystem functions and human benefits are maintained.

Watershed changes, including land cover, climate and dam development, have resulted in significant negative impacts on surface water thermal regimes around the world (Adrian et al., 2009). Deforestation and agriculture also can cause warmer surface runoff, thermally polluting downstream water bodies (Beschta, 1997;Brown & Krygier, 1970;Johnson & Jones, 2000). Dams have been shown to warm or cool downstream waters, depending on the depth of the water layer from which water is released from the dam (Niemeyer, Cheng, Mao, Yearsley, & Nijssen, 2018). Global warming is causing increased lake temperatures around the world (Ilha, Schiesari,
6 Yanagawa, Jankowski, & Navas, 2018; Schneider and Hook, 2007). Thus, it is critical to better understand how changes upstream and throughout the watershed landscape are impacting the thermal water quality of Tonle Sap Lake as well.

There is broad concern over the recent declines in fish population and size in Tonle Sap Lake (Hortle, 2007;van Zaline, 2002), noting that fish provide most of animal protein and vitamin A (>80%) to Cambodians (Hortle, 2007). Although the exact causes of this observed change to the fishery are currently unclear, it is imperative that ecological conditions that provide stable ecosystem services to the region persist into the future. Dam development, for example, has already had a greater impact on Tonle Sap's hydrological regime than any other human impact (Cochrane, Arias, & Piman, 2014). Dams are expected to decrease average maximum wet-season water levels and increase the dry season water levels over time, with some of these hydrologic impacts already being observed (Cochrane et al., 2014;Kummu & Sarkkula, 2008). A modest rise in the dry season lake water level would permanently immerse disproportionally large areas of the floodplain, resulting in permanent flooding of valuable land that currently supports farming operations and ecologically important gallery forests (Kummu & Sarkkula, 2008). Land cover changes such as deforestation and irrigation schemes also impact the lake's natural systems. Most forested areas around Tonle Sap Lake, for example, have been cleared for farming, settlements and timber harvesting, altering the land cover around the permanent lake boundaries (Campbell et al., 2006).

Climate change impacts on the hydrological regime of Tonle Sap Lake, including the warming of air temperature, are also expected to become more significant over the long term (Keskinen et al., 2010).
Manton et al. (2001) reported significant increasing trends in the an- 7
nual number of hot days and nights, and decreasing trends in the annual number of cool days and nights throughout Southeast Asia. How such changes will impact Tonle Sap and the implications for its fishery, however, are currently unclear. Further, direct observations of physical and biological conditions over time are extremely limited for Tonle Sap Lake and the Mekong River, in part because of the troubled social and political history of the region. Thus, resilient and adaptive water and natural resource management for Tonle Sap Lake requires new observation methods for understanding recent ecological change so as to better manage the future of the lake.

To this end, the present study uses space-based remote sensing techniques to estimate previously unavailable long-term water surface temperature trends in Tonle Sap Lake that have occurred as a result of natural and anthropogenic changes in its surrounding watershed. Water temperature is a key parameter of many physical processes that sustain the natural resources that are vital for the regional economy. Thus, a major objective of the present study is to improve understand recent temperature trends, the primary drivers of these trends and also how anthropogenic perturbations in the local watershed are impacting temperature. As dam, land and agriculture development continues in the region, changes to local food security are inevitable with alterations to these natural cycles are compounded in the near future and over the long term. Thus, identifying the trends in lake temperature and understanding their potential drivers are key to developing appropriate and optimal management strategies for the thermal stability of the Tonle Sap Lake.

2 | METHODOLOGY

2.1 | Study region

Tonle Sap Lake is centrally located in Cambodia, between the Mekong River and its delta draining to the South China Sea. The lake's tropical climate and flow regime are typically categorized into two seasons, namely dry (low-water-level period) and monsoon (high water-level period). The dry period extends from November through April, while the monsoon season is between May and October. The lake's surface area changes from 2,500 km^2 in the dry season to more than 15,000 km^2 during the peak inflow during the monsoon season, while the lake depth typically fluctuates between 1.5 and 10-m between the two seasons (Arias et al., 2012;Oyagi, Endoh, Ishikawa, Okumura, & Tsukawaki, 2017). The Tonle Sap River flows into the southeast portion of the lake, filling it with water draining directly from the Mekong River during the monsoon season, while reversing the flow to carry Tonle Sap water back to the Mekong River during the dry season (Figure 1). The lake's water quality is also characterized uniquely by these two seasons, with a larger influence by the local watershed on the lake's water quality during low-water-level periods, and insignificant anthropogenic impacts observed during the monsoon seasons (Oyagi et al., 2017).

Two regions within Tonle Sap Lake were used in the present study to capture any unique contrasts between the northwest (NW) and southeast (SE) portions of the lake. Water quality data in the SE region tends to be more influenced by inflows from the Tonle Sap River during high-water periods, while the NW region tends to be influenced by the other eleven tributaries to the lake (Yen et al., 2008). Tonle Sap's watershed was delineated according to the HydroSHEDS watershed boundary (Lehner, Verdin, & Jarvis, 2008). Three locations of the size satellite pixels in the Mekong River (MKR) were included in the water surface temperature analyses to compare trends occurring just upstream to trends occurring within the lake (Figure 1), with three sites selected in each location to minimize the bias that might be observed if only using a single point in each river.

2.2 | Historical surface and air temperature data

Geophysical parameters were compared directly to annual and monthly trends of Tonle Sap Lake's water surface temperature (LWST) to determine the influence of each on the lake's thermal regime. Water surface temperature estimates from multiple satellite products were utilized to determine monthly and annual temperature trends, number of warm days/nights and number of cool days/nights per year. Satellite-based NOAA AVHRR Pathfinder Version 5.3 Nighttime Sea Surface Temperature (Pathfinder V5.3) was chosen to analyse long-term trends, with the data being preprocessed to convert from at-sensor brightness to surface kinetic temperature. Pathfinder V5.3 data were processed in the Google Earth Engine for the available period 1981to 2014 at a 4-km resolution with a twice-daily repeat (Baker-Yeboah et al., 2016). The Pathfinder V5.3 product combines sensor information aboard the NOAA-7, NOAA-9, NOAA-11, NOAA-14, NOAA-16, NOAA-17, NOAA-18, NOAA-19 satellite platforms to collate into a single, twice-daily time series of daytime and night-time surface temperature. The Pathfinder V5.3 collates the data by optimizing different satellites for different time periods to minimize any biases occurring because of orbital drift. Because Tonle Sap Lake is relatively shallow (<10-m average depth) and located in a tropical climate with continuous mixing, little thermal stratification occurs (Sabo et al., 2017). Thus, the satellite-based surface temperature trend can be considered a reasonable proxy for the lake's depth-averaged thermal characteristic at any given time or location.

Dry-season Pathfinder V5.3 night-time sea surface temperature was processed and extracted for the northwest and southeast study regions of Tonle Sap Lake over the available period, except for 11 July 2002 through 6 June 2005, during which observations aboard the NOAA-17 satellite platform are reported because of significant

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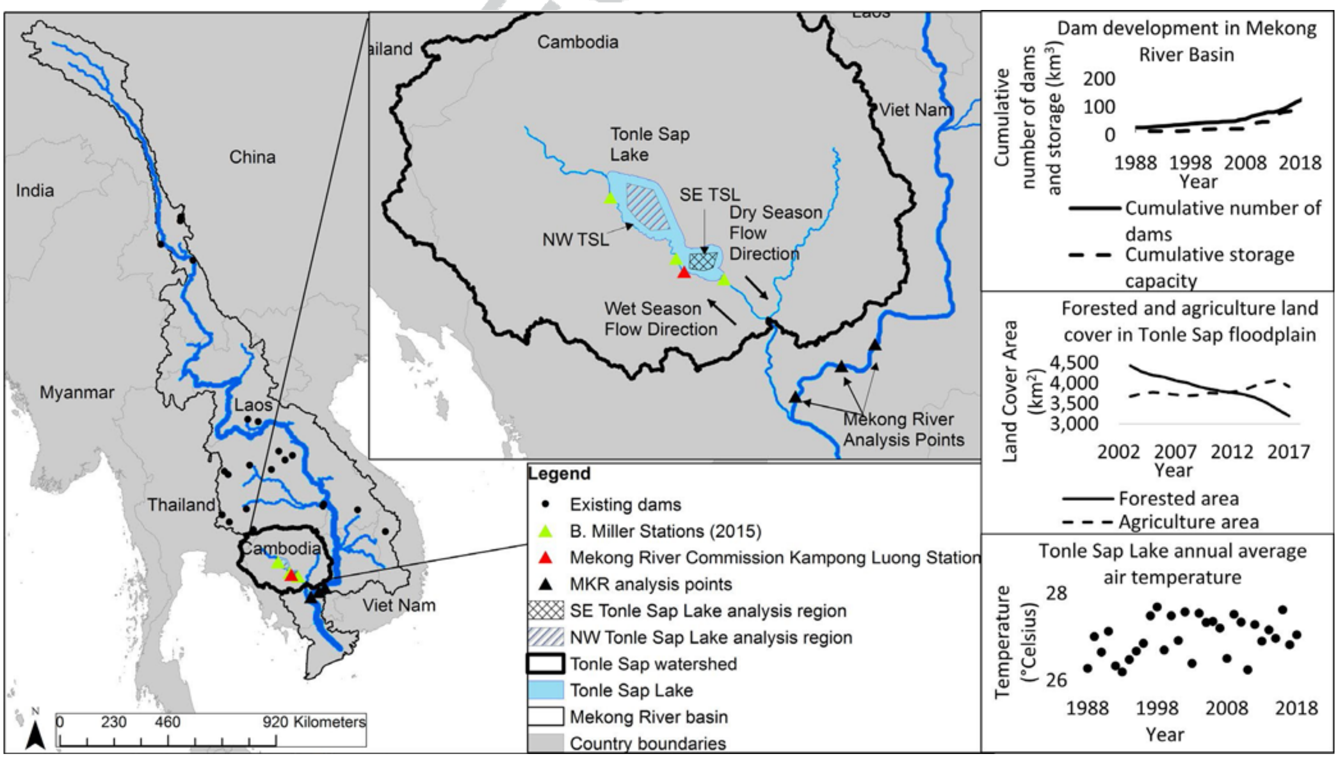

FIGURE 1 Map of the Mekong River Basin, Tonle Sap Lake and watershed, existing dam locations and study analysis locations

temporal differences between this satellite and the other aforementioned NOAA satellites. Night-time data were analysed, rather than daytime data, to further minimize any bias that may occur from orbital drift (Schneider & Hook, 2010). The upstream study locations in the Tonle Sap and Mekong Rivers were excluded from this long-term analysis because of the coarse-spatial resolution of the Pathfinder V5.3 products. A total of 712 cloud-free nights were available for the analysis in the NW region, and 323 cloud-free nights in the SE region, removing ~5,000 cloudy nights from the analysis. On average, the NW and SE regions were found to be very similar in temperature (<1°C difference).

Cool and warm day and night trends were evaluated using Moderate Resolution Imaging Spectroradiometer (MODIS) aboard the Aqua satellite mission. This dataset, called the MYD11A1 Version 6, provides land surface day and night-time temperatures from 2002 to 2018 at a 1-km resolution (Wan, Hook, & Hulley, 2015). Pathfinder V5.3 data were used to analyse long-term trends because of its longer period of record. MODIS data were analysed for the cool and warm day and night trends because of its higher frequency of observation (2 per day). Air temperature trends were analysed based on data from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) Reanalysis Project for the same period (1988–2018) at 2.5 arc degree resolution (Kalnay et al., 1996).

Temperature data were averaged over pixels masked to each study area to produce an average temperature twice daily (daytime and night-time) for the Pathfinder V5.3 dataset and per day for the MODIS and Reanalysis datasets. For the Mekong River and Tonle Sap River points, only the temperature record of the pixel at each point was extracted. Two additional post-processing steps were executed in order to discard images that may have been overly skewed by cloud interference. The first was conducted by removing days with more than 40% of the pixels within the study area were flagged as clouds. The second utilized an advanced filter-based assessment of the interquartile range of LWST derived approximately every 16 days to obtain a lower and upper threshold, being applied using Equations 1 and 2, respectively (Ghent, 2012;Metz, Rocchini, & Neteler, 2014), as follows:

$$\text{Lower threshold} = \text{1st quartile} - 1.5\left(\text{3rd quartile} - \text{1st quartile}\right) \quad (1)$$

$$\text{Upper threshold} = \text{1st quartile} - 1.5\left(\text{3rd quartile} + \text{1st quartile}\right) \quad (2)$$

The final Pathfinder V5.3 and Reanalysis time series were averaged monthly and annually to analyse long-term trends. The number of warm days was calculated as the number of days exhibiting temperatures exceeding the long-term monthly average temperature from the MODIS dataset. The same step was carried out with the night-time time series to calculate the number of warm nights per year. The non-parametric Mann–Kendall test was applied to all temperature time series to identify statistical significance in the presence of monotonic upward or downward trends within a given confidence level. Sen's slope method, which is insensitive to outliers, was utilized for a robust estimation of significant trends (Sen, 1968).

No direct validation of the satellite surface temperature datasets was possible because of the lack of long-term in situ surface temperature measurements. However, two in situ datasets collected locally and from Mekong River Commission's (2011) Kampong Luong sampling site (Station ID H02106) were available for various depths and points across the lake. Because the in situ data differ from the remote sensing data temporally and spatially, they are not directly comparable. However, the satellite remote sensing data were compared to the in situ data to determine if it was within a reasonable range of the in situ data. This was done by subtracting the in situ near-surface temperature data from the satellite remote sensing surface temperature instantaneous values observed on the same day. The NOAA AVHRR Pathfinder V5.3 data were not compared to the Miller (2015) in situ data because these satellites were decommissioned by 2014, while the Miller in situ data were observed in 2015. However, AVHRR and MODIS were compared to another dataset of the Kampong Luong provided by the tMRC (2011). Only six days were available to compare the MRC in situ data to both satellites. Because the satellite data exhibited cloud interference for several days, the in situ data for all days were comparable. Satellite remotely sensed points deviating the most from the in situ data either exhibited a masked pixel in MODIS or AVHRR, indicating cloud interference was likely the reason for the relatively large error. The MODIS satellite product does not perform as well against the MRC dataset as it does against the Miller (2015) dataset. Both satellites performed reasonably well, however, considering several unknowns within the MRC in situ data, which include the time of day and reliability of the sensor. The MRC in situ data are also measured at a lower depth than the Miller (2015) sites, being closer to the shore where the thermocline is likely more apparent. On average, the MODIS performs better than the AVHRR.

Overall, the satellite remotely sensed data exhibited a reasonable range of the in situ measurements. As the satellite remotely sensed data are measured as brightness temperature and were subsequently converted to kinetic temperature, various parameters in the conversion can exhibit various levels of uncertainty. The emissivity values can range from 0.97 to 0.99 for water, dependent mostly on the water salinity, a range that can result in an error between 0.2 and 0.5°C. Many of the MODIS datapoints fell within this, and several AVHRR datapoints also fell within that range. Overall, the satellite remotely sensed data deviated from the in situ data by <2–3°C maximum, and 1°C on average, which is reasonable considering the two data sources were measured at different times of day and depths.

2.3 | Historical land cover data

Land cover data were retrieved from the International Geosphere-Biosphere Programme (IGBP) supervised land cover classification of MODIS Aqua and Terra reflectance data (Friedl & Sulla-Menashe, 2015). One land cover type is included for each pixel at a 500-m spatial resolution and 1-year interval. Land cover change was determined for each year by calculating the change in total area of each land cover classification type. Relevant land cover types were grouped into two categories. The 'forested' area category summed up the areas whose pixels were categorized as 'evergreen broadleaf forests', 'deciduous broadleaf forests', 'mixed forests' and 'woody savannas'. The 'agriculture' category summed up the areas of pixels that were categorized as 'croplands' and 'cropland/natural vegetation mosaics'. These classes are adequate to capture the influence of species diversity existing in the lake's floodplain, as described by Campbell et al. (2006). Only the area in the lake's approximated floodplain area, spanning 17,300 km^2, was included in the land cover analysis.

2.4 | Dam development

Tonle Sap's LWST trends were compared directly with the construction of numerous dams in the Mekong River Basin. The rate of increase in the number of dams and water storage volume per year for the Mekong River Basin was derived utilizing the dataset CGIAR Research Program's Dataset on the Dams of the Mekong (Lapointe et al., 2018). The dataset includes a comprehensive list of dams constructed since 1956 through the end of the analysis period. All dams located within the Mekong River Basin were incorporated into the analysis to derive the cumulative number of dams constructed and water storage added to the river system for each year. These trends were compared to annual trends in warm days and nights to determine if dam development trends corresponded to any warming or cooling trends seen in Tonle Sap LWST, as well as in the Tonle Sap and Mekong River surface temperatures.

3 | RESULTS

3.1 | Long-term temperature trends

Dry-season monthly mean daytime and night-time water surface temperature trends were computed for northwest (NW) and southeast (SE) Tonle Sap LWST, and the lake and watershed air temperatures for the period from 1981 to 2014. The wet-season months were not included because of insufficient satellite remote sensing data resulting from cloud interference. During the dry season months, the Tonle Sap River discharges water from Tonle Sap Lake to the Mekong River. Including the Mekong River upstream of the Tonle Sap River confluence in the temperature trend analyses provides insights into whether or not trends observed in the lake are also occurring in the nearby regional surface waters, or if they are unique to the lake. Pathfinder V5.3 pixels, however, are too large to obtain data solely from within the rivers without bias because of the land area along the riverbanks. Thus, the river analyses points are not included in the analysis of the long-term recent temperature trends. Figure 2 illustrates and compares each trend, and also highlights the monthly average water level observed at the Kampong Luong site in order to provide seasonal context for temperature trends. The air temperature trends averaged over the entire watershed were found to be approximately equal to the SE and NW trends (Figure 2). All months and regions indicate warming trends, except for SE Tonle Sap Lake in January, while NW Tonle Sap Lake exhibits a slight negative trend in March. The dry-season LWST trend for both regions indicates warming at an average rate (Sen's slope) of 0.02°C/yr. The LWST Sen's slope warming trends range from −0.01 to 0.06°C/year for the NW and SE regions. Two points illustrate cooling trends, which may be attributable to noise in the raw data. Finally, the air temperatures over the NW and SE lake regions ranged from −0.07 to 0.08°C/year. The air temperature trends between November and March exhibited a statistical significance, with a *P* value ranging from 0.01 to 0.05. LWST exhibited a statistical significance (p = .05) relationship in March in the SE lake analysis region.

The long-term trend analysis revealed warming or cooling trends are generally consistent among all the regions analysed and consistent between air and surface water temperatures. This finding indicates the local surface water temperature trends are highly linked to the warming and cooling trends in the local air temperatures. Thus, the drivers of change in the region's air temperature such as human-induced global warming may be impacting the local surface

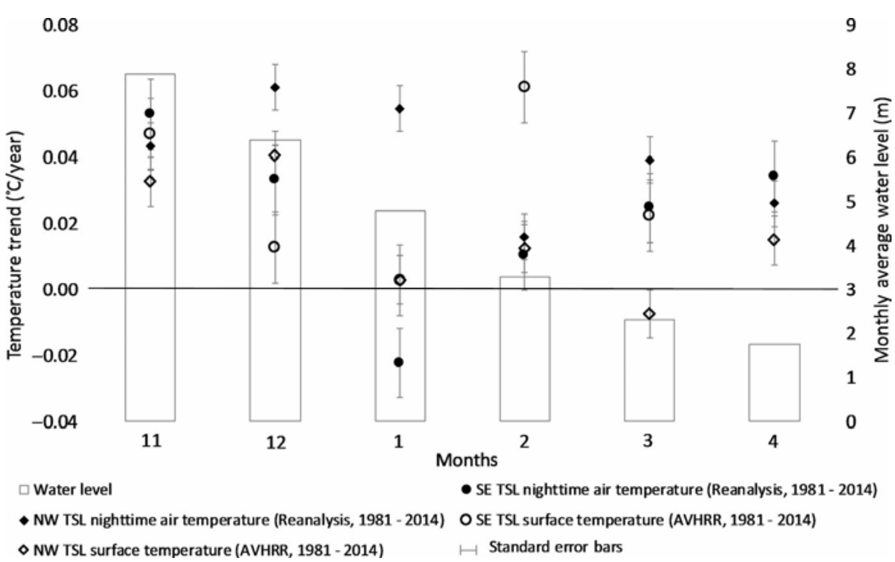

FIGURE 2 Long-term monthly temperature trends for southeast (SE) and northwest (NW) Tonle Sap Lake air and water surface temperature, and Tonle Sap and Mekong River water surface temperatures (error bars shown for all trends; water level expressed as elevation above mean sea level in Hatien, Vietnam)

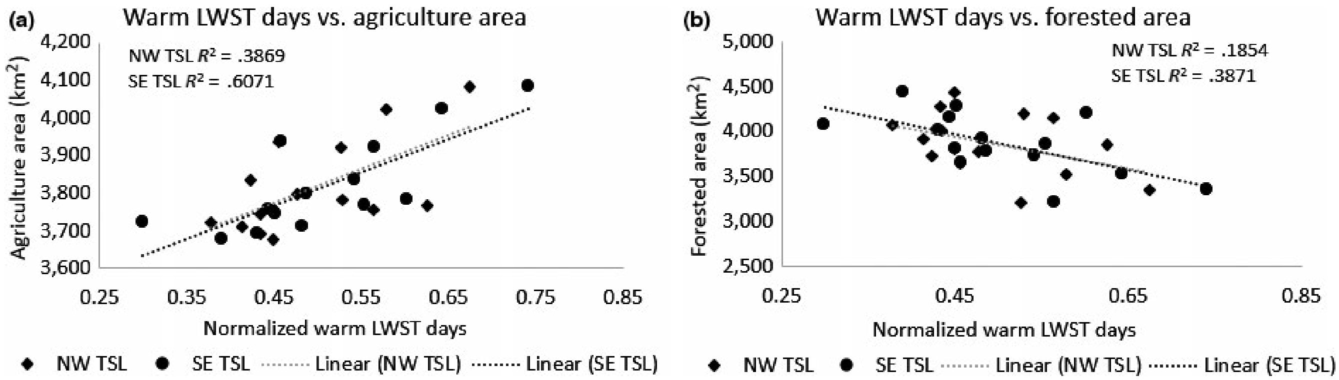

FIGURE 3 Plots of number of warm surface water temperature days and nights, normalized by sample size per year and (a) agriculture area; and (b) forest area in the lake floodplain)

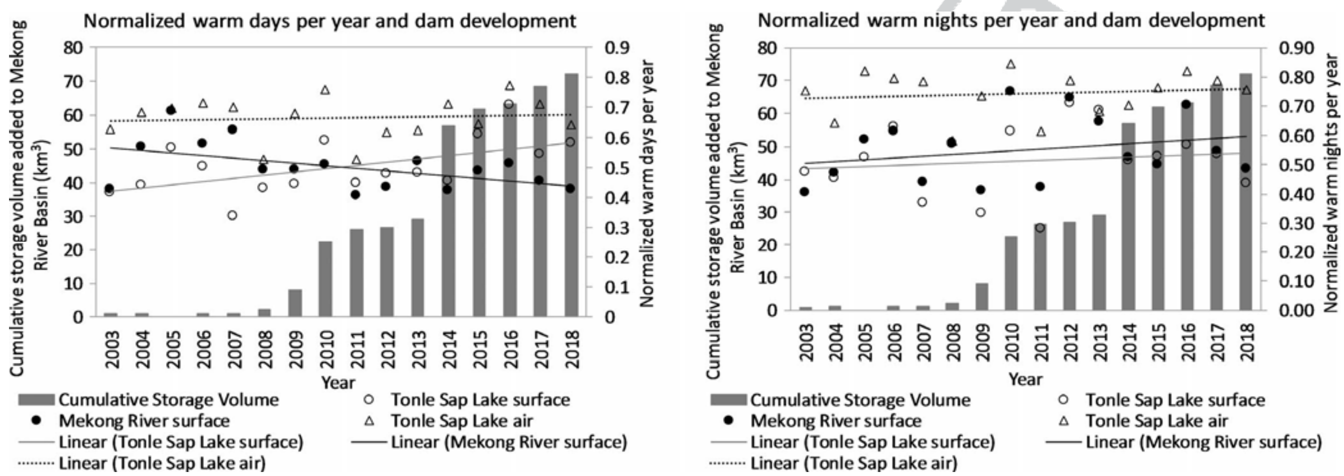

FIGURE 4 Plot showing annual cumulative water storage added to Mekong River Basin since 2003, and number of warm surface water temperature days per year (normalized by sample size) for Tonle Sap Lake air and surface temperature and Mekong River surface temperature

water temperature trends. Interestingly, the warming trends tend to weaken with the seasonal water level declines from November through January, although they strengthen again in March and April. The NW region of the lake appears to be warming at approximately the same rate as the SE region for most months.

3.2 | Watershed impacts on temperature trends

Deforestation, agriculture and dam development trends were analysed and compared directly with the number of warm LWST days and warm LWST nights per year, utilizing the MODIS LWST and IGBP/MODIS land cover datasets for the available period between 2003 and 2017. The total agriculture land in the lake's floodplain during this period increased by ~245 km^2, and the forest cover decreasing by ~1,220 km^2. Much of the deforested area was converted into woody savannah, grassland and permanent wetland, based on classifications developed by IGBP. As pointed out in the product's user-guide, however, cropland in the immediate lake's floodplain are likely underestimated. The NW TSL region was also frequently found to be cooler than the SE TSL region for most dry-season days during this period, based on the MODIS LWST data, as illustrated in Figure 3. It illustrates a map of the annual average temperature across the lake and its floodplain for 2003, 2015 and the difference between the two years. It should be noted that the relationship between area and warm LWST in Figure 3 is mostly linear, since a non-linear relationship such as power-law did not capture the variability very well.

The number of warm LWST days per year (i.e., days above long-term average), as observed by MODIS satellites and normalized by sample size, was plotted against the area of agriculture and forest in the lake's floodplain (Figure 4). Both plots demonstrate correlations between the number of warm days per year and the land cover type in the lake's floodplain. The highest correlation was between increases in agriculture area and increases in the number of warm days, particularly in the SE region (R^2 = .61), indicating the lake's warming trends are likely linked to these land cover changes. The SE region of the lake exhibits a stronger correlation between the extent of agriculture and forested area than in the NW region in both plots. Because an insignificant correlation was observed between the land cover and warm nights per year, they are not shown in Figure 4.

Dam development in the entire Mekong River Basin increased the volumetric water storage behind dams by 72 km^3 between 2003 and 2008. The largest dams were built in China on the mainstem Mekong River in 2010 and 2014, damming ~24 and 15 km^3, respectively. Cumulative water storage behind dams constructed in the Mekong River Basin was compared annually to the number of warm days per year in both Tonle Sap Lake and the Mekong River near the Tonle Sap River confluence. Figure 5 illustrates the cumulative water volume stored behind the dams constructed since 2003, and warm anomalies in both Tonle Sap Lake and Mekong River analysis regions. While Mekong River exhibits a decreasing trend in the number of warm days experienced during the dry season of each year, Tonle Sap's LWST trends exhibit an increased number of warm days per year at a rate higher than the air temperature. The normalized warm days per year are fairly similar between the two systems during the period from 2003 through 2014. The deviation begins in 2015, coinciding with a major dam development in 2014. Interestingly, both Tonle Sap Lake and the Mekong River exhibited an approximately equal rate in the increase of number of warm nights per year, which mirrors the air temperature trend.

Figure 5 illustrates three apparent phases in dam development in the Mekong River Basin during 2003–2009, 2010–2013 and 2014–2018, respectively. Approximately 8-km^3 of water storage was added to the Mekong River Basin because of dam development during 2003 to 2009, while 21 km^3 was added during 2010 to 2013, and 43 km^3 was added during 2014 to 2018. The average daily daytime and night-time NW and SE TSL LWST was calculated over these three periods to examine the lake's temperature trends corresponding to these three time periods. These are shown by month only for the dry-season period only in Figure 6, along with the average daily and daytime air temperature trends. The greatest addition of water storage volume from the dam developments in the Mekong River Basin occurred between phases two and three, during which a meaningful cooling trend was only observed during January and February. The daytime air temperature, however, also illustrates a cooling trend in February. For all the other months, the night-time LWST indicates little change in average temperature over the three phases, except for a warming trend in November and December. Figure 6 illustrates warming trends in the daytime temperature, despite dam development, for all months except February through April, wherein the LWST trends are consistent with the air temperature trends that illustrate either slight cooling or relatively no change from the previous phase(s).

4 | DISCUSSION AND CONCLUSIONS

The Tonle Sap hydrological and ecological resources are the lifeblood of the Mekong region, and the lake is currently warming coincident with the regional climate. Schneider and Hook (2010) found over one hundred lakes around the world to be warming at a rate of 0.045°C/year on average, with Tonle Sap Lake following closely with an average dry-season warming rate of 0.03°C/year. Tonle Sap's LWST temperature trends also follow local air temperature trends, as expected for a large, shallow lake. Tonle Sap Lake and its floodplain have been experiencing heavy exploitation of resources for at least several decades, with the newly observed warming trends adding additional concerns over the future ability of the lake ecosystem to provide services to society. A recent study examining tropical fish physiological responses to warming under controlled conditions (including species from Tonle Sap Lake) indicated an unexpected tolerance and ability to perform at water temperatures up to 4°C above current maxima (Lapointe et al., 2018). While this observation is encouraging from the perspective of individual fish, temperature is a critical ecological variable that can impact ecosystems at all levels of organization from genes to biogeochemical cycles, and there is evidence that temperatures above those optimal for fish health can lead to habitat loss, a shift towards smaller fish body sizes and ultimately to losses in ecosystem functions (Walberg, 2011).

Beyond the direct observation of recent warming, the present study also found significant correlations between deforestation and increased agriculture development and the lake's warming trends. This finding suggests the thermal regime of the lake is highly sensitive to local land use and agricultural practices. Land use changes

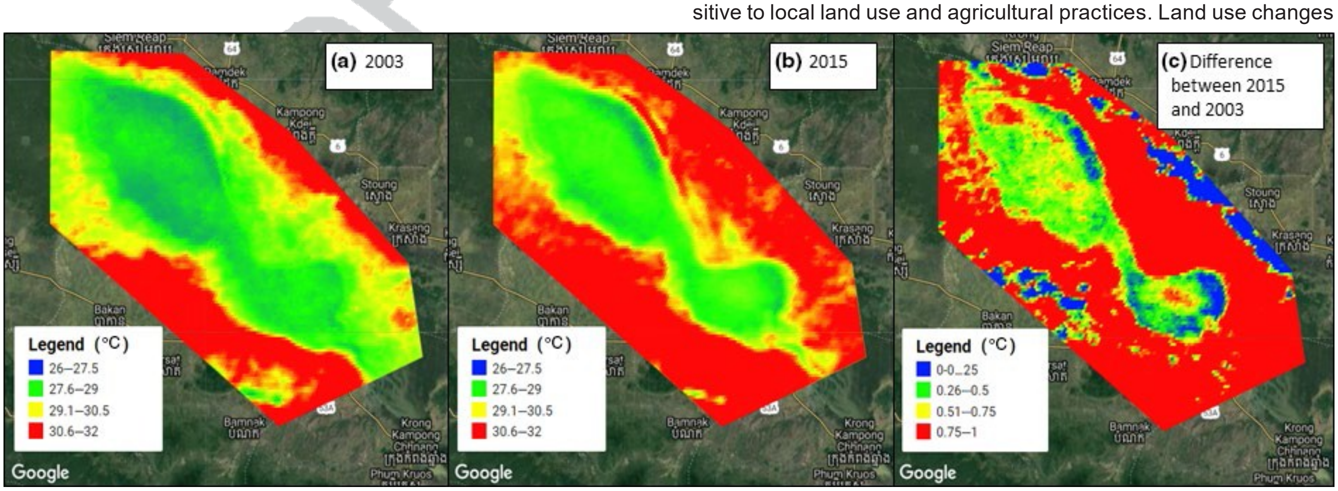

FIGURE 5 Map of MODIS daytime surface temperature for (a) annual average of 2003 (relatively cool year); (b) annual average of 2015 (relatively warm year); and (c) difference between both images (units in legend expressed in °C)

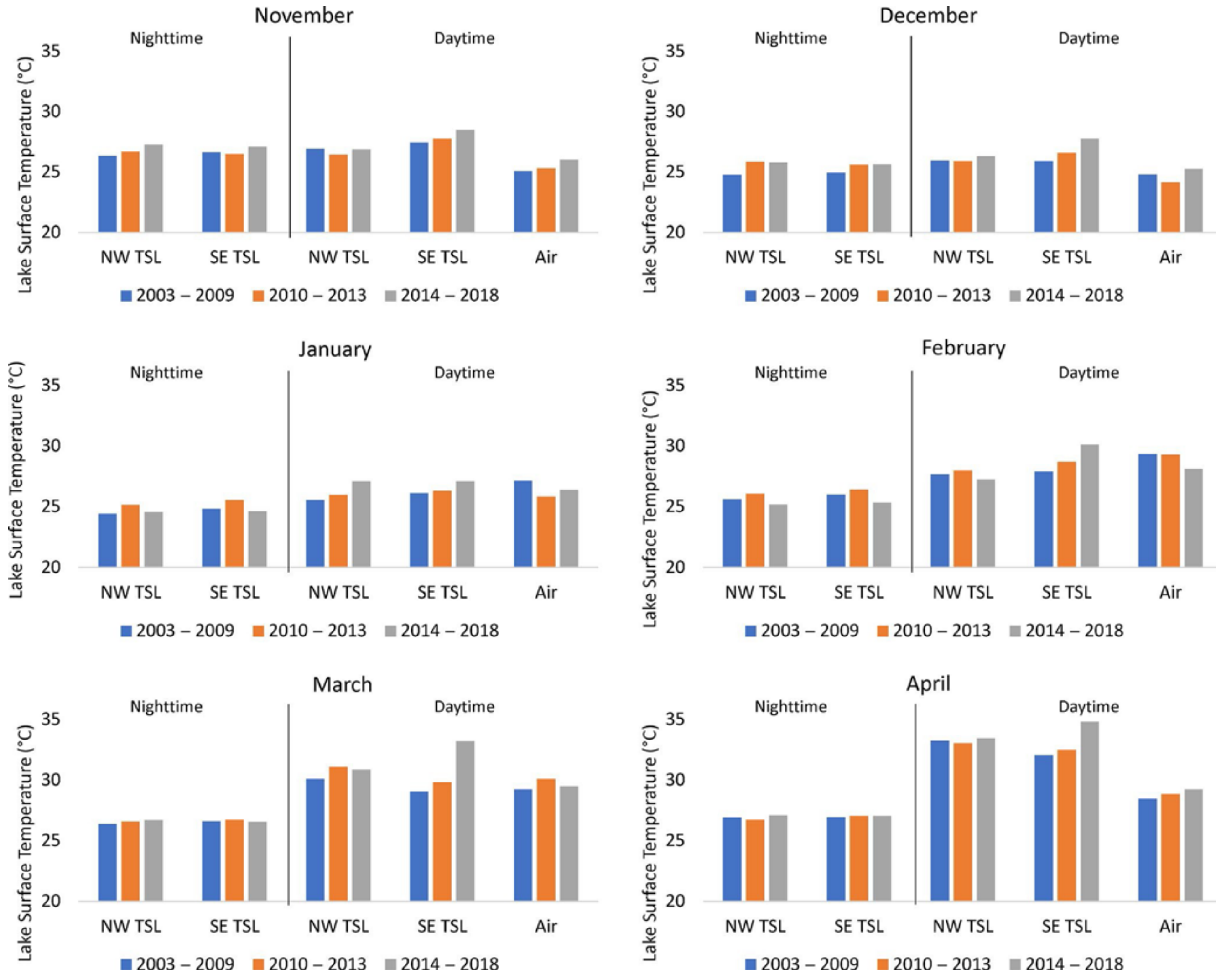

FIGURE 6 Surface temperatures of water for different locations in Tonle Sap Lake during dry season

from forest to agriculture are expected to continue in the region as the lower basin countries pursue policies of increased rice export. While troubling in the near term, this coupling of land use and lake temperature also presents opportunities for coordinated forest restoration and agricultural management as a potential mitigation strategy to lessen the lake's warming trends, a strategy shown successful in other parts of the world (Cunningham et al., 2015).

The continued and seemingly inevitable development of hydropower dams remains a major concern for the Tonle Sap Lake ecosystem. Thus, it is imperative such development is designed so as to minimize impacts to downstream systems, including Tonle Sap Lake. It remains to be seen if dams can be designed to send cooler waters downstream as a potential management strategy to potentially help mitigate the warming trends observed in Tonle Sap Lake. Correlations between the Tonle Sap Lake temperature trends and dam development are currently low. It is difficult, however, to conclude if further development will show a clear impact, especially as more dams are constructed on the main stem of the Mekong River and closer to the lake. At present, it has yet to be determined if existing hydropower schemes are warming or cooling downstream river waters. Further research into this topic would help local water resource managers to identify vulnerabilities of schemes and land use practices that can intensify warming trends or opportunities to manage these schemes to maintain a stable thermal regime in Tonle Sap Lake.

Temperature is a fundamental parameter in natural and managed ecosystems that comprise the basis of rural livelihoods on a global scale. Natural thermal regimes around the world are being disrupted by patterns of global warming, with the results of the present study also indicating Tonle Sap Lake's thermal regime is also warming. While the results of the present indicate warming air, temperatures are likely driving much of the thermal regime changes in Tonle Sap Lake, many lakes around the world, including Tonle Sap Lake, appear to be warming faster than their regional air temperatures. Thus, further studies are recommended to understand the processes that may be driving deforestation and agriculture to coincide with the warming of Tonle Sap Lake in order to help identify potential mitigation strategies. It is imperative the impacts of this issue in regard to the biological species in the lake's ecosystem are better understood since their populations are already declining.

ACKNOWLEDGEMENTS

This research was supported by National Science Foundation project NSF EAR 1740042 (INFEWS/T1: Linking Current and Future Hydrologic Change to Hydropower, Human Nutrition, and Livelihoods in the Lower Mekong Basin). The authors thank Ben Miller and the Asian Disaster Preparedness Center for providing in situ temperature data.

AUTHOR CONTRIBUTIONS

K. Daly ran the data analyses and wrote the paper. F. Hossain conceptualized the study and coordinated among authors who built the modelling and data platform for the INFEWS project to initiate the study. M. Bonnema and S. Ahmad assisted in temperature analyses code, remote sensing data, lake's hydrologic characterization and review of the paper. C. Beveridge, B. Nijssen and G. Holtgrieve assisted in reviewing this paper. All the authors helped in discussing ideas, interpreting results and editing the paper.

DATA AVAILABILITY STATEMENT

All data, codes and analyses used in this study are available on request.

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How to cite this article: Daly K, Ahmad S, Bonnema M, et al. Recent warming of Tonle Sap Lake, Cambodia: Implications for one of the world's most productive inland fisheries. *Lakes & Reserv*. 2020;00:1–10. ~~https://doi.org/10.1111/lre.12317~~