Note: The comments from the reviewer are in black while the responses from the authors are in blue.

Reviewer 2

Overall, the paper represents an important advance in global water quality modeling using SWAT+, offering a solid foundation for future community-driven improvements. However, uncertainty, representation of in-stream processes, and data generalization remain key challenges. My comments mainly concern the quality and scope of the validation.

Response: We sincerely thank the reviewer for their positive feedback and welcoming our work. We appreciate the recognition of the potential and significance of the CoSWAT-WQ model for advancing global water quality research. We also acknowledge the concerns regarding the discussion of uncertainty and validation, and we will address these points carefully in the revised manuscript.

I feel that the authors primarily consider spatial validation, comparing modeled and observed nutrient loads across catchments. At the same time, temporal validation (e.g. monthly or seasonal nutrient concentrations) is largely absent. In my opinion, uncertainty analysis is also sorely lacking. While some indicators are reported, uncertainty in input data (especially for fertilizers/manures and point sources) is insufficiently considered.

Response: Thank you for this valuable comment. While our original manuscript focused primarily on spatial validation, we agree that temporal validation and a more thorough uncertainty analysis could make the manuscript stronger. Although we included a monthly evaluation of nutrient concentrations (Fig. 8 and Supplementary Material A), we acknowledge that this aspect was not sufficiently discussed. In the revised manuscript, we will expand the discussion of temporal performance to better demonstrate the model's ability to simulate seasonal dynamics. Additionally, as the model relies on several global input datasets, this inherently introduces uncertainties into our simulations. While these datasets are essential for achieving global coverage, they come with limitations that can affect model accuracy in multiple ways. For example, point source nutrient loads, which are derived from global gridded datasets, also carry substantial uncertainty, especially because such data distribute emissions over grid cells, whereas in reality, wastewater discharges occur at specific point locations. This spatial generalization may lead to mismatches between modelled and actual nutrient input locations, particularly in urban or industrial regions. Similarly, fertilizer/manure data at a 0.5-degree resolution may fail to capture the heterogeneity of fertilizer/manure application rates. This can lead to misrepresentation of nutrient source areas at the local level. Similarly, using gridded climate data (e.g., precipitation) at the same resolution can significantly influence hydrological processes such as runoff generation, which are key drivers of nutrient mobilization and transport. These issues are further compounded in regions with sparse observational data, where global datasets rely more heavily on interpolation or modelling assumptions. As a result, model outputs in such areas may be less reliable in absolute terms, although they may still be useful for identifying relative patterns, trends, or hotspots. Thus, to improve the robustness of future simulations, regionally validated input datasets should be integrated wherever available.

We will revise the manuscript to better discuss the temporal (monthly) evaluation and also expand on the uncertainties of the input data (fertilizer/manure and point sources).

Regarding fertilizer and manure inputs, these are based on national statistics, which introduce large uncertainties in local management practices.

Response: Thank you for this valuable comment. Yes indeed, most of the crop management datasets we use are prepared from national statistics which inherently introduce uncertainties in local management practices. For example, crop management data at a 0.5-degree resolution may fail to capture the heterogeneity of agricultural practices, including crop types, fertilizer application rates, and management intensity. This can lead to misrepresentation of nutrient source areas at the local level. Unfortunately, to our knowledge, there are currently no globally consistent datasets with higher spatial resolution available for these inputs. However, one strength of our workflow is its flexibility, if higher-resolution data becomes available in the future, our approach can incorporate and reflect that added heterogeneity.

We intend to expand our discussion of these limitations and address the implications of the current global management datasets.

In the paper, the authors do not assess the sensitivity of nutrient results to stream process parameters - a significant gap in water quality modelling at this scale.

Response: Thank you for your insightful comment. We agree that instream process parameters are an important but often underexplored aspect in global water quality modelling. In this version of the model, we do not explicitly assess the influence of instream parameters, which we recognize as a limitation. This is an area we intend to explore in future model versions, particularly as we begin calibrating different components of the system. Beyond this study, a likely reason for the limited attention to instream process sensitivity or calibration in large-scale nutrient models is the inverse relationship between nutrient retention potential and stream depth. This means that smaller streams, which offer greater solute-benthos contact, tend to have higher nutrient retention capacities than larger rivers (Ye et al., 2012; Ensign and Doyle, 2006). As a result, input sources may have a more dominant influence on nutrient loads at larger scales, possibly leading to a reduced emphasis on instream processes. While our study did not explore this aspect in detail, we agree it could be significant, particularly at local or regional scales.

We will make sure to note this limitation more clearly in the revised manuscript.

The authors assume that the SWAT+ structure and parameters are universally applicable - but in reality, hydrological and biogeochemical processes vary with climate, soil, and management. For example, the same set of parameters may perform poorly in tropical systems but well in temperate ones. This is not explained.

Response: Thank you for this important observation. We agree that a discussion on the use of default model parameters is necessary, especially given the variability in hydrological and biogeochemical processes across different climatic, soil, and land management contexts. To give a bit of context here, SWAT+ can still provide reasonable outputs in ungauged basins when default or parameters are used. For example; Chen et al. (2023) and Niraula et al. (2011) compared critical source areas (CSAs) for sediment and nutrients of a calibrated and uncalibrated SWAT model in southwest China and southeast U.S respectively. Both studies showed that CSAs locations had high similarity (81–93%) with and without calibration. These studies show that the SWAT model can be applied to identify pollution hotspots without calibration in watersheds especially data poor cases. That said, we fully acknowledge that the default parameter set is not universally optimal as performance can vary substantially between tropical and temperate systems, for example. Calibration remains essential wherever observational data are available, as it significantly improves model performance and reliability.

We will clarify this point in the revised manuscript and expand the discussion to reflect on the use of default parameters and their subsequent implications.

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