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

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Ye Wang^{1,2}, Lian Feng^{2,*}, Junguo Liu² and Deliang Chen³

¹ School of Hydraulic Engineering, Dalian University of Technology, Dalian, People's Republic of China

- ² School of Environmental Science and Engineering, Southern University of Science and Technology, Shenzhen, People's Republic of China
 - Regional Climate Group, Department of Earth Sciences, University of Gothenburg, Gothenburg, Sweden

* Author to whom any correspondence should be addressed.

E-mail: fengl@sustech.edu.cn

Hydrological and environmental changes of the Mekong River system have drawn extensive investigations and sometimes debates, due primarily to its transboundary nature and ecological importance (Bonheur and Lane 2002, Baran and Myschowoda 2009, Arias et al 2012, Kuenzer et al 2012, Lu et al 2014). In our original paper published recently (Wang et al 2020), satellite observations revealed an evident decreasing trend in the inundation area of Tonle Sap Lake, a crucial component of the Mekong River system and the largest lake in Southeast Asia. Hydrological analysis indicated that inundation shrinkage was due primarily to the precipitation decrease in the Mekong River Basin, rather than the dam construction in China. However, Kallio and Kummu (2021) (hereafter referred to as KK) challenged our conclusion by using modeled discharges at the Mekong River and simulated inundation areas of the lake. We disagree with their data interpretation and arguments and address the major issues raised by KK and revisit the conclusions of our original paper here.

KK commented that we failed to 'address the key component of the flood pulse system' by only using the annual mean data. However, the objective of Wang *et al* (2020) is to 'explore inundation and turbidity changes in Tonle Sap Lake in the past three decades, and reveal the major factors contributing to the recent lake changes'. In fact, in our original paper, we have also acknowledged the importance of flood pulse in the production of the lake's floodplain and estimated the ratio between the annual maximum and minimum ratio and their long-term trend (figure S2(d) in Wang *et al* (2020)).

KK argued that 'using annual mean discharges, Wang *et al* (2020) fail to take into account the impact of hydropower dams'. We plot the quarterly mean discharges collected at Kratie station in the Mekong River (see figure 1), which is the nearest hydrological station to the confluence point of the Tonle Sap River and Mekong River. The discharges of all four seasons demonstrated statistically significant (P < 0.05) decreasing trends, leading to an overall decreasing tendency for annually aggregated datasets (see figure 5(e) in Wang et al 2020). Moreover, the Moderate Resolution Imaging Spectroradiometer (MODIS)-derived inundation areas also showed statistically significant (P < 0.05) shrinking trends in three quarters (quarters 2, 3 and 4), and the correlations to seasonal discharges of Mekong River are also significant except for quarter 2 (figure 1). Although we could not reproduce the changes in Area5 (high inundation area) and Area95 (low inundation area) demonstrated by KK, differences are expected between their simulated and our satellite observed datasets. Indeed, our original paper also indicated that the annual maximum, mean and minimum inundation areas showed statistically significant trends (figure S2 in Wang et al 2020), clearly suggesting a pronounced decreasing trend in lake inundation.

KK raised another concern that 'Wang *et al* (2020) ignore the flooded forest part of the floodplain'. We have acknowledged in our original paper that the optical remote sensing technique cannot penetrate the flooded forest and thus the water underneath is not considered in our study. However, as already stated in Wang et al (2020), MODIS-observed open water areas should be highly correlated with the area of inundated flooded forest, as they are connected (directly or indirectly) and belong to the same hydrological unit. This argument can be supported by the close agreement between Moderate Resolution Imaging Spectroradiometer (MODIS)-delineated inundation areas and Gravity Recovery and Climate Experiment (GRACE)-detected terrestrial water storage within the lake region (Tangdamrongsub et al 2016).



Figure 1. Long-term quarterly mean inundation area of Tonle Sap Lake (blue curves) and the discharges of Mekong River (red curves, gauged at Kratie station). The change rates of these two parameters and their correlations (R^2) are annotated within each panel.



By comparing observed discharge and modeled discharge driven by a global reanalysis dataset, KK pointed out that the dam construction upstream has caused remarkable changes of discharge in the Mekong River. Having said these, we do agree that the dam built in China may have modulated the discharge at Chiang Saen (the first station after the Chinese border); but this is not necessarily true for Stung Treng (\sim 1600 km away from the Chinese border and studied by us). This argument can be well supported by two facts: (a) the differences between modeled and observed discharge at Stung Treng were up to 5-fold larger than that at Chiang Saen (see figures 1 and 2 in KK); and (b) the fraction of the annual

mean discharge at Chiang Saen to Kratie (a station slightly downstream of Stung Treng) is only 17% (see figure 4(a) in Wang *et al* 2020) and with minor inter-and intra-annual changes. Further, we estimated the minimum flows (Q95) and high flows (Q5) at the Kratie station (figure 2), where the water level demonstrates a stronger correlation with the inundation of Tonle Sap Lake than other hydrological stations in the Mekong River (see table S1 in Wang *et al* 2020). Both Q95 and Q5 at the Kratie station demonstrated decreasing trends over past decades, which appear different from the pronounced increasing trends presented by KK that observed from other stations whose impacts on the Tonle Sap





Lake are fewer. Therefore, hydrological processes/ alterations between Chiang Saen and Stung Treng represented larger contributions to the discharge changes (seasonally or annually) at Stung Treng than that within China.

To determine whether inundation changes of Tonle Sap Lake at seasonal scales can be attributed to precipitation dynamics in the upstream Mekong Basin, we estimated the relationship between quarterly mean inundation of Tonle Sap Lake and mean precipitation at each location in the Mekong River Basin (figure 3(a)). For four seasons, precipitation in substantial areas in the Mekong River Basin (locations varied between different seasons) demonstrated statistically significant correlations with the lake inundations. These results are consistent with the relationship at the annual scale shown in Wang *et al* (2020), where the annual mean precipitation in the high correlation zone is highly correlated with annual mean inundation. Indeed, the precipitation in the Mekong River shows a pronounced decrease in three quarters (see figure 3(b)), and therefore the decreased riverine water levels tended to cause inundation shrinkage in the Tonle Sap Lake in recent years.

KK commented that the generalized linear model (GLM) should also be performed in different seasons to determine the contribution of different factors

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to the inundation dynamics. However, as precipitation shows decreasing trends in all seasons (except for quarter 3, see figure 3), the dominant role of precipitation should be expected at both seasonal and annual scales. The GLM is used to quantify the relative contributions of the examined variables (precipitation in the high correlation zone, the number of dams and the Evapotranspiration (ET) within the drainage basin) to lake inundation changes. The GLM analysis was conducted using R (version 3.6.3), and further details on GLM can refer to McCulloch (2000). KK was also concerned that 'hydropower dams should be represented by their active storage volumes rather than their counts'. Actually, we used both of them to conduct the GLM, and the results are very similar between one another (with limited impacts of dams). This is possible because of the intrinsic high correlation between active storage volumes and the count of dams. Nevertheless, we acknowledge that neither the counts of the dam nor the active storage volumes are optimal indicators for dam regulations, and we expect more reliable contribution estimates can be obtained when the detailed datasets on dam operations are available.

Overall, although we appreciate the interests and detailed comments by KK, the above lines of evidence strongly support our original conclusions: the recent inundation shrinkage of Tonle Sap Lake was mainly caused by the decreased precipitation in the upstream Mekong River rather than the dam construction in China. Having said this, we do welcome any further discussions supported by additional datasets and new techniques, to help understand the potential impacts of climate changes and human activities on the hydrological dynamics of Tonle Sap Lake and the Mekong River.

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ORCID iDs

Lian Feng (a) https://orcid.org/0000-0002-4590-3022 Junguo Liu (a) https://orcid.org/0000-0002-5745-6311

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