RC3: **'Comment on hess-2021-151', Steve Lyon,**

This study investigates climate and human impacts on water towers in East Africa. The analysis is conducted in a Budyko framework. The target region is often considered vulnerable to changes in water resources making this investigation warranted and the result likely informative. Overall, the study is well-conceived. However, I feel there are some considerable limitations in the structure of the presentation. Further, some of the mechanistic interpretations are not fully supported given the potential of confounding impacts and potential uncertainty in data and analysis.

We thank the reviewer for the constructive comments. We have considered all comments and suggestions in our revised manuscript.

1. In the introduction (especially around P2, L15-L20), I would expect to see some more consideration of the strengths and weaknesses of various approaches for assessing climate and land-use change on water resources. Do we have some results or previous work that are relevant for the region? What is the motivation for selecting the Budyko approach over other approaches? There is not many reviews of current science offered up in the introduction. This should be expanded to help the reader understand the motivations for the current study and approach.

Answer: We thank the reviewer for the remark. We have reviewed additional literature. We have also described the strengths and weaknesses of various approaches for assessing climate and land-use change on water resources. A justification has also been added on the motivation for selecting the Budyko approach. The following text is an extract from the revised manuscript describing the strengths and weaknesses of various approaches and justification for selecting the Budyko framework:

...Various approaches have been used for studying the effects of climate and land-use changes on streamflow. Jiang et al. (2015) categorized such methods into two: (a) deterministic rainfall-runoff models and (b) statistical methods. Ma et al. (2014) combined the two categories by running rainfall statistics and recorded land-use change patterns in reverse order in calibrated process-based models. Dey and Mishra (2017) reviewed the existing approaches and categorized these approaches into four categories; (i) experimental approach e.g. paired catchment method (Bosch and Hewlett, 1982), (ii) hydrological modeling e.g. SWAT (Tech, 2019), (iii) conceptual approaches e.g. Budyko approach (Budyko, 1974), and (iv) analytical approaches e.g. climate elasticity method (Schaake, 1990).

Generally, the different approaches can be grouped into modeling and non-modeling (conceptual) approaches (Marhaento et al., 2017). The advantage of modeling approaches is that the results are more reliable (Booij et al., 2019). However, the challenges of modeling approaches (e.g. SWAT) are that the underlying processes must be explicit, require complex and multiple data inputs, and a time-consuming calibration and validation (Zhang et al., 2012). Application of modeling approaches is therefore limited to relatively small watersheds where detailed streamflow observations are available or in watersheds that are well monitored with extensive, long-term available data on vegetation, soil, topography, land use, hydrology, and climate (Wei and Zhang, 2011). Non-modeling approaches such as Budyko conceptual frameworks require fewer data, hence flexible in *their application from small to large study areas and generally give logical primary results (Booij et al., 2019; Marhaento et al., 2017). These primary results can be crucial for data-limited regions such as East Africa and can form the basis for detail hydrological studies. In this study, we selected the Budyko framework assuming steady-state to analyze the impact of land-use and climate changes on water yield for the selected forested water towers of East Africa...*

....Generally, the Budyko framework, either in the original format (i.e. steady-state) or in the modified format (i.e. non-steady-state conditions) is a quick first-order tool for estimating precipitation partitioning into evaporation and water yield (Mianabadi et al., 2020; Teng et al., 2012; Zeng et al., 2020)...

In addition, the lack of framing the study in a research question or a hypothesis is a major weakness. The result is that the study is some exploration of data that does not seem to address a problem or help advance the science. Such exploration ("can-we-do-it" type of work) is fine for a technical report but more would be needed for publication in a peer-reviewed journal. I am confident the authors can put this study in a research framework and present a clean and testable hypothesis or a some societally relevant research question.

Answer: We agree with the reviewer and we have now included a focused research question:

"What are the effects of climate and land-use changes on water yield for the selected forested water towers?"

We tested the following hypothesis:

In areas considered as pristine or protected zones (i.e. high elevated forested areas), with AI≥0.65, changes in water yield would majorly be attributed to climate changes and negligibly due to land use/cover changes. The high elevated forested areas would then be expected to fall on the reference Budyko curve over the study period.

2. The study mixes direct observation data interpolated across sites and remotely sensed data at various scales. I'm wondering if there is any potential impact of the various assumptions and approaches in each dataset? Synthesizing across various approach can often compound huge amounts of uncertainties and errors as we build composite analysis (in space and time). How has uncertainty been considered in your analysis and what role would data error have on your results/interpretation? Some consideration and discussion of uncertainty impacts must be presented to help the reader understand how robust the findings are in this study. This should be fairly straight forward given how the water balances were constructed using 100 random points. Perhaps perform a re-selection of random point and assess the difference or use some sort of calibration/validation approach on a sub-division of the 100 points (like a boot strap).

Answer: We thank the reviewer for this comment. A discussion on uncertainties has now been included in the revised manuscript. The feedback by the reviewer on water balance construction using 100 random points made it clear that clarification and reorganization of the manuscript is required. We used the 100 random points to develop the Budyko curves and not for constructing water balances. The Budyko equation was applied for the whole region to simulate ET and Q. To increase clarity, we have introduced sub-sections in the revised manuscript. The sub-section that describes the use of 100 random points is called:

*...**Developing the Budyko curves***

To develop Budyko curves that are representative of the selected forested water towers, 100 random points were generated for each of the water towers in ArcGIS. The random points were used to extract values from raster P, PET, and ET grids into Spreadsheet for developing the Budyko curves. For maximum representation, the minimum allowed distance between the random points was set to 100 meters. The random points generated were assigned the respective values of PET, ET, and P using the Extract Multi Values to Points tool in ArcGIS. The Evaporative index (EI) values -calculated as a ratio of ET and P, and Dryness index (DI) values -a ratio of PET and P were used to draw the Budyko curves. In this study, the Budyko curve for the 1981-1990 period was used as the reference condition for the water balance, to effectively assess the trends in the succeeding periods of 1991-1990, 1991-2000, 2001-2010, and 2011-2019...

For calibration/validation purposes, the simulated water yield (Q) was evaluated against observation-based runoff. This is now provided in a subsection called:

*...**Comparison of simulated streamflow with observation-based runoff***

The simulated streamflow of the water towers was compared with composite runoff data downloaded from the Global Runoff Data Centre (GRDC). The composite runoff fields, developed through combining observed river discharge information with a climate-driven water balance model, provide the "best estimate" of terrestrial runoff over large domains (Fekete et al., 2002). A total of 312 points above 2000 meters above sea level, which is the focus of this study (i.e. elevated water towers), were randomly generated in ArcGIS. For maximum representation, the minimum allowed distance between the random points was set to 100 meters. The selected random points and their respective values of simulated streamflow and composite runoff were compared...

3. Further, I am not sure about the 100 random points in the methodology. Why was this done? Is it just too difficult to define the spatial extent of the water towers (which would allow using all the spatial data in the area)? Seems there would be some value in conducting this experiment at various elevations to assess the impact of elevation (as temperature proxy) on the results. Please outline why the method of 100 random point was selected and what the impacts would be on the results relative to another method.

Answer: We thank the reviewer for the remark. As explained in the above response, we agree a clear presentation in the manuscript is needed which we have now provided by organizing the manuscript into sub-sections. In fact, we did not use the 100 random points to construct the water balances. Rather, the water balances were constructed using all spatial data generated (gridded data for P, PET, NDVI etc). Actually, the water balances were constructed with gridded data for the entire East-African region, before selecting the data for our focus regions by masking out the spatially delineated extents of the water towers.

The 100 random points were only used to extract data from raster outputs with the sole purpose of developing Budyko curves - which was done using a spreadsheet model (MS Excel). The 100 points were generated for each of the water towers.

We agree with the reviewer's suggestion to include the elevation element in the analysis – this has been done in the simulation of longterm actual evapotranspiration (ET) and water yield (Q), potential evapotranspiration (PET), and precipitation (P). As a result, we have added the following figure as Figure A4 in the revised manuscript.

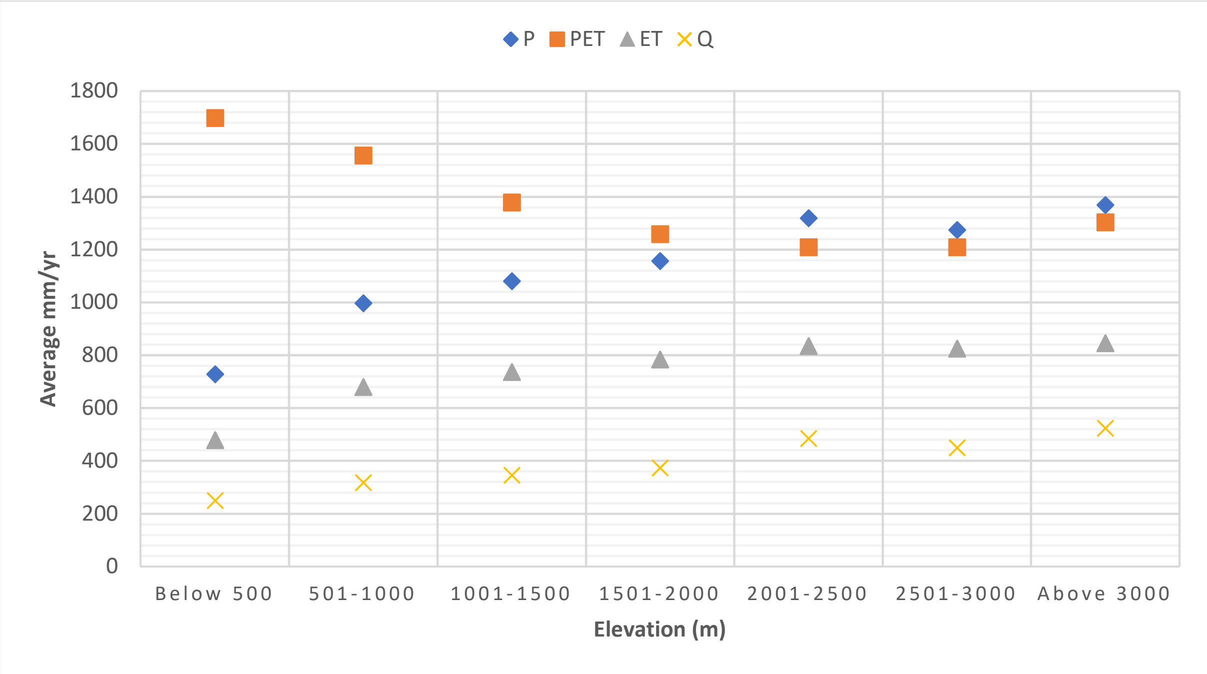


Figure 1: The Impact of elevation on hydroclimatic conditions in the East African region

...The elevation influences hydroclimatic conditions in the East African region. The average atmospheric demand increases with a reducing elevation gradient. There is a steady increase in P, ET, and Q as elevation increases. For regions above 2000 m a.s.l, the precipitation exceeds potential evapotranspiration as shown in Fig 4A. This demonstrates the importance of the elevated humid zones in generating and sustaining water yield to the adjacent lowland areas...

4. There appears to be a large amount of mechanistic speculation on why points depart from the Budyko curve. There has been ample research over recent decades explaining how we can see variations along and from the curve. Further, many different explanations have been offered as to why catchments would deviate from theoretical curves with time. Could you outline some motivation for how you can be certain you are isolating mechanisms with your analysis? We would anticipate much interaction and coupled response that could be masked in the movement of points in Budkyo space (see van der Velde et al., 2014). It i likely that this lack of consideration of complexity relates back to the weakness and lack of thorough literature review seen in the introduction.

Answer: We thank the reviewer for this comment. We have provided more details regarding our basis of interpretation in the revised manuscript. We have added the following text in the methodology section.

....In this study, we used the Budyko framework and two recently introduced Budyko metrics (deviation and elasticity) (Creed et al., 2014b) to study the changes in the water yields. Similar methodologies were adopted by Helman et al. (2017) to determine the resilience of forested catchments and Sinha et al. (2018) to understand the involvement of anthropogenic stress and climatic variance on the partitioning of precipitation. Based on these studies, catchments can be assumed to shift predictably along the Budyko curve. This acts as a basis for interpreting the vertical and horizontal deviations as a result of changes in climate and anthropogenic effects. The elasticity is defined as a measure of a catchment's ability to maintain hydroclimatic conditions as the climate varies. In contrast to other studies using the Budyko framework to look at different drivers of change, we use Budyko-derived data rather than observations. Therefore, the deviations are thereby constructed and presented as a way to visualize the results. Beyond the maps and graphs presented following the Budyko equation we further illustrate the movement of water towers within the Budyko space...

5. Along these same lines, what role would other factors such as CO2 increase and/or human alteration to water usage have in these regions? I could envision shifts in water cycling due to an intensification of plant activity through increased NPP or agricultural intensification. Warmer and CO2 richer climates could behave differently. Further, how much pumping and/or movement through irrigation schemes takes place in some of these systems? I understand they should be pristine or high-elevation forest without impact, but are they really without abstraction or other anthropogenic impacts?

Answer: We thank the reviewer for this comment. First, we have made it clear in the revised manuscript that the water towers are the high elevated forested areas, that are humid (i.e. aridity index AI≥0.65) and are considered pristine (under protection). The forests are under a continuous forest block from the footslope to the mountain peak. Based on our hypothesis, we are investigating whether such regions' changes in water yield would majorly be attributed to climate changes and negligibly due to land use/cover changes. The high elevated forested areas would then be expected to nicely fall on the reference Budyko curve over the study period.

Given the framework used, we only look at human alterations in the form of land cover changes without going into details about the type and sources of effects e.g. effect of CO_2 increase, irrigation schemes/ agricultural intensification, etc. We believe the impact of warming is captured in the potential evapotranspiration. In fact, by looking at NDVI we are accounting for possible CO_2 effects on vegetation growth (though not on stomatal opening and ET directly).

That said, in the discussion section, we have added details of other factors that would also affect the results. We have reviewed additional publications that looked at CO_2 and human alteration of the water usage and hypothesize potential effects that could be contributing to the observed changes. This can further inform areas of further research. The following relevant text has been added in the discussion section:

...This study focussed on the role of water towers in the supply of blue water to downstream parts of the watershed. These findings can be improved further by studying the role of water towers in the supply of green water (i.e. the role of water towers in regional rainfall

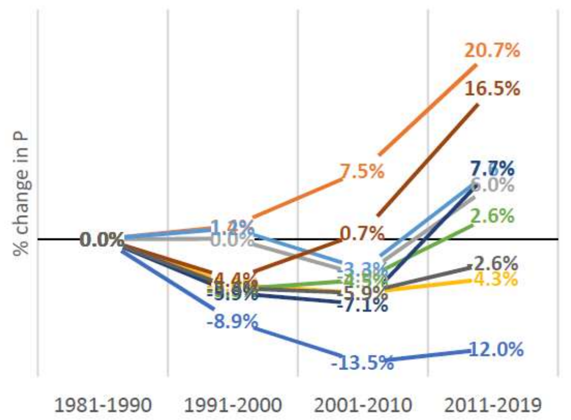
recycling). We also recognize other factors that may influence the results in this study. For instance, increasing atmospheric CO_2 concentrations may affect terrestrial water cycling through changes in climate and changes in transpiration (i.e. stomatal conductance) (Frank et al., 2015; Huntington, 2008; Mamuye, 2018). We also note that if CO_2 leads to higher NDVI, then this effect is accounted for in our modeling approach. Some studies have reported that NDVI linear trends can be linked to increasing CO_2 levels (Krakauer et al., 2017; Yuan et al., 2017). However, further investigations are recommended. Other factors that may affect our results include the human alteration to water usage. Kiteme et al. (2008) reported unregulated abstraction of water in the upstream of Mt Kenya water tower leading to hydrological droughts in the downstream. Intensification of irrigated agriculture and a growing human population was reported at the foot slopes of the water towers (Liniger et al., 2005; Ulrich et al., 2012). The effects of anthropogenic presence at the foot slope of the water towers have not been accounted for and further studies are required to understand how humans affect the pristine/protected water towers...

6. In general, the results as presented are dense and not easy to follow. Read things a few times and not sure I can understand all the nuance of what is being shown here due to how things are being presented. This is not helped by poorly constructed figures with overlapping number, limited axis labels, and multiple colors to track. A major effort to organize the results into a concise section is required. Start by group the various results into sub-sections and cleaning up the figures. Structuring this section could also be aided by a more thoughtful research question or hypothesis setup. Then the results could be organized into how they answer the research question(s).

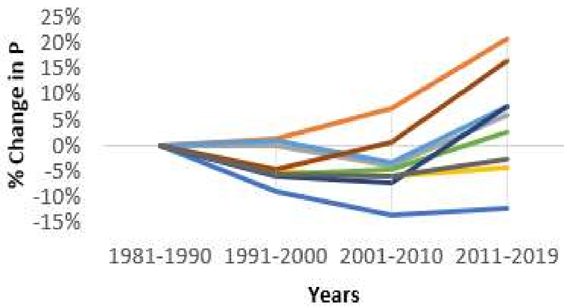
Answer: We thank the reviewer for this feedback. The results section is now organized into sub-sections. The figures have been cleaned up to remove the overlapping numbers and shading also recommended by Reviewer RC2. We have constructed the research question which has also been reflected in the results and discussion sections. The results section is now organized according to the following sub-sections:

- *Climate characteristics over the period 1981 – 2019 (Precipitation and Potential evapotranspiration)*
- *Land cover characteristics over the period 1981 – 2019*
- *Simulation of Evapotranspiration*
- *Simulation of Water Yield*
- *Comparison of simulated streamflow with existing runoff data*
- *The effects of land use and climate changes on water yield*
- *Analyzing the water towers in the Budyko space*

All figures are cleaned as demonstrated in the following example:



Old figure with overlapping numbers, with no X-axis label



A revised figure, with no overlapping numbers. X-axis label now included

7. The discussion section is lacking rigor. At best it repeats the results with more interpretation. I miss a connection to the literature and how the results help inform and advance the science. Also, what are the strengths and limitations of the approach considered and how do these impact interpretation? Could not see what value the discussion added to the paper overall. Rather, it felt like the results were being explained again and the assumptions behind interpretation being ignored. Lastly, while there are no rules, the length of the discussion is rather short relative to the length of the results presented. In my experience, that can be indicative of a study that is exploring data rather than an experiment to test a hypothesis.

Answer: We thank the reviewer for bringing this to our attention. Together with comments from the reviewer (RC1), we have revised the discussion section to ensure the results are better interpreted, linking to existing literature, and a discussion on uncertainties/limitations. The discussion section has been revised and expanded as follows:

Discussion

We found that within the water towers, water yield was more sensitive to climate changes than to land-use changes. In contrast, outside the water towers, the water yield was observed to be more sensitive to land-use changes than to climate changes. This suggests that anthropogenic influences are relatively higher outside the water towers. Contrary to our expectation, our analysis showed that most of the water towers (i.e. 7 out of 9) did not plot on the reference Budyko curve over the study period. This is a relevant finding since all water towers were considered pristine and protected. Only two water towers, Mt Elgon and Imatong mountains showed no deviations from the reference Budyko curve. Generally, our investigation highlights the importance of elevated water towers in a semi-arid region in the generation and supply of water to adjacent lowland areas. The forested water towers located in drier environments (such as Mt Kilimanjaro, Mt Meru, Mt Kenya, and Aberdare ranges) are important rainfall regions as they receive relatively higher rainfall than the adjacent areas. This ensures water availability in the adjacent lowlands in the arid and semi-arid (ASAL) regions.

Our results indicate that changes in precipitation and potential evapotranspiration are the major determinants of blue water availability from high elevated forested water towers in *the East African region. Related observations have been made - that climate changes in Africa have a relatively higher impact on water yield compared to other drivers such as land-use changes (Alcamo et al., 2007; Niang et al., 2014). However, the lack of evidence of sensitivity to land-use changes within the water towers themselves may be linked to existing institutional arrangements. We presume that the results would be different if such rules would be relaxed. That said, the movement of water towers in the Budyko space revealed that anthropogenic influence within the water towers cannot be ruled out. Our analysis revealed vertical deviations (d) from the Budyko curve for 7 out 9 forested water towers. According to Creed et al. (2014), these vertical deviations may indicate the presence of anthropogenic effects within the water towers. The two water towers where no deviations were observed (i.e. Mt Elgon and Imatong mountains), indicate that the hydroclimatic conditions in the study period did not vary much from the reference conditions of 1981-1990 and any changes in water yield in the two water towers can largely be associated with climatic changes in P and PET.*

Moreover, the lack of deviations in the two water towers may indicate the resilience of forested regions (i.e. adaptable nature of forests) as described in (Creed et al., 2014; Helman et al., 2017; Van der Velde et al., 2014). Such resilience (measured as elasticity) could be a key factor in forested water towers indicating their ability to resist change or bouncing back to their initial natural conditions, hence plotting along the reference Budyko curve. Long-term adaptations of forests have been achieved by trees even in the most water-limited forests (Helman et al., 2017). However, our investigations on elasticity (that refers to the degree of initial change using 1981-1990 as the reference period) did not support the above science as lower elasticity values were observed in most of the water towers. Given that low elasticity indicates broad ranges in the evaporative index (EI) compared to the dryness index (DI), this may further indicate the presence of anthropogenic influence within the water towers. According to Creed et al. (2014), elastic catchments are expected to plot along the Budyko curve (i.e. high elasticity = resilient to climate changes) while inelastic catchments (i.e. low elasticity = non-resilience to climate changes) would deviate from the Budyko curve.

Further illustrations can be shown in the Budyko space based on the horizontal shifts relative to the dryness index (DI). The horizontal shifts are important indicators of the behavior of the water towers towards warmer or humid conditions. These horizontal deviations reflect a change in the climatic conditions specifically, temperature and precipitation (Creed and Spargo, 2012a). This study observed that the majority of the water towers (7 out of 9) plotted within humid conditions (i.e. DI <1). On the other hand, two of the water towers (i.e. Mt Meru and Bale mountains) demonstrated warmer conditions (i.e. DI >1). One major observation is that water towers in Eastern Africa seem to shift towards the left, an indication of the increased humid conditions especially in the period of 2011-2019. At the same time, a gradual increase in PET was observed in all the water towers. A climate shift to wetter conditions and simultaneous increases in regional temperatures have also been reported in the East African region and projected to increase by the end of 21st century (Giannini et al., 2018; Niang et al., 2014; Omambia et al., 2012).

The effects of increasing temperatures have already been identified to have decreased the surface area of glaciers by 80 % in East African water towers (EAC et al., 2016), affecting runoff and water resources downstream. According to Niang et al. (2014), the temperatures in Africa is projected to rise faster than other parts of the world, which could exceed 2°C by the mid-21st century and 4°C by the end of the 21st century. Therefore, the water towers are under pressure from climate changes and PET is proving to be an important climate driver influencing water availability in the region. There are chances that the shifts to wetter conditions in the water towers may also be as a result of the extended impact of increasing PET on the El Nino-Southern Oscillation (ENSO), a phenomenon that influences precipitation in the East African region. Li et al. (2016) investigated annual flood frequencies, from 1990 to 2014, and observed upward trends that were linked to the ENSO phenomenon. Additionally, the shifts to wetter conditions also coincide with the recent reports on the 'rising lake levels phenomenon' in the Eastern Africa region (Chebet, 2020; Chepkoech, 2020; Patel, 2020; Wambua, 2020). We however do not believe we have the data to link the climatic shifts and 'swelling' of lakes to ENSO variations in our study which requires detail scientific investigations.

The simulated evapotranspiration (ET) and water yield (Q) revealed longitudinal differences with low to high values ranging from East to West. A related pattern on climate varying across East Africa from arid conditions in the east to more humid conditions in the west was also observed by Daron (2014). However, the individual water towers revealed independent variations that do not follow the longitudinal pattern. For instance, a higher mean annual water yield was observed at Mt Kilimanjaro despite being located in the drier environment on the Eastern side. This emphasizes the importance of elevated forested areas in ensuring water availability in semi-arid areas. For instance, in high elevated forested zones, the precipitation exceeds potential evapotranspiration, which ensures a surplus of blue water that eventually flows downstream.

The extreme opposite temporal trends observed in water yields from the different water towers confirm a strong variation in the regional climatic patterns. For instance, while there was a consistent increase in annual mean water yield at Mt Elgon, the opposite was true at Mt Kilimanjaro where a steady decline in water yield was observed. Our results further revealed that precipitation (P) is the dominant driver in the East African region. For instance, a consistent increase in Q at Mt Elgon coincided with a steady increase in land surface characteristics (ω) as shown in Figure 3 C. Ideally, a reduction in Q would have occurred due to the increase in ET (associated with increases in land surface characteristics), but this was diffused by the increases in rainfall as shown in Figure 2 C. At Kilimanjaro water tower, a continuous reduction in Q coincided with a steady reduction in ω. Again, an increase in Q would have been expected due to a decrease in ET. Therefore, precipitation is the dominant driver in the generation and supply of blue water from the forested water towers in the East African region.

As a first-order tool, the Budyko framework provides an important reference point for relating variations in water yield to variations in climatic conditions and catchment properties. In this study, the spatial pattern of the simulated streamflow in the Budyko framework closely resembles the pattern observed in the GRDC composite runoff. We however noted overestimation of water yield in the comparison. This type of observation *was also reported by (Teng et al., 2012), where the Budyko equation was found to overestimate water yield in drier regions. Moreover, other factors such as soil type, topography, seasonality, water storage, interception, etc were not accounted for in the quantitative framework which can affect the simulations in the selected forested water towers.*

Canopy interception, for instance, plays an important role in the water balance of forested ecosystems as noted in several studies (Astuti and Suryatmojo, 2019; Gash et al., 1980; Teuling et al., 2019; Zimmermann et al., 1999). In their study, (Teuling et al., 2019) found many forested points to have average yearly evapotranspiration (ET) that exceeds the average potential evapotranspiration (PET). Van Dijk et al. (2015) opined that this is possible due to underestimation of evapotranspiration which was attributed to evaporation of interception water by energy not captured in the formulation of PET. The forest evapotranspiration paradox is further discussed in (Teuling, 2018). The correction of underestimation in (Teuling et al., 2019) indicates the need for long-term lysimeter observations for studies focussing on forested ecosystems. Availability of meteorological data in the upper slopes of the East African mountains is a big gap as the majority of meteorological observations are conducted below 1500 m a.s.l and most of the upper slopes data rely on extrapolation of hydrological analysis in the lowlands (Røhr and Killingtveit, 2003).

Local-based runoff measurements would have helped to interpret if there is indeed an overestimation in our study. That said, we observed positive KGE which indicates a "good" model performance (Knoben et al., 2019). Therefore, we considered the Budyko simulations as acceptable. However, it should be noted that this comparison is added for reference only and should not be seen as validation. This is because, the Global composite runoff (Fekete et al., 2002) is not a strictly observational dataset, and it is used here as the "best estimate" available for long-term estimates of streamflow in the East African region. The fact the Budyko framework uses lesser data and parameters that are easily measurable at a regional scale makes it a suitable approach for data-limited regions such as East Africa.

Besides the strengths in using the Budyko approach, uncertainties may exist which could have affected our results. The study used data from different datasets (CHIRPs, CRU, GIMMS/AVHRR) at various scales which could potentially affect results due to various assumptions and approaches in the processing of each dataset. For instance, the CRU dataset is fairly coarse and contains rather few observations in Africa. One substantial weakness of the current CHIRPS algorithm is the lack of uncertainty information provided by the inverse distance weighting algorithm used to blend the CHIRP data and station data (Funk et al., 2015). The overall NDVI3g uncertainty comes from spatial and temporal coherence variability which gives approximately an error of ±0.002 NDVI units. However, this NDVI error is considered low uncertainty hence applicable to study seasonal and inter-annual non-stationary phenomena (Pinzon and Tucker, 2014). Uncertainties may also arise in the general assumption that estimation of land surface characteristics (ω) based on NDVI formulation provides values that represent integrated conditions for soil, topography, and climate seasonality. Some studies using various hydrological approaches have reported the significance of these factors in influencing catchment hydrology (Kirkby et al., 2002; Troch *et al., 2013; Western et al., 2004; Woods, 2002). There is a need for more research to come up with methodological consistency in estimating ω parameters when using the Budyko framework. Although the focus of the study was in the elevated forested areas, empirical adjustment of the Budyko model may be needed to capture special features such as desert wadis in the application of the Budyko equation in the lowland areas.*

We also recognize other factors that may influence the results in this study. For instance, increasing atmospheric CO_2 concentrations may affect terrestrial water cycling through changes in climate and changes in transpiration (i.e. stomatal conductance) (Frank et al., 2015; Huntington, 2008; Mamuye, 2018). We also note that if CO_2 leads to higher NDVI, then this effect is accounted for in our modeling approach. Some studies have reported that NDVI linear trends can be linked to increasing CO_2 levels (Krakauer et al., 2017; Yuan et al., 2017). However, detailed investigations are recommended within the East African region. Other factors that may affect our results include the human alteration to water usage. Kiteme et al. (2008) reported unregulated abstraction of water in the upstream of Mt Kenya water tower leading to hydrological droughts downstream. Intensification of irrigated agriculture and a growing human population was reported at the foot slopes of the water towers (Liniger et al., 2005; Ulrich et al., 2012). The effects of anthropogenic presence at the foot slope of the water towers have not been accounted for and further studies are needed to understand how humans living at the footslope of protected water towers affect the pristine conditions of the water towers at high elevations.

Notwithstanding these limitations, our study offers important findings on the sensitivity of water yield to climate and land-use changes and the importance of these water towers in the generation and supply of blue water to adjacent lowland areas. These results can be used by decision-makers, policymakers, stakeholders, and scientists to emphasize the need to protect and conserve the high elevated forested areas in the region, particularly forest ecosystems above 2000 m a.s.l – where there is a surplus of blue water. The Budyko framework provides primary results that can inform detail hydrological assessments. For instance, our findings show that elevated forested water towers are important areas for maintaining high ET in the region. This finding can be explored further by studying the role of water towers in the supply of green water in the region (i.e. the role of water towers in regional rainfall/moisture recycling) (Ellison et al., 2017; Keys et al., 2014) - including the effect of mountain rain shadows on water yield (Van den Hende et al., 2021). The major reference period for this study was the 1981-1990 period based on the CHIRPs rainfall dataset with data beginning 1981 onwards. We believe the results would be different if an older reference period was used e.g. 100 years ago (presumably actual pristine conditions). This would help to strengthen the findings of this study especially after the evidence of climatic shifts towards wetter conditions in all the water towers. The anthropogenic presence both inside and outside the forested water towers indicates the relevance of local context, and ground research for understanding forest-water-people nexus (Noordwijk et al., 2020) is recommended. This will help in understanding in detail the dynamics and co-evolution of coupled human-forest-water systems.

Minor edits

P1,L23: "atmospheric demand" is a bit wonky language for the abstract – could you phrase this differently?

Answer: The term "atmospheric demand" in the abstract is now replaced with "potential evapotranspiration"

P1,L35: Consider changing to "Mountain forests capture, store, purify and release water" to avoid ambiguity. Also, was "they" in reference to "mountain forests" or something else?

Answer: Revised as suggested to remove the ambiguity. Yes, "They" was in reference to mountain forests.

P2,L40: Are these all the water towers in the region? If so, state that. If not, justify why these towers.

Answer: We thank the reviewer for the comment. No, these are not all the water towers in the region. The focus was on elevated forested water towers in the regions (based on humidity scale) sampled in the different East African countries. The definition of the water towers has now been included in the revised manuscript:

...The selection of water towers was based on aridity index (AI), high elevation, and continuous forest block. The selected water towers have AI≥0.65 (i.e humid), located in high elevated areas under a continuous forest block from the footslope contour to the peak...

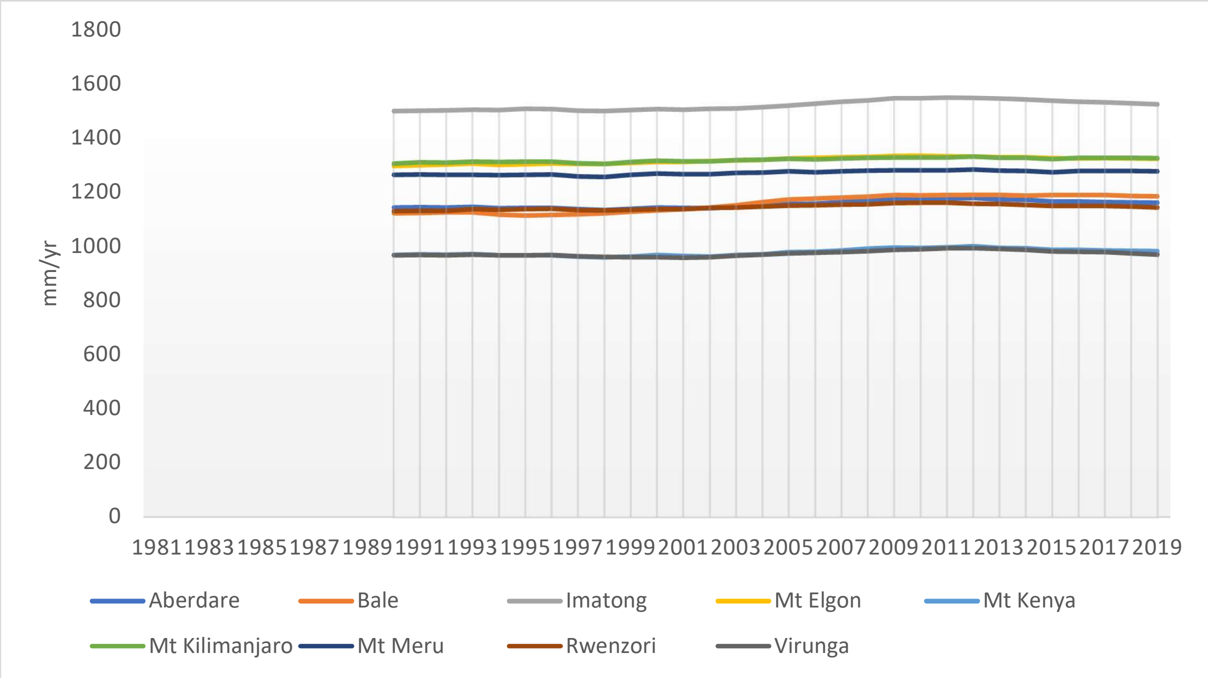
We selected a few of the water towers from different East African countries (see Table 1). For instance, the MAU Forest complex (the largest water tower in the region) did not meet the above criteria as its highest pick is relatively low compared to (Mt Kenya, Aberdare ranges, Mt Elgon, etc). It is also made up of 22 distinct forest blocks with other types of Land uses in between (including urban areas) – which could not meet our pristine assumption. Again, the idea was to sample a few water towers - at least 2 major water towers that met our criteria from each country.

P3,L4: The CRU data set is fairly course and known to contain rather few observations in Africa. Can you justify the use of these data here? Could another remote sensing product provide more accurate data?

Answer: We thank the reviewer for the remark. Studies on the East African region suffer from insufficient local-based climate data. Other datasets such as IRI[1] and Maprooms[2] had been considered during the conceptualization of the study, but due to lack of consistency and data gaps among the different countries, were ruled out. The fact that the study looks at the past changes in the elevated forested areas (where there are minimal local measurements upslope of the mountains) warranted going for a dataset that is consistent over different decades and already acceptable in the scientific world.

[1] https://iri.columbia.edu/resources/enacts/
[2] http://maproom.meteorwanda.gov.rw/maproom/index.html

We also don't see drastic changes in the PET over time (i.e. more of a homogenous pattern) as shown in Fig A3 and pasted below. We argue that the course resolution suffices.



P3,L4: I do not know how CRU gets PET. Could you provide some more information on how these data are prepared? This holds for all the data sets considered.

Answer: We thank the reviewer for the comment. More information on data processing of PET, P, and NDVI has been provided in the revised manuscript. The following is a relevant extract from the revised manuscript:

...Precipitation (P) data were gathered from the Climate Hazards Group Infrared Precipitation with Stations (CHIRPS-v2) with a temporal coverage beginning 1981 and a spatial resolution of 0.05°. CHIRPS uses the Tropical Rainfall Measuring Mission Multi-satellite Precipitation Analysis version 7 (TMPA 3B42 v7) to calibrate global Cold Cloud Duration (CCD) rainfall estimates (Funk et al., 2015). Potential Evapotranspiration (PET) data were sourced from the Climate Research Unit (CRU) database with temporal coverage beginning 1981 and a spatial resolution of 0.5°. The CRU-PET is calculated using the Penman-Monteith formula (Ekström et al., 2007; Harris et al., 2020). Normalized Difference Vegetation Index (NDVI) data to estimate land surface characteristics were sourced from the Global Inventory Monitoring and Modeling System (GIMMS) Third Generation (3 g) Advanced Very High-Resolution Radiometer (AVHRR) sensor onboard the National Oceanic and Atmospheric Administration (NOAA) satellites at a spatial resolution of 0.07° (Kalisa et al., 2019; Pinzon and Tucker, 2014; Tucker et al., 2005) The NDVI is derived using the Bayesian methods with high quality well-calibrated SeaWiFS NDVI data. The resulting NDVI values give an error of ± 0.005 NDVI (Pinzon and Tucker, 2014)...

P3,L16: Break these longer sections up into sub-section to help the reader follow along.

Answer: The sub-sections have now been added in the revised manuscript.

P3,L31: What is “FU”?

Answer: This has been revised to Fu which refers to a type of Budyko equation as given by (Zhang et al., 2004).

P4,L11: 2011-2019?

Answer: P4,L11 is an equation (4), but we assume you refer to P4,L9. This has been corrected from 201-2019 to 2011-2019

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