TECHNICAL RESPONSE

SUSTAINABILITY

Response to Comments on "Designing river flows to improve food security futures in the Lower Mekong Basin"

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Sabo *et al*. presented an empirically derived algorithm defining the socioecological response of the Tonle Sap Dai fishery in the Cambodian Mekong to basin-scale variation in hydrologic flow regime. Williams suggests that the analysis leading to the algorithm is flawed because of the large distance between the gauge used to measure water levels (hydrology) and the site of harvest for the fishery. Halls and Moyle argue that Sabo *et al*.'s findings are well known and contend that the algorithm is not a comprehensive assessment of sustainability. We argue that Williams' critique stems from a misunderstanding about our analysis; further clarification of the analysis is provided. We regret not citing more of the work indicated by Halls and Moyle, yet we note that our empirical analysis provides additional new insights into Mekong flow-fishery relationships.

Sabo *et al.* (*1*) presented an empirical analysis that mathematically defines the socioecological response of an ecosystem (fish catch) to an increasingly human-controlled physical ecosystem driver worldwide (hydrology). This analysis yielded three critical findings: (i) The timing of river discharge, as much as the magnitude, controls fish catches in the Tonle Sap River Dai fishery; (ii) the two aspects of the hydrology most closely related to fish catch—water height during the flood and duration of the low-flow period—have been changing with existing dam development in the direction opposite to what promotes fish catches; and (iii) a "designed" hydrograph has the potential to maintain or even improve fish catches without the constraint of maintaining a completely natural hydrologic regime. Together, these results provide a new perspective on managing flow regimes in heavily developed rivers and thus provide directions for future research, while simultaneously presenting a potentially viable approach for mitigating some of the impacts of dam development on capture fisheries in the Mekong River system.

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In his Comment, Williams (*2*) contends that this empirical analysis is flawed because of the distance between the river gauging station used in the analysis and the location of the fishery, and that the "good design" flow scenario presented in Sabo *et al.* is thus unable to be implemented. Both questions are addressed below, which we believe arise from Williams' misunderstanding of the analysis presented in Sabo *et al.* In a second Comment, Halls and Moyle (*3*) note that previous research by Halls and others has identified flood magnitude and duration as important to Dai fishery catches, which were not cited by Sabo *et al.* They also question the use of the Stung Treng gauging station on the Mekong River for our analysis as opposed to the more proximate Prek Kdam gauging station on the Tonle Sap River. Lastly, Halls and Moyle raise concerns about implementation of a designed-flow regime and messaging to regional policy-makers that designed-flow regimes are a complete solution to environmental impacts arising from dam development in the Mekong. We appreciate the contributions of Williams (*2*) and Halls and Moyle (*3*) and the opportunity to discuss these issues.

It is indeed unfortunate that Sabo *et al.* did not cite the full complement of research showing the relationship between fishery catches and flood-pulse magnitude and duration, as we agree that there is substantial literature in support of this result. Beyond this, however, Sabo *et al.* also discerned that the magnitude and duration of the low-flow period is equally as important to fisheries as the high-flow period. This more novel and unexpected result is nonetheless consistent with other research and general theories suggesting that the production of organic matter and nutrients in floodplains during the dry season supports the exceptionally high productivity of flood-pulse ecosystems observed worldwide (*4*–*6*). Governing mechanisms and the magnitude of nutrient and organic transfer from floodplains to fishes remain active areas of research, but current information suggests that their importance to fishery productivity is substantial [e.g., (*7*–*9*)].

The multivariate autoregressive modeling approach used by Sabo *et al.* reveals a statistical relationship between multiple aspects of hydrologic variance at the Stung Treng gauging station—namely, water height at maximum flood and duration of the low-flow period—and annual fish catches at the Dai fishery on the Tonle Sap River. Stung Treng was chosen because it had the longest period of record, which was important for quantifying pre-dam hydrologic conditions. The gauging station in the Tonle Sap River at Prek Kdam is the closest to the fishery, but the water level record was too short to carry out the full analysis. The distance between the gauge station and the fishery is irrelevant, however, as long as the hydrology at the reference location and at the fishery location are consistently related to each other. The two records need not be identical in shape or magnitude in order to be valid for analysis and forecasting, as systematic differences in hydrology between the locations are inherently captured in the empirical analysis.

The data presented in figure 1 of Williams (*2*) are from the Tonle Sap Lake itself at Kampong Luong, yet despite the issues inherent in attempting to compare height of water in a lake basin to height in a flowing river for only 2 years, the data show a high degree of systematic coherence. The more appropriate comparison between the Mekong stage at Stung Treng and the Tonle Sap River stage at Prek Kdam is given in Fig. 1 here. We have also extended the comparison to a 27-year period to better represent interannual variability. This figure shows two important aspects of the system hydrology: (i) the strong coherence between the two records (Fig. 1A), and (ii) the nonlinear relationship on the falling limb of the hydrograph, with stage decreasing faster in the Mekong than at Prek Kdam (Fig. 1B). The former validates the use of Stung Treng as the reference station in our analysis. The latter indicates that because of landscape morphometry, declining river stage at Stung Treng will precede and be more rapid than declines in stage in the Tonle Sap River. Because this effect is inherently captured in our analysis, it renders the calculation by Williams moot, as the "good design" presented in Sabo *et al.* is for the hydrograph at Stung Treng, not at the Tonle Sap River, and it is wrong to assume that the two stations should have identical hydrographs. In short, Williams has made an incorrect assumption that our "good design" hydrograph is to be applied at any location in the basin; it is applicable at Stung Treng only, with the response of fish catch applicable at the Dai fishery only.

Any meaningful assessment of the implementation of designed-flow scenarios in the Mekong will involve a complex modeling exercise that

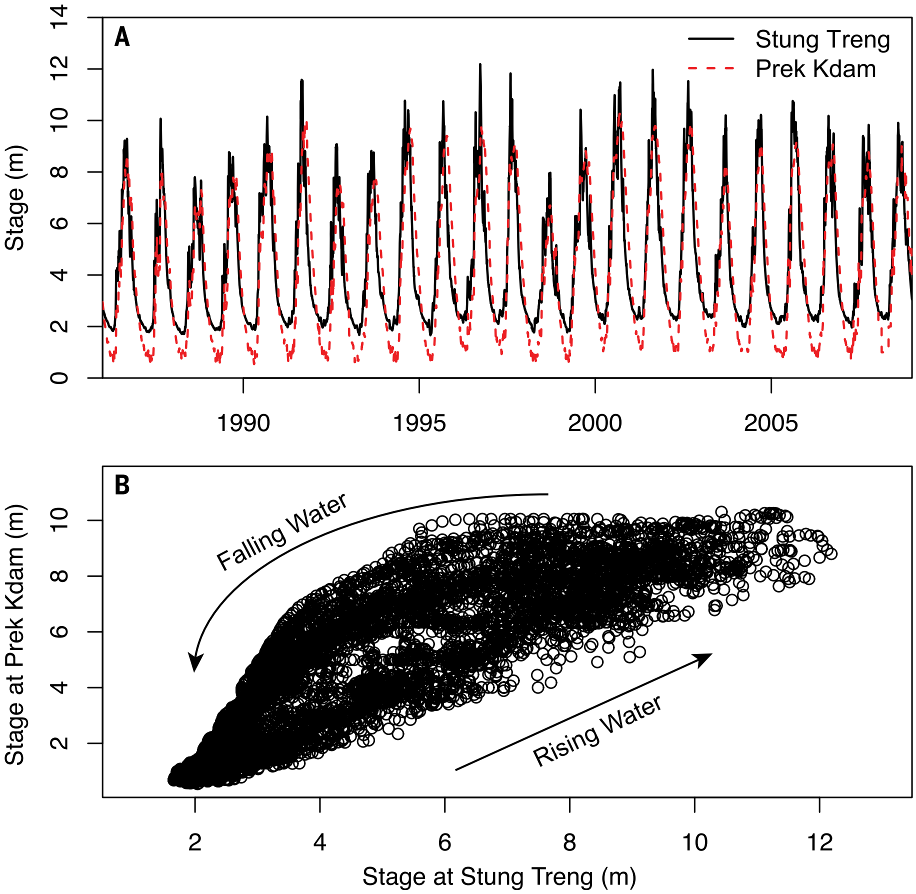

Fig. 1. Hydrograph coherence and nonlinearity in the Lower Mekong Basin. (**A**) River stage at Stung Treng on the Mekong River and Prek Kdam on the Tonle Sap River from 2 January 1986 to 31 December 2008. The correlation coefficient (Pearson *r*) of $\log_{10}$-transformed stage is 0.89. (**B**) The same data plotted against each other, showing a linear relationship in water height between the two stations on the rising limb of the hydrograph but a nonlinear relationship on the falling limb.

considers, at least, movement of water across the landscape and through time, the number and placement of dams throughout the watershed, operation rules for electricity production, coordination (or lack thereof) of dam operations, and future climate. Similarly, as Halls and Moyle (*3*) note, multiple other societal objectives beyond fisheries—such as rice production, flood mitigation, biodiversity protection, and electricity production—must also be taken into account when considering how river hydrology might be managed in the future. This was obviously beyond the scope of Sabo *et al.*, and continued future research is needed to provide a more comprehensive multisectoral analysis. The goal of such an analysis should be to present a broader suite of futures to local policy-makers to better highlight critical cross-sector interdependencies.

Finally, as rapid economic development proceeds in the Lower Mekong Basin, an altered flow regime is one of many ecosystem changes likely to have an impact on fish production and fisheries. Sabo *et al.*'s focus on flow regime does not imply that other potential impacts—for example, barriers to migration, reduced sediment supply, and eutrophication—are unimportant or need not be considered. The potential for unintended ecosystem consequences of a non-natural flow regime must also be further researched and fully considered in the decision-making process. Designing flow regimes is one area where there is scope for management action, however, and Sabo *et al.* provide a method to robustly quantify the relationship between flow regime and fisheries catches in a way that managers can use. With this, there is now means for formal trade-off evaluation useful to policy-makers and a potential path toward mitigating some of the impacts that dam development will have on lower Mekong fisheries. Exactly how designed flow regimes might be implemented in the real world will require substantial additional research and stakeholder engagement.

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