RC2: **'Comment on hess-2021-151'**, **Anonymous Referee #2**

General comments:

This is a very interesting study; however, I feel that it suffers from two main deficiencies that would need to be addressed in a revised version of the manuscript.

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

1. The first is that there does not appear to be an overarching research question that is being addressed. Given what the authors know about the general climate of eastern Africa, it should be possible to suggest where the various water towers should plot on the baseline Budyko curve, and then test to see if in fact that was the case.

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 second issue is the absence of any specific consideration of the uncertainties associated with the estimates of the variables (P, PET, NDVI) used in the analysis. My concern here is that the authors spend considerable time discussing temporal changes in water balance components that may or may not fall outside the range of uncertainty associated with these components.

Answer: We thank the reviewer for this comment. A discussion on uncertainties has now been included in the discussion section. The following is the relevant extract from the revised manuscript:

...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 however assume 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...

Specific comments:

Page/line

3/3 How was potential evaporation estimated?

Answer: Thank you for this comment. We have now included more details on the processing of the datasets used (P, PET, NDVI) in the revised manuscript. The CRU-PET is calculated using the Penman-Monteith formula (Ekström et al., 2007; Harris et al., 2020). The following is the 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)...

3/2-8 What are the uncertainties associated with the estimates of P, PET and NDVI?

Answer: We have now included a discussion of the uncertainties and limitations of the study in the revised manuscript.

3/27-30 Can catchments deviate from the Budyko curve under stationary conditions?

Answer: Thank you for the comment. Our assumption as mentioned on page 3, line 26 (in the preprint version), is that, under stationary conditions (i.e. naturally occurring fluctuations due to P and PET), catchments will fall on the Budyko Curve, and in non-stationary conditions (i.e. presence of anthropogenic influence), catchments will deviate from Budyko curve. We have revised this part as follows:

...One important feature of the Budyko curve is the assumption that, under stationary conditions ((i.e. naturally occurring fluctuations due to P and PET), study areas will fall on the Budyko Curve. However, under non-stationary conditions (i.e. anthropogenic influence manifested in ET changes), each catchment will deviate from the Budyko curve depending on land cover and physical catchment characteristics (Creed and Spargo, 2012; Mwangi et al., 2016). *This feature can be used to separate land cover change effects from climate change...*

This assumption was critical in testing our hypothesis that in areas considered as pristine or protected zones, 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.

7/Figure 3c How significant are these changes given the uncertainty associated with w?

Answer: We thank the reviewer for this comment. Figure 3C displays the % changes of land surface characteristics using 1981-1990 as the reference period. These changes are significant when connected to the study results especially on the trends of rainfall and water yield over the study period. A discussion on uncertainties associated with ω has also been included. The following are the relevant extracts from the revised manuscript:

...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...

...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...

12/Figure 8 Why is there a general overprediction of Q?

Answer: We thank the reviewer for the comment. We have now included a discussion on possible reasons why there is an overestimation of water yield when a comparison with GRDC runoff was done. The following is the relevant extract from the revised manuscript:

...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...

12/3-4 How much of the greater sensitivity of water yield to climate changes rather than land use changes is due to the form of equation 1? Is the differential sensitivity simply a function of the formulation of the Budyko curve, or is it real?

Answer: We thank the reviewer for this comment. We have extended our discussion by linking our study results to the latest publications. The sensitivity of water yield to climate changes could actually be true and the Buydko equation can therefore be said to simulate the reality. We have also acknowledged the fact that these water towers are under institutional governance hence controlled anthropogenic influence. The following is the relevant extract from the revised manuscript:

...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, it would also be paramount to point out that lack of evidence of sensitivity to land-use changes within the water towers, may also be due to existing institutional arrangements, hence a limited degree of actual change. We presume that the results would be different if such rules would be relaxed...

15/2-4 "… which further proves the presence of anthropogenic influence …" – does it really "prove" it?

Answer: Thank you for the remark. We have replaced the term 'proves' with 'indicates' in the revised manuscript:

19/Figure A4 How can you get different shapes for the baseline Budyko curves for the same w value (e.g. Aberdare Ranges vs. Mt Meru)?

Answer: We thank the reviewer for this comment. In our study, each water tower was treated independently in the development of Budyko curves. As explained on page 4 lines 12-20, 100 random points were selected from each of the water towers and assigned relevant parameters for the calculation of EI and DI indices. Therefore, each water tower has a distinct point-relationship of precipitation (P), potential evaporation (PET), and actual evapotranspiration (ET).

I have attached other specific comments and suggested edits on the manuscript.

Answer: Thank you for the supplement with suggested edits. We have revised all areas highlighted.

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References included in the responses

Alcamo, J., Flörke, M. and Märker, M.: Future long-term changes in global water resources driven by socio-economic and climatic changes, Hydrol. Sci. J., 52(2), 247–275, doi:10.1623/hysj.52.2.247, 2007.

Astuti, H. P. and Suryatmojo, H.: Water in the forest: Rain-vegetation interaction to estimate canopy interception in a tropical borneo rainforest, IOP Conf. Ser. Earth Environ. Sci., 361(1), doi:10.1088/1755-1315/361/1/012035, 2019.

Creed, I. and Spargo, A.: Budyko guide to exploring sustainability of water yields from catchments under changing environmental conditions, Meet. IAHS-PUB (Prediction Ungauged Basins) Symp. "Completion IAHS Decad. Predict. Ungauged Basins W. ahead," 59, 2012.

Van Dijk, A. I. J. M., Gash, J. H., Van Gorsel, E., Blanken, P. D., Cescatti, A., Emmel, C., Gielen, B., Harman, I. N., Kiely, G., Merbold, L., Montagnani, L., Moors, E., Sottocornola, M., Varlagin, A., Williams, C. A. and Wohlfahrt, G.: Rainfall interception and the coupled surface water and energy balance, Agric. For. Meteorol., 214–215, 402–415, doi:10.1016/j.agrformet.2015.09.006, 2015.

Ekström, M., Jones, P. D., Fowler, H. J., Lenderink, G., Buishand, T. A. and Conway, D.: Regional climate model data used within the SWURVE project projected changes in seasonal patterns and estimation of PET, Hydrol. Earth Syst. Sci., 11(3), 1069–1083, doi:10.5194/hess-11-1069-2007, 2007.

Fekete, B. M., Vörösmarty, C. J. and Grabs, W.: High-resolution fields of global runoff combining observed river discharge and simulated water balances, Global Biogeochem. Cycles, 16(3), 15-1-15–10, doi:10.1029/1999gb001254, 2002.

Frank, D. C., Poulter, B., Saurer, M., Esper, J., Huntingford, C., Helle, G. and Treydte, K.: Water-use efficiency and transpiration across European forests during the Anthropocene, , 5(May), doi:10.1038/NCLIMATE2614, 2015.

Funk, C., Peterson, P., Landsfeld, M., Pedreros, D., Verdin, J., Shukla, S., Husak, G., Rowland, J., Harrison, L., Hoell, A. and Michaelsen, J.: The climate hazards infrared precipitation with stations - A new environmental record for monitoring extremes, Sci. Data, 2, 1–21, doi:10.1038/sdata.2015.66, 2015.

Gash, J. H. C., Wright, I. R. and Lloyd, C. R.: Comparative estimates of interception loss from three coniferous forests in Great Britain, J. Hydrol., 48(1–2), 89–105, doi:10.1016/0022-1694(80)90068-2, 1980.

Harris, I., Osborn, T. J., Jones, P. and Lister, D.: Version 4 of the CRU TS monthly high-resolution gridded multivariate climate dataset, Sci. Data, 7(1), 1–18, doi:10.1038/s41597-020-0453-3, 2020.

Huntington, T. G.: CO2□induced suppression of transpiration cannot explain increasing runoff, Hydrol. Process., 22(2), 311–314, doi:10.1002/hyp.6925, 2008.

Kalisa, W., Igbawua, T., Henchiri, M., Ali, S., Zhang, S., Bai, Y. and Zhang, J.: Assessment of climate impact on vegetation dynamics over East Africa from 1982 to 2015, Sci. Rep., 9(1), 1–20, doi:10.1038/s41598-019-53150-0, 2019.

Kirkby, M., Bracken, L. and Reaney, S.: The influence of land use, soils and topography on the delivery of hillslope runoff to channels in SE Spain, Earth Surf. Process. Landforms, 27(13), 1459–1473, doi:10.1002/esp.441, 2002.

Kiteme, B. P., Liniger, H. and Notter, B.: Dimensions of Global Change in African Mountains : The Example of, , 18–22, 2008.

Knoben, W. J. M., Freer, J. E. and Woods, R. A.: Technical note: Inherent benchmark or not? Comparing Nash-Sutcliffe and Kling-Gupta efficiency scores, Hydrol. Earth Syst. Sci., 23(10), 4323–4331, doi:10.5194/hess-23-4323-2019, 2019.

Krakauer, N. Y., Lakhankar, T. and Anadón, J. D.: Mapping and Attributing Normalized Difference Vegetation Index Trends for Nepal, , 1–15, doi:10.3390/rs9100986, 2017.

Liniger, H., Gikonyo, J., Kiteme, B. and Wiesmann, U.: Assessing and Managing Scarce Tropical Mountain Water Resources, Mt. Res. Dev., 25(2), 163–173, doi:https://doi.org/10.1659/0276-4741(2005)025[0163:AAMSTM]2.0.CO;2., 2005.

Mamuye, M.: Review on Impacts of Climate Change on Watershed Hydrology, , 8(1), 91–99, 2018.

Mwangi, H. M., Julich, S., Patil, S. D., McDonald, M. A. and Feger, K. H.: Relative contribution of land use change and climate variability on discharge of upper Mara River, Kenya, J. Hydrol. Reg. Stud., 5, 244–260, doi:10.1016/j.ejrh.2015.12.059, 2016.

Niang, I., Ruppel, O. C., Abdrabo, M. A., Essel, A., Lennard, C., Padgham, J. and Urquhart, P.: Africa. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability, in Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. [Barros, V.R., C.B. Field, D.J. Dokken, M.D. Mastrandrea, K.J. Mach, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estr, edited by V. R. Barros, C. B. Field, D. J. Dokken, M. D. Mastrandrea, and K. J. Mach, pp. 1199–1265, Cambridge University Press, Cambridge., 2014.

Pinzon, J. E. and Tucker, C. J.: A non-stationary 1981-2012 AVHRR NDVI3g time series, Remote Sens., 6(8), 6929–6960, doi:10.3390/rs6086929, 2014.

Røhr, P. C. and Killingtveit, Å.: Rainfall distribution on the slopes of Mt Kilimanjaro, Hydrol. Sci. J., 48(1), 65–77, doi:10.1623/hysj.48.1.65.43483, 2003.

Teng, J., Chiew, F. H. S., Vaze, J., Marvanek, S. and Kirono, D. G. C.: Estimation of climate change impact on mean annual runoff across continental Australia using Budyko and Fu equations and hydrological models, J. Hydrometeorol., 13(3), 1094–1106, doi:10.1175/JHM-D-11-097.1, 2012.

Teuling, A. J.: A Forest Evapotranspiration Paradox Investigated Using Lysimeter Data, Vadose Zo. J., 17(1), 170031, doi:10.2136/vzj2017.01.0031, 2018.

Teuling, A. J., De Badts, E. A. G., Jansen, F. A., Fuchs, R., Buitink, J., Van Dijke, A. J. H. and Sterling, S. M.: Climate change, reforestation/afforestation, and urbanization impacts on evapotranspiration and streamflow in Europe, Hydrol. Earth Syst. Sci., 23(9), 3631–3652, doi:10.5194/hess-23-3631-2019, 2019.

Troch, P. A., Carrillo, G., Sivapalan, M., Wagener, T. and Sawicz, K.: Climate-vegetation-soil interactions and long-term hydrologic partitioning: Signatures of catchment co-evolution, Hydrol. Earth Syst. Sci., 17(6), 2209–2217, doi:10.5194/hess-17-2209-2013, 2013.

Tucker, C. J., Pinzon, J. E., Brown, M. E., Slayback, A., Pak, E. W., Mahoney, R., Vermote, E. F. and Saleous, N. E. L.: An extended AVHRR 8-kni NDVI dataset compatible with MODISand SPOT vegetation NDVI data, Int. J. Remote Sens., 26(20), 2005.

Ulrich, A., Ifejika Speranza, C., Roden, P., Kiteme, B., Wiesmann, U. and Nüsser, M.: Small-scale farming in semi-arid areas: Livelihood dynamics between 1997 and 2010 in Laikipia, Kenya, J. Rural Stud., doi:10.1016/j.jrurstud.2012.02.003, 2012.

Western, A. W., Zhou, S. L., Grayson, R. B., McMahon, T. A., Blöschl, G. and Wilson, D. J.: Spatial correlation of soil moisture in small catchments and its relationship to dominant spatial hydrological processes, J. Hydrol., 286(1–4), 113–134, doi:10.1016/j.jhydrol.2003.09.014, 2004.

Woods, R.: The relative roles of climate, soil, vegetation and topography in determining seasonal and long-term catchment dynamics, Adv. Water Resour., 30(5), 1061, doi:10.1016/j.advwatres.2006.10.010, 2002.

Yuan, W., Piao, S., Qin, D., Dong, W., Xia, J., Lin, H. and Chen, M.: Influence of Vegetation Growth on the Enhanced Seasonality of Atmospheric CO2, Global Biogeochem. Cycles, 32, 32–41, doi:https://doi.org/10.1002/ 2017GB005802, 2017.

Zimmermann, L., Frühauf, C. and Bernhofer, C.: The role of interception in the water budget of spruce stands in the Eastern Ore Mountains/Germany, Phys. Chem. Earth, Part B Hydrol. Ocean. Atmos., 24(7), 809–812, doi:10.1016/S1464-1909(99)00085-4, 1999.