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Changes of inundation area and water turbidity of Tonle Sap Lake: responses to climate changes or upstream dam construction?

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Abstract

Using long-term Moderate Resolution Imaging Spectroradiometer (MODIS) and Landsat satellite observations, the inundation changes of Tonle Sap Lake between 1988 and 2018 were investigated. The results show that the inundation area was stable before 2000, followed by a significant shrinking trend between 2000 and 2018. Quantitative remote sensing retrievals for concentrations of the total suspended sediments (TSS) also demonstrate an evident increasing trend ($7.92\ \mathrm{mg\ l^{-1}\ yr^{-1}}$) since 2000. A strong correlation ($R^2 = 0.67$) was found between the annual mean inundation area and concurrent precipitation in a region located in the lower basin of the Mekong River (mostly outside the drainage basin of Tonle Sap Lake). A multiple general linear model (GLM) regression further pointed to the precipitation variation as a major contributor (76.1%) to the interannual fluctuation of the inundation area, while the dams constructed in China only contributed to 6.9%. The limited impacts of Chinese dams on the inundation area of the lake could be revealed through the limited fraction of water discharge from the Mekong River within China (∼17%). The analysis also found significant impacts of inundation changes on the recent lake turbidity increase in the dry seasons. We clearly revealed that the contribution of dam construction in China to the recent lake shrinkage was insignificant when compared with the impacts of the precipitation decrease. The results of this study provide important scientific evidence for settling water volume-related transboundary disputes regarding the control of the inundation area and water turbidity of Tonle Sap Lake.

1. Introduction

Lakes provide us with water supplies for human consumption and socioeconomic development. Thus, their healthy ecological functions are critical for the sustainability of regional ecosystems (Pereira *et al* 2010, Boretti and Rosa 2019). Influenced by both human activities and global climate changes, numerous lakes worldwide have experienced significant changes in terms of size, morphology, marginal wetlands, water quality, etc (Foley *et al* 2005, Elimelech and Phillip 2011, Feng *et al* 2013, Liu *et al* 2013). Accompanied by these changes are various types of ecological and environmental problems, such as droughts/floods, eutrophication, biodiversity decreases and wetland degradation among many others (Piao *et al* 2010, Creed *et al* 2017, Shi *et al* 2019, Qin *et al* 2020). Here, we would like to focus on changes over the last decades in the largest lake in Southeast Asia, Tonle Sap Lake.

Tonle Sap Lake is located in Cambodia in the lower basin of the Mekong River, a transboundary river that drains and crosses six countries: China, Myanmar, Laos, Thailand, Cambodia and Vietnam (see figure 1). The water flow direction between Tonle Sap Lake and the Mekong River can reverse between the dry and wet seasons, thus forming an annual flood pulse and favoring the productivity of the river-lake ecosystem (Frappart *et al* 2006, Dang *et al* 2016, Tangdamrongsub *et al* 2016). Indeed, the annually occurred flood pulse have commonly been considered the most important factor in maintaining the high

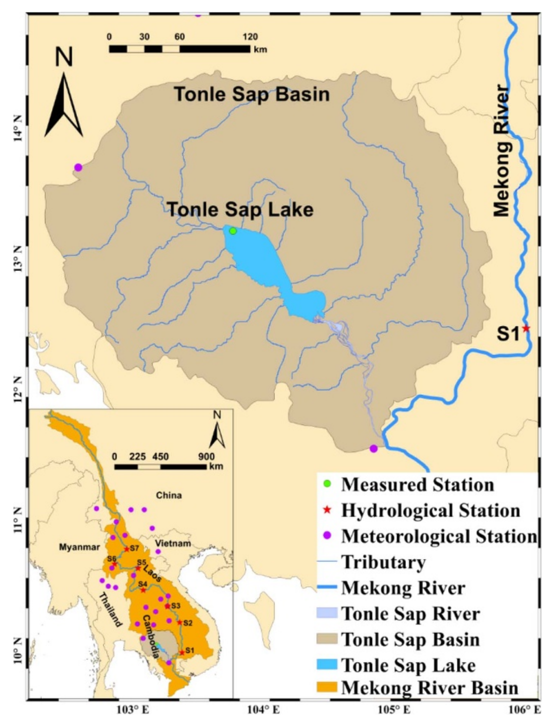

Figure 1. Hydrological map of Tonle Sap Lake, the Mekong River and their drainage basins. The locations of the hydrological and meteorological stations on the Mekong River are annotated.

productivity of Tonle Sap Lake, where the biomass accounts for half of that of the entire Mekong River Basin (Lamberts 2006, Kummu *et al* 2010, Piman *et al* 2013).

The Tonle Sap Lake is facing several threats from both global warming-associated climate changes (Arias *et al* 2012; Nuorteva *et al* 2010, Lauri *et al* 2012, Oeurng *et al* 2019) and population increase-associated excessive human activities (Gabriel Lamug-Nañawa 2011, Kuenzer 2014, Lu *et al* 2014). Currently, one of the most concerning issues for Tonle Sap Lake (and even the Mekong River) appears to be hydrological alterations (dam construction and reservoir impoundment) in the upstream of the Mekong River (Arias *et al* 2012; Cochrane *et al* 2014, Dang *et al* 2016, Pokhrel *et al* 2018, Binh *et al* 2020), where the river flow dominates the water storage in Tonle Sap Lake (Lauri *et al* 2012, Kummu *et al* 2014, Ji *et al* 2018). This issue is particularly important because diverging opinions on the impacts of upstream dams may potentially lead to serious international disputes due to the transboundary nature of the Mekong River (Zhao *et al* Arias *et al* 2012, Kuenzer *et al* 2012, Lu *et al* 2014).

Multiple techniques have been attempted to examine the hydrological transitions of Tonle Sap Lake and the lower Mekong system since the impoundment of upstream dams in China. Data from hydrological gauge stations have revealed a sharp decrease in sediment discharge on the Mekong River in the past two decades; furthermore, there was a substantial decline in the annual maximum water level in Tonle Sap Lake by 0.52 m between the periods of 1925–1935 and 1996–2002 (Campbell *et al* 2006). Various numerical models have also been introduced to predict such hydrological regime shifts (Hecht *et al* 2019), and their possible impacts on regional water quality, habitats, biodiversity have been investigated (Arias *et al* 2012; Orr *et al* 2012). Satellite remote sensing, with synoptic and large-scale observations, has also recently been utilized to explore historical changes in the surface and groundwater of the Tonle Sap Lake system (Siev *et al* 2016, Tangdamrongsub *et al* 2016, Lin and Qi 2017, Frappart *et al* 2018, Ji *et al* 2018, Wei *et al* 2018, Chang *et al* 2020), the strength of its annual flood pulse (Qu *et al* 2018), spatiotemporal distributions of water turbidity (Siev *et al* 2018), and the evolution of the Mekong River Delta (Li *et al* 2017b).

Because of the considerable efforts in the past, a consensus among the relevant countries regarding the impacts of dam construction on the downstream Mekong River channel, including trapping downstream sediment discharge (Kuenzer *et al* 2012, Wackerman *et al* 2017), modifying the distribution of seasonal water discharge (Lauri *et al* 2012, Piman *et al* 2013, Hoang *et al* 2019), and eroding the Mekong River Delta (Li *et al* 2017a), could be established. However, the effect of dam construction upstream of the Mekong River, particularly the completed cascade dams in China, on the hydrological dynamics of the Tonle Sap Lake still remains controversial (Bonheur and Lane 2002, Campbell *et al* 2006, Kummu and Sarkkula 2008, Lamberts 2008, Lin and Qi 2017, Frappart *et al* 2018). Moreover, how the long term hydrological changes of the Tonle Sap Lake could impact the water turbidity is also generally unknown (Siev *et al* 2018, Hoshikawa *et al* 2019).

Using long-term remote sensing images from several satellite missions (e.g. Moderate Resolution Imaging Spectroradiometer (MODIS) and the Landsat series), the current study was designed to address the aforementioned research gaps. The main objectives were as follows: (1) explore inundation and turbidity changes in Tonle Sap Lake in the past three decades; (2) reveal the major factors contributing to the recent lake changes; and (3) determine the linkage between inundation and water turbidity for the lake and discuss the future implications of the historical changes. The datasets and methods used in this study are detailed in supporting materials.

2. Results

2.1. Three decades of inundation changes

The long-term monthly mean inundation areas of Tonle Sap Lake determined from both Landsat (red) and MODIS (black) are demonstrated in figure 2(a), and the monthly mean climatological inundation areas (i.e. multiyear monthly mean) derived using

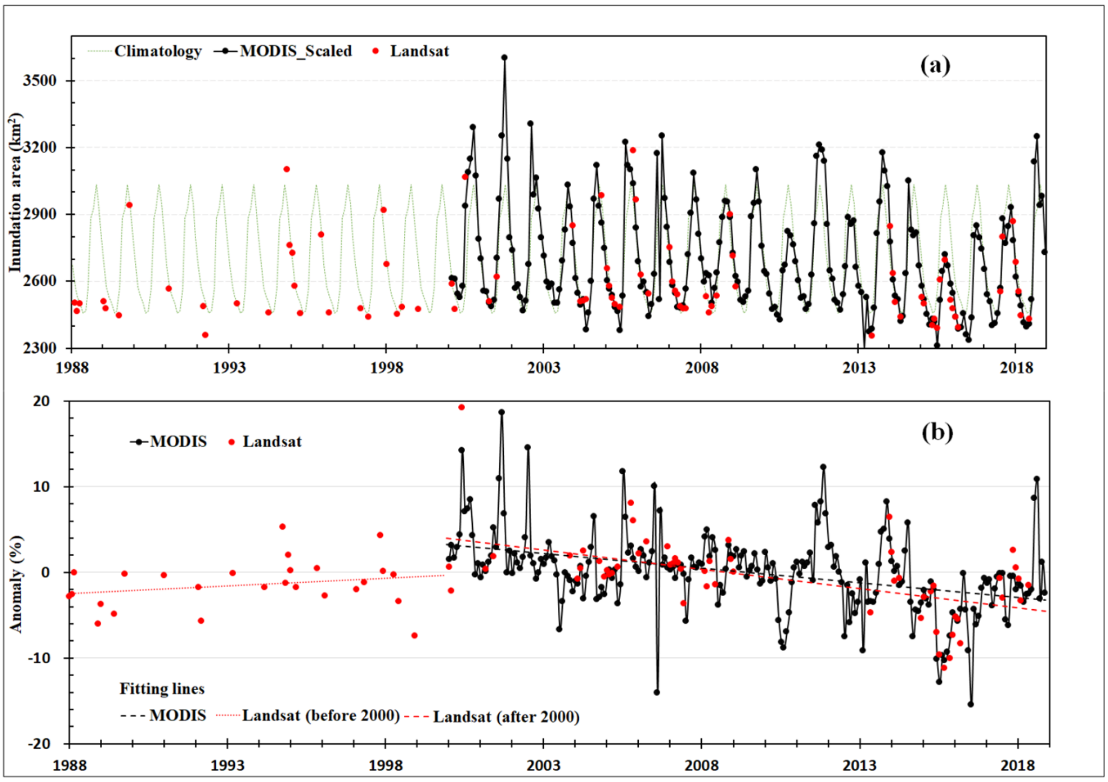

Figure 2. (a) Long-term monthly mean inundation area of Tonle Sap Lake between 1988 and 2018 obtained using the MODIS and Landsat observations (detailed methods see supporting materials). The multiyear monthly mean values derived from the MODIS-extracted results are also plotted. Note that the area of flooded forest associated with Tonle Sap Lake was excluded due to the limitation of optical remote sensing technique. (b) Long-term monthly inundation anomalies were estimated as deviations from the multiyear monthly mean. The interannual trends (fitting line) during different periods (before and after 2000) and satellite missions (red for Landsat and black for MODIS, respectively) are also demonstrated. Note that, sensitivity analysis performed with other start years (e.g. 2001 and 2003) to conduct the trend analysis resulted in very similar fitting lines.

MODIS data are annotated with green dashed lines (temporal distribution of the used images refers to figure S1 (stacks.iop.org/ERL/15/0940a1/mmedia)). When inundation in the current month was smaller than the monthly climatology, the corresponding point would fall below the green line and vice versa. Monthly anomalies, estimated as the deviation from monthly climatologies (in percent), reveal the inundation trends in the past three decades, as shown in figure 2(b). Note that the areas of flooded forest associated with Tonle Sap Lake were excluded due to the incapability of optical remote sensing technique in penetrating vegetation canopy.

The inundation area of Tonle Sap Lake fluctuated rapidly in the observed period and ranged between 3599.8 km^2 in October 2001 and 2304 km^2 in March 2013. Significant inundation seasonality was also revealed, which was primarily due to seasonal changes in regional precipitation and river-lake water interactions (Gasith and Resh 1999, Frappart *et al* 2018). Together with substantial seasonal cycles, noticeable lake shrinkage was demonstrated in recent years. The lake area remained at stable levels (monthly anomaly <5%) before 2000 with an insignificant increasing trend between 1988 and 2000 when only Landsat observations were available. In contrast, significantly decreased inundation was found in most years in the recent two decades (see figures 2(a) and (b)), and the decreasing patterns from 2000 to 2018 were similar between the MODIS and Landsat observations despite substantial differences in their data availabilities.

The recent shrinking trend for Tonle Sap Lake was further revealed via consistent decreasing tendencies in the annual mean (8.22 km^2 yr^{-1}, $P < 0.05$), annual minimum (5.93 km^2 yr^{-1}, $P < 0.05$) and annual maximum (17.82 km^2 yr^{-1}, $P < 0.05$) areas (see figure S2), which were derived with the MODIS-extracted inundation results between 2000 and 2018 (Landsat data is insufficient to derive annual mean conditions). In addition, a non-significant decreasing trend for the lake area was also indicated by diminished values in the annual maximum and minimum ratio ($P > 0.05$), suggesting a possible reduced strength of the dry/wet season flood pulse in the MODIS observational era (see figure S2(d)).

2.2. Long-term variability in the TSS concentrations

The annual mean TSS maps and values of Tonle Sap Lake from 2000 to 2018 are illustrated in figures 3 and S3, respectively. A statistically significant increasing

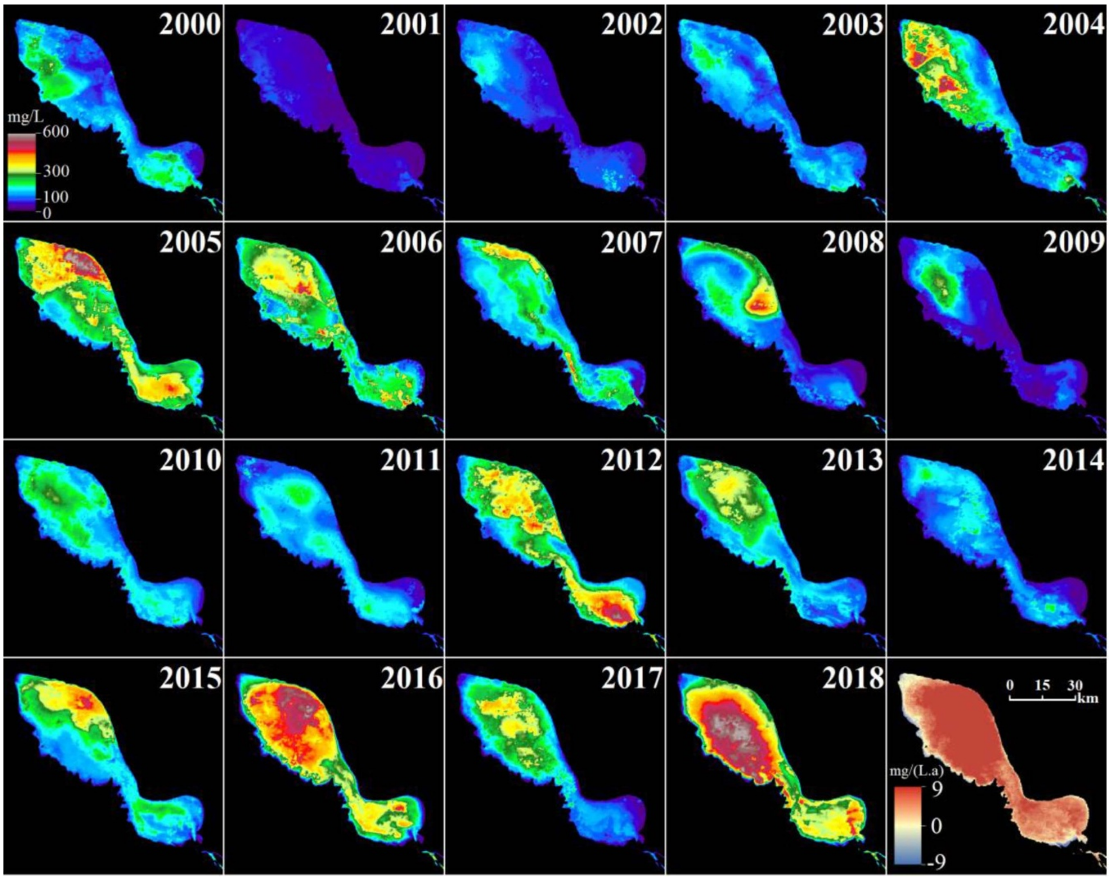

Figure 3. TSS concentration of Tonle Sap Lake from 2000 to 2018. The last panel shows the change rate for the annual mean TSS concentration at each location in Tonle Sap Lake between 2000 and 2018.

trend between 2000 and 2018 could be found for the annual mean TSS concentration of the entire lake (see figure S3(a), 7.92 mg l^{-1} yr^{-1}, $P < 0.05$). In terms of seasonal patterns, when significant TSS increasing trends occurred in quarters 1 & 4, non-significant trends were found in quarters 2 & 3 (figures. S3(b)–(e)). Moreover, the TSS concentrations showed remarkable spatial heterogeneity. For example, higher values (sediment plume) in the riverine estuaries in the southeastern, northwestern and northern parts of the lake were found in most of the years. The spatial heterogeneities of the annual TSS maps should be partially due to the significant seasonal TSS dynamics. The annual mean TSS concentration of the entire lake was generally below 100 mg l^{-1} (bluish to greenish) before 2004, and the values were mostly above 100 mg l^{-1} in most of the later years, leading to TSS increase in almost every location of the lake (see the last panel of figure 3).

2.3. Forces driving the recent lake shrinkage

Three decades of inundation changes for Tonle Sap Lake were documented using satellite observations between 1988 and 2018, and a significant shrinking trend was found in the last two decades. The fluctuation patterns (e.g. large inundations in 2000 and 2001, and dry conditions in 2010 and 2015) of the inundation area, the diminished strength of the dry/wet flood pulse, and the decreasing trend were consistent with the findings of various previous studies, which were based on different types of long term remote sensing techniques, including optical (e.g. MODIS), radar altimetry, Synthetic Aperture Radar, and gravity (. GRACE) (Tangdamrongsub *et al* 2016, Lin and Qi 2017, Frappart *et al* 2018, Ji *et al* 2018, Chang *et al* 2020). To determine the potential factors driving the recent lake shrinkage, three parameters contributing to the water budget of Tonle Sap Lake were examined, including the discharge of the Mekong River (upstream Tonle Sap Lake) as well as the precipitation and ET within the drainage basin of Tonle Sap Lake.

The R^2 value between the annual mean inundation and annual mean precipitation within the drainage basin of Tonle Sap Lake was 0.28 ($P < 0.05$) (figure S4(a)). In contrast, a non-significant relationship between the annual mean inundation and ET was found ($R^2 = 0.08$, $P > 0.05$) (figure S4(b)). Regarding long-term changes, both the annual mean precipitation and ET throughout the Tonle Sap Lake's drainage basin demonstrated non-significant increasing trends from 2000 to 2016 or 1988 to 2016 (figures S4(c) and (d)). A correlation analysis between the annual mean inundation and concurrent runoff collected at

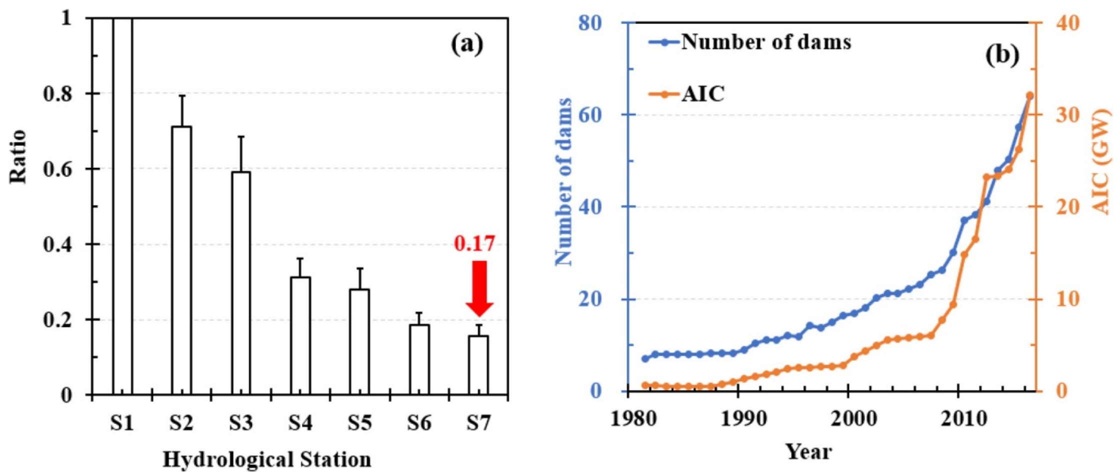

Figure 4. (a) Long term (i.e. 1988–2016) mean ratios of the annual total discharges between six upstream stations (S2 to S7) and the most downstream station (S1), and the error bars represent standard deviations within this period. The ratio between S7 (Chinese Border) and S1 was 0.17 ± 0.03. (b) Long-term changes in the number of dams, active reservoir storage and accumulated installed capacity (AIC) of hydropower electricity generation. The data were obtained and recompiled from WLE-Mekong (2017) and MRC (2015).

the seven hydrological stations in the Mekong River was conducted (see table S1). In general, the closer the proximity of a hydrological station to the lake, the better the expected correlation. For example, the best correlation ($R^2 = 0.84$) was found for station S1 (Kratie) that was nearest to the confluence point of the Tonle Sap River and Mekong River. Indeed, the runoff at Station S1 also demonstrated statistically significant decreasing trend (see figure S5). Such trend appears different from that were found by Lu and Siew (2006) and Park *et al* (2020), due primarily to the disparities in observed time period. In contrast, low correlations ($R^2 < 0.5$) were recorded with the stations that were >1000 km away, where the decreasing trends of runoff were also less significant than that of at station S1.

The above analysis revealed that changes of discharge from the Mekong River were likely the major contributor to the recent lake shrinkage rather than the precipitation and ET within the lake drainage basin. This finding is consistent with the results of several previous studies (Kummu and Sarkkula 2008, Kummu *et al* 2014), and the dominant role of the Mekong River on the area of Tonle Sap Lake was further demonstrated in our study. Thus, a question that follows is whether the upstream dam impoundment in China is the main contributor for the runoff dynamics at the Mekong River and whether this contribution has further influenced the lake area in recent years.

To answer this question, we first estimated the contributions of the surface runoff accumulated in different upstream locations to the downstream Mekong-Tonle Sap region (see figure 4(a)). Clearly, the mean ratio of the total discharge between six upstream stations (e.g. S2 to S7) and S1 decreases with increasing distance to S1. Particularly, the mean ratio between S7 (Chinese Border) and S1 was 0.17 ± 0.03 during the period of 1988–2016, indicating that the total runoff of the Mekong River within China accounts for ~17% of that upstream the confluence point of the Mekong and Tonle Sap rivers. Therefore, the dam construction-associated modulations of the limited portion of water resources within China (a maximum of ~17% of the upstream Mekong River) were unlikely to cause dramatic inundation variations in the downstream Tonle Sap Lake (see figure 2), even if the runoff of Mekong River within China showed certain correlation ($R^2 = 0.51$, see table S1) with the area of Tonle Sap Lake. Long-term changes in the number of dams, active reservoir storage and accumulated installed hydropower electricity generation capacity are plotted in figure 4(b). The three types of data increased since the 1980s, and the numbers surged in the most recent decades. However, these monotonously increasing trends were different from those of the fluctuation patterns in inundation area (see figures 2 & S2). Moreover, the reduced annual inundation minima appeared to contrast with the expectations of many previous studies, which assumed that the water control of upstream reservoirs in the dry seasons could increase the water level of the Mekong River downstream and thus impede the lake-river water flow (Kummu and Varis 2007, Campbell 2009). Therefore, the contribution of dam construction to the recent lake shrinkage, if any, should be insignificant.

To further examine the possible drivers of the recent inundation changes, a correlation analysis was conducted between the annual mean precipitation at each location in the Mekong River Basin and the annual mean lake area, and this process was conducted between 2000 and 2016 due to the availability of precipitation and MODIS inundation datasets. As

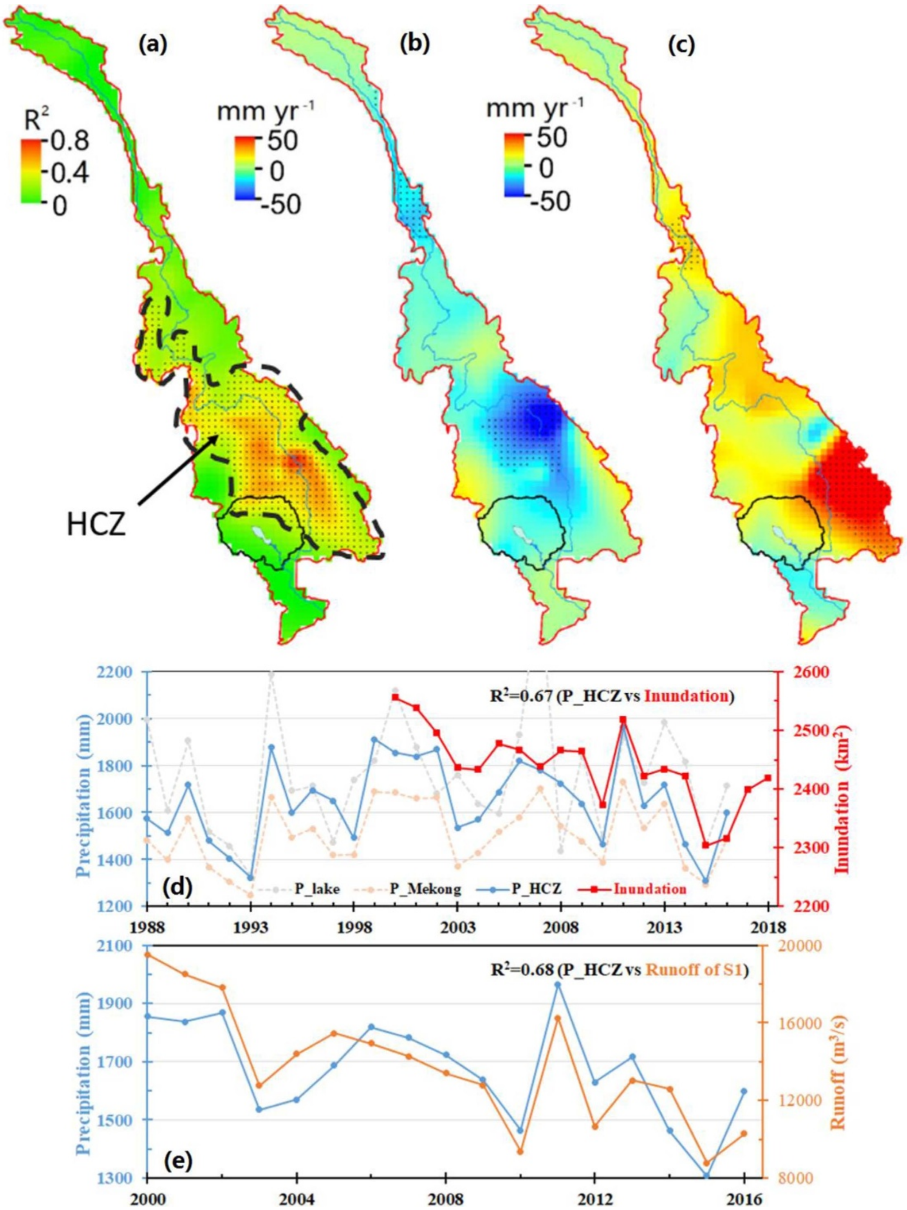

Figure 5. (a) Coefficient of determinations (R^2) between the annual mean precipitation at each location (the pixel size was $0.25° \times 0.25°$) in the Mekong River Basin and the annual mean inundation area of Tonle Sap Lake between 2000 and 2016, where a HCZ was found north of the drainage basin of Tonle Sap Lake (encircled with dashed line). (b) Annual mean precipitation change rate from 2000 to 2016 for each location in the Mekong River Basin; (c) same as (b) but with a time period from 1988 to 2000. The black dots in (a-c) represent pixels with statistically significant ($P < 0.05$) precipitation trends. (d) Long-term annual mean precipitation throughout Tonle Sap Lake (P_lake), the Mekong River Basin (P_Mekong) and the HCZ (P_HCZ). A high correlation ($R^2 = 0.67$, $P < 0.05$) between the annual P_HCZ and inundation areas was revealed. (e) Long-term patterns and correlations between annual mean precipitation of the HCZ (P_HCZ) and runoff discharge of Mekong River at S1 (i.e. the closet station to the confluence point of the Mekong and Tonle Sap rivers, see the location in figure 1).

shown in figure 5(a), a high correlation zone (HCZ) (encircled with dashed line) was found in the region north of the drainage basin of Tonle Sap Lake (yellowish to reddish color), and this region represents >50% of the area of the entire Mekong River Basin. In contrast, most of the data within the drainage basin of this lake showed non-significant correlations. When the change rate of annual mean precipitation between 2000 and 2016 was estimated (color-coded in figure 5(b)), the locations with a statistically significant decreasing trend were primarily located within the HCZ. Indeed, the interannual changing patterns of the mean precipitation of the HCZ mimicked those of the inundation area of Tonle Sap Lake ($R^2 = 0.67$, $P < 0.05$) (figures 5(d)), and a similarly higher correlation ($R^2 = 0.68$, $P < 0.05$) was found between the annual mean runoff at S1 and the precipitation in the HCZ (figure 5(e)). Therefore, the recent inundation shrinkage of Tonle Sap Lake was likely due to the runoff decline in Mekong River that was caused by the reduced precipitation in the HCZ. Spatially, the HCZ is located in lower basin of the Mekong River and mostly outside the drainage basin of Tonle Sap Lake. Reports have suggested that reduced precipitation in

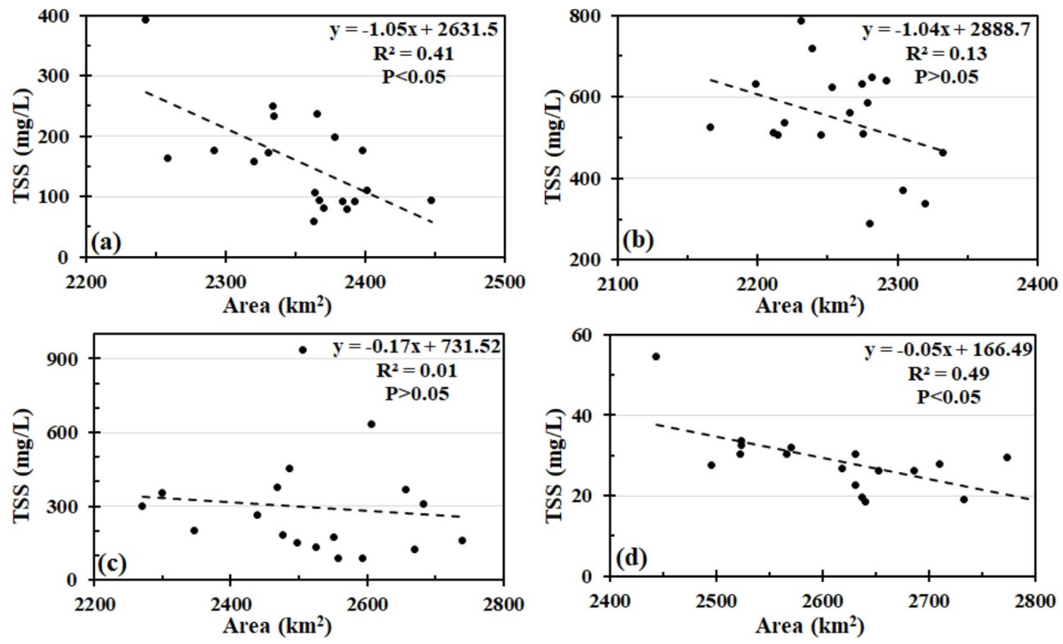

Figure 6. Relationships between the seasonal mean TSS and inundation areas of Tonle Sap Lake. (a-d) Quarters 1–4.

the Mekong River Basin in recent years could be well explained by the combined effects of the El Niño/La Niña events and the Indian and Western North Pacific Monsoons (Frappart *et al* 2018), suggesting that the decreased runoff from the Mekong River was primarily caused by climate change rather than human perturbations. In contrast, the precipitation trend for most Mekong River Basin between 1988 and 2000 was non-significant (figure 5(c)), which could also partially explain the stabilized inundation during this period (see figure 2).

A multiple GLM regression (Tao *et al* 2015) was conducted to further quantify the relative contributions of the three aforementioned potential factors on the interannual inundation changes of Tonle Sap Lake, including the precipitation of the HCZ (figure 5(a)), the number of dams (figure 4(b)), and the ET of the drainage basin of the lake (figure S4(b)). Numerically, the relative contributions were 76.1% for the precipitation of the HCZ, 6.9% for the number of dams and 2.0% for the ET. These results clearly illustrate that precipitation changes in the HCZ are the predominant contributor towards the interannual lake inundation dynamics.

3. Discussion

3.1. Impacts of inundation shrinkage on water turbidity

Without significant disturbance via human activities (such as sand dredging), the turbidity of Tonle Sap Lake may be primarily controlled by two factors: (1) sediment resuspension driven by external (i.e. wind within the lake and sediment discharge within the lake basin) or internal forces (hydrodynamics) (Hoshikawa *et al* 2019) and (2) sediment exchanges between Tonle Sap Lake and the Mekong River. However, as demonstrated by numerous previous studies (Kummu and Varis 2007, Li *et al* 2017b), the sediment discharge of the Mekong River has reportedly declined in recent years; therefore, this sediment discharge likely did not contribute to the increasing trends in TSS in Tonle Sap Lake. Similarly, the correlation analysis revealed nonsignificant relationship between the annual mean TSS and wind speed (see figure S6(a)). Since precipitation often show high correlations with riverine sediment load, precipitation within the drainage basin of Tonle Sap Lake has been used as the surrogate for riverine sediment discharge to examine its impacts on lacustrine TSS. As indicated in figure S6(b), annual mean TSS also showed nonsignificant relationships with precipitation within the lake's drainage basin. Therefore, the recent increase in water turbidity as observed by satellite retrievals, was likely due to hydrodynamic changes associated with lake shrinkage. Specifically, the impacts may potentially be attributed to the fact that the decreased water depth could result in higher chances of sediment resuspension from the bottom, even when external forces are stable. Indeed, the validity of this hypothesis could be at least partially confirmed by the statistically significant correlations between the annual TSS concentration and inundation area in two quarters ($R^2 = 0.41$ for quarter 1 and $R^2 = 0.49$ for quarter 4, both with $P < 0.05$, see figures 6(a) and (d)). Such correlations were also consistent to the results of Hoshikawa *et al* (2019), where constant significant relationships were found between water depth and TSS in dry seasons. Therefore, an increase of sediment resuspension (either through wind or gravity flow) was associated with the inundation shrinkage (i.e. water depth decline) and thus caused the recently increased water turbidity in Tonle Sap Lake (Siev *et al* 2018). In contrast, the non-significant TSS trend and TSS-inundation correlations in quarters 2 and 3 were due to the reversed flow of the Mekong River to Tonle Sap Lake during these wet seasons (figures 6(b) and (c)). Specifically, the annual mean sediment flux from the Tonle Sap River to the lake varies between 5.1 Mt $year^{-1}$ (Kummu *et al* 2008) and 6.4 Mt $year^{-1}$ (Koehnken 2012), and the annual mean sediment discharge from the lake to the river ranges between 1.4 Mt $year^{-1}$ (Kummu *et al* 2008) to 1.5 Mt $year^{-1}$ (Koehnken 2012). As such, the turbidity of the lake could be considerably impacted by the sediment-rich reversal flows from the Mekong River, which overwhelm the inundation shrinkage associated impacts in wet seasons. Note that, the changes in grain size of sediment (due to dam construction or other factors) and thus the water turbidity in the Mekong River has not been considered here (Hackney *et al* 2020). Nevertheless, the determination of the responsible mechanisms and quantification of their exact contributions require further physical modeling and additional *in situ* hydrological measurements.

3.2. Limitations and implications

Water area extraction is theoretically a straightforward task when using remote sensing techniques due to the strong absorption of water molecules (Jensen 2006, Hou *et al* 2017). Large signal contrasts are expected between land and water, and a simple threshold for single band or spectral indices (e.g. NDVI and NDWI) could be used to separate land and water (Mcfeeters 1996). However, this task is not trivial for delineating the surface area in long-term images. The threshold for a single band or band combinations, could differ considerably due to disparities between different images regarding the illumination conditions and observational geometries and residual errors from the atmospheric correction process, water turbidity, etc. Therefore, the optical threshold for each individual image was selected to obtain the best possible land/water classifications. The comparison between concurrent inundation areas extracted from MODIS and Landsat imagery demonstrated favorable consistency between the two independent observations ($R^2 = 0.84$, $p < 0.01$), indicating the validity of the derived area for Tonle Sap Lake with moderate resolution MODIS images (see figure S7(a)).

Another limitation for the optical remote sensing images (such as MODIS and Landsat) is that, flooded forest associated with Tonle Sap Lake cannot be captured due to their incapability in penetrating vegetation canopy, and the associated area could even exceed that of the open water. Theoretically, L-band SAR images could be used to detect the inundated areas under vegetation, due to their strong penetration strength (Martinez and Le Toan 2007). However, such effort has been prohibited due to the unavailability of L-band datasets. For example, historical ALOS-1 PALSAR data (2006–2011) is restricted for users reside within the US (https://asf.alaska.edu/restricted-data-access-request/), while each recent ALOS-2 PALSAR image (2014-now) costs thousands of US dollars. The global mosaic PALSAR products provided by the Japan Aerospace Exploration Agency (JAXA) (https://www.eorc.jaxa.jp/ALOS/en/palsar_fnf/fnf_index.htm#description), although freely accessible, the one-year time interval makes them impossible to study dynamic land features. Nevertheless, the inundation area of the flooded forest is expected to highly correlate with the open water within the lake. This argument could be supported by the high consistency between MODIS-based inundation of the lake and GRACE-measured terrestrial water storage changes (TWS) within the lake basin (see figure 11 in Tangdamrongsub *et al* 2016). Specifically, the TWS variations observed through GRACE includes all water components (e.g. surface water, soil moisture, and groundwater), and with a coarse spatial resolution of >300 km. Therefore, we believe the inundation trend derived from MODIS and Landsat in our study should be valid.

The MODIS data had a moderate spatial resolution (250 m), and the area values were systematically lower than the Landsat values (see figure S7(a)); however the observation frequency of MODIS allowed us to capture the short-term inundation dynamics of Tonle Sap Lake. We acknowledge that one of the limitations for inundation study of the lake were the missing data problems for some years (or months) in the past three decades, particularly before 2000 (see figure S1), due to the frequent presence of clouds and long revisiting period of the Landsat observations (16 d). However, even with the substantial difference in valid observations, the Landsat-derived decreasing trend after 2000 was almost identical to that of MODIS. Therefore, the stable inundation before 2000 observed using Landsat imagery is likely to be true. In short, while Landsat provided the multidecadal inundation changes for Tonle Sap Lake, the MODIS observations helped reveal the short-term variability and validate the Landsat-based trends. Nevertheless, with higher spatial resolutions (tens of meters) and fairly frequent observations (several days), the recently launched satellite missions (such as the Sentinel series instruments from the European Space Agency and the Gaofen series of satellites from China) may provide more accurate inundation maps and long-term trends for Tonle Sap Lake and other global water bodies in the future. Additionally, the integration of multi-source satellite missions are also expected to provide more frequent (up to daily) observations of this lake (Chang *et al* 2020).

4. Conclusions

The current study clearly reveals that the recent shrinkage of Tonle Sap Lake was primarily due to the precipitation decrease in the upstream Mekong River, thus providing strong evidence to help end water volume-associated debates among the countries in the Mekong River Basin. Moreover, the flood pulse of Tonle Sap Lake, which is the key factor determining the high productivity of the lake (Gabriel Lamug-Nañawa 2011, Kuenzer 2014), has declined in recent years (Fig. S2d). Therefore, ecosystem modeling is required to investigate whether lake inundation changes could pose threats to local biodiversity. Finally, although our analysis demonstrated the dominant role of lake size changes in enhancing lake water turbidity, considerable efforts (in terms of numerical modeling and *in situ* observations) are needed to examine whether the limited effects of dam building on inundation and water turbidity are similar or much larger for other water quality parameters (such as nutrient concentrations) and ecological functions.

Our study provided an example of how multiple sources of long-term satellite observations could be used to monitor the environmental transitions in a highly dynamic region. Furthermore, the results provide critical information to address international disputes. The method used here is easily extendable to other similar regions worldwide to help understand climate/human-induced environmental changes.

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Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Conflict of interest

The authors declare that they have no conflict of interest.

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