Author Responses to Reviewer Comments

We would like to thank the reviewer for taking time to make comments and suggestions. We have revised the manuscript based on the feedback and have answered questions raised. We hope these revisions are satisfactory for the further processing of this paper.

In this response document, Orange is the quoted comment/question while blue is response text. *Italicised text is text extracted from the manuscript after implementing suggested changes.*

Reviewer 2

The model calibration part has been completely referred to a previous paper. It is necessary to explain the relavant calibration principles and details here in brief. Please try to make the paper self explanatory to the extent possible. It can be provided as appendix if the authors feel so. The term soft data has been defined only in Chawanda et al. (2020a) and not here.

We thank the reviewer for raising this comment. We have adopted the suggestion and included a paragraph in Section 2.3 describing Hydrological Mass Balance Calibration (HMBC) and included a definition of Soft Data referencing Arnold et al. (2015).

> *Unlike traditional calibration methods which predominantly rely on hard data, such as time series of hydrological quantities at a specific point in the watershed, the Hydrological Mass Balance Calibration (HMBC) uses soft data to improve model accuracy, especially for larger scale applications. Soft data refers to information on individual processes, such as long-term annual average estimates (Arnold et al., 2015). This type of data provides insights into the broader patterns and averages, setting constraints during hard calibration to enhance the representation of hydrological processes. Using soft data reduces computational and time expenses (Chawanda et al 2020a). HMBC aims to adjust model parameters to ensure that the simulated long-term average water balance components align with observed averages which enhances the model's performance in impact studies by more accurately simulating hydrological mass balance components. The procedure involves running the model, evaluating results against soft data, estimating new parameter values, re-running the model, and repeating this cycle until certain criteria are met. Generally, a hydrological component such as ET is calibrated within five iterations before progressing to the next component in each region.*

We have also revised more areas to make the manuscript stand more independent where brief overviews were missing.

I could not read the previous paper in full (Chawanda et al., 2020a). However, I think that this paper is somewhat similar to the previous paper referred here in terms of assessment of climate change impact. A comparison of results over the common landmass is needed to be presented in the current manuscript.

Chawanda et al, (2020a) introduces HMBC and demonstrates the role of conducting calibration on Climate Change (CC) projections made. However, as CC assessment itself was not the focus of the paper, there are significant differences that prevent a direct comparison between the results from that paper and the results presented in this study. To begin with, the previous paper's projections were made only using RCP 6.5 and for a different period 2060 - 2090, not 2070 – 2100. This is in addition to having different historical reference period (1970 – 2000 versus 1976 – 2005 for the current study) For these reasons, a one-to-one comparison could not be made. However, it is worth noting that the signal for change in ET and Runoff for CC RCP 6.0 is consistent despite these period differences.

What is the benefit of doing this climate change and LULC study? The results are averaged over large basins for long time periods. Hence, how beneficial this study will be for local scale adaptation or management?

Addressing the broader implications and concerns of climate change and LULC (Land Use and Land Cover) is indeed essential at both the large and local scales. While our report offers results at the major-basin level to provide an encompassing perspective, the depth and granularity of our model simulations and data inputs are usable at national and regional levels for more local-scale insights and adaptation strategies. We based our model on a 300m resolution Digital Elevation Model to ensure that local topographical variations are represented. Our challenge was with the land use harmonization project (LUH2) data (Hurtt et al., 2020) which is presented as netCDF. This data format is not compatible with SWAT+ and the resolution was 0.25 decimal degrees. However, since each pixel had the percent cover for each land use type contained in the pixel, details were not really lost for simulation purposes (Figure 1).

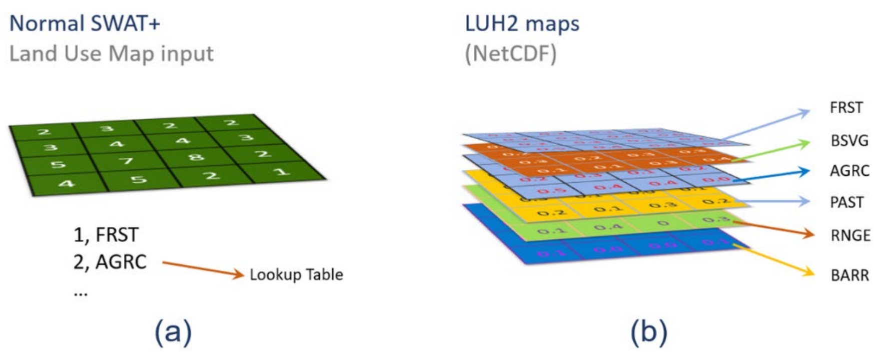

Figure 1: Contrast between the raster format accepted by SWAT+ and the Format of Land Use data from the Land Use Harmonisation Project 2 (LUH2)

We adapted SWAT+ to use this data and we describe the details in Chawanda et al. (2020a). Furthermore, the applicability and utility of our model at intra-basin level are underscored by its successful use in two separate studies focusing on sediments (Nkwasa et al., 2022a) and crop management representations (Nkwasa et al., 2022b), both within the Nile basin. Thus, indeed we present holistic basin-level views while retaining the potential for local insights as can also be seen in the maps.

Results should be presented for near term periods (e.g. 2030-2050, 2050-2070). Only presenting long term results may not be useful and verifiable in a possible time frame.

We thank the reviewer for the valuable feedback. We concur that presenting findings for nearer-term periods, such as 2030-2050 and 2050-2070, holds is valuable especially when considering strategies and immediate responses to climatic and shifts and land use changes.

However, the emphasis of our study was on end-of-century projections. This is primarily due to the lasting implications decisions in areas like infrastructure development and land-use management carry, often spanning several decades. By focusing on end-of-century data, we highlight the extended consequences these decisions might have, making it instrumental for far-reaching planning. Moreover, many of the profound repercussions of climate change on catchments might only emerge more overtly towards the latter part of the century. Our chosen timeline allows us to identify the evolving transformations and better understand the cumulative effects of both climate change and land use changes. Thus, highlighting projections toward the century's end serves as a reminder of the lasting implications of our current choices—or lack thereof—as argued in studies like that of Thiery et al. (2021). Such a perspective underlines our ethical commitments to the generations that follow.

Nevertheless, we fully endorse the idea that more studies that zero in on more immediate impacts and in specific regions would greatly complement this study to better guide and inform on both near and far term periods.

It has been mentioned that over some zones where streamflow data is not available, calibration was done only using ET. Highlight those zones and explain how this ET calibration was done.

Notably, we mention Congo and Nile, with the latter experiencing significant restrictions in river flow data access. In these specific regions, the HMBC was constrained to just ET data, thus initial parameters that are derived from inputs are used to estimate surface runoff and groundwater components, but ET parameters were optimised to align simulations with remotely sensed ET datasets for these areas. We refer to supplementary material, which includes a map highlighting areas within major basins where only ET was used in the HMBC process.

> *In contrast to a previous Southern Africa SWAT+ model application* (Chawanda et al., 2020a)*, the Nile and Congo River basins had very few gauging stations from which long term average surface runoff could be derived. This was a major problem in the Nile Basin where river data availability from public sources is even more restricted. As such, only ET was calibrated by HMBC in some calibration zones where gage data was not available (Figure S1).*

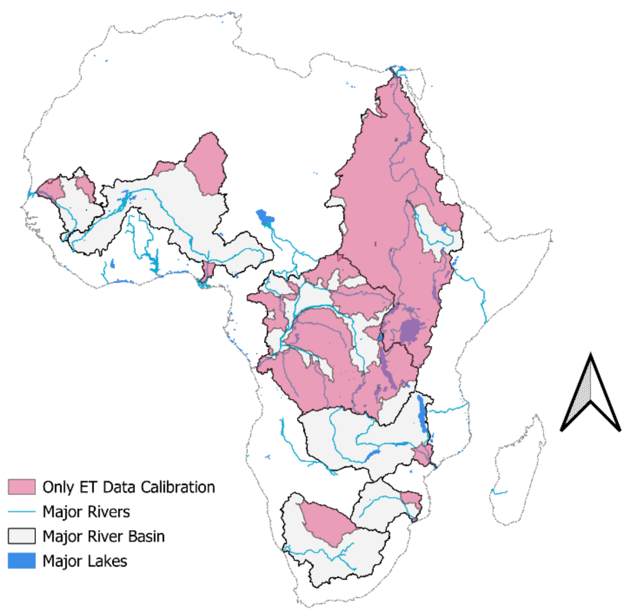

Figure S1: A highlight of areas within major river basins where Hydrological Mass balance (HMBC) only used Evapotranspiration (ET) Soft Data.

The calibration is based on preserving the long term averages of the water cycle components. Please explain conceptually how this can be used to model yearly dynamics of the water cycle.

Thanks for this comment. SWAT+ models these dynamics based on inputs such as climate data and parameters derived from soil maps, land use maps and topography data from DEM. This includes seasonal cycles of river flow, ET and other variables. By calibrating for long-term averages, we ensure that internal processes are better represented in the long-term in addition to the seasonal variations already simulated by the default model configuration. However, to better capture more detailed temporal river flow patterns instead of long-term, a more detailed calibration approach is required which was beyond the scope of this study.

I understand that ground water component for calibration was calculated as a residual of longterm averaged water budget. Hence, the uncertainties in the other datasets would have propagated to the GW data. Please explain how far this will affect the result.

We appreciate the reviewer's insight on this aspect of our hydrological modeling study. It is indeed a correct assessment that when calculating the groundwater component as a residual of the long-term averaged water budget, uncertainties from other datasets may propagate to the calculated groundwater data. This is indeed a limitation when direct observational data for a component like groundwater is lacking, especially over large scales like Africa.

We would like to highlight a few points regarding our approach. Firstly, at the scale of our study, direct observations of groundwater are virtually nonexistent, making it challenging to calibrate or validate groundwater components using traditional methods. Secondly, while there are uncertainties associated with each component of the water balance, the relative impact of these uncertainties on the groundwater component, when computed as a residual, is not straightforward since some uncertainties might offset each other, while others might accumulate. However, propagating the uncertainties to ground water was beyond the scope of this study.

While we acknowledge the potential for uncertainties to propagate to the calculated ground water data, our approach was a pragmatic solution given the data constraints. We are keen to refine our methodologies as more granular and accurate data becomes available.

Is it safe to assume that the catchment proeprties and the model parameters are stationary in time for such a long time period? How to account for the non-stationarity in catchment properties and model parameters?

The reviewer brings an important issue of non-stationarity in catchment properties and model parameters over long periods. As correctly pointed out earlier, our projections incorporate Land Use and Land Cover (LULC) changes, which account for a significant portion of the variability in catchment properties by considering variations due to factors such as urbanisation, deforestation, agricultural activities, and much more.

In terms of topography, it's generally safe to assume that significant changes do not occur over the typical timeframes of hydrological studies, unless there are extreme events like large-scale landslides or significant human-made modifications. For the duration of our study, we believe this assumption holds. However, while the fundamental soil type remains relatively constant over time, properties such as soil compaction or organic matter content, can change due to land management practices and natural processes. Thus, it is indeed important to note that in specific catchments where intensive land-use activities occur, there might be some level of change in soil properties.

As per the question to address non-stationarity in catchment properties, in studies where fundamental changes to topography or soil are observed in each catchment, one could consider adaptive calibration techniques where the model is recalibrated at regular intervals to adjust to changing conditions. In this case Dynamic Parameters would be useful to allow for parameters to change over time based on predefined rules or relationships. This can capture some of the non-stationarity inherent in catchments. At present, SWAT+ limits such updates to the curve number parameter through decision tables (Arnold et al., 2018).

Please use continous colour bar instead of ranges for presenting ET, rainfall and their differences (figures 5-9). The class ranges are quite large and a continous colour bar will provide more information that these maps I feel. Especially, with the current ET difference maps, I get an impression that there are large differences between the SWAT+ ET and WaPOR ET. A continous colour bar may help to understand this better.

Thanks for this suggestion. We have adopted it in the revised manuscript.

Please limit the y-axis value range in figure 10. I think the flow value is maximising at 40000 cubic metre per second. This will help us visualise the temporal variation in the flow better.

This has been done.

Hydrological modelling exercises are generally not useful for simulating extreme events such as floods and droughts. Please include your views on how to model extremes under future climate change and land cover change scenarios.

Thanks for raising such an important issue about the utility of hydrological modeling in capturing extreme events. While hydrological modeling has its challenges, especially in simulating extremes, it remains a valuable tool when used appropriately.

Modern hydrological models are able to capture both average and extreme conditions which studies have demonstrated (Peredo et al., 2022; van Kempen et al., 2021). The effectiveness of a hydrological model in simulating extreme events depends on the quality, extent and objectives of the calibration and validation process and whether datasets that include extreme events are used (Onyutha, 2019). In addition, incorporating projections from climate models and scenarios of land cover change in simulations allows hydrological models to simulate potential changes in hydrological extremes under different future scenarios. An example: if a climate model projects more intense rainfall events in the future, a hydrological model can simulate the resulting flood conditions given it accounts for land cover change scenarios. Downscaling techniques can also play a role in simulating hydrological extremes as they allow high-resolution meteorological inputs from coarse-resolution climate models which makes a difference in areas with high climate variability in space (such as mountainous areas).

Some hydrological models have more detailed representation of physical processes, allowing them to better simulate extreme conditions. For example, SWAT+ has been coupled with GW-Flow and modflow ground water modules which makes it better at simulating droughts. Thus, we argue otherwise, that hydrological models are very essential and useful in simulating extremes.

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