Below Ice-Caps and Cloud Forests: Sustainable Water Management Practices Among the Chagga, MT Kilimanjaro Region, Tanzania

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Abstract

Mt Kilimanjaro has a unique ecology that include glaciers on its summit and a rainforest where numerous perennial and sub-perennial rivers and streams emanate. The Chagga people who cultivate the lower slopes of the mountain use this water to irrigate their home gardens (vihamba). This water supply is now under threat due to climate change and human encroachment of the rainforest. The glaciers on the mountain summit further add to variable water flows downslope. Using historical, ethnoarchaeological surveys, climate and other data, we demonstrate that these events reflect centuries-long developments encouraging the adoption by the Chagga of sustainable water management practices. Chagga settlement of Kilimanjaro coincides with the Little Ice Age (1300-1850), characterised in Africa by declining temperatures and cooling, reduced rainfall and severe droughts. Such climate and environmental change must have triggered the construction of irrigation furrows (mfongo) to direct regular water supplies to the vihamba and nduwa (mini dams) to regulate water flow. With over 2000 mfongo, the hillslopes of Mt Kilimanjaro were significantly modified to support a subsistence system that has remained largely unaltered for centuries.

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Introduction

Chagga settlement on the southern and western slopes of Mt Kilimanjaro (Figure 1) since the sixteenth centuries AD attests to human adaptation to a mountain ecosystem characterised primarily by water management practices supporting home gardens (vihamba) for agricultural production (Silayo & Pikirayi 2023) (Figure 2). In a context that increasingly witnessed high population densities, the Chagga must have employed sustainable water management strategies to secure long-term water supplies for the residents living on the lower mountain slopes. In the process, they identified threats to water availability and quality and adopted equitable strategies to respond to them (UNEP et al., 2016). According to Waite (2010), sustainable water management strategies require measures, technologies, and practices to ensure safe, reliable water supplies at an affordable cost. Such strategies focus on managing, preserving, and distributing available water amid multiple environmental factors to meet agricultural and household needs. In sub-Saharan Africa where high population densities in semi-arid to arid environments are also confronted by climate change, such strategies are vital in sustaining humans, since this entails balancing the use and supply of water, where the quantity utilised is equivalent to or less than the amount feeding the source or catchment. It would appear that the Chagga practised sustainable water management to ensure continued success of the vihamba. A compelling factor was ensuring that sufficient water was captured from rivers emanating from the rainforest and channeled to the vihamba. Although the Chagga were involved in regional trade with neighbouring polities, including the slave trade during the nineteenth century, there is no evidence of conflict over water resources. According to oral history, it was unthinkable for Chagga warriors, and for any other Chagga in that matter, to destroy water infrastructure even during a war. Mfongo would cross several villages undisrupted (Silayo 2017, Silayo & Pikirayi 2023).

Figure 1.

Figure 2.

Archaeology, history, ethnography and hydrological studies attest to centuries of intensive cultivation on the terraced hillslopes of Kilimanjaro, irrigated by water supplied through mfongo (Kimaro et al., 2019; Masao 1974; Silayo 2017; Silayo & Pikirayi, 2023; Sunday 2015; Sutton 1994). Complex levels of socio-political and ritual organisation involved in the constructing such water infrastructures indicate the development of Chagga society over several centuries and an indication of water management and sustainability. Such water infrastructures have transformed the hillslopes of Kilimanjaro from a montane forest into a cultivation zone (Figure 3).

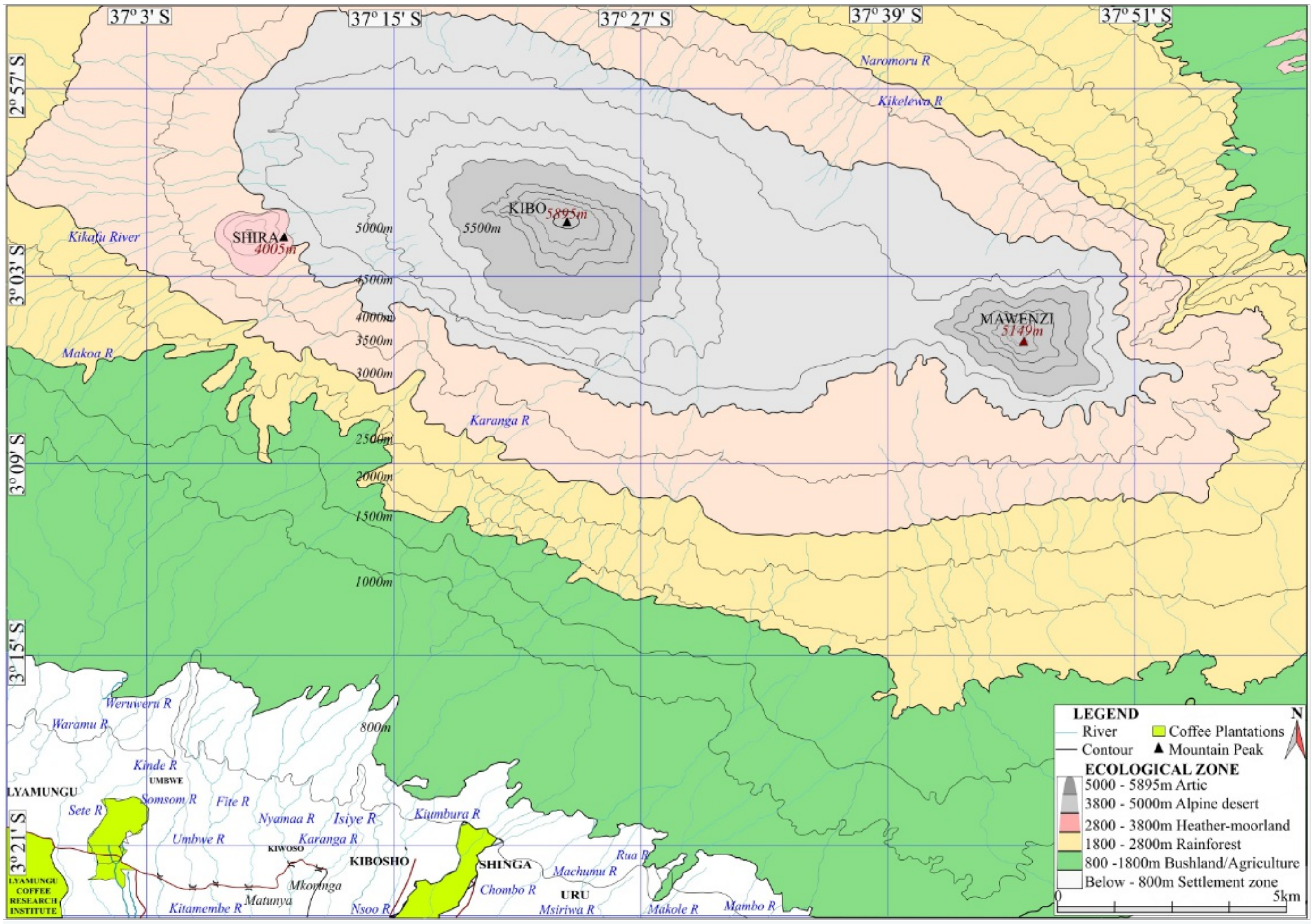

Figure 3.

The Chagga stopped building irrigation canals due to interference by early European settlers living in Moshi, on the foot of the mountain, as a measure to stem water diversion and thus channel more mountain water towards their farms (Grove, 1993). European settlers complained about that the increasing Chagga population resulted in the over-construction of mfongo, leading to increased water consumption in the vihamba, resulting in less water in European farms. European settler society thus perceived sustainability in narrow terms, measured merely in terms of downstream impact and the needs for colonial farming. Oral history also attests that during the Chagga considered diverting or obstructing water infrastructure because Europeans wanted to monopolise the resource. On the contrary, the Chagga appear to have measured the same in terms of equitable distribution of and access to the resource. This would see Europeans perceiving the furrow irrigation systems of Kilimanjaro as "wasteful and in need of improvement" (Lein 2004, 155), ostensibly to control water use among the Chagga. However, the system has remained relatively intact and continues to play a vital role among indigenous people in crop and livestock farming and agroforestry (Lein, 2004). Evidently, with growing human settlements on the foothills of the mountain, water flows to either the vihamba or European farms became variable and reduced. While variable and low water flow is typically a seasonal phenomenon, it is an essential component of the flow regime in any river or stream (Smakhtin, 2021). Droughts aggravate such phenomenon. A further aggravating factor is human usage of water. In Kilimanjaro, water flow is affected by seasonal variation in rainfall, snowmelt, land use including water infrastructures, localised rock and soil conditions, stream gradient, etc. This excerpt from a scoping study on sustainable mountain development in East Africa motivates this paper:

> *"Mount Kilimanjaro is threatened by warming climate which has consequently led to melting its ice-caps. The ice fields atop Mt. Kilimanjaro have lost 80 per cent of their area during the last 100 years, and, despite persisting for over 10,000 years, the ice caps are likely to disappear in the coming decades…. Since 1976, fires instigated by a warming climate have degraded 13,000 ha of forest (mainly Erica Forest in the upper parts of Mount Kilimanjaro), which in turn has severely disturbed the water balance. This is particularly significant given that the forest belt functions as the main water catchment for the surrounding area. As a result of the receding ice cap and deforestation, several rivers are drying up, affecting the forests and farmland below. A stark example of this is the serious water shortage in the town of Moshi, located on the foothills of the mountain. It also threatens the livelihoods of the Chagga people, who depend on a steady river discharge for their irrigation systems. Water shortages are becoming increasingly common during the dry seasons, especially on the lower foothills…." (E.A.C., UNEP and GRID-Arendal 2016: 24)*

The 2020 long rain season in Kilimanjaro highlighted the ripple effects such developments have on the cultivation zone and beyond. These indicate climate and ecological change and anthropogenic impacts on the environment. Almost all the major rivers in Mt Kilimanjaro are overflooded, devastatingly impacting on communities in the lower plains. However, the floods did not affect traditional water infrastructures such as mfongo and nduwa. According to our ethnographic surveys, such a flooding episode has never been experienced during the last four decades or so. While this attests to significant developments synonymous with global warming, more research is needed to understand how the Chagga coped with such unusual weather phenomena. It is also evident that their water infrastructures were resilient enough to withstand such weather extremes, attesting to their ability to sustain vihamba for centuries. Studies on climate change and the changes within the mountain ecosystem, particularly the depletion of the montane forest and the melting glaciers (Cullen et al. 2006, 2013; Hemp 2006a, b, 2009, Thompson 2000; Thompson et al. 2002), also trigger questions on what conservation measures the Chagga adopted and are still using today, to cope with either reduced and variable water flows from the mountain. Rapid changes in the ecological zones further up the cultivation zone (Said et al. 2019, 2021) indicate significant hydrological changes that are already negatively impacting water supplies among the Chagga, posing a threat to vihamba and, ultimately, their livelihoods.

In this paper we contribute to ongoing discussion on sustainable water management practices among the Chagga using perspectives of deep time. We argue that due to climate change, the Kilimanjaro region has for centuries experienced variable water flows from the summit glaciers and rainforest to the lower slopes of the mountain. To cope with such variations, the Chagga employed water regulation practices, including the construction of water infrastructures to sustain their home gardens. Organised in six parts, this paper first highlights the variable water flow to the cultivation zone. A literature review and conceptual frame then presents the physiography of the Kilimanjaro region, broadly contextualized in mountain landscapes practicing steep-slope agriculture requiring sustainable water management to mitigate the impacts of climate change. The paper uses ethnography, history, archaeology and climate data to understand variable water flows to the cultivation zone over centuries of Chagga settlement in the mountain region. The results are presented in the fourth section. The discussion is framed in the context of sustainable water management strategies in the long durée. The conclusion highlights the importance of adopting deep-time perspectives to understand sustainability to enlist lessons from the past in which sustainable futures can be made to work.

Literature Review and Conceptual Frame

Mt Kilimanjaro, in northern Tanzania, is a stratovolcano occupying a region measuring approximately 100 kilometres long and 65 kilometres wide. It comprises five ecological zones: cultivation zone/hillslopes (800-1800m above sea level), montane forest (1800-2800m), heather-moorland (2800-4000m), alpine desert (4000-5000m) and arctic summit, over 5000m (Figure 4). The artic summit is dominated by several melting glaciers (see, e.g., Cullen et al. 2006, 2013; Hemp 2009; Thompson 2000; Thompson et al. 2002; Wilcockson 1956; William 2001). According to Hemp (2006a) and Lovett (1993) the mountain forest zones comprise a colline or hilly lowland; submontane, lower and middle montane forest; upper montane forest; and a subalpine forest. They define 'cloud forests' as forests of the middle, upper montane and subalpine zone based on fog water input and structure. There is also a significant difference between the main vegetation types viewed from the northern slopes of the mountain, which are dry, and the southern slopes, which are wet. This paper employs these terms in reference to the cloud forests while explicitly mentioning the rainforest in the lower-middle montane zone. With some areas of the cultivation zone straddled by what Hemp (2006a) and Lovett (1993) as identify as colline or hilly lowland from 1500 meters a.s.l., it is evident the Chagga have been extending the cultivation zone upslope towards the cloud forest.

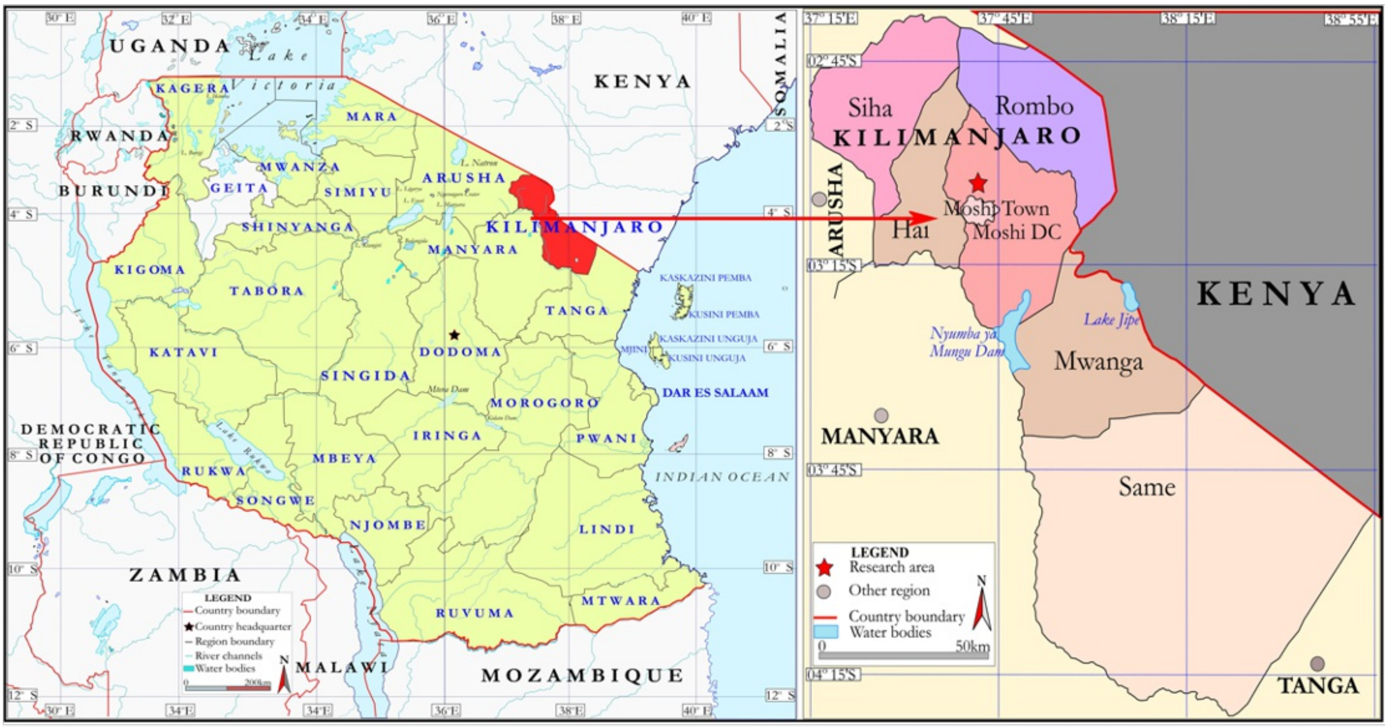

Figure 4.

The lower slopes of the Kilimanjaro region are endowed with cultural and natural resources, which have sustained human populations living there for over 2000 years (Lwoga and Maturo 2020, Schmidt 1989; Silayo 2017, Sunday 2015). The Chagga lived and still live on the hillslopes of Mt Kilimanjaro, where they cultivate maize, beans, millet, cassava, yams, potatoes, coffee and banana. Banana is their staple, and each Chagga homestead lies in the middle of a banana grove (Fernandes et al., 1985). The mountain is a vital Chagga livelihood, regulating every aspect of their lives, including water use, farming, and worldview. As the population increased such that the original settlement defined by vihamba could not support it, the shamba system was adopted (Chuhila, 2021). This entailed moving to the lower plains, which were usually disregarded and found unsuitable for settlement. These were marginal dry land full of tsetse fly and disease and of less value when compared to vihamba.

For centuries, the Chagga have been organized in different clans ruled by mangi (chiefs), who sometimes fought each other or formed alliances to leverage power (Silayo 2016). This history is remembered in oral accounts and is reflected in archaeology, which shows complex stone structures, underground fortifications, and water management structures (Bender 2013; Hunter 2009, Silayo 2017). Unfortunately, Chagga history is often overshadowed by research focusing mainly on biodiversity, ecology and climate change (e.g., Peters et al. 2019; Thompson 2000; Thompson et al. 2002). An understanding of human-environmental interactions in the region requires transdisciplinary approaches.

The Kilimanjaro region experiences a bimodal rainfall pattern characterised by long rains from March to June and short rains from November to December (Appelhans et al. 2015; Otte et al. 2017; Røhr and Killingtveit 2003). The rains feed many rivers and streams and regulate the climate patterns of the region as well as adjacent ecosystems such as Amboseli (Agrawala et al. 2003). The highly fertile southern slopes of the mountain host rivers and many streams such as Kikafu, Weruweru, Kikuletwa, Mue, Karanga, Rau and Wona (Figure 5), which for centuries have contributed to the livelihood of the Chagga and communities in the broader Pangani River basin and cathment (Deutch et al. 2017; Mckenzie et al. 2010; Mwende 2009; N.B.T. 2018; Ramsay 1965, Røhr and Killingtveit 2003; Sarmett and Faraji 1991; Silayo 2017, URT 2013). The lower plains are increasingly receiving less water than before, posing a considerable threat to human survival. This puts pressure on resources and accelerates environmental degradation (Byerlee et al.2024; Daluti 1994; Fisher et al. 2010; Foely et al. 2005; Mul 2009; Tagseth 2008, 2010; Bender 2016, 2019). In much of sub-Saharan Africa, increased resource use since early Holocene times resulted in ecosystem shifts from forest to savannah, signaling palaeoecological and climate change (Claussen et al. 2013).

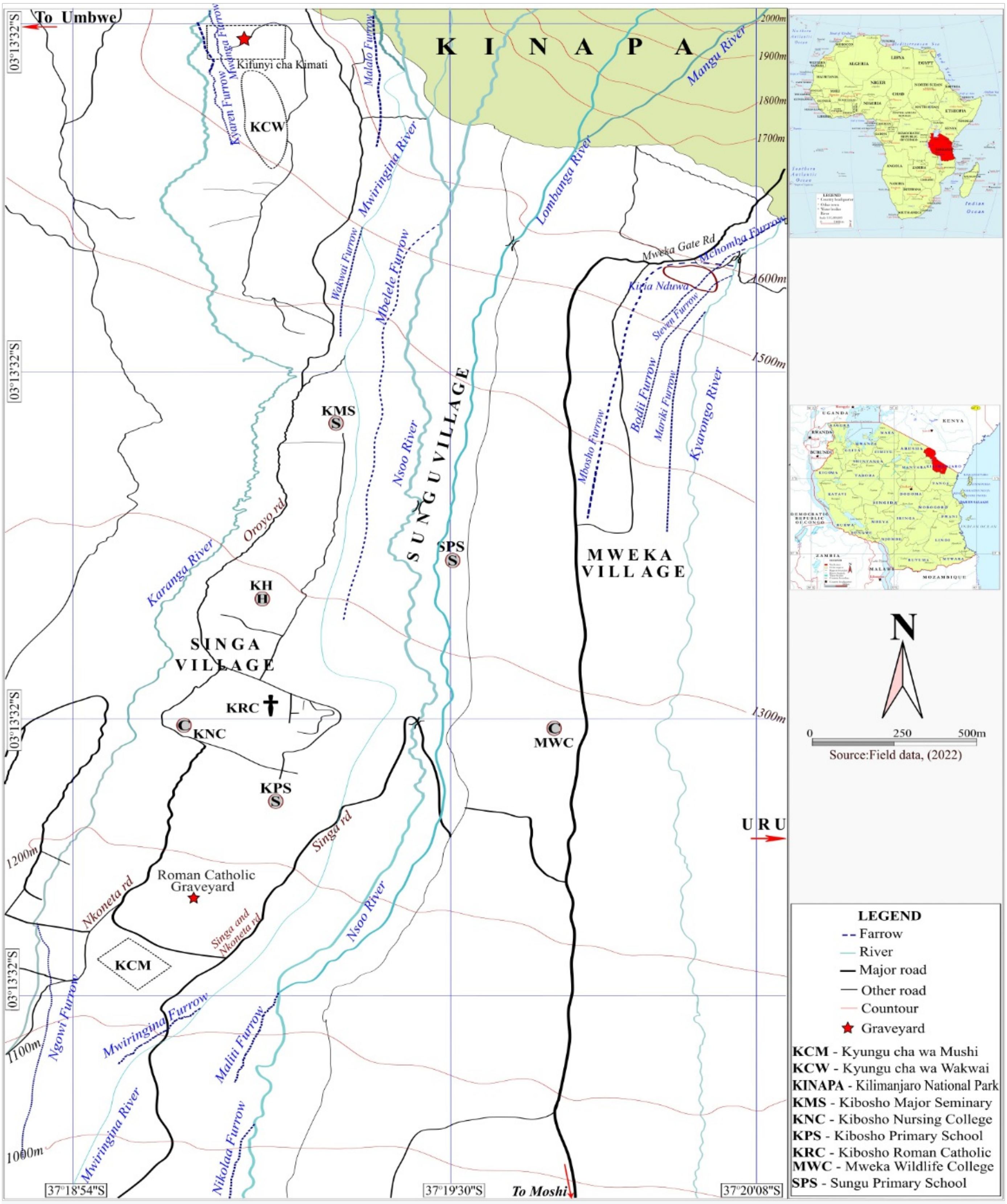

Figure 5.

This study is contextualised in mountain landscapes with steep slopes (see e.g., Borga et al. 2014; Drenkhan et al. 2022; Wang et al. 2022; Xing et al. 2008). Steep-slope agricultural landscapes require sustainable water management approaches to mitigate the impacts of climate change. According to Wang et al. (2022), episodes of high-intensity rainfall are increasingly becoming intense, triggering flash floods and slope failure. This represents a threat to agriculture. Further, there are indications of significant expansion of arid zones towards steep slope agricultural systems, negatively impacting agriculture due to increasing water scarcity (Morante-Carballo et al. 2022). This calls for sustainable water resource management to mitigate climate change-induced droughts (Muralikrishnan et al. 2022). In some steep-slope mountain zones, indigenous worldviews on water conservation and the roles these play in managing water resources, have been documented to understand human optimal resilience (see, e.g., Östberg 2014). Recently, the Kilimanjaro region has been experiencing a shortage of rainfall and the drying of rivers, triggering a decrease in staple crop yields and rising temperatures placing pressure on natural resources (Said et al. 2019). Such a scenario calls for assessing the impacts of climate change and anthropogenic influences in the region and their impact on sustainable biodiversity and the ecosystem.

Climate change discussions are relevant since mountains such as Kilimanjaro represent a microcosm of the earth's climate zones. The summit glaciers contribute to the hydrology of the mountain region (Adhikari et al., 2015; Cullen et al., 2006, 2013; Hemp 2005; Kaser et al. 2004; Mölg et al., 2008, 2014; Mote and Kaiser, 2007; Said et al. 2019; Thompson 2000). Thompson et al. (2002) 's projections regarding the disappearance of the summit glaciers point not only to regional and global climate change, but also imply a decrease in precipitation and water supply for residents living on the hillslopes. Although scholars have different opinions on the impact of climate change on the glaciers on Mt Kilimanjaro (see, e.g., Said et al. 2019), a notable or significant decrease in precipitation by the middle of the 21st century suggests there will be significant water shortages in the region, which will impact on agriculture and livestock production (Said et al. 2019). Other pointers to climate change impacts in the Kilimanjaro region are seen in decreased vegetation species composition during the past 100 years (Hemp 1999, 2005, 2006a, b). The causes for the changes are associated with decreased precipitation and increased anthropogenic impacts (Hemp 2005). Evidently, the mountain region is increasingly experiencing environmental pressures due to population increase (National Bureau of Statistics, 2018), the expansion of agriculture and overexploitation of the montane or cloud forest and other resources.

Drenkhan et al. (2022) show that mountain climate system changes impact the water security of downstream societies and the resilience of water-dependent ecosystems and their services. For the Chagga of Kilimanjaro, this involved an intricate interaction with water supply from the cloud forest, augmented by glacial meltwater. This is informed by trends towards more integrated social-ecological stidies of the wider catchment hydrology for the region. According to Drenkhan et al. (2022), this requires locally relevant knowledge-production strategies and integrating such knowledge within collaborative science–policy–community framework. It is believed this approach, combined with hydrological risk assessment, may support the development of robust, locally tailored and transformational adaptation strategies to ensure water security beyond mountain glaciers. Research by Said et al. (2021) on land cover changes on the water balance in the Kikafu-Weruweru-Karanga watershed area of Kilimanjaro identifies the expansion in cultivation land and built-up area as the primary attributes in changes in water yield, surface run-off, evapotranspiration, and groundwater flow. Improving the vegetation cover on the hillside and abandoned land area could help reduce direct surface run-off in the watershed (see Wang et al. 2022). Said et al. (2021) discovered that this area is experiencing recurring flooding and with the ongoing expansion in agricultural land and built-up areas, the study warns of profound, immediate negative impacts on the water balance of the watershed.

Forest fires are an increasing occurrence on the mountain and these consume much of the montane forest. According to Hemp (2009) cloud forests are essential in the hydrological functioning of watersheds in eastern Africa, especially the montane forests, which are heavily threatened by global change impacts. Satellite images for the period 1976-2000 focusing on vegetation plots show significant land-cover changes on the mountain, which may also have impacted on the water balance. Although glaciers on the mountain summit may be disappearing rapidly, the increase in frequency and intensity of fires on the slopes of Kilimanjaro, though less conspicuous, is perhaps ecologically far more significant. Fires have led to changes in species composition and structure of the forests and a downward shift in the upper forest line by several hundred meters. During the last century or more, the mountain has lost nearly a third (150 square kilometres) of forest cover due to both fire and clearance, causing a significant reduction in water yield (Hemp 2009).

Studies by Peters et al. (2019) on Kilimanjaro show how human land use affects tropical mountain ecosystems' biodiversity and ecological functionality. They demonstrate that land use leads to a significant loss of biodiversity and alters the ecosystem functions of tropical mountains. For Kilimanjaro, the intensity of such changes varies in different altitudinal zones, strongly correlated with the climatic context. Land use has severe detrimental consequences for the biodiversity and ecosystem functions of the cultivation zone on the foothills of Kilimanjaro. Therefore, protecting and promoting land use approaches that are sustainable and compatible with biodiversity is vital to preserving the diversity of species and nature-based ecosystem functions. A significant development is decreased precipitation and water in the mountain's lower slopes, which affects Chagga agriculture and food production. It is thus vital to understand how such developments took place over centuries, and how the Chagga interacted with such developments.

Methodology

The study used ethnographic data acquired through oral interviews, historical accounts and archaeological surveys to understand past and present water management practices among the Chagga. Climate and ecological data were consulted to understand variations in precipitation and water flows in the mountain over time, which also impacted on the Chagga.

Archival and published historical sources on water management practices among the Chagga (Dundas 1968; Håkansson et al. 2008; Masao 1974; Mitten 1886; Moore and Puritt 2017; Morison 1933; Oliver 1887; Pike 1965; Stahl 1964, 1965, Thomson 1887; von Clemm 1964) were consulted to understand flows regulation. The nineteenth century caravan trade (see, e.g., Alpers 1969, 1975) and conflict between various chiefdoms did not disrupt Chagga water infrastructure and supply. According to Groove (1993), such substantial infrastructure involves 1800 km of primary channels and an estimated throughput of 200 million m3 of water annually. The persistent assumption is that water resources and supplies from the montane zone, particularly the rainforest, have always been permanent. Rather, an important development in Chagga water infrastructures was the building of nduwa to regulate supply. Furrow management was a daily operation, with the elders responsible for directing and redirecting the water depending on the need and availability of the resource. This also included scheduling the times to release water to the fields, to the domestic animals to drink, and for household consumption. Clan or equivalent management of the water infrastructures ensured that these infrastructures were community-owned and traditions of such ownership were passed from generation to generation. The cooperative nature of the Chagga, according to Huxley (1956: 67), could be seen in the need to keep the "irrigation furrows in good order; to maintain maximum water flow; to repair the banks; and to regulate the use of the furrow"

We also used ethnographic data to collect details on water infrastructures (Silayo and Pikirayi 2023), which involved interviewing 90 informants between 2013 and 2019. These interviews completed the archaeological surveys conducted particularly in the Kibosho area of the mountain. In this paper, we attempt to establish the extent to which centuries-long construction of mfongo and reservoirs was also an attempt to regulate water supplies to the cultivation zone, to sustain vihamba.

Results

Oral interviews highlight Chagga reliance on irrigation watering their crops, which allowed them to cultivate their farms throughout the year. Quoting Mr Rafael from Sungu village in Mweka, Kibosho; "We took every possible measure to ensure a steady flow of water to our farms, including building nduwa (See Figure 3). According to Matthew Bender (2011: 191), "Most farmers cultivated the grain (finger millet) not in the rainy seasons, but rather in the dry season months using irrigation". Irrigation, coupled with the fertile Chagga land and good organisation from chiefs and their associates, made the country greener while increasing agricultural output. Charles New, who visited Kilimanjaro in 1871, reported the land of the Chagga as "extremely picturesque and beautiful; its productivity is extraordinary, and its climate is not only pleasant, but it is also perfectly salubrious... It is the Canaan of East Africa, for it may be said to flow with milk and honey" (New 1971[1873]).

Our ethnographic surveys also reveal that for Chagga, water supply represents "large-scale climatic patterns" and determines climatic development. Our informants stated that variation in water supply means a change in climate and seasons which also influences cultural and social life. To keep pace with the climate and seasonality, the Chagga had to pay attention to the direction and movements of the clouds. Oral histories contend that with the traditional knowledge of climate and seasons, the Chagga could tell when they would receive heavy rain and the direction of the shower (see, e.g., Tagseth 2010), and used this knowledge to prepare their farms promptly. Mfongo and nduwa bear testimony to centuries of water management, including catchment management practices designed to capture water upslope and supply vihamba efficiently. The Chagga regard water as one of the “gifts of the forest”, in addition to the many household and medicinal products, fuel wood, beekeeping, hunting, charcoal production and logging. Their knowledge of the seasons and climate, according to Blot (2006), is shaped by their immediate worldview.

According to the ethnography, the hillslopes of Mt Kilimanjaro region are undergoing massive landscape transformation through widespread, sustained deforestation, replanting of alien species for commercial farming and logging. Studies of the past two decades or so have also recorded the destruction of the montane forest mainly due to forest fires, with massive conservation repercussions forest ecology (Beck et al. 1983, Eva and Lambin 2000; Gamassa 1991; Gathaara et al. 1999). Our 2018 fieldwork observations suggest that despite the establishment of a national park to protect nearly 1700 square kilometres of the mountain ecosystem above the tree line (over 2700 m a.s.l.) in 1973, the move in 2005 to include the montane forest zone (over 1800 m) was as an attempt to conserve the broader mountain ecosystem in an already depleting forest. The rainforest is vital in stabilising the climate of the mountain. For residents living in the cultivation zone, it helps to maintain the water cycle by adding water into the atmosphere. Critically, they protect the cultivation zone against flooding, droughts, and erosion (e.g., Bjørndalen 1992).

Archaeological research points to fewer mfongo in Rombo district in northern Kilimanjaro, in comparison with other parts of the mountain. Our interview with Mr Tobias Milioni Mushi in August 2019 reveled that the Kibosho ward had more mfongo than any other area of Kilimanjaro due to the stability of the chiefdoms and the ability to keep their enemies at bay, allowing them ample time to engage in agriculture and the irrigation systems to run undisturbed. While from a physiographic viewpoint Rombo lies in a rain shadow area, receiving less rainfall and with few perennial rivers to support mfongo, it is also important to highlight that it was ruled by Mangi Horombo (1720-1802), who believed in military might at the expense of his own and other chiefdoms (Silayo, 2017).

Along several rivers or streams flowing from the arctic zone through the moorland to the alpine forest, we noticed substantial evidence of increased river or stream speed and, by extension, erosive power (Figure 6). This development may attest to summit glaciers melting, and increased water flow downslope. According to Joseph Mapima (pers.com, 18 December 2020), who assists climbers to the summit, this is an unusual development on the mountain, which now makes crossing some of the rivers extremely difficult due to enhanced vertical erosion. This is perhaps an indication of how the mountain region is experiencing climate change. This is critical in protecting the Chagga from droughts, ensuring that food production is stable (for Kenya, see Nicholson 1936). However, this is contradicted by the available rainfall data presented above. Using mfongo to channel water to the vihamba is a convenient resource management method. According to the ethnographic evidence, such furrows were owned and managed by various Chagga lineages, a practice which has now been replaced by villagisation. Continuing local control over mfongo ensures the survival of the central traditions governing their distribution and maintenance. All this speaks to sustainable management of a variable and increasingly scarce resource.

Discussion

Sustainability must always be understood in relative terms, as what is considered "sustainable" in one location may challenge sustainability elsewhere (Waite 2010). Sustainable water systems should provide adequate amounts of water to those in need without compromising the future ability to provide this capacity. Another point Waite (2010) makes and is relevant to the hillslopes of Kilimanjaro is that water systems in the realm of sustainable development may not literally include water use but systems where water use has traditionally been required. Sustainable ecosystem use is crucial. This goes beyond that of Peters et al. (2019) by examining human efforts towards protecting and promoting land use over a long period. This research places humans at the centre of biodiversity and ecosystem change and as critical agents in transforming the montane ecosystem and the cultivation zone. Studying the Kilimanjaro Mountain region is also about studying environmental and climate change and the broader changes these phenomena are triggering across the globe. This calls for forecasting future land use patterns, water availability, and possible climate change mitigation. There is need to develop adaptive strategies for responding to climate change and anthropogenic impacts on the hillslopes of Mt Kilimanjaro now and into the future.

For the Chagga to continuously sustain the vihamba system in a mountain region characterised by climate change, loss of montane forest, and the intense human footprint on the hillslopes, management of water has been vital, not only within recorded or remembered history but as far back as the earliest Chagga settlement in Kilimanjaro. Thus, sustainable water management in the cultivation meant coping with a changing climate, variable and increasingly below-average rainfall since the sixteenth or seventeenth centuries, droughts, and consequently reduced or low water flows from the rainforest. We contend that the construction of water infrastructures such as mfongo was in response to these developments to enhance direct access to water and sustain the vihamba. Such practices must consider climate change, water availability, land availability and usage, and population increase.

Climate data indicates a decrease in precipitation and water supplies in the cultivation zone in the lower slopes of the Mt Kilimanjaro region. While historical records confirm such a decrease from the 1850s, climate data also points to the same for 1350-1550 AD, which generally coincides with the inception of the Little Ice Age (1300-1850). In Africa, this climate episode is associated with declining temperatures, droughts, and desiccation (Nicholson and Yin 2001). Agrawala et al. (2003) highlight the contrasting climatic conditions experienced in equatorial East Africa since the early first millennium AD, starting with the Medieval Warm Period or Medieval Climate Anomaly (1000-1300 AD), followed by the Little Ice Age (1300-1850 AD). Data on Medieval Climatic Anomaly in eastern Africa is somewhat limited, especially in mountain regions such as Kilimanjaro (Lüning et al. 2017). However, the evidence from lakes Challa, Hausberg Tarn, Tanganyika and Turkana attests to warming during the time, though there was an earlier cold spell for Lake Turkana, and Mount Kenya experienced a warm phase between two significant periods of glacier activity dated 650–850 AD and 1350–1550 AD (Karlén et al. 1999). Studies on glacial retreats (see, e.g., Thompson et al. 2002, 2009, Mölg et al. 2009, Hastenrath and Kruss 1992), while not detailed on climate change during the second millennium AD, must be read in conjunction with other sources or records of climate change in the region.

Lake sediment records from western Uganda suggest regional variability of East African climate during the Little Ice Age. Severe droughts have been recorded in the western areas of the region, verging towards central Africa (Russel et al. 2007). However, a wet Little Ice Age has been recorded for Lake Naivasha (Russel and Johnson 2007). This variable nature of the climate attests to the solid regional nature of climate change, which must have had a bearing on the rainfall patterns on the African continent during the entire period. Verschuren et al. (2000) point to a drastic climatic dislocation during the last two decades of the nineteenth century, characterised by episodes of persistent aridity, reportedly more severe than any recorded drought since then. East Africa and the broader sub-Saharan region witnessed significant drops in lake levels due to reduced annual precipitation of as much as 150-200 mm in some places, e.g., Lake Victoria, and glacier recession due to enhanced solar radiation (see also Hastenrath 1984, 2001, Hastenrath and Kruss 1992, Hastenrath and Greischar 1997, Nicholson 2000, Nicholson and Yin 2001). The retreat of some glaciers on Mt Kenya and Mt Kilimanjaro during the last quarter of the nineteenth century is attributed to significant decreases in annual precipitation (Kruss 1983, Hastenrath and Kruss 1992).

The retreating glaciers on the summit and artic slopes of Mt Kilimanjaro are changing the landscape character of the mountain (see Altmann et al. 2002). This is also a phenomenon that is strongly linked to climate change. For discussion on these glaciers on Mt Kilimanjaro, the reader is referred to Hastenrath (1984), Hastenrath and Greischar (1997), Kaser (1999, 2001), Kaser et al. (1996, 2004), Thompson (2000), Thompson et al. (2002, 2009). For glaciers on Mt Kenya, please see Hastenrath and Kruss (1992), Karlen et al. (1999) and Kruss (1993). According to Kaser (1999), in the nineteenth century, they witnessed the rapid melting of glaciers and a significant increase in the number and intensity of wildfires on Mt. Kilimanjaro. Altmann et al. (2002) implicate enhanced anthropogenic influence.

Available rainfall data indicate decreased water supplies in the mountain's lower slopes since the 1880s. According to Agrawala et al. (2003), there has been a declining trend in precipitation in the Kilimanjaro region at least since 1880. A noticeable warming trend in the mountain region has also occurred since 1950. Amboseli's observations indicate a local warming rate of 0.275 °C per decade between 1976-2000, significantly higher than globally averaged warming. According to Altmann et al. (2002), proxy data reveals that annual precipitation decreased by 150 mm between 1880 and 1900. The daily rainfall records from the Lyamungu Coffee Research Institute in the sub-montane cultivated zone on the southern slope of Mt. Kilimanjaro show a decrease in precipitation since 1935 of about 2.6 mm/year. Extrapolating this figure back to the year 1900 means an annual loss of over 400 mm compared to pre-1880. Based on Hay et al. (2002), the rainfall records from the Lyamungu Coffee Research Institute are consistent with a general reduction in rainfall throughout most of Africa since 1950 (Nicholson 2000) and in the Kilimanjaro area for the periods 1941-1960 and 1971-1995. Data from the same station reveal that the number of dry months with less than 30 mm increased, whereas wet months with more than 125 mm were stable. Temperatures in the mountain region rose between 1951-1960, stabilised or decreased slightly between 1960-1981, and increased again between 1981-1995. Temperature records from 1976 from the Amboseli mountain region show dramatic increases throughout the same 25-year period (Altmann et al. 2002). So, what does this mean regarding water supplies to the cultivation zone, both in terms of the present and the past?

While the results confirm the variable climate of eastern Africa more broadly, they do not refer directly to the Kilimanjaro region. However, we treat these results as a proxy for the mountain. The climate data points to increased cooling during the past five centuries, more broadly synonymous with developments attributed to the Little Ice Age in eastern and southern Africa (Johnson et al. 2001). This also influenced rainfall patterns in these regions, although some regions may have received above-normal rainfall, albeit for limited phases. Documented observations since the middle of the nineteenth century for the Kilimanjaro region show decreasing trends in precipitation until the second half of the twentieth century, punctuated here and there by episodes of high rainfall. More broadly, the implications of such developments regarding water supply from the rainforest and the montane forest are enormous. If climate change data is considered, the Chagga must have experienced reduced or variable water volumes towards the vihamba for centuries. Coupled with a growing population, they may have felt some constraints around water management, including control, sharing and distribution (as attested by mfongo).

Chagga vihamba must have consumed considerable quantities from the cloud forest. These gardens are, in effect, irrigated lands, and the productivity of such land is often measured at approximately three times greater than that of rain-fed land (F.A.O., 2010), making irrigation an essential factor for sustainable agriculture systems. Archaeological survey of some vihamba allowed us to observe and re-think their physical and conceptual connection with the montane forest. These are an anthropogenic reformulation of the montane forest ecosystem, attested by how plants are spaced and how they are differentiated in terms of height to reflect the multiple levels of their growth (Blot 2006, Hemp 2006a, Hemp and Hemp 2009). This reformulation of the montane forest ecosystem takes place in the hillslopes of the mountain, where vihamba may have initially been connected to the water through fast-flowing streams, rivers and rivulets. This re-creation and replacement of the montane forest ecosystem was characterised by small-scale but intensive cultivation of crops, fertilized by cow manure. The banana grove was developed to become the ultimate forest among the Chagga. The construction of water infrastructures in the form of irrigational channels and reservoirs provided a regulated connection between montane forest and the homesteads, that elevated the Chagga to a level synonymous with the development of a complex agrarian system.

Ichinose et al. (2020) point out that cultivating different species and genotypes of crops is one of the strategies implemented by smallholder farmers to maintain their livelihood. In the Kilimanjaro highlands, the Chagga people run small-scale but intensive farming. The development of such an agrarian system was not static but evolved in response to other factors. The Chagga people altered their farmland management strategies by increasing banana and maize cultivation and decreasing coffee cultivation in their vihamba based on the significance of each crop within their livelihoods. Banana cultivation has assumed considerable importance among the Chagga because it is a source of income and staple food. Ichinose et al. (2020) suggest that maintaining diverse variants of bananas is one adaptation strategy that brings a stable food supply and income to Chagga. This also enables them to maintain their livelihood in the context of changing socio-economic conditions.

The increasing Chagga population must have accelerated food production in the Kilimanjaro region, which also increased the demand for water for irrigating vihamba (U.N. 2005). However, agriculture is also responsible for some surface and groundwater degradation due to run-off. According to Waite (2010), water has a dual role when assessed in the context of supply, which involves efficient usage for irrigation and protecting surface and groundwater resources. Chagga vihamba employs sustainable water supply techniques, including organic farming practices that ensure continued soil fertility, limited tillage, and limited water and soil contamination. Such practices were clearly inherited from the past and may date to the introduction of crops such as the banana in the mountain region.

Montane forests' depletion is the primary reason behind the changing climate patterns within and around the mountain. According to Bjørndalen (1992), these montane forests are vital water catchments, supplying water to populations living on the lower slopes. They are also vital towards the hydrological functioning of watersheds in sub-humid East Africa (Hemp 2009). A reduced forest canopy results in less cloud formation and, consequently, less rain and water. Such clouds are necessary for transporting moisture to the mountain's lower slopes. For how long the montane forest has been subjected to this requires further research. It would be safe to assume that the montane forest of Kilimanjaro was much more extensive than the present. It is also safe to assume that some of these declining water supply trends were triggered and enhanced by increased human settlement on the mountain slopes, now numbering more than two million people. All of these rely on the water from the montane or cloud forest. However, we do not know the consequences of the continued loss of the forest. Human impact around and inside some forest reserves is evident in the heavy population pressure surrounding them, leaving them "isolated, fragmented 'islands'" (Bjørndalen 1992). Hemp (2009) highlights the impact of fires in the montane forest, pointing out that climate change-induced fires have led to changes in species composition and structure of the forests and to a downward shift of the upper forest line by several hundred metres. Since the late 1930s, Mt Kilimanjaro has lost nearly a third of its forest cover in the upper areas due to fire and the lower forest border due to land clearance (Eva and Lambin 2000; Hemp 2009, Hemp 2006b; Hemp and Beck 2001).

Less discussed in terms of the water needs for the residents living in the cultivation zone are the melting glaciers on the artic summit and hillslopes. Some researchers believe these contribute only to a very small fraction of the water needs of the cultivation zone (see Cullen et al. 2006, 2013; Kaser et al. 2004). However, how this is measured negates groundwater and the impact of increasing snow melting. While original estimates by Thompson (2000) and Thompson et al. (2002) that the ice caps on Kilimanjaro would have disappeared by now, evidence of dry river beds, according to Altmann et al. (2002), is not necessarily an indicator of long-term climatic changes or shrinking glaciers, but rather, more likely the result of forest destruction or increasing water demands of the rapidly growing human population in the cultivation zone.

While the impact of the melting glaciers on the Chagga is still unknown, it is essential to pay attention to the potential consequences of increased water flow to the lower mountain slopes. The observations made by some of our informants regarding rapid stream flows and deep gullying are vital to the discussion here. According to the IPCC (2019), melting glaciers can affect river run-off and freshwater resources available to human communities close to the glacier and distant from mountain areas. Glaciers release water from long-term storage as they shrink in response to a warmer climate. Initially, glacier run-off increases due to the glacier melting faster and, thus, more water from the glacier downslope. This is referred to as 'peak water'. However, this glacier's run-off and contribution to stream and river flow downslope will decline after several years or decades. Peak water run-off from glaciers may increase the quantity of water downstream. For the Kilimanjaro region, given the increasing trend in the melting of glaciers, the melt adds to the water generated in the cloud forest, thus providing additional water for vihamba. If the mountain region has passed the peak water stage, this additional water will decrease with continued glacier shrinkage and retreat and projected disappearance. This implies that the Chagga and other downstream communities are losing additional water sources.

Given the equatorial location of Kilimanjaro, slight variations in seasonal air temperatures and alternating wet and dry seasons are the primary control of the amount and timing of glacier run-off throughout the year (e.g., IPCC 2019). With Kilimanjaro summit glaciers some 30-40 kilometres from the cultivation zone, meltwater run-off from the ice shrinkage is unlikely to cause flooding but is expected to be negligible. Thompson (2000) and Thompson et al. (2002) highlighted that if Kilimanjaro were to lose its glaciers, the repercussions on the Chagga in the cultivation zone would be immense. Give more than four centuries of Chagga settlement in Kilimanjaro, their clan histories require re-writing to understand how they have coped with the changing mountain ecosystems. Also, developments since 1850 significantly altered their circumstances, e.g., the shifting to the lowlands for agriculture and settlement as well as urban areas. Such an understanding should also highlight that the loss of Mount Kilimanjaro's forests is critical in triggering a water crisis as rivers dry up. Since 1976, climate change has destroyed 13,000 hectares of the mountain's forests. The mountain has witnessed increased incidences of wildfires and accelerated destruction of forests. This alters the mountain's precipitation and hydrology, resulting in villages and towns in the cultivation zone and beyond experiencing water losses. This requires more research.

Conclusion

Located in the context of indigenous populations in Africa using traditional irrigation systems (Adams 1989; Adams et al. 1988; Silayo 2017; Sunday 2015; Sutton 1994) and also in an environment dominated by steep slopes and mountain topography (see, e.g., Xing et al. 2008), the study contributes to a growing body of work on sustainability in relation to climate change (see, e.g., Drenkhan et al. 2022; Östberg 2014; Sulas and Pikirayi 2018; Waite 2010; Wang et al. 2022). Chagga's sustainable water supply involved integrated water resource management, including catchment management approaches, which pooled together multiple stakeholders, such as chiefs and village elders, furrow engineers and constructors, to determine how water should best be harvested, and conveyed to the rest of the population on the mountain slopes (Silayo and Pikirayi 2023). Such collective and integrated approaches must have prioritised not only Chagga's subsistence and other socio-economic needs but also the broader needs of the mountain ecosystem. Thus, centuries-long of Chagga indigenous knowledge, historical experiences of the mountain environment, and interactions with other groups must have generated sustainable approaches to water management in the Kilimanjaro region. Given the current threats of global warming and human encroachment to ecological zones in the mountain, such as the montane forest, it is now uncertain whether the Chagga will continue providing this capacity without compromising the present and the future. The impacts of emerging agricultural practices on groundwater quality in some catchments are now known (Lwimbo et al., 2019).

While there is a wide range of scholarly views regarding the impacts of climate change on the glaciers on Mt Kilimanjaro, the hydrological impacts remain poorly known. The impact of climate change and anthropogenic pressure on resources require more structured, historical data documenting what happened and predicting what is likely to occur in the future. Data on current and future land use/cover and change is also limited in the Kilimanjaro region. Also relevant are studies on fog water deposition for equatorial and tropical rainforests in eastern Africa. These forests serve as the water towers of rivers and streams, including those emanating from the mountains. Our review only highlights how climate and anthropogenic impacts may affect the ecosystem in the region. For a region with traditions of indigenous irrigation, there is need to develop adaptive strategies for responding to climate change and anthropogenic impacts on the hillslopes of some of eastern Africa's largest mountain systems, now and into the future.

Sustainable development of mountain communities, where human activity responds to the changing nature of mountain systems, is a crucial strategy for minimising the impacts of climate change, both in the mountains and in surrounding areas. The Chagga have achieved this for centuries by adapting their cultivation needs to the cloud forest and possibly beyond. This included constructing water infrastructures to control the water required for their home gardens and recreating the rainforest to conserve the original lower montane forest destroyed due to expansion and for agriculture and settlement. It is evident that mfongo, nduwa, and vihamba are resilient infrastructure to weather and climate extremes, adding towards protecting livelihoods and the broader mountain environment as sites of geological, ecological and cultural heritage. IPCC (2022) states that these interventions can help limit climate change impacts on sensitive mountains in Africa and elsewhere.

Statements and Declarations

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Scope Statement

Mt Kilimanjaro has a unique ecology, including the glaciers on its summit and a cloud, subsuming a rainforest where numerous perennial and sub-perennial rivers and streams emanate. The Chagga in the cultivation zone use this water to irrigate their home gardens (vihamba). This water supply is now under threat due to climate change and human encroachment into the rainforest. The summit glaciers further add to variable water flows downslope. Using historical, ethnoarchaeological surveys, climate and other data, we demonstrate that these events reflect centuries-long developments encouraging the Chagga adoption of sustainable water management practices. Chagga settlement in the lower slopes of Kilimanjaro coincides with the Little Ice Age (1300 -1850), characterised in Africa by declining temperatures and cooling, reduced rainfall and severe droughts. Such climate and environmental change must have triggered the construction of irrigation furrows (mfongo) to direct regular water supplies.

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Conflict of interest statement

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest

CRedIT Author Statement

- Innocent Pikirayi: Conceptualization, Data curation, Funding acquisition, Investigation, Methodology, Resources, Writing – original draft, Writing – review & editing. Valence
- Valerian Silayo: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Writing – review & editing.

Data availability statement

While some ethnographic data is unavailable due to privacy or ethical restrictions, the data used in this paper is archived with Figshare (https://figshare.com/) and is accessible upon request.

Ethics statements

Studies involving animal subjects

Generated Statement: No animal studies are presented in this manuscript.

Studies involving human subjects

Generated Statement: The studies involving humans were approved by Tumaini University Postgraduate Research Ethics Committee. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Inclusion of identifiable human data

Generated Statement: No potentially identifiable images or data are presented in this study.

References

- Adams, W. M. (1989). Definition and Development in African Indigenous Irrigation. Azania: Archaeological Research in Africa 24 (1): 21–27. https://doi.org/10.1080/00672708909511394
- Adams, W. M., and Anderson, D. M. (1988). Irrigation Before Development: Indigenous and Induced Change in Agricultural Water Management in East Africa. African Affairs 87 (349): 519–35. https://doi.org/10.1093
- Adhikari, U., Nejadhashemi, A. P., Herman, M. R. (2015). A review of climate change impacts on water resources in East Africa. Transactions of the ASABE 58 (6): 1493–1507. https://doi.org/10.13031trans.58.10907
- Agrawala, S., Moehner, A., Hemp, A., van Aalst, M., Hitz, S., Smith, J., Meena, H., Mwakifwamba, S. M., Hyera, T. and

Mwaipopo, O. U. (2003). Development and Climate Change in Tanzania: Focus on Mount Kilimanjaro. Environment Directorate Development Co-Operation Directorate. Working Party on Global and Structural Policies Working Party on Development Co-operation and Environment. Paris: Organisation for Economic Co-operation and Development.

- Alpers, E. A. (1969). "The coast and the development of the caravan trade". In Kimambo, I. N. and Temu, A. J. (eds). A History of Tanzania. Nairobi: East African Publishing House, 35– 56.
- Alpers, E. A. (1975). Ivory and Slaves in East Central Africa: Changing international trade patterns to the later nineteenth century. London: Heinemann.
- Altmann, J., Alberts, S. C., Altmann, S. A. and Roy, S. B. (2002). Dramatic change in local climate patterns in the Amboseli basin, Kenya. African Journal of Ecology 40: 248-251. https://doi.org/10.1046/j.1365-2028.2002.00366.x
- Appelhans, T., Mwangomo, E., Otte, I., Detsch, F., Nauss, T. and, Hemp, A. (2015). Eco- meteorological characteristics of the southern slopes of Kilimanjaro, Tanzania. International Journal of Climatology 36 (9): 3245–3258. https://doi.org/10.1002/joc.4552
- Beck, E., Scheibe, R. and Senser, M. (1983). The vegetation of the Shira plateau and the western slopes of Kibo (Mount Kilimanjaro, Tanzania). Phytocoenologia 11: 1-30. https://doi.org/10.1127/phyto/11/1983/1
- Bender, M. V. (2013). Being 'Chagga': Natural resources, political activism, and identity on Kilimanjaro. The Journal of African History 54, (2): 199–220. https://doi.org/10.1017/S0021853713000273
- Bender, M. V. (2016). "Do not Imagine that Every Cloud Will Bring Rain: A history of irrigation on Kilimanjaro, Tanzania," In Tvedt, Terje., Oestigaard, Terje (eds), A History of Water Series 3, vol. 3, Water and Food: From Hunter-Gatherers to Global Production in Africa. London: I. B. Tauris, 185-209.
- Bender, M. V. (2019). Water Brings No Harm: Management knowledge and the struggle for the waters of Kilimanjaro. Athens: Ohio University Press.
- Bjørndalen, J. E. (1992). Tanzania's vanishing rain forests — assessment of nature conservation values, biodiversity and importance for water catchment. Agriculture, Ecosystems and Environment 40 (1-4): 313-334. https://doi.org/10.1016/0167-8809(92)90100-P
- Blot, J. (2006). "Development of plant ground cover, ecological factors". In Bart, F., Mbonile, J. and Devenne, F. (eds). Kilimanjaro: Mountain, memory, modernity. Dar es Salaam: Mkuki na Nyota publishers.
- Borga, M., Stoffel, M., Marchi, L., Marra, F. and Jakob, M. 2014. Hydrogeomorphic response to extreme rainfall in headwater systems: Flash floods and debris flows. Journal of Hydrology 518 (Part B): 194-205. https://doi.org/10.1016/j.jhydrol.2014.05.022
- Byerlee, D., Stevenson, J. and Villoria, N. (2014). Does intensification slow cropland expansion or encourage deforestation? Global Food Security 3 (2): 92–98. https://doi.org/10.1016/j.gfs.2014.04.001
- Chuhila, M. (2021). Socio-economic and cultural practices of land tenure systems on the slopes of Mt. Kilimanjaro, Tanzania from 1920–1950s. Journal of the Geographical Association of Tanzania 41 (1): 97–115.
- Claussen, M., Bathiany, S., Brokvin, V., Kleinen, T. (2013). Simulated climate-vegetation interaction in semi-arid regions affected by plant diversity. Nature Geoscience. Band 6 (11): S. 954–958. https://doi.org/10.1038/ngeo1962
- Cullen, N. J., Mölg, T., Kaser, G., Hussein, K., Steffen, K. and Hardy, D. R. (2006). Kilimanjaro Glaciers: Recent areal extent from satellite data and new interpretation of observed 20th-century retreat rates. Geophysical Research Letters

33: L16502. https://doi.org/10.1029/2006GL027084

- Cullen, N. J., Sirguey, P., Mölg, T., Kaser, G., Winkler, M. and Fitzsimons, S. J. (2013). A century of ice retreat on Kilimanjaro: The mapping reloaded. The Cryosphere 7 (2): 419-443. https://tc.copernicus.org/articles/7/419/2013
- Daluti, L. R. (1994). Report on the Agro-socio-economic Situation in Pangani River Catchment. Moshi: United Republic of Tanzania-Zonal Irrigation Office.
- Detsch, F., Otte, I., Appelhans, T. and Nauss, T. (2017). A glimpse at short-term controls of evapotranspiration along the southern slopes of Kilimanjaro. Environmental Monitoring and Assessment 189, Article number 465. https://doi.org/10.1007/s10661-017-6179-9
- Drenkhan, F., Buytaert, W., Mackay, J. D., Barrand, N. E., Hannah, D. M., and Huggel, C. (2022). Looking beyond glaciers to understand mountain water security. Nature Sustainability. https://doi.org/10.1038/s41893-022-00996-4
- Dundas, C. (1968). Kilimanjaro and Its People: A history of the Wachagga, their laws, customs and legends, together with some account of the highest mountain in Africa. London: Cass.
- E.A.C., UNEP and GRID-Arendal (2016). Sustainable Mountain Development in East Africa in a Changing Climate. Arusha, Nairobi and Arendal: East African Community, United Nations Environment Programme and GRID-Arendal.
- Eva, H. and Lambin, E. F. (2000). Fires and land-cover change in the tropics: A remote sensing analysis at the landscape scale. Journal of Biogeography 27: 765-776. https://doi.org/10.1046/j.1365-2699.2000.00441.x
- Fernandes, E. C., Oktingati, A. and Maghembe, J. (1985). The Chagga home gardens: a multistoried groforestry cropping system on Mt. Kilimanjaro (Northern Tanzania). Agroforestry Systems 2: 73–86. https://doi.org/10.1007/BF00131267
- Fisher, B., Kulindwa, K., Mwanyoka, I., Turner, R. K. and Burgess, N. D. (2010). Common pool resource management and P.E.S.: Lessons and constraints for water P.E.S. in Tanzania. Ecological Economics 69 (6): 1253-1261. https://doi.org/10.1016/j.ecolecon.2009.11.008
- Foley, J. A., Defries, R., Asner, G. P., Barford, C., Bonan. G., Carpenter, S. R., Chapin, F. S., Coe, M. T., Daily, G. C., Gibbs, H. K., Helkowski, J. H., Holloway, T., Howard, E. A., Kucharik, C. J., Monfreda, C., Patz, J. A., Prentice, I. C., Ramankutty, N. and Snyder, P. K. (2005). Global consequences of land use. Science 309 (5734): 570-574. https://doi.org/10.1126/science.1111772
- Gamassa, D. M. (1991). “Historical change in human population on Mount Kilimanjaro and its implications”. In Newmark, W. D. (ed.) The Conservation of Mount Kilimanjaro. The IUCN Tropical Forest Programme, 1-8. https://portals.iucn.org/library/sites/library/files/documents/FR-TF-017.pdf (Accessed 04 February 2023)
- Gathaara, G. N., Woodley, B and Lambrechts, C. (1999). Aerial survey of the destruction of Mt. Kenya, Imenti and Ngare Ndare Forest Reserve. Kenya Wildlife Service/Kenya Forestry Research Institute. Food and Agriculture Organisation of the United Nations. https://www.unep.org/resources/report/aerial-survey-destruction-mt-kenya-imenti-and-ngare-ndare-forests-reserves (Accessed 06 February 2023).
- Grove, A. (1993). Water Use by the Chagga on Kilimanjaro. African Affairs 92 (368): 431-448. http://www.jstor.org/stable/723292
- Håkansson, N., Widgren, M. and Börjeson, L. (2008). Introduction: Historical and regional perspectives on landscape transformations in north-eastern Tanzania, 1850-2000. The International Journal of African Historical Studies, 41 (3):

369-382.

- Hastenrath, S. (1984). The Glaciers of Equatorial East Africa. Dordrecht, Boston, Lancaster: D. Reidel Publishing Company.
- Hastenrath, S. (2001). Variations of East African Climate during the Past Two Centuries. Climatic Change 50, 209–217. https://doi.org/10.1023/A:1010678111442
- Hastenrath, S. and Greischar, L. (1997). Glacier recession on Kilimanjaro, East Africa, 1912-89. Journal of Glaciology 43: 455-459. https://doi.org/10.3189/S0022143000035048
- Hastenrath, S. and Kruss, P. D. (1992). The dramatic retreat of Mount Kenya's glaciers between 1963 and 1987: greenhouse forcing. Annals of Glaciology 16: 127-133. https://doi.org/10.3189/1992AoG16-1-127-133
- Hay, S. I., Cox. J., Rogers, D. J., Randolph, S. E., Stern, D. I., Shanks, G. D., Myers, M. F. and Snow, R. W. (2002). Climate change and the resurgence of malaria in the East African highlands. Nature 415 (6874): 905-9. https://doi.org/10.1038/415905a
- Hemp, A. (1999). An ethnobotanical study on Mt. Kilimanjaro. Ecotropica 5: 147-165
- Hemp, A. (2005). Climate change-driven forest fires marginalise the impact of ice cap wasting on Kilimanjaro. Global Change Biology 11 (7): 1013-1023. https://doi.org/10.1111/j.1365-2486.2005.00968.x
- Hemp, A. (2006a). Vegetation of Kilimanjaro: Hidden endemics and missing bamboo. African Journal of Ecology 44: 305–328. https://doi.org/10.1111/j.1365-2028.2006.00679.x
- Hemp, A. (2006b). “The impact of fire on diversity, structure and composition of the vegetation on Mt. Kilimanjaro”. In Spehn, E. M., Liberman, M., and Korner, C. (eds). Land Use Change and Mountain Biodiversity, 51-68. Boca Raton, FL: CRC Press.
- Hemp, A. (2009). Climate change and its impact on the forests of Kilimanjaro. African Journal of Ecology 47(s1): 3-10. https://doi.org/10.1111/j.1365-2028.2008.01043.x
- Hemp, A. and Beck, E. (2001). Erica excelsa as a fire-tolerating component of Mt. Kilimanjaro's forests. Phytocoenologia 31: 449-475.
- Hemp, A. and Hemp, C. (2009). “Environment and Worldview: The Chaga Homegardens. Part I: Ethnobotany and Ethnozoology”. In Clack, T. A. R. (eds). Landscapes of Inhabitation in the Mount Kilimanjaro Area, Tanzania Essays in honour of Paramount Chief Thomas Lenana Mlanga Marealle II (1915-2007). B.A.R. International Series 1966. Oxford: British Archaeological Reports, 235-271.
- Hunter, E. (2009). “In pursuit of the 'higher medievalism': Local history and politics in Kilimanjaro”. In Peterson, D.R., and Macola, G. (eds). Recasting the Past: History Writing and Political Work in Modern Africa. Athens: Ohio University Press, 149-167.
- Huxley, E. J. (1956). Race and Politics in Kenya: A Correspondence between Elspeth Huxley and Margery Perham (with an introduction by John Lugard): London: Faber and Faber.
- Ichinose, Y., Higuchi, H., Kubo, R., Nishigaki, T., Kilasara, M., Shinjo, H. and Funakawa, S. (2020). Adaptation of farmland management strategies to maintain livelihood by the Chagga people in the Kilimanjaro highlands. Agricultural Systems 181, 102829. https://doi.org/10.1016/j.agsy.2020.102829
- IPCC, (2019). IPCC Special Report on the Ocean and Cryosphere in a Changing Climate [H.- O. Pörtner, D.C. Roberts,

V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría, M. Nicolai, A. Okem, J. Petzold, B. Rama, N.M. Weyer (eds.)]. Cambridge, UK and New York, NY, U.S.A.: Cambridge University Press. https://doi.org/10.1017/9781009157964.017

- IPCC, (2022). Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge, UK and New York, NY, U.S.A.: Cambridge University Press. https://doi.org/10.1017/9781009325844
- Johnson, T. C., Barry, S. L., Chan, Y. and Wilkinson, P. (2001). Decadal record of climate variability spanning the past 700 yrs. in the Southern Tropics of East Africa. Geology 29 (1): 83–86. https://doi.org/10.1130/0091-7613(2001)029%3C0083:DROCVS%3E2.0.CO;2
- Karlen, W., Fastook, J.L., Holmgren, K., Malmstrom, M., Matthews, J.A., Odada, E., Risberg, J., Rosquist, G., Sandgren, P., Shemesh, A. and Westerberg, L.-O. (1999). Glacier fluctuations on Mount Kenya since 6000 cal. years B.P.: implications for Holocene climatic change in Africa. Ambio 28: 409-418.
- Kaser, G. (1999). A review of the modern fluctuations of tropical glaciers. Global and Planetary Change 22: 93-103. https://doi.org/10.1016/S0921-8181(99)00028-4
- Kaser, G. (2001). Glacier-climate interaction at low latitudes. Journal of Glaciology 47(157): 195-204. https://doi.org/10.3189/172756501781832296
- Kaser, G., Hardy, D. R., Mölg, T., Bradley, R. S., and Hyera, T. M. (2004). Modern glacier retreat on Kilimanjaro as evidence of climate change: observations and facts. International Journal of Climatology 24 (3): 329-339. https://doi.org/10.1002/joc.1008
- Kaser, G., Hastenrath, S. and Ames, A. (1996). Mass balance profiles on tropical glaciers. Zeitschrift fur Gletscherkunde und Glazialgeographie 32: 75-81.
- Kilungu, H., Leemans, R., Munishi, P. K. T., Nicholls, S. and Amelung, B. (2019). Forty Years of Climate and Land-Cover Change and its Effects on Tourism Resources in Kilimanjaro National Park. Tourism Planning and Development 16 (2): 235-253. https://doi.org/10.1080/21568316.2019.1569121
- Kimaro, J. G., Scharsich, V., Kolb, A., Huwe, B., and Bogner, C. (2019). Distribution of Traditional Irrigation Canals and their Discharge Dynamics at the Southern Slopes of Mount Kilimanjaro. Frontiers in Environmental Science 7: https://doi.org/10.3389/fenvs.2019.00024
- Kruss, P. (1983). Climate change in East Africa: a numerical simulation from the 100 years of terminus record at Lewis Glacier, Mount Kenya. Zeitschrift fur Gletscherkunde und Glazialgeographie 19 (1): 43-50.
- Lein, H. (2004). Managing the water of Kilimanjaro: Water, peasants, and hydropower development. GeoJournal 61: 155-162. https://doi.org/10.1007/s10708-004-2870-9
- Lovett, J. C. (1993). Eastern arc moist forest flora. In Lovett, J. C. and Wasser, S. K. (eds). Biogeography and ecology of the rain forests of Eastern Africa. Cambridge: Cambridge University Press, 33-56. https://doi.org/10.1017/CBO9780511895692.004
- Lüning, S., Gałka, M. and Vahrenholt, F. (2017). Warming and Cooling: The Medieval Climate Anomaly in Africa and Arabia. Paleoceanography and Paleoclimatology 32 (11): 1219-1235. https://doi.org/10.1002/2017PA003237

- Lwimbo, Z. D., Komakech, H. C. and Muzuka, A. N. (2019). Impacts of emerging agricultural practices on groundwater quality in Kahe catchment, Tanzania. Water 11: 2263. https://doi.org/10.3390/w11112263
- Lwoga, N. B. and Maturo, E. (2020). Motivation-based segmentation of rural tourism market in African villages. Development Southern Africa 37 (5): 773-790. https://doi.org/10.1080/0376835X.2020.1760791
- Masao, F. T. (1974). The Irrigation System in Uchagga: An ethno-historical approach. Tanzania Notes and Records 75: 1-8.
- Mckenzie, J. M., Mark, B. G., Thompson, L. G., Schotterer, U. and Lin, P-N, (2010). A hydrogeochemical survey of Kilimanjaro (Tanzania): Implications for water sources and ages. Hydrogeology Journal 18: 985–995. https://doi.org/10.1007/s10040-009-0558-4
- Mitten, William 1886. The mosses and hepaticae collected in Central Africa by the late Right Rev. James Hannington, Bishop of Mombasa, F.L.S., F.G.S., &c., with some others, including those gathered by Mr. H. H. Johnston on Kilimanjaro. Journal of the Linnean Society of London, Botany 22 (146): 298–329. https://doi.org/10.1111/j.1095-8339.1886.tb00649.x
- Mölg, T., Cullen, N. J., Hardy, D. R. H, Kaser, G. and Klok, L. (2008). Mass balance of a slope glacier on Kilimanjaro and its sensitivity to climate. International Journal of Climatology 28 (7): 881-892. https://doi.org/10.1002/joc.1589
- Mölg, T., Cullen, N. J., Hardy, D. R., Winkler, M. and Kaser, G. (2009). Quantifying climate change in the tropical midtroposphere over East Africa from glacier shrinkage on Kilimanjaro. Journal of Climate 22: 4162-4181. https://doi.org/10.1175/2009JCLI2954.1
- Mölg, T., Cullen, N. J., Hardy, D.R., Kaser, G., Nicholson, L., Prinz, R. and Winkler, M. (2014). East African glacier loss and climate change: corrections to the UNEP article "Africa without ice and snow". Environmental Development 6 (1): 1-6. https://doi.org/10.1016/j.envdev.2013.02.001
- Moore, S. F. and Puritt, P. (2017). The Chagga and Meru of Tanzania. London: Routledge.
- Morante-Carballo, F., Montalván-Burbano, N., Quiñonez-Barzola, X., Jaya-Montalvo, M. and Carrión-Mero, P. (2022). What Do We Know about Water Scarcity in Semi-Arid Zones? A Global Analysis and Research Trends. Water 14 (17): 2685. https://doi.org/10.3390/w14172685
- Morison, T. (1933). The Wachaga of Kilimanjaro: Reminiscences of a war-time district officer. African Affairs 32 (127): 40–147. https://doi.org/10.1093/oxfordjournals.afraf.a100846
- Mote, P. W. and Kaser, G. (2007). The shrinking glaciers of Kilimanjaro: Can global warming be blamed? American Scientist 95 (4): 318-325. https://doi.org/10.1511/2007.66.318
- Muralikrishnan, L., Padaria, R.N., Choudhary, A.K., Dass, A., Shokralla, S., El-Abedin, T.K.Z., Abdelmohsen, S.A.M., Mahmoud, E.A. and Elansary, H.O. Climate Change-Induced Drought Impacts, Adaptation and Mitigation Measures in Semi-Arid Pastoral and Agricultural Watersheds. Sustainability 2022, 14, 6. https://doi.org/10.3390/su14010006
- Mul, M. L. 2009. Understanding hydrological processes in an ungauged catchment in sub- Saharan Africa. UNESCO-IHE PhD Thesis. Boca Raton, FL: CRC Press.
- Mwende, E. A. 2009. Hydro-geological aspects in the Kilimanjaro region for water development and management. Freiberg Online Geoscience 24: 49-54.
- National Bureau of Statistics, 2018. Population estimates by districts for the year 2016 and 2017. Dar es Salaam:

Ministry of Finance.

- New, C. 1971 [1873]. Life, wanderings, and labours in Eastern Africa: with an account of the first successful ascent of the equatorial snow mountain, Kilima Njaro, and remarks upon East African slavery. London: Hodder and Stoughton/Cass.
- Nicholson, J. W. 1936. The influence of forests on climate and water supply in Kenya. East African Agricultural and Forestry Journal 2: 48-53, 164-170, 226-240.
- Nicholson, S. E. 2000. The nature of rainfall variability over Africa on time scales of decades to millennia. Global and Planetary Change 26: 137-158. https://doi.org/10.1016/S0921-8181(00)00040-0
- Nicholson, S. E. and Yin, X. 2001. Rainfall conditions in Equatorial East Africa during the nineteenth century as inferred from the record of Lake Victoria. Climatic Change 48: 387-398. https://doi.org/10.1023/A:1010736008362
- Oliver, D. 1887. Enumeration of the plants collected by Mr. H. H. Johnston on the Kilima- Njaro expedition, 1884. Transactions of the Linnean Society of London. 2nd Series: Botany 2 (15): 327–55. https://doi.org/10.1111/j.1095-8339.1887.tb01008h.x
- Östberg, W., 2014. Irrigated Fields Are Wives: Indigenous irrigation in Marakwet, Kenya. In Håkansson, N. Thomas and Widgren, M. (eds.), Landesque Capital: The Historical Ecology of Enduring Landscape Modifications. Walnut Creek, CA: Left Coast Press: Walnut Creek, CA, 197-214.
- Otte, I., Detsch, F., Mwangomo, F., Hemp, A., Appelhans, T. and Nauss, T. 2017. Multidecadal trends and interannual variability of rainfall as observed from five lowland stations at Mt. Kilimanjaro, Tanzania. Journal of Hydrometeorology 18: 349-361. https://doi.org/10.1175/JHM-D-16-0062.1
- Pangani Basin Water Board (PBWB) and the International Union for Conservation of Nature (IUCN) 2011. Pangani Basin Groundwater Assessment Study PBWB-IUCN. Final Report, 121-128.
- Peters, M. K., Hemp, A., Appelhans, T. et al. 2019. Climate–land-use interactions shape tropical mountain biodiversity and ecosystem functions. Nature 568: 88–92. https://doi.org/10.1038/s41586-019-1048-z
- Pike, A. G. 1965. Kilimanjaro and the Furrow System. Tanganyika Notes and Records 64: 95- 96.
- Ramsay, J. C. 1965. Kilimanjaro sources of water supplies. Tanganyika Notes and Records 64: 92-94.
- Røhr, P. C., and Killingtveit, Å. 2003. Rainfall distribution on the slopes of Mt Kilimanjaro. Hydrological Sciences Journal 48: 65-77. https://doi.org/10.1623/hysj.48.1.65.4348
- Russell, J. M. and Johnson, T. C. 2007. Little Ice Age drought in equatorial Africa: Intertropical Convergence Zone migrations and El Niño–Southern Oscillation variability. Geology 35 (1): 21-24. https://doi.org/10.1130/G23125A.1
- Russell, J. M., Verschuren, D. and Eggermont, H. 2007. Spatial complexity of 'Little Ice Age' climate in East Africa: sedimentary records from two crater lake basins in western Uganda. The Holocene 17 (2): 183-193 https://doi.org/10.1177/0959683607075832
- Said, M., Komekech, H. K., Munishi, L. K., and Muzuka, A. N. N. 2019. Evidence of climate change impacts on water, food and energy resources around Kilimanjaro, Tanzania. Regional Environmental Change 19: 2521-2534. https://doi.org/10.1007/s10113-019-01568-7
- Said, M.; Hyandye, C.; Mjemah, I. C.; Komakech, H. C. and Munishi, L. K. 2021. Evaluation and prediction of the impacts of land cover changes on hydrological processes in data constrained southern slopes of Kilimanjaro,

Tanzania. Earth 2 (2): 225-247. https://doi.org/10.3390/earth2020014

- Sarmett, J. D. A. and Faraji, S. A. 1991. The hydrology of Mount Kilimanjaro: An examination of dry season run-off and possible factors leading to its decrease. In Newmark, W. D. (ed) The Conservation of Mount Kilimanjaro. The IUCN Tropical Forest Programme, 53–70
- Schmidt, P. R. 1989. Early exploitation and settlement in the Usambara Mountains. In Hamilton, A. and Bensted-Smith, R. (eds) Forest Conservation in the East Usambara Mountains, Tanzania. Gland and Cambridge, 75–78
- Silayo, V., 2017. Reconnoitring the pre-colonial chiefdoms and the emergence of social complexity in Kilimanjaro, Tanzania. PhD Thesis, La Trobe University, Melbourne, Australia.
- Smakhtin, V. U. 2001. Low flow hydrology: a review. Journal of Hydrology 240 (3-4): 147-186. https://doi.org/10.1016/S0022-1694(00)00340-1
- Stahl, K. M. 1964. The Chagga and their chiefs: History of the Chagga people of Kilimanjaro. The Hague: Mouton Press.
- Stahl, K. M. 1965. Outline of Chagga history. Tanganyika Notes and Records 64: 35-49.
- Sulas, F. and Pikirayi, I. (eds) 2018. Water and Society from Ancient Times to the Present: Resilience, decline and revival. London and New York: Routledge/Taylor & Francis Group.
- Sunday, S. 2015. Adaption, Resilience and Transformability: A historical ecology of a traditional furrow irrigation system on the slopes of Kilimanjaro." Masters Dissertation in Historical Ecology, Uppsala University, Sweden.
- Sutton, J. E. G. (ed.) 1989. History of African Agricultural Technology and Field Systems. Special volume of Azania: Journal of the British Institute in Eastern Africa 24: 98-112.
- Tagseth, M. 2008. Oral History and the Development of Indigenous Irrigation: Methods and examples from Kilimanjaro, Tanzania. Norsk Geografisk Tidsskrift - Norwegian Journal of Geography 62 (1): 9–22. https://doi.org/10.1080/00291950701864898
- Tagseth, M. 2010. Studies of the Waterscape of Kilimanjaro, Tanzania: Water management in hill furrow irrigation. Norwegian University of Science and Technology, Faculty of Social Sciences and Technology Management, Department of Geography.
- Thompson LG, Brecher HH, Mosley-Thompson E, Hardy DR, Mark BG. 2009. Glacier loss on Kilimanjaro continues unabated. Proceedings of the National Academy of Sciences of the United States of America 106 (47): 19770-199775. https://doi.org/10.1073/pnas.0906029106
- Thompson, L. G. 2000. Ice core evidence for climate change in the tropics: implications for our future. Quaternary Science Reviews 19 (1-5): 19–35. https://doi.org/10.1016/S0277-3791(99)00052-9
- Thompson, L.G., Mosley-Thompson, E., Davis, M.E., Henderson, K. A., Brecher, H. H., Zagorodnov, V. S., Mashiotta, T. A., Lin, P-N., Mikhalenko, V. N., Hardy, D. R., and Beer, J. 2002. Kilimanjaro ice core records: evidence of Holocene climate change in tropical Africa. Science 298 (5593): 589–593. https://doi.org/10.1126/science.1073198
- Thomson, J. 1887. Through Masai land: A Journey of exploration among the snowclad volcanic mountains and strange tribes of eastern equatorial Africa. London: Sampson Low, Marston, Searle, and Rivington.
- Verschuren, D., Laird, K. R. and Cumming, B. F. 2000. Rainfall and drought in equatorial east Africa during the past 1,100 years. Nature 403: 410-414. https://doi.org/10.1038/35000179

- von Clemm, Michael. 1964. Agricultural productivity and sentiment on Kilimanjaro. Economic Botany 18 (2): 99–121. https://doi.org/10.1007/BF02862706
- Waite, M. 2010. Sustainable Water Resources in the Built Environment. London: I.W.A. Publishing, Volume 9. https://doi.org/10.2166/9781780401454
- Wang, W., Straffelini, E., Pijl, A. and Tarolli, P. 2022. Sustainable water resource management in steep-slope agriculture. Geography and Sustainability 3 (3): 214-219. https://doi.org/10.1016/j.geosus.2022.07.001
- Wilcockson, W. 1956. Preliminary notes on the geology of Kilimanjaro. Geological Magazine 93 (3): 218-228. http://doi.org/10.1017/S0016756800066590
- Xing, M., Jianchu, X., and Jie, Q. 2008. Water resource management in a middle mountain watershed: A case study in Xizhuang, Yunnan, China. Mountain Research and Development 28 (3): 286-291. https://doi.org/10.1659/mrd.0796