https://doi.org/10.5194/hess-2021-151
Preprint. Discussion started: 29 March 2021

Hydrology and Earth System Sciences
Discussions
Open Access
EGU

Land-use and climate change effects on water yield from East African Forested Water Towers

Charles Nduhiu Wamucii[1], Pieter R. van Oel[2], Arend Ligtenberg[3], John Mwangi Gathenya[4], Adriaan J. Teuling[1]

[1]Hydrology and Quantitative Water Management Group, Wageningen University & Research, 6700 AA Wageningen, The Netherlands

[2]Water Resources Management Group, Wageningen University & Research, 6700AA Wageningen, The Netherlands

[3]Laboratory of Geo-information Science and Remote Sensing, Environmental Sciences, Wageningen University & Research, 6708 PB Wageningen, The Netherlands

[4]Soil, Water and Environmental Engineering Department, School of Biosystems and Environmental Engineering, Jomo Kenyatta University of Agriculture & Technology, P.O Box 62000 - 00200 Nairobi, Kenya

Correspondence to: Charles Nduhiu Wamucii (charles.wamucii@wur.nl)

Abstract. East-African forested mountain regions are vital in generating and supplying water resources to adjacent arid and semi-arid lowlands. However, these ecosystems are under pressure from both climate and land-use changes. This study aimed to analyze the effects of climate and land-use changes on water yield using the Budyko conceptual framework. For 9 selected forested water towers in East Africa, the amount and distribution of water resources and their decadal changes were analyzed. Results show that most areas inside and outside the water towers are under pressure from human influences. Water yield was ~~observed to be~~ more sensitive to climate changes compared to land-use changes within the selected East African water towers themselves. However, for the surrounding lowlands, the effects of land-use changes ~~have~~ greater impacts on water yield. We conclude that the East-African water towers have seen a strong shift towards wetter conditions, especially in the period of 2011-2019 while at the same time, the atmospheric demand is gradually increasing. Given that ~~majority~~ of the water towers were identified as non-resilient to these changes, future water yield is likely to also experience more extreme variations.

Keywords: Water towers, Climate changes, Land-use changes, Water yield, Budyko framework

1. Introduction

Many mountainous areas act as water towers by generating and supplying water resources to adjacent lowlands that would otherwise be much drier. An area is considered a water tower if it has a high elevation and high precipitation, consequently generating streamflow to lowland areas (Dewi et al., 2017; Immerzeel et al., 2010; Viviroli et al., 2007). Although research on water towers has focused mainly on glaciated mountain chains (Immerzeel et al., 2020), there is growing awareness that forested mountains can provide similar services (Viviroli and Weingartner, 2004). Mountainous areas in Africa cover approximately 20 % of Africa's surface area and receive significantly more rain than adjacent lowlands (EAC et al., 2016; UNEP, 2014). They capture water, store it, purify it, and release it to lowland areas (UNEP, 2014). The East-African region is one of the most mountainous areas of Africa with several peaks above 4,500 meters and hosts the three highest mountains on the continent: Kilimanjaro (5,895 m), Mount Kenya (5,119 m), and the Rwenzori Mountains (5,109 m) (UNEP, 2014).

Montane forest ecosystems in the East-African region are classified as water towers due to their high elevations and high humidity thus generating water yield for adjacent lowland areas. There is a high dependency on surface water in the East-African region (Jacobs et al., 2018), but rainfall distribution is meager in most parts of the region, with several areas experiencing frequent ~~occurrence of~~ severe droughts (Nicholson, 2017). Therefore, the forested water towers in the region are important sources of water that sustain environmental and human water demands in the lowland areas.

The water towers of East Africa are under pressure from human intensification and climate change (Gebrehiwot et al., 2014; WWF, 2005). According to the Intergovernmental Panel for Climate Change (IPCC) Fifth Assessment Report, the average annual temperature for Africa has risen by at least 0.5 °C during the last 100 years and ~~this~~ is predicted to increase by approximately 3.2 °C by 2080. This will dramatically diminish glaciers in East-African

https://doi.org/10.5194/hess-2021-151
Preprint. Discussion started: 29 March 2021

Hydrology and Earth System Sciences
Discussions
Open Access
EGU

water towers whose surface area has already decreased by 80 % since the 1990s (EAC et al., 2016), affecting runoff and water resources downstream. The East-African montane forest zones continue to be lost to agriculture and other anthropogenic uses. This is mainly attributed to high and increasing population density which is a major driving force of environmental change in the mountainous areas (UNEP, 2014).

Understanding historical climate change and human-induced land-use changes and their impacts on streamflow generation from the forested water towers can explain some of the extreme hydrological events experienced in the adjacent lowlands such as floods and hydrological droughts. To ~~the best of~~ our knowledge, there are no studies that have focused on the East-African forested water towers and their ability to generate streamflow under a changing climate and land-use in the East-African region. That said, Guzha et al. (2018) in their review emphasized the importance of forests in streamflow generation in the region, with forest degradation leading to increased stream discharges and surface runoff. Moreover, Muthoni et al. (2019)~~,~~ focused on spatial-temporal trends and variability of precipitation within East and Southern Africa. However, there is limited information on the partitioning of the available precipitation into water yield and evapotranspiration from the forested water towers of the East-African region.

Various approaches have been used for studying the effects of climate change and land-use on streamflow. Jiang et al. (2015) categorized such methods into two~~s~~ (a) deterministic rainfall-runoff models and (b) statistical methods. Dey and Mishra (2017) categorized these approaches into four categories; (i) experimental approaches, (ii) hydrological modeling, (iii) conceptual approaches, and (iv) analytical approaches. The Budyko model (Budyko, 1974) is a conceptual approach that considers both water and energy constraints in hydrological processes over a long-term period. The framework has been applied to quantify or separate the impacts of climate change and human activities on runoff (Jiang et al., 2015; Roderick and Farquhar, 2011; Xu et al., 2013).

The Budyko framework has been applied successfully in numerous studies focusing on the partitioning of precipitation into streamflow and evapotranspiration (Creed et al., 2014; Jiang et al., 2015; Mwangi et al., 2016; Roderick and Farquhar, 2011; Xu et al., 2013; Zhang et al., 2004). The framework works well both at coarse global grid resolution and in smaller basins of less than 10 km² (Redhead et al., 2016; Teuling et al., 2019; Zhang et al., 2004). This paper aims to analyze the effects of climate and land-use changes over the past decades and their impacts on the amount and distribution of water resources from selected forested water towers of East Africa. The water yield simulations were evaluated against observation-based runoff.

2. Data and Methodology

The Budyko conceptual framework was adopted to evaluate the impacts of land-use changes and climate changes on water yield from the selected forested water towers. The study area is the East-African region. The montane forest ecosystems are the major forest types in Eastern Africa. They range from Ethiopian highlands to Albertine rift mountains stretching along the Congo DRC and bordering Uganda, Rwanda, Burundi, and Tanzania. This study focused on montane forest ecosystems and their moorlands. The selected water towers are shown in Fig 1, and summarized in Table 1~~)~~.

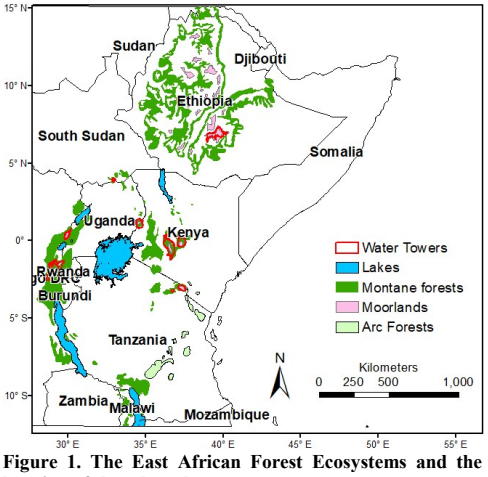


Figure 1. The East African Forest Ecosystems and the location of the selected water towers

https://doi.org/10.5194/hess-2021-151
Preprint. Discussion started: 29 March 2021

Hydrology and Earth System Sciences
Discussions
Open Access
EGU

Table 1. The selected water towers of East Africa

Mountain Ecosystems	Location	Peak Elevation – asl (m)	Foot slope contour - asl (m)
Mt Kilimanjaro	Tanzania	5,895	2000
Mt Kenya	Kenya	5,199	2000
Mt Elgon	Kenya/Uganda	4,321	2000
Aberdare Ranges	Kenya	3,999	2100
Rwenzori Mountains	Uganda/Congo	5,109	2000
Mt Meru	Tanzania	4,565	2000
Virunga Mountains	Congo/Rwanda/Uganda	4,507	2000
Bale Mountains	Ethiopia	4,337	2600
Imatong Mountains	South Sudan/Uganda	3,187	2000

Precipitation data ~~(P) was~~ gathered from Climate Hazards Group Infrared Precipitation with Stations (CHIRPS-v2) with a temporal coverage beginning 1981 and a spatial resolution of 0.05°. Potential Evapotranspiration (PET) data ~~was~~ sourced from Climate Research Unit (CRU) database with temporal coverage beginning 1981 and a spatial resolution of 0.5°. Normalized Difference Vegetation Index (NDVI) data to estimate land surface characteristics ~~was~~ sourced from 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). The research borrows from the concept of quantifying the long-term impact of climate and land-use changes on mean annual evapotranspiration and water yield at catchment scales based on data and parameters that are easily measurable at a regional scale (Zhang et al., 2001). Forested catchments generally have higher evapotranspiration than other land covers such as grassed catchments. Therefore changes in land use and forest management have an impact on catchment water balance and hence water yield (Teuling and Hoek van Dijke, 2020; Zhang et al., 2001).

One way of estimating water yield (Q) and actual evaporation (ET) is to assume that evapotranspiration from land surfaces is controlled by water availability and atmospheric demand (Zhang et al., 2001). The water availability can be approximated by precipitation; the atmospheric demand represents the maximum possible evapotranspiration and is often considered as the potential evapotranspiration (PET). Under very dry conditions, PET exceeds precipitation (P) and actual evapotranspiration (ETa) equals precipitation. Under very wet conditions water availability exceeds PET, and ET will asymptotically approach the potential evapotranspiration (Zhang et al., 2001), (see Fig A1 for key assumptions on energy and water limits). The Budyko Curve provides a "business as usual" reference condition for the water balance. Assuming that it can depict the expected partitioning of P into ET and Q, then it is possible to account for the reasons why some points depart from the baseline (Creed and Spargo, 2012b). The vertical deviations reflect a change in the partitioning of P into ET and Q, hence, the higher the evaporative index (EI), the less the streamflow (Q). The horizontal deviations reflect the change in climatic conditions (i.e. temperature and precipitation); thus, the higher the dryness index (DI), the warmer/drier the conditions. One important feature of the Budyko curve is the assumption that, under stationary conditions, hydrologic partitioning of study areas will ~~follow~~ on the Budyko Curve. However, under non-stationary conditions, each catchment will deviate from the Budyko curve depending on land cover and physical catchment characteristics (Creed and Spargo, 2012b), and this feature might be used to separate land cover change effects from climate change.

Several analytical equations have been proposed for the Budyko curve. In this study, FU's equation was used (Equation 1). The equation has been applied in different studies (Li et al., 2013; Teuling et al., 2019).

$$\frac{ET}{P} = 1 + \frac{PET}{P} - \left[1 + \left(\frac{PET}{P}\right)^{\omega}\right]^{1/\omega} \quad (1)$$

where *P*, *PET*, and *ET* are the precipitation, potential evaporation, and actual evapotranspiration. *PET/P* and *ET/P* are termed ''dryness index'' and ''evaporation ratio'', respectively.

Parameter (ω) is an empirical parameter that controls how much of the available water will be evaporated given the available energy. It reflects the impact of other factors such as land surface characteristics and climate seasonality on water and energy balances (Li et al., 2013). Land surface hydrology varies due to variations in different factors such as vegetation, soil types, and topography, climate seasonality, ~~etc~~ (Li et al., 2013). Vegetation

https://doi.org/10.5194/hess-2021-151
Preprint. Discussion started: 29 March 2021

Hydrology and Earth System Sciences
Discussions
Open Access
EGU

information can serve as a good integrated indicator of these ecohydrological impacts on water and energy balances as it reflects the integrated landscape and climatic features (Donohue et al., 2007). The fact that vegetation coverage integrates the effects of the eco-hydrological processes on water and energy balances warrants a simple parameterization for ~~(ω)~~ using only vegetation information in ~~the~~ large-scale basins (Li et al., 2013). According to Li et al. (2013), ~~(ω)~~ ~~parameters~~ can be calculated using the following ~~equation~~:

$$\omega = 2.36M + 1.16 \quad (2)$$

~~W~~here ~~(M)~~ represents the vegetation coverage – which is calculated based on NDVI indices (Yang et al., 2009):

$$M = \frac{NDVI - NDVI_{min}}{NDVI_{max} - NDVI_{min}} \quad (3)$$

In this study, the M values were calculated for 1985, 1995, 2005, and 2015, and assumed to represent the (ω) parameters for the respective periods of 1981-1990, 1991-2000, 2001-2010, and 201~~-~~2019.

Over a long period (i.e. 5-10 years) it is reasonable to assume that changes in soil water storage are zero (Creed et al., 2014; Teuling et al., 2019; Zhang et al., 2001). Therefore, water yield is estimated using the following equation:

$$Q = P - ET \quad (4)$$

~~W~~here ~~(Q)~~ represents the water yield, P ~~(~~precipitation~~)~~, and ~~(ET)~~ the simulated actual evapotranspiration.

To develop ~~the~~ Budyko curves that are representative of the selected forested water towers, 100 random points were generated in each of the water towers in ArcGIS. The random points were used to extract values from raster P, PET, and ET grids into excel format for external analysis. For maximum representation, the minimum allowed distance between the random points was set to 100 m~~eters~~. 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 ETa 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.

To evaluate the impacts of climate and land-use changes, the sensitivity of climate and land-use changes was conducted. The climate and land-use values for the years 1981-1990 were used as the reference conditions in the Budyko framework. The climatic conditions (i.e. P and PET) for the years 1981-1990 were held constant in the Budyko framework to evaluate the impacts under changing land-use conditions in the succeeding periods of 1991-2000, 2001-2010, and 2011-2019. Similarly, the land-use conditions (i.e. (ω) parameters) for the years 1981-1990 were held constant in the Budyko framework to evaluate the impacts under changing climatic conditions in the succeeding periods of 1991-2000, 2001-2010, and 2011-2019.

~~Additionally, the d~~eviations from the Budyko curves were also investigated to give a further understanding of the type of changes observed in the different water towers. Vertical deviations from the Budyko curve indicate anthropogenic effects which result in increases or decreases in water yield (Creed and Spargo, 2012b, 2012a). ~~The~~ horizontal deviations reflect a shift to warmer or humid conditions mainly due to resultant variations in temperature and precipitation (Creed and Spargo, 2012b, 2012a). The deviation (d) and elasticity (e) are ~~the~~ two indices used to describe the potential departure from the theoretical Budyko curve of a catchment's DI and EI points with time (Creed et al., 2014). The deviation (d) was calculated using the following formula;

$$d = EI_{Sim} - EI_{Bud} \quad (5)$$

Where EI_{Sim} represents EI simulated for periods in 1991-2000, 2001-2010 and 2011-2019 and EI_{Bud} represents the predicted theoretical Budyko value for the reference period of 1981-1990. A negative ~~(d)~~ represents a downward shift from the Budyko curve and hence an increase in Q. A positive ~~(d)~~ represents an upward shift from the Budyko curve and hence a decrease in Q. The elasticity (e) was calculated as a ratio of DI ranges to EI ranges ~~as shown in the following formula below;~~

$$e = \frac{\Delta DI}{\Delta EI} \quad (6)$$

https://doi.org/10.5194/hess-2021-151
Preprint. Discussion started: 29 March 2021

Hydrology and Earth System Sciences
Discussions
Open Access
EGU

Where ΔDI represents a range in DI values and ΔEI represents a range in EI values observed in the periods of 1991-2000, 2001-2010, and 2011-2019 using the period of 1981-1990 as the reference period. The water towers with lower elasticity values indicate greater ranges in their EI values and the water towers with higher elasticity values demonstrate lesser ranges in their EI values.

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. Results

Higher long-term mean annual rainfall of above 1000 mm yr^{-1} was observed ~~majorly~~ in the mountainous forest ecosystems located in the western region and the Ethiopian highlands in the north of East Africa (Fig 2a). The mountainous forest ecosystems are important rainfall regions in drier environments as represented by Mt Kilimanjaro (average 1800 mm yr^{-1}), Mt Meru (average 1200 mm yr^{-1}), Mt Kenya (average 1400 mm yr^{-1}), and Aberdare ranges (average 1200 mm yr^{-1}) as shown in Fig 2a and Fig 2b. The 10-year moving averages analysis revealed patterns of high and low trends in precipitation in the different water towers (Fig A2).

~~Using the 1981-1990 period as the reference period, c~~hanges in Precipitation showed a Longitudinal gradient. Negative changes in rainfall were observed in the water towers located towards the eastern side except for the Virunga mountains. Positive trends were observed in the water towers located towards the western side with exception of Aberdare ranges. Mt Kilimanjaro experienced a strong mean annual rainfall reduction with an average annual reduction of 13.5 % and 12 % observed in ~~the periods of~~ 2001-2010 and 2011-2019 respectively (Fig 2c). Contrastingly, a steady increase in mean annual rainfall was observed in Mt Elgon with an average increase of over 20 % recorded in the years of 2011-2019 (Fig 2c).

Long-term assessment of atmospheric demand (PET) showed areas with relatively higher mean annual PET to coincide with areas of low rainfall and vice-versa (Fig 2d). Generally, atmospheric demand continued to increase over time in all the water towers with a peak observed in ~~the years of~~ 2001-2010 (Fig 2e and Fig A3). Imatong Mountains water tower had the highest atmospheric demand with an average long-term mean of appx 1500 mm yr^{-1}, followed closely by Mt Elgon with an average long-term mean of appx 1400 mm yr^{-1}. The water towers located towards the western side exhibited lower atmospheric demand (examples are Virunga mountains – long-term mean of 990 mm yr^{-1} and Rwenzori mountains – long-term mean of 1100 mm yr^{-1}).

~~Using the 1981-1990 period as the reference period, a~~ll water towers experienced increases in the annual atmospheric demand (Fig 2f.) Bale mountains saw a sharp increase in atmospheric demand ~~by~~ approximately 6 % in ~~the periods of~~ 2001-2010 and 2011-2019. A minimal increase in atmospheric demand was observed in Mt Kilimanjaro with an average annual increase of 0.1 %, 1.0 %, and 0.8 % in ~~the periods of~~ 1991-2000, 2001-2010, and 2011-2019 respectively as shown in Fig 2f.

https://doi.org/10.5194/hess-2021-151
Preprint. Discussion started: 29 March 2021

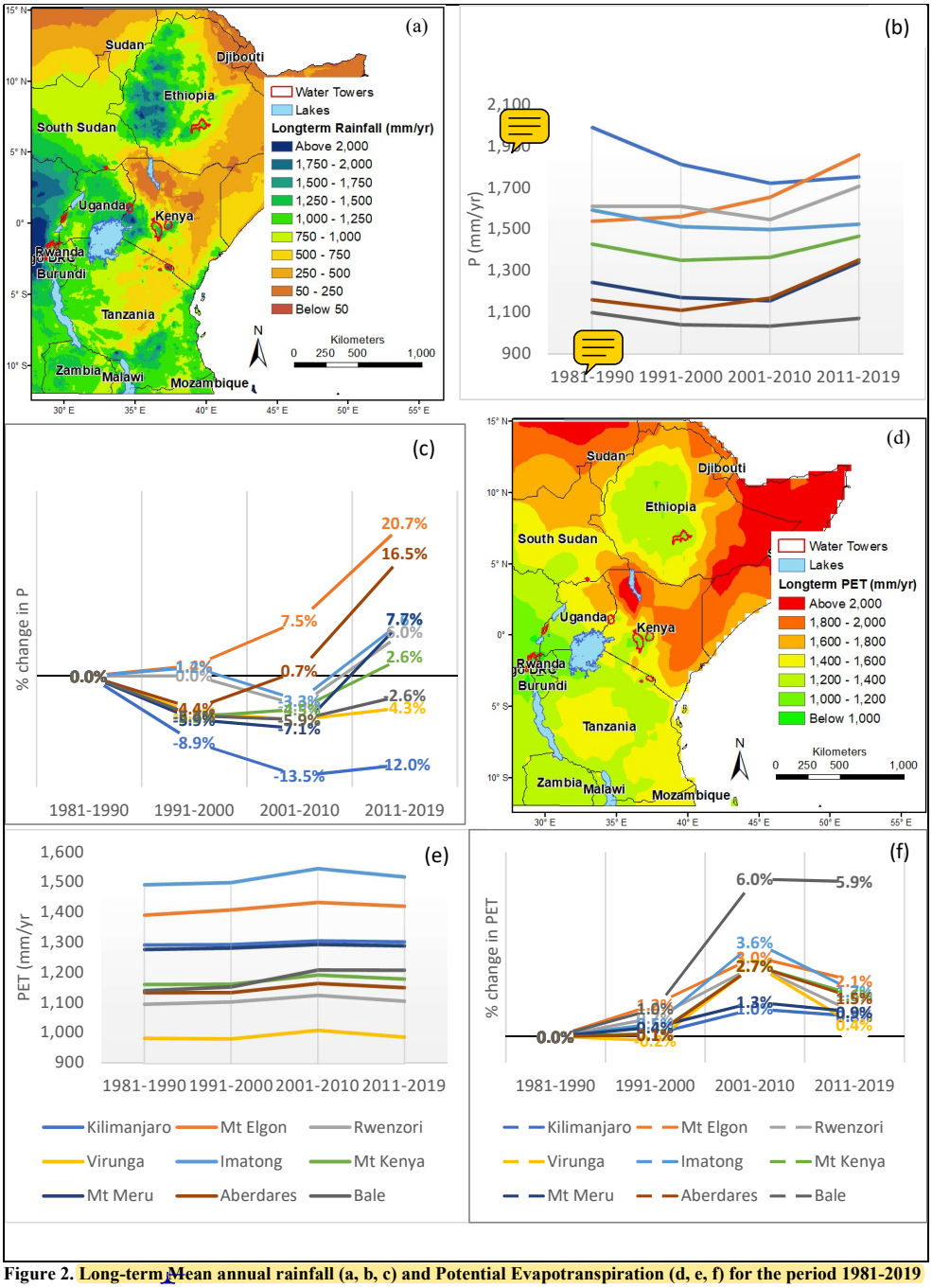
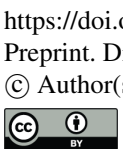


Figure 2. Long-term Mean annual rainfall (a, b, c) and Potential Evapotranspiration (d, e, f) for the period 1981-2019

https://doi.org/10.5194/hess-2021-151
Preprint. Discussion started: 29 March 2021



Hydrology and Earth System Sciences
Discussions
Open Access
EGU

Higher values for the Budyko parameter (ω) were observed in the western part of Congo/Uganda, the Ethiopian Highlands and along the coastline of Tanzania, Kenya, and Somalia (Fig 3a). The land surface characteristics (ω)~~,~~ ranged between 2.4 and 3.1 in the different water towers, with exception of Bale mountains where a drop to 2.3 was observed in 2015 (Fig 3b). Using ~~the year~~ 1985 as the reference for the land cover characteristics, different patterns of negative changes and positive changes were observed. A major drop was observed in Mt Meru and Mt Kilimanjaro while Mt Elgon and Imatong mountains maintained a positive change (Fig 3c).

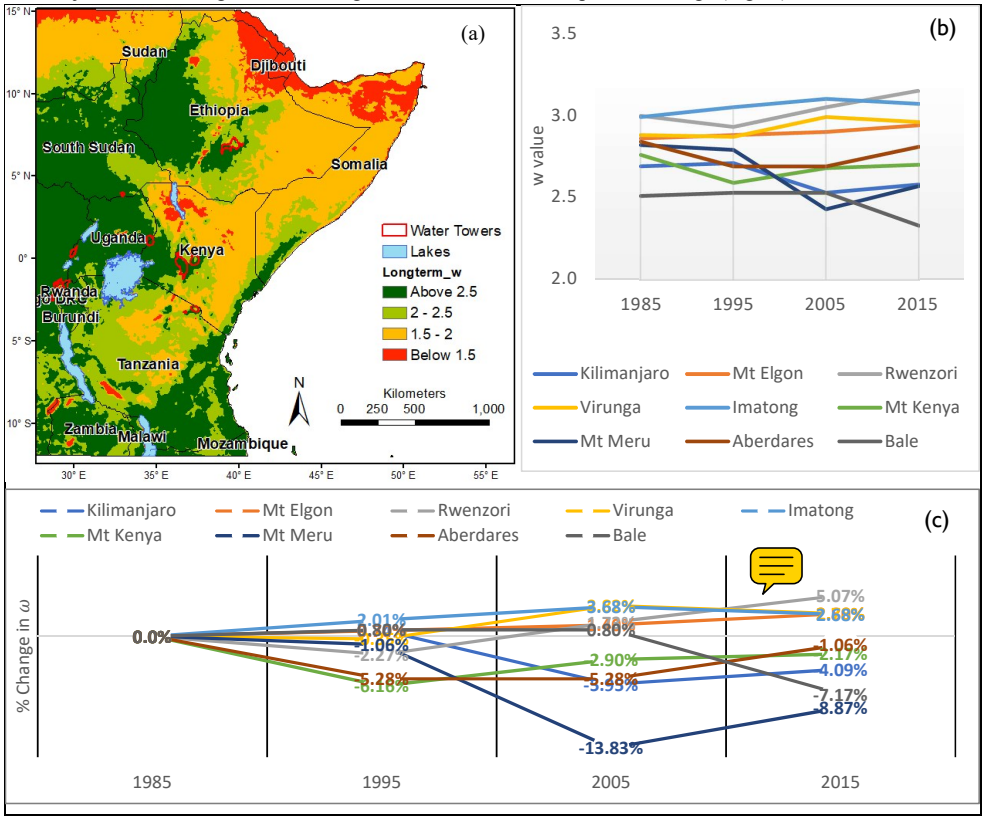


Figure 3. The Land surface characteristics (ω) for 1985 to 2015 (a), the changes observed between 1985 and 2015 (b) & and (c)

The long-term actual evapotranspiration (Eta) assessment revealed longitudinal differences in the spatial distribution. The water towers towards the west were observed to be located in regions with higher ETa (examples are Mt Elgon, Imatong mountains, Rwenzori mountains, and Virunga mountains). The water towers towards the east are located in regions with relatively lower ETa (examples are Mt Meru, Mt Kilimanjaro, Aberdare Ranges, and Mt Kenya~~.~~ (Fig 4a and Fig 5a, 5b, 5c, 5d). The changes in ETa in the region were analyzed using the 1981-1990 period as the baseline (Fig 4a). ~~The d~~decreases in ETa were observed in the ~~S~~south-~~E~~eastern parts of Ethiopia, ~~N~~north-south gradient in Kenya, central Tanzania, and the western side of Congo/Burundi region as shown in Fig 4b, 4c, and 4d. ~~The i~~increases in ETa were observed in northern parts of Eastern Africa (i.e. Sudan, South Sudan, Djibouti, Northern Somalia, the Kenyan-Somali border, and parts of north-western Kenya bordering Uganda and South Sudan (Fig 4b, 4c, and 4d).

https://doi.org/10.5194/hess-2021-151
Preprint. Discussion started: 29 March 2021

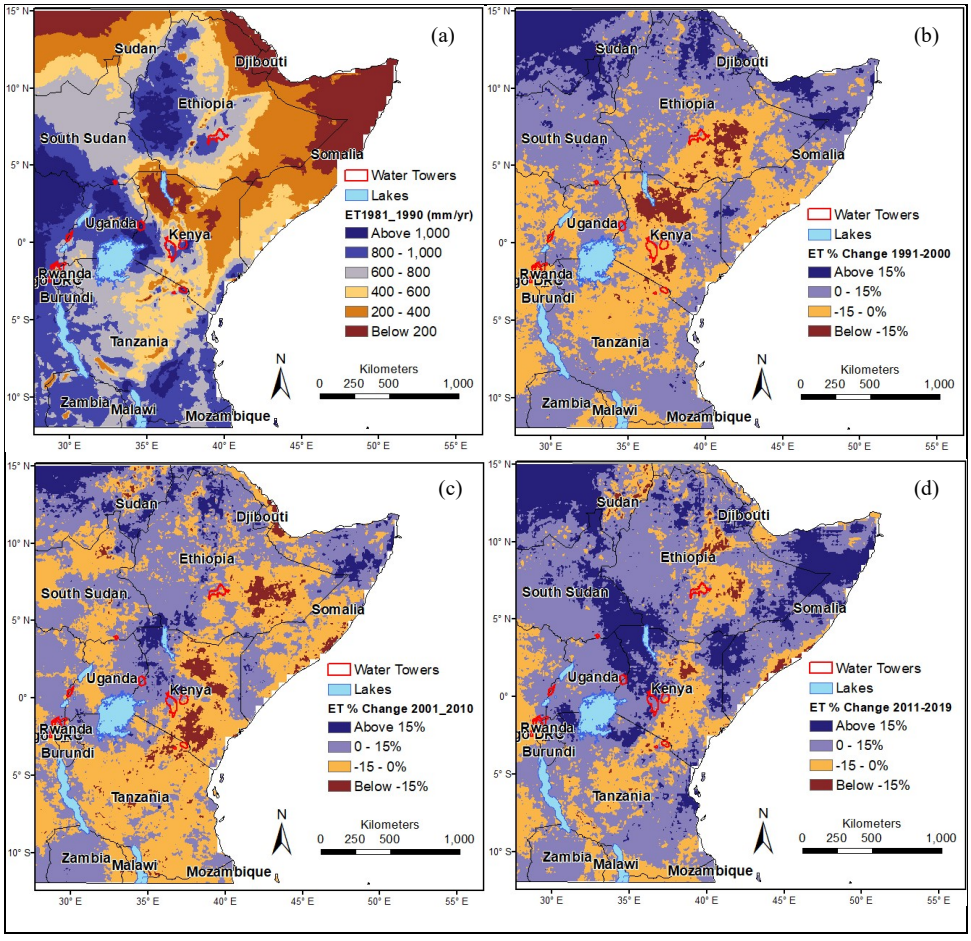


Figure 4. Simulation of Actual Evapotranspiration (Eta) in the East African region: (a) **ETa for 1981-1990,** (b) **ETa changes in 1991-2000,** (c) **ETa changes in 2001-2010, and** (d) **ETa changes in 2011-2019**

Despite the longitudinal differences, the individual water towers recorded varied ETa values. Higher ETa values were simulated around the Imatong Mountains – with a long-term mean of 1107 mm yr^{-1}, Mt Elgon – with long-term a mean of 1097 mm yr^{-1}, and Mt Kilimanjaro – with long-term a mean of 1012 mm yr^{-1}. The lowest ETa values were observed in the Bale mountains – with a long-term mean of 747 mm yr^{-1} (Fig 5j). Using the 1981-1990 period as the reference period, Mt Elgon recorded a steady increase in annual mean ET with an average increase of the order of 10 % ~~observed~~ between 2011 and 2019. Pronounced decreases in ET were observed in Mt Kilimanjaro and Mt Meru water towers (Fig 5k), consistent with the decreasing trend in precipitation.

https://doi.org/10.5194/hess-2021-151
Preprint. Discussion started: 29 March 2021

Hydrology and Earth System Sciences
Discussions
Open Access
EGU

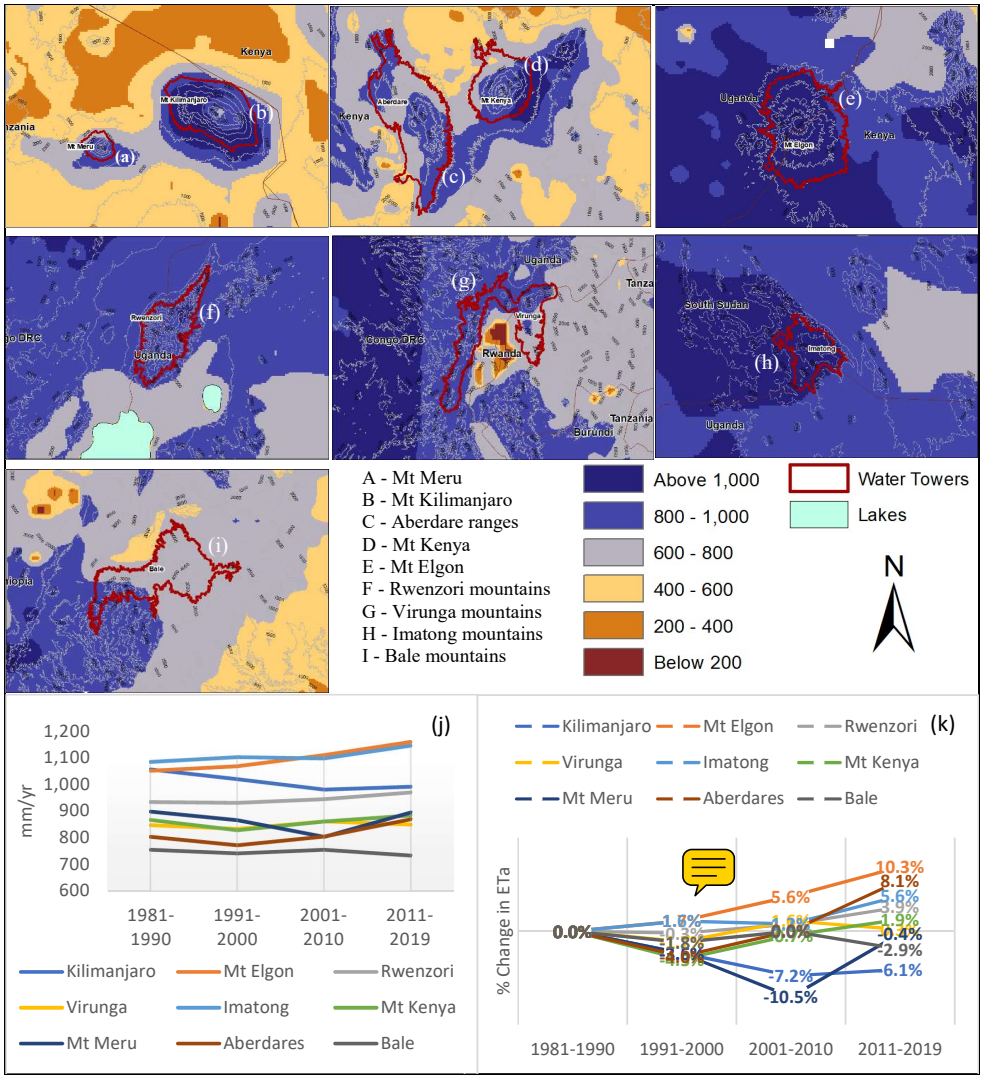


Figure 5. The Long-term Actual Evapotranspiration (ETa) in and around the water towers (a-i) and Simulated Annual Mean Evapotranspiration in the water towers (j&k)

Similarly to what was observed in ETa spatial distribution, the long-term water yield (Q) assessment also showed that the water towers located towards the east are surrounded by regions with low water yield potential below 200 mm yr^{-1} (examples are Mt Meru, Mt Kilimanjaro, Aberdare Ranges, and Mt Kenya (Fig 6a and Fig 7a, 7b, 7c, 7d). Using the period 1981-1991 as the baseline, major increases in Q were observed in areas of Sudan, and the Kenya-Somali border as shown in Fig 6b, 6c, and 6d.

https://doi.org/10.5194/hess-2021-151
Preprint. Discussion started: 29 March 2021

Hydrology and Earth System Sciences
Discussions

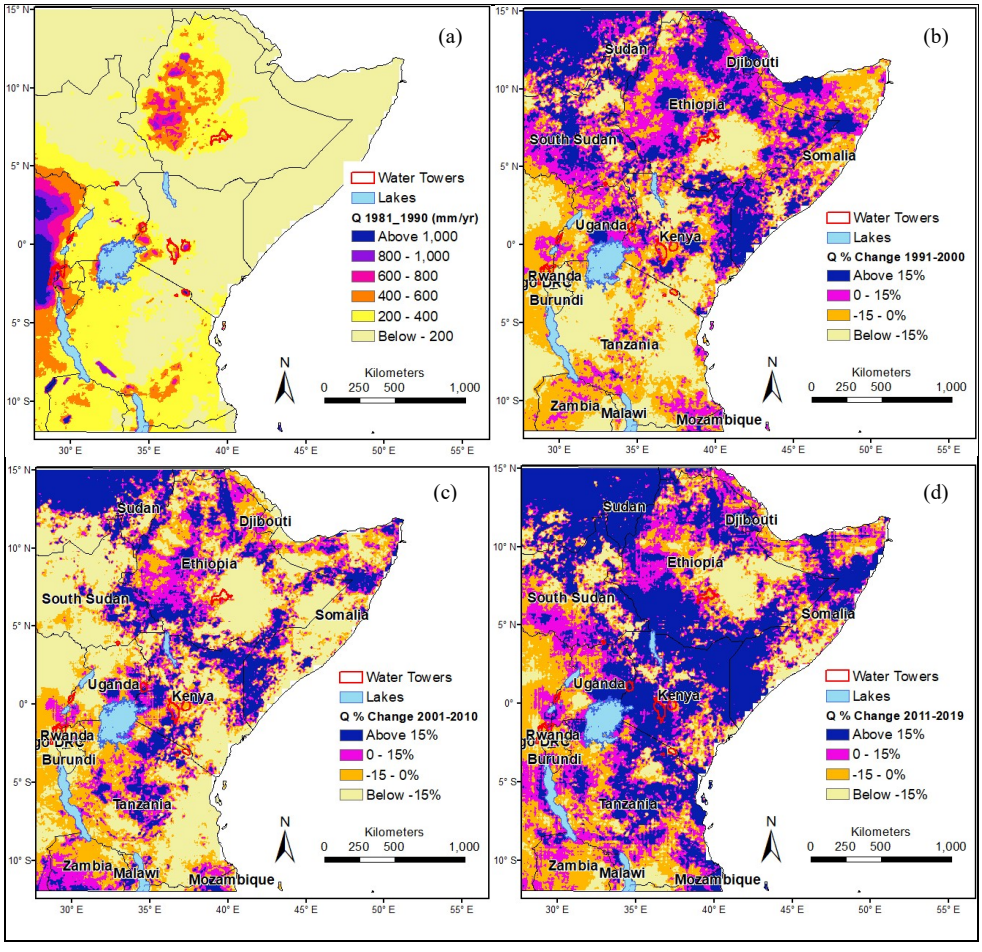


Figure 6. Simulation of Water Yield (Q) in the East African region: (a) **Q for 1981-1990,** (b) **Q changes in 1991-2000,** (c) **Q changes in 2001-2010, and** (d) **Q changes in 2011-2019**

Despite longitudinal differences, the higher mean annual water yield was ~~however~~ observed ~~in~~ Mt Kilimanjaro water tower located on the eastern side – with the long-term annual mean of 794 mm yr^{-1}, followed by two water towers located on the western side (i.e. Virunga mountains – with a long-term annual mean of 676 mm yr^{-1} and Rwenzori mountains – with a long-term annual mean of 650 mm yr^{-1}. The lowest annual mean water yield was observed in Bale mountains – with a long-term annual mean of 315 mm yr^{-1} (Fig 7j). Conversion of water yield units from mm/yr to m^3/s per unit area revealed that Mt Kilimanjaro and Mt Kenya are important sources of water in the drier part of the East African region (Table A1).

Using the period 1981-1990 as the reference point, ~~the~~ positive and negative changes were observed ~~in~~ the different water towers. There was a consistent increase in annual mean water yield ~~in~~ Mt Elgon water tower with ~~an order~~ of 11.4 % and 42.9 % recorded in ~~the periods of~~ 2001-2010 and 2011-2019 respectively (Fig 7k). There was a decrease in water yield in the Aberdare and Mt Meru water towers during the 1991-2000 period, after which an increase in annual mean water yield was recorded in the later years. A consistent decline was observed ~~in~~ Mt Kilimanjaro and the Virunga mountains during the study period.

https://doi.org/10.5194/hess-2021-151
Preprint. Discussion started: 29 March 2021

Hydrology and Earth System Sciences
Discussions
Open Access
EGU

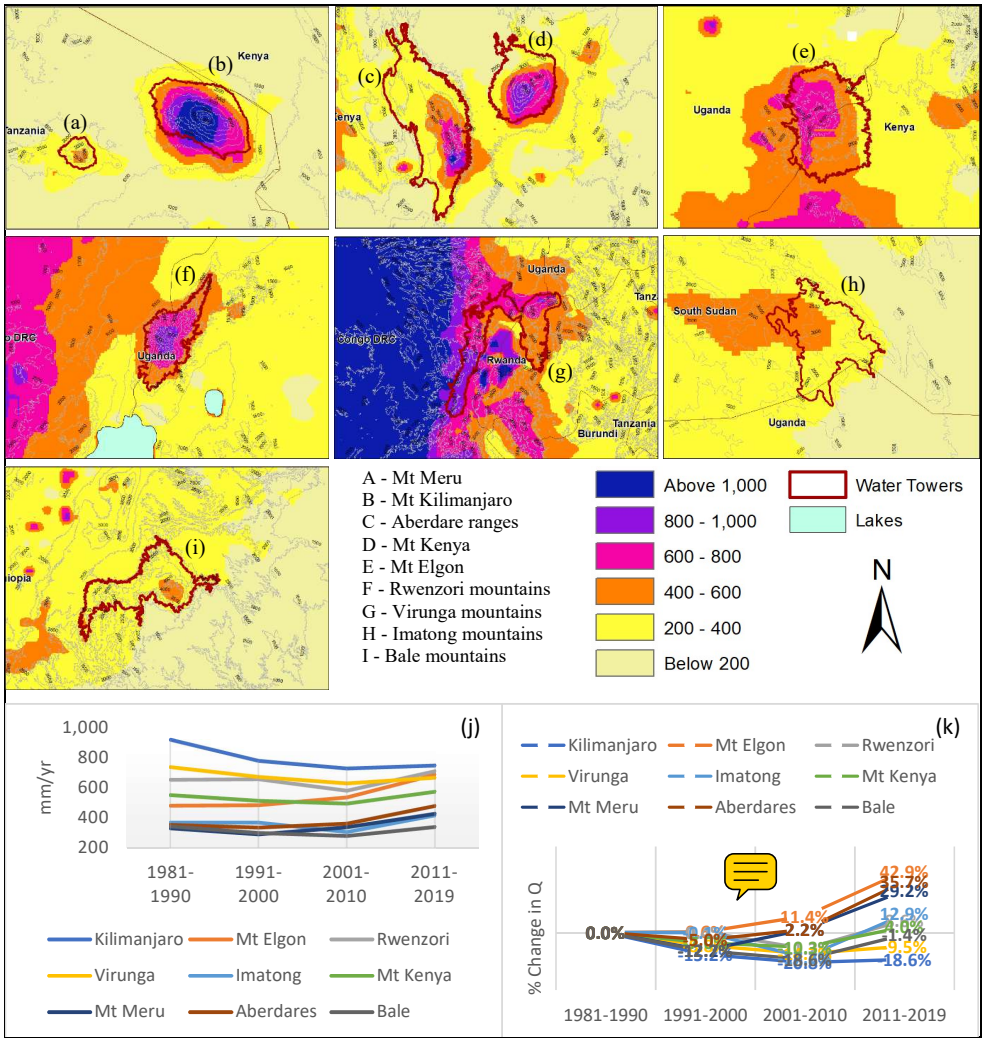
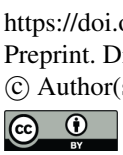


Figure 7. The ~~L~~long-term ~~W~~water yield (Q) ~~in~~ and around the water towers (a-i) and Simulated Annual Mean Water Yield ~~in~~ the Water Towers (j&k)

The simulated streamflow was compared with composite runoff data downloaded from the Global Runoff Data Centre (GRDC) (Fekete et al., 2002). The spatial pattern of the simulated streamflow closely resembles the pattern produced by GRDC composite runoff as shown in Fig 8a and 8b. A total of 312 points above 2000 meters above sea level, the focus of this study (i.e. elevated water towers), were randomly selected and their respective values of simulated streamflow and composite runoff were compared. The Kling-Gupta efficiency test revealed positive values, KGE=0.33 as shown in ~~(~~Fig 8c~~)~~.

https://doi.org/10.5194/hess-2021-151
Preprint. Discussion started: 29 March 2021



Hydrology and Earth System Sciences
Discussions
Open Access
EGU

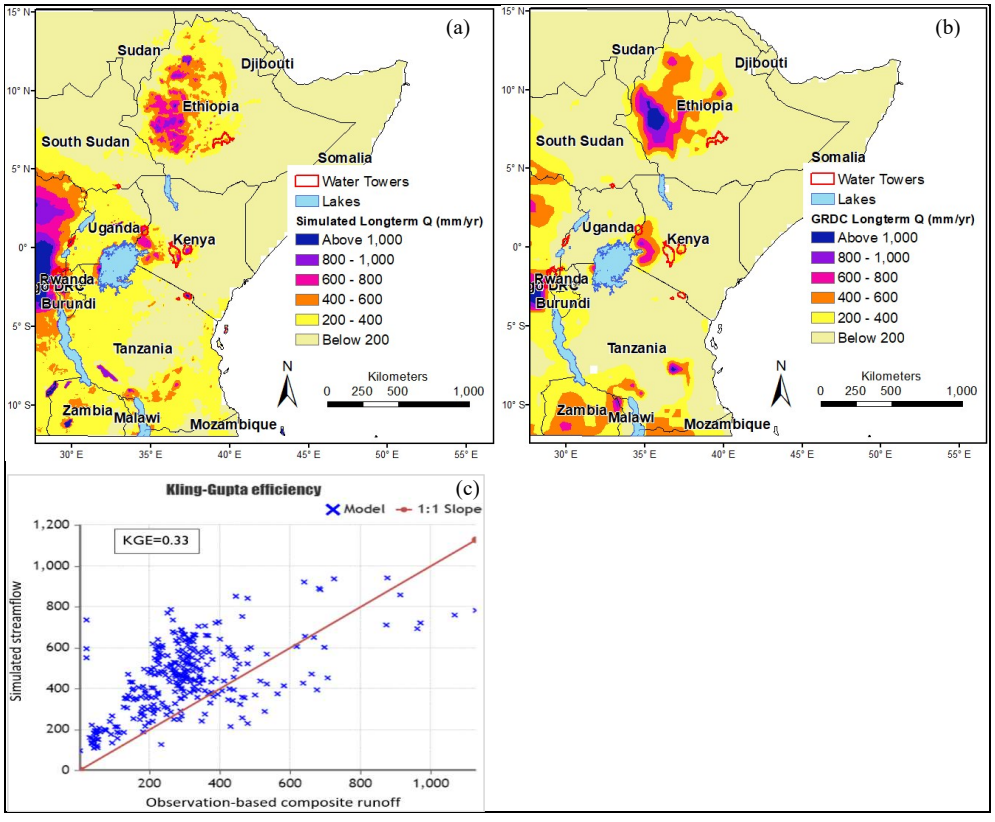
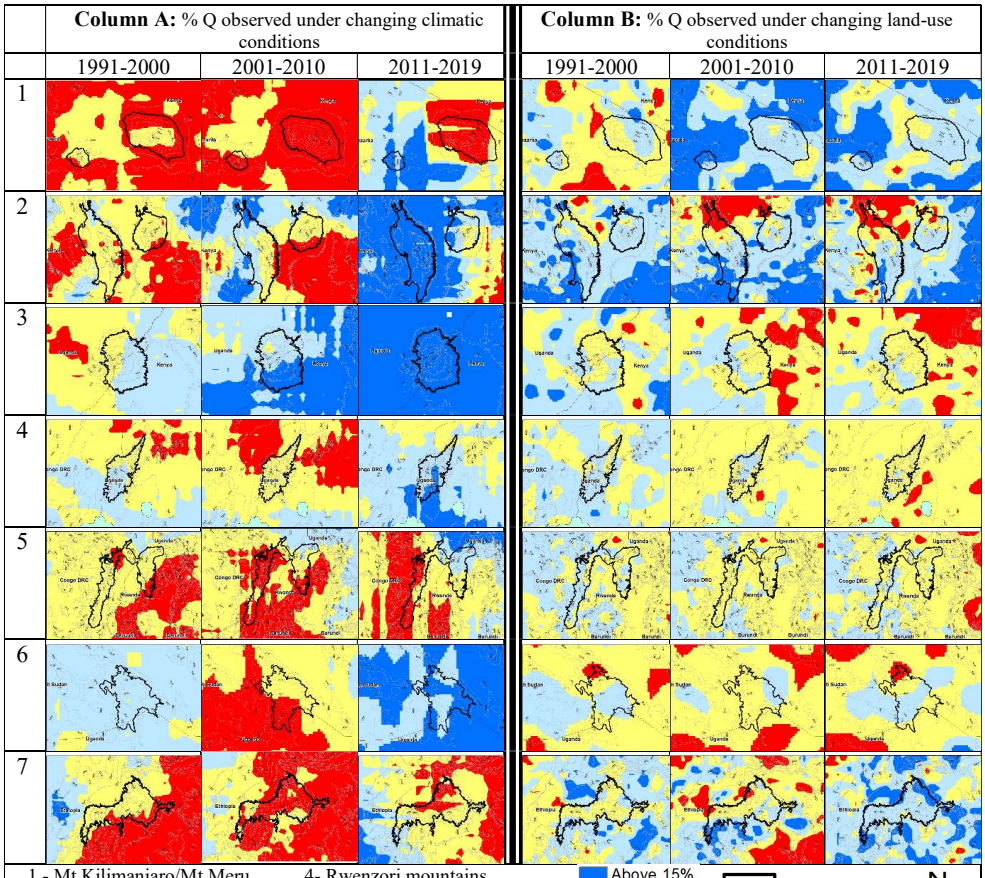


Figure 8. Spatial distribution of streamflow in the East African region: (a) **Simulated streamflow,** (b) **Observation-based composite runoff, and** (c) **Kling-Gupta efficiency calculation**

The water yield was observed to be relatively more sensitive to climate changes (i.e. P and PET) than land-use changes within the selected East African water towers. However, a closer look at the regions surrounding the selected water towers revealed that the effects of land-use changes have greater impacts on water yield outside the water towers boundaries (Fig 9). An example is on the Eastern side of Mt Elgon where there was a major reduction in water yield especially in the periods of 2001-2010 and 2011-2019, (Fig 9 Row no 3, column B). Climate changes showed a reduction of water yield in seven water towers in the periods of 1991-2000 and 2001-2010. However, in the years of 2011-2019, climate changes triggered increased water yield in seven water towers (Fig 10). The climate changes in Mt Elgon resulted in a consistent increase in water yield, while a consistent decrease was inferred for Mt Kilimanjaro.

https://doi.org/10.5194/hess-2021-151
Preprint. Discussion started: 29 March 2021

Hydrology and Earth System Sciences
Discussions



Summary:

1. Mt Kilimanjaro/Mt Meru: In column A the changes are observed both inside and outside water towers. In column B extreme changes are observed outside the water towers.

2. Aberdare ranges/Mt Kenya: In column A, major reductions were observed on the south-eastern side. In column B, major reductions were observed on the north-western side.

3. Mt Elgon: In column A, increases observed inside water towers. In column B, major decreases outside the water tower. No major changes inside water towers.

4. Rwenzori mountains: In column A, major changes inside the water tower. No major changes inside the water towers in column B.

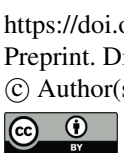
5. Virunga mountains: In column A, there are major changes that also affect water yield inside the water tower. In column B, no noticeable changes inside the water tower. ~~But~~ extreme reductions were observed outside the water tower.

6. Imatong mountains: In column A, noticeable changes inside the water tower. In column B, no obvious changes inside the water towers, but extreme changes outside the water tower.

7. Bale mountains: In column A, there are apparent changes inside the water tower. In column B, no major changes inside the water tower.

Figure 9. Effects of Land-use and Climate change on Water yield (Q)

https://doi.org/10.5194/hess-2021-151
Preprint. Discussion started: 29 March 2021



Hydrology and Earth System Sciences
Discussions
Open Access
EGU

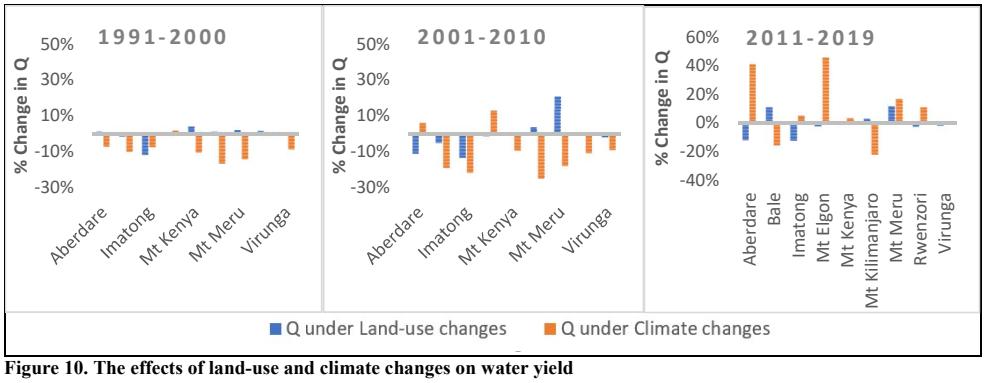


Figure 10. The effects of land-use and climate changes on water yield

The analysis of vertical deviations revealed downward shifts and upward shifts from the Budyko curve in the different water towers. The vertical deviations (d) ranged from negative (-)0.05 to positive (+)0.02 (Fig 11a). There were no vertical deviations observed in Mt Elgon and Imatong mountains indicating that the values observed (between 1991 and 2019) were approximately close to those predicted by the Budyko curve. The elasticity (e) values ranged from 0.49 to 17.6 with most of the water towers recording lower elasticity values as shown in Fig 11b. The higher elasticity (e) values were observed in Mt Kenya water tower in the years of 1991-2000, Bale mountains in the period of 2011-2019, and Aberdare ranges in the periods of 1991-2000 and 2001-2010.

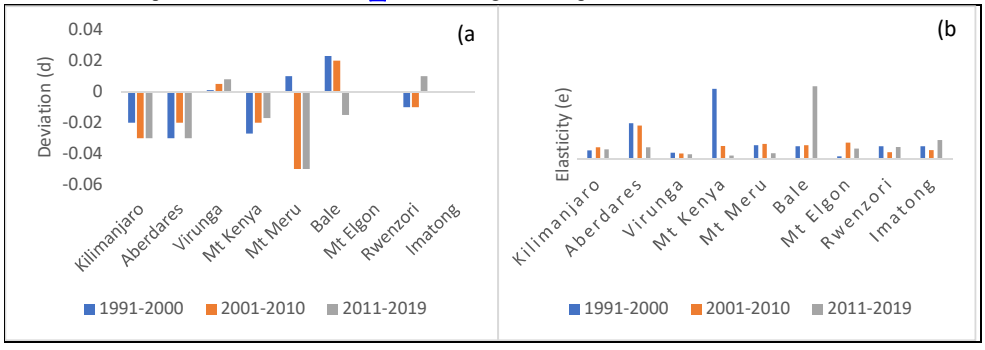


Figure 11. The Deviation from the Budyko curve (a) and Elasticity (b) in the Water Towers

The horizontal shifts either to the left or to the right relative to the dryness index (DI) were observed in the water towers. It was observed that 7 out of the 9 water towers plotted in the left (i.e. DI values less than 1, towards humid conditions) (see Fig A4 a-i in the appendix). However, 2 of the water towers (i.e. Mt Meru and Bale mountains) plotted more towards the right (i.e. DI values greater than 1). Mt Meru seems to have shifted from warmer to humid conditions in the period of 2011-2019 as shown in Fig A4.

4. Discussion

The sensitivity analysis revealed differences brought about by climate changes and land-use changes on water yield within and outside the water towers. Within the water towers, water yield was more sensitive to climate changes compared to land-use changes. Outside the water towers, the water yield was observed to be more sensitive to land-use changes than climate changes. This study, therefore, suggests that the direct anthropogenic influences have a stronger impact outside the water towers. However, the Budyko metrics analysis revealed vertical deviations (d) from the Budyko curve. According to Creed et al. (2014), these deviations indicate the presence of anthropogenic effects within the water towers. In some of the water towers such as Mt Elgon and Imatong mountains, no vertical deviations were observed indicating that the changes in the two water towers can majorly be associated with naturally occurring oscillations.

https://doi.org/10.5194/hess-2021-151
Preprint. Discussion started: 29 March 2021

Hydrology and Earth System Sciences
Discussions
Open Access
EGU

Lower elasticity values were also observed in most of the water towers. Low elasticity indicates broad ranges in the evaporative indexes (EI) compared to Dryness indexes (DI) which further proves the presence of anthropogenic influence within the water towers. According to Creed et al. (2014), elasticity can be used as a measure of resilience. Elastic catchments are expected to plot along the Budyko curve (i.e. resilient to climate changes) while inelastic catchments (non-resilience to climate changes) would deviate from the Budyko curve.

The horizontal shifts of the water towers either to the left or to the right relative to dryness index (DI) is an important indicator of the behavior of the water towers towards warmer conditions 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. This includes Mt Meru which shifted from warmer conditions observed in 1991-2000 and 2001-2010 to humid conditions in the years of 2011-2019.

A gradual increase in PET was observed in all the water towers. This indicates that the atmospheric demand is rising, an important signal of temperature increases in the East-African region. The effects of increasing temperature 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. (2015), the temperature in Africa is projected to rise faster than the rest 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. The mountainous forest ecosystems 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.

The simulated evapotranspiration (ETa) 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, the higher mean annual water yield was observed in 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. The extreme opposite trends observed in water yields from the different water towers confirm a strong variation in the climatic patterns. For instance, while there was a consistent increase in annual mean water yield in Mt Elgon, the opposite was true in Mt Kilimanjaro where a steady decline in water yield was observed.

The Budyko framework is a suitable approach for analyzing the partitioning of rainfall into precipitation and water yield. The framework gives the possibility for analyzing the combined effects or separating the effects of climate and land-use changes on water yield. In this study, the spatial pattern of the simulated streamflow in the Budyko framework closely resembles the pattern observed in the GRDC composite runoff. The Kling-Gupta efficiency test revealed positive values, KGE=0.33 which are seen as “good" model performance (Knoben et al., 2019). Therefore, the Budyko simulations in this study were considered 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 data and parameters that are easily measurable at a regional scale makes it a suitable approach for regions such as East Africa where there is a gap in the availability of detailed and quality local climatic data.

The major reference period for this study was the 1981-1990 period based on the CHIRPs rainfall with precipitation data beginning 1981 onwards. Further research using a reference period earlier than 1981 would help to strengthen the findings of this study especially after the evidence of shifts towards wetter conditions in all the water towers. Further studies on human-water interactions are also recommended to understand in detail the dynamics and co-evolution of coupled human-water systems.

https://doi.org/10.5194/hess-2021-151
Preprint. Discussion started: 29 March 2021

Hydrology and Earth System Sciences
Discussions
Open Access
EGU

5. Conclusions

Climate changes (i.e. changes in precipitation and potential evapotranspiration) have a relatively large effect on water yield within the East African water towers. The effects of land-use changes on water yield are larger in the adjacent regions surrounding the water towers. The majority of East-African water towers are under pressure from human influences both within and outside the water towers. Generally, the patterns in water yield showed a strong longitudinal difference (East to West), though the elevation is a key factor that ensures the generation of water in the water towers located in drier environments. A hydroclimatic phenomenon is occurring in the East-African region as the water towers show a strong shift towards wetter conditions (especially in the period of 2011-2019) while at the same time, the atmospheric demand is gradually increasing. Given that ~~majority~~ of the water towers were identified as non-resilient to changes, it means there are greater possibilities of extreme variations in water yield under changing climatic conditions. The Budyko framework provides a suitable approach especially for regions that lack detailed and quality data.

6. Appendices

A. Extended Figures and Tables

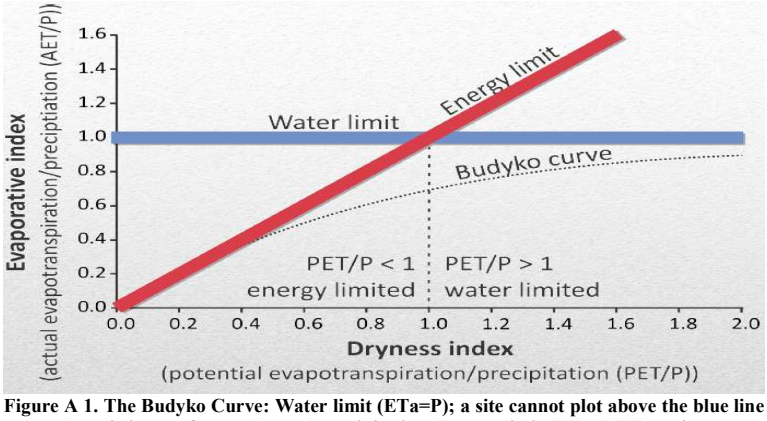


Figure A 1. The Budyko Curve: Water limit (ETa=P); a site cannot plot above the blue line unless there is input of water beyond precipitation. Energy limit (ETa=PET); a site cannot plot above the red line unless precipitation is being lost from system by means other than discharge (adapted from Creed and Spargo, 2012a).

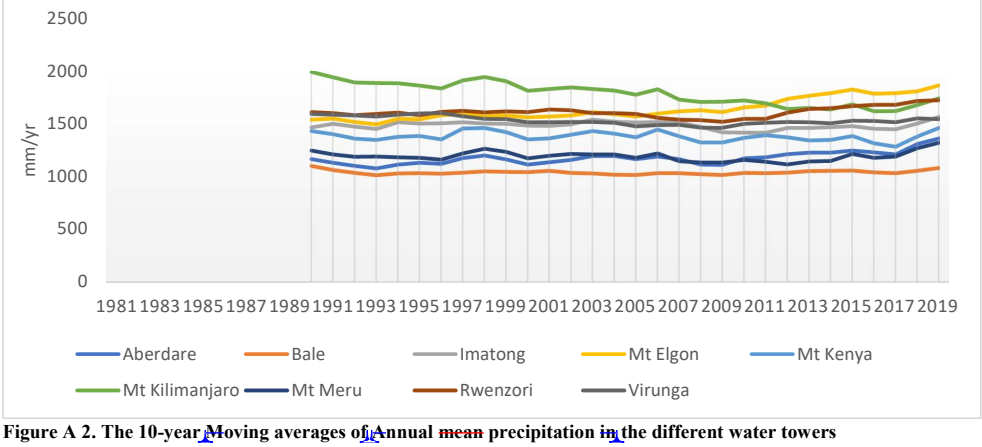


Figure A 2. The 10-year ~~M~~moving averages of ~~A~~annual ~~mean~~ precipitation ~~in~~ the different water towers

Higher levels of annual precipitation were observed in 1990-1992, 1998-1999, and 2013-2015. Lower levels of annual precipitation were observed in 1987, 1995-1996, 2004-2005, and 2017. Mt Kilimanjaro was observed to have a consistent decline in annual mean rainfall between 1981 and 2017. Mt Elgon water tower recorded a consistent increase in annual mean rainfall during the study period.

https://doi.org/10.5194/hess-2021-151
Preprint. Discussion started: 29 March 2021

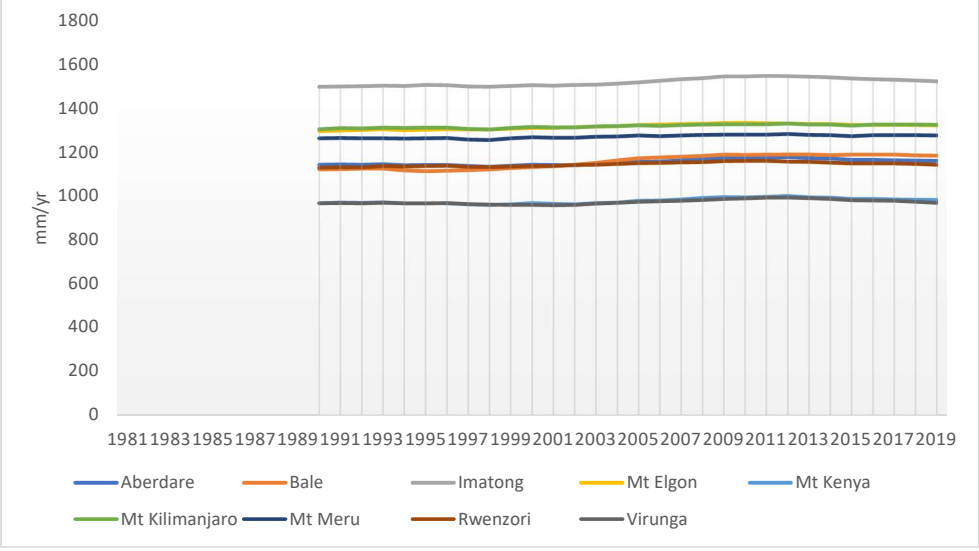


Figure A 3. The 10-year ~~M~~oving averages of ~~Annual~~ mean PET ~~in~~ the different water towers

https://doi.org/10.5194/hess-2021-151
Preprint. Discussion started: 29 March 2021

Hydrology and Earth System Sciences
Discussions
Open Access
EGU

Table A 1. Summary of simulated evapotranspiration (ET) and water yield (Q) given the precipitation (P) between 1981 and 2019

Mountain Ecosystems	PE	FSC	A	1981-1990					1991-2000					2001-2010					2011-2019				
				P	ET	Q	Q	RR	P	ET	Q	Q	RR	P	ET	Q	Q	RR	P	ET	Q	Q	RR
Units	m	m	km^2	mm/yr			FR	%	mm/yr			FR	%	mm/yr			FR	%	mm/yr			FR	%
Mt Kilimanjaro	5,895	2000	1513.0	1989.1	1056.3	919.1	0.029	46	1811.2	1019.2	779.3	0.025	43	1720.7	980.7	727.9	0.023	42	1751.4	991.4	748.0	0.024	43
Mt Kenya	5,199	2000	3298.3	1429.0	867.5	551.5	0.017	39	1350.5	828.5	512.7	0.016	38	1365.0	861.7	494.6	0.016	36	1466.4	884.0	573.7	0.018	39
Mt Elgon	4,321	2000	2548.0	1538.4	1051.3	480.8	0.015	31	1560.0	1068.7	483.6	0.015	31	1653.8	1110.2	535.5	0.017	32	1856.9	1159.5	686.9	0.022	37
Aberdare Ranges	3,999	2100	6671.8	1161.0	804.3	353.0	0.011	30	1110.2	772.1	335.2	0.011	30	1169.3	804.7	360.9	0.011	31	1352.8	869.7	479.1	0.015	35
Rwenzori Mountains	5,109	2000	1465.0	1609.5	934.1	653.6	0.021	41	1610.1	931.1	656.1	0.021	41	1546.0	944.7	580.4	0.018	38	1705.7	970.2	710.0	0.023	42
Mt Meru	4,565	2000	225.5	1244.4	898.2	330.6	0.010	27	1171.1	866.2	290.2	0.009	25	1156.1	803.7	338.0	0.011	29	1340.6	894.8	427.2	0.014	32
Virunga Mountains	4,507	2000	5288.2	1591.8	847.6	737.1	0.023	46	1512.4	833.5	672.0	0.021	44	1498.2	861.4	629.0	0.020	42	1523.9	850.0	666.8	0.021	44
Bale Mountains	4,337	2600	5030.7	1099.4	755.3	343.3	0.011	31	1040.5	741.9	299.7	0.010	29	1034.4	755.2	279.6	0.009	27	1071.3	733.5	338.4	0.011	32
Imatong Mountains	3,187	2000	396.7	1464.9	1084.4	369.2	0.012	25	1482.5	1102.1	368.8	0.012	25	1416.7	1097.1	305.7	0.010	22	1576.6	1145.6	416.8	0.013	26

Note:
P = precipitation
ET = actual evapotranspiration
Q = water yield
RR = Runoff Ratio
m = meters
km^2 = square Kilometers
FR = Flow rate in m^3/s per km^2
PE = Peak Elevation
FSC = Foot slope contour
A = Area

https://doi.org/10.5194/hess-2021-151
Preprint. Discussion started: 29 March 2021

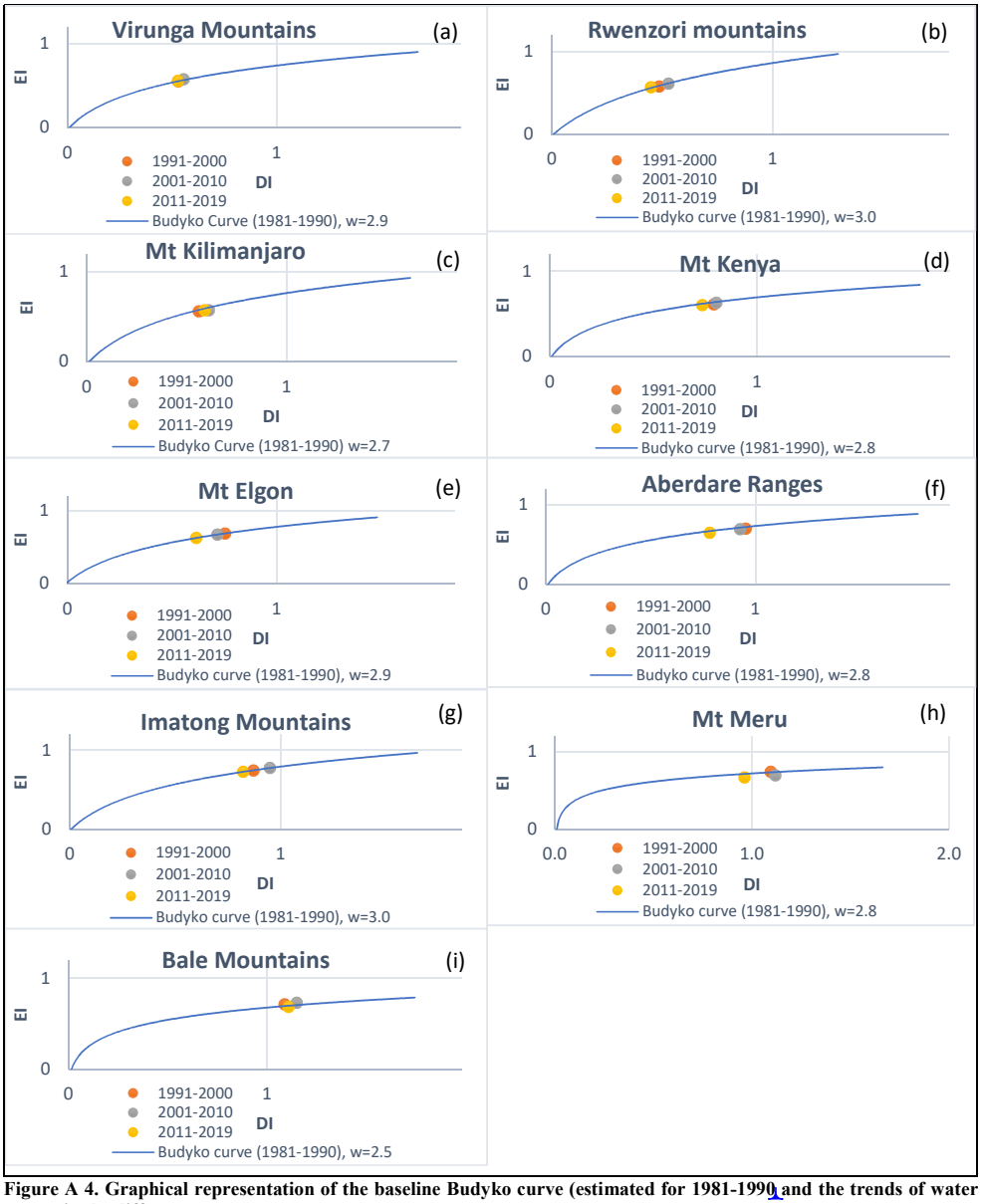


Figure A 4. Graphical representation of the baseline Budyko curve (estimated for 1981-1990) and the trends of water towers in the different years

https://doi.org/10.5194/hess-2021-151
Preprint. Discussion started: 29 March 2021

Hydrology and Earth System Sciences
Discussions

7. Data availability

All climatic data used in this study (i.e. (P, PET, and NDVI) are publicly available. Precipitation data (P) was downloaded from Climate Hazards Group Infrared Precipitation with Stations (CHIRPS-v2) https://www.chc.ucsb.edu/data/chirps (last accessed 31 July 2020). Potential Evapotranspiration (PET) data was downloaded from the CRU database https://crudata.uea.ac.uk/cru/data/hrg/ (last accessed 22 July 2020). Normalized Difference Vegetation Index (NDVI) was sourced from 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 https://ecocast.arc.nasa.gov/data/pub/gimms/3g.v1/ (last accessed 12 July 2020). The water towers analyzed data sets are summarized in Table A1 for each water tower and the full analysis is available in the SESAM project SharePoint. The data can be provided upon request from the 1st author (charles.wamucii@wur.nl).

8. Author contributions

CNW and AJT designed the study. CNW performed the analysis and wrote the manuscript. All authors helped with the interpretation of the results and commented on the manuscript.

9. Competing interests

The authors declare that they have no conflict of interest.

10. Acknowledgments

This research was made possible by Wageningen University through the Scenario Evaluation for Sustainable Agro-forestry Management (SESAM) project that was funded by its Interdisciplinary Research and Education Fund (INREF).

11. References

Budyko, M. I.: Climate and Life., 1974.

Creed, I. and Spargo, A.: Application of the Budyko curve to explore sustainability of water yields from headwater catchments under changing environmental conditions, in Ecological Society of America, August 5-10, 2012. Portland. [online] Available from: http://www.uwo.ca/biology/faculty/creed/PDFs/presentations/APRE47.pdf, 2012a.

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, 2012b.

Creed, I., Spargo, A., Jones, J., Buttle, J., Adams, M., Beall, F. D., Booth, E. G., Campbell, J. L., Clow, D., Elder, K., Green, M. B., Grimm, N. B., Miniat, C., Ramlal, P., Saha, A., Sebestyen, S., Spittlehouse, D., Sterling, S., Williams, M. W., Winkler, R. and Yao, H.: Changing forest water yields in response to climate warming: Results from long-term experimental watershed sites across North America, Glob. Chang. Biol., 20(10), 3191–3208, doi:10.1111/gcb.12615, 2014.

Daron, J. D.: Regional Climate Messages for East Africa, Cariaa Assar, 1–30, 2014.

Dewi, S., Van Noordwijk, M., Zulkarnain, M. T., Dwiputra, A., Hyman, G., Prabhu, R., Gitz, V. and Nasi, R.: Tropical forest-transition landscapes: a portfolio for studying people, tree crops and agro-ecological change in context, Int. J. Biodivers. Sci. Ecosyst. Serv. Manag., 13(1), 312–329, doi:10.1080/21513732.2017.1360394, 2017.

Dey, P. and Mishra, A.: Separating the impacts of climate change and human activities on streamflow: A review of methodologies and critical assumptions, J. Hydrol., 548, 278–290, doi:10.1016/j.jhydrol.2017.03.014, 2017.

Donohue, R. J., Roderick, M. L. and McVicar, T. R.: On the importance of including vegetation dynamics in Budyko's hydrological model, Hydrol. Earth Syst. Sci., 11(2), 983–995, doi:10.5194/hess-11-983-2007, 2007.

EAC, UNEP and GRID-Arendal: Sustainable Mountain Development in East Africa in a Changing Climate, East African Community, United Nations Environment Programme and GRID-Arendal. Arusha, Nairobi and Arendal. [online] Available from: https://www.grida.no/publications/119, 2016.

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,

https://doi.org/10.5194/hess-2021-151
Preprint. Discussion started: 29 March 2021

doi:10.1029/1999gb001254, 2002.

Gebrehiwot, S. G., Gärdenäs, A. I., Bewket, W., Seibert, J., Ilstedt, U. and Bishop, K.: The long-term hydrology of East Africa's water tower: Statistical change detection in the watersheds of the Abbay Basin, Reg. Environ. Chang., 14(1), 321–331, doi:10.1007/s10113-013-0491-x, 2014.

Guzha, A. C., Rufino, M. C., Okoth, S., Jacobs, S. and Nóbrega, R. L. B.: Impacts of land use and land cover change on surface runoff, discharge and low flows: Evidence from East Africa, J. Hydrol. Reg. Stud., 15(December 2017), 49–67, doi:10.1016/j.ejrh.2017.11.005, 2018.

Immerzeel, W. W., Van Beek, L. P. H. and Bierkens, M. F. P.: Climate change will affect the asian water towers, Science (80-.)., doi:10.1126/science.1183188, 2010.

Immerzeel, W. W., Lutz, A. F., Andrade, M., Bahl, A., Biemans, H., Bolch, T., Hyde, S., Brumby, S., Davies, B. J., Elmore, A. C., Emmer, A., Feng, M., Fernández, A., Haritashya, U., Kargel, J. S., Koppes, M., Kraaijenbrink, P. D. A., Kulkarni, A. V., Mayewski, P. A., Nepal, S., Pacheco, P., Painter, T. H., Pellicciotti, F., Rajaram, H., Rupper, S., Sinisalo, A., Shrestha, A. B., Viviroli, D., Wada, Y., Xiao, C., Yao, T. and Baillie, J. E. M.: Importance and vulnerability of the world's water towers, Nature, 577(7790), 364–369, doi:10.1038/s41586-019-1822-y, 2020.

Jacobs, S. R., Timbe, E., Weeser, B., Rufino, M. C., Butterbach-Bahl, K. and Breuer, L.: Assessment of hydrological pathways in East African montane catchments under different land use, Hydrol. Earth Syst. Sci., 22(9), 4981–5000, doi:10.5194/hess-22-4981-2018, 2018.

Jiang, C., Xiong, L., Wang, D., Liu, P., Guo, S. and Xu, C. Y.: Separating the impacts of climate change and human activities on runoff using the Budyko-type equations with time-varying parameters, J. Hydrol., doi:10.1016/j.jhydrol.2014.12.060, 2015.

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.

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.

Li, D., Pan, M., Cong, Z., Zhang, L. and Wood, E.: Vegetation control on water and energy balance within the Budyko framework, Water Resour. Res., 49(2), 969–976, doi:10.1002/wrcr.20107, 2013.

Muthoni, F. K., Odongo, V. O., Ochieng, J., Mugalavai, E. M., Mourice, S. K., Hoesche-Zeledon, I., Mwila, M. and Bekunda, M.: Long-term spatial-temporal trends and variability of rainfall over Eastern and Southern Africa, Theor. Appl. Climatol., 137(3–4), 1869–1882, doi:10.1007/s00704-018-2712-1, 2019.

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, Clim. Chang. 2014 Impacts, Adapt. Vulnerability Part B Reg. Asp. Work. Gr. II Contrib. to Fifth Assess. Rep. Intergov. Panel Clim. Chang., 1199–1266, doi:10.1017/CBO9781107415386.002, 2015.

Nicholson, S. E.: Climate and climatic variability of rainfall over eastern Africa, Rev. Geophys., 55(3), 590–635, doi:10.1002/2016RG000544, 2017.

Redhead, J. W., Stratford, C., Sharps, K., Jones, L., Ziv, G., Clarke, D., Oliver, T. H. and Bullock, J. M.: Empirical validation of the InVEST water yield ecosystem service model at a national scale, Sci. Total Environ., 569–570, 1418–1426, doi:10.1016/j.scitotenv.2016.06.227, 2016.

Roderick, M. L. and Farquhar, G. D.: A simple framework for relating variations in runoff to variations in climatic conditions and catchment properties, Water Resour. Res., 47(6), 1–11, doi:10.1029/2010WR009826, 2011.

Teuling, A. J. and Hoek van Dijke, A. J.: Forest age and water yield, Nature, 578(7794), E16–E18, doi:10.1038/s41586-020-1941-5, 2020.

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.

UNEP: Africa Mountains Atlas, United Nations Environment Programme (2014), available online:

https://doi.org/10.5194/hess-2021-151
Preprint. Discussion started: 29 March 2021

https://wedocs.unep.org/handle/20.500.11822/9301. [online] Available from: https://wedocs.unep.org/handle/20.500.11822/9301, 2014.

Viviroli, D. and Weingartner, R.: The hydrological significance of mountains: from regional to global scale, Hydrol. Earth Syst. Sci., 8(6), 1017–1030, doi:10.5194/hess-8-1017-2004, 2004.

Viviroli, D., Dürr, H. H., Messerli, B., Meybeck, M. and Weingartner, R.: Mountains of the world, water towers for humanity: Typology, mapping, and global significance, Water Resour. Res., 43(7), 1–13, doi:10.1029/2006WR005653, 2007.

WWF: Water towers of eastern Africa Policy, issues and vision for community-based protection and management of montane forests, WWF East. Africa Reg. Program. Off., (1/07), 54, 2005.

Xu, X., Liu, W., Scanlon, B. R., Zhang, L. and Pan, M.: Local and global factors controlling water-energy balances within the Budyko framework, Geophys. Res. Lett., 40(23), 6123–6129, doi:10.1002/2013GL058324, 2013.

Yang, D., Shao, W., Yeh, P. J. F., Yang, H., Kanae, S. and Oki, T.: Impact of vegetation coverage on regional water balance in the nonhumid regions of China, Water Resour. Res., 45(7), 1–13, doi:10.1029/2008WR006948, 2009.

Zhang, L., Dawes, W. R. and Walker, G. R.: Response of mean annual evapotranspiration to vegetation changes at catchment scale, Water Resour. Res., 37(3), 701–708, doi:10.1029/2000WR900325, 2001.

Zhang, L., Hickel, K., Dawes, W. R., Chiew, F. H. S., Western, A. W. and Briggs, P. R.: A rational function approach for estimating mean annual evapotranspiration, Water Resour. Res., 40(2), 1–14, doi:10.1029/2003WR002710, 2004.