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Reconstructing Kenya's total freshwater fisheries catches: 1950–2017

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Abstract. Most freshwater fisheries occur in developing countries, where freshwater fish underpin local food security and small-scale fisheries livelihoods. Comprehensive catch data are fundamental to support the sustainable management of freshwater fisheries. However, freshwater catch data reported by the Food and Agriculture Organization of the United Nations (FAO) on behalf of countries under-represent freshwater fisheries because they are dominated by fragmented and highly dispersed small-scale sectors, often with no designated landing sites. Kenya is an emerging economy with socioeconomically important freshwater fisheries and ongoing food security concerns. We undertook a reconstruction of freshwater fisheries catch data for Kenya for the period 1950–2017, aiming to improve the comprehensiveness of existing reported baseline data and to provide a more ecologically and spatially relevant time series dataset for research and management uses. We reconstructed catches for 16 major waterbodies in Kenya and found catches to be 32% higher than the data reported by the FAO on behalf of the country. The subsistence sector (small-scale, non-commercial, personal consumption) accounted for 71% of unreported catches, compared with 29% for artisanal sector catches (small-scale, commercial), suggesting that non-commercial catches for direct local consumption are substantially under-represented in nationally reported statistics and should receive greater attention to support sustainable food security in Kenya.

Keywords: artisanal, developing country, food security, inland fisheries, Lake Victoria, lakes, rivers, subsistence.

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Introduction

Capture fisheries in freshwater systems, which account for ~12% of reported global fisheries catches (Food and Agriculture Organization of the United Nations 2020*a*), are an important source of affordable animal protein in developing countries, but mainly a source for recreational activities in most developed countries. Furthermore, freshwater fisheries in developing countries, which account for 90% of global reported freshwater catches, support over 60 million jobs (Bartley *et al.* 2015; Food and Agriculture Organization of the United Nations 2020*a*). Despite this, they receive limited attention in national and international fisheries policy discussions compared with their marine counterparts (Funge-Smith and Bennett 2019). The small-scale nature of most freshwater fisheries results in high levels of local catch consumption and fisheries-related employment and livelihoods, low discards and nutrient-rich food sources for people in low socioeconomic and often poorly represented populations, including women and children (Coates 1995; Bank 2012; Funge-Smith 2018; Funge-Smith and Bennett 2019). As a result, freshwater fisheries have been identified as an overlooked but crucial factor in meeting the United Nations Sustainable Development Goals (SDGs) (see https://sdgs.un.org/goals, accessed 11 August 2021) for ending poverty (SDG 1) and hunger (SDG 2) by 2030 (Lynch *et al.* 2017). In Africa, freshwater fish are an important source of protein and nutrients (Vianna *et al.* 2020), making these fisheries a valuable component for Kenya in meeting the United Nations SDGs, as well as improving local nutrition, a fundamental component of human health and a major goal of the 2016–25 United Nations Decade of Action on Nutrition (Branca *et al.* 2020).

Freshwater catch data reported by the FAO on behalf of member countries are known to be questionable and likely grossly underestimate the true contribution of freshwater fisheries to global capture fisheries (Welcomme 2011; Bartley *et al.* 2015; Fluet-Chouinard *et al.* 2018; Ainsworth *et al.* 2021). The often poor quality of freshwater catch data reported by countries to the FAO is a reflection of the often under-resourced data collection systems in many countries. Only 25% of reported freshwater catches are taxonomically identified to species level, compared with ~60% in marine fisheries (Pauly and Palomares 2005; Bartley *et al.* 2015). Furthermore, there are many cases of aquaculture production data being erroneously assigned as wild capture data in official data records, and vice versa, indicating deep quality issues in nationally and internationally assembled freshwater fisheries data (Bartley *et al.* 2015).

Internationally reported catch data do not differentiate between waterbodies within countries, making the global catch data and their taxonomic breakdowns relatively uninformative as an indicator for assessing freshwater fisheries and ecosystem status or health at various spatial, temporal and taxonomic levels. Parallel problems of this nature in marine fisheries have more recently started to be addressed (Pauly and Zeller 2016*a*, 2019*a*; Zeller *et al.* 2016). National fisheries agencies may have data differentiated by waterbody, but such differentiations are not included in the data reported to and by the FAO. Furthermore, national data are often only collected at commercially important landing sites, and therefore catch and effort (e.g. number of vessels or fishers) from other sectors, particularly the non-commercial subsistence and recreational sectors, are often not included in national statistics despite often accounting for an equal, if not larger, weight of catch than the commercial sector (Lorenzen *et al.* 2016). Although freshwater aquaculture and cage culture contribute substantially to food supply in Kenya (Kenya Marine and Fisheries Research Institute, Aquaculture Business Development Programme for Small Water Bodies 2020) and data on aquaculture production volumes from small-scale farmers are often underestimated and poorly presented in production and trade statistics (Ottinger *et al.* 2016), we focus here on wild capture fisheries and thus did not consider aquaculture production in the present study.

Comprehensive fisheries statistics are a foundational resource for the sustainable management of freshwater ecosystems and the fisheries they support (Cooke *et al.* 2016), just as they are in marine fisheries (Pauly and Zeller 2016*a*, 2019*b*). In addition, having comprehensive and uninterrupted long-term time series of such data is crucial to avoid both shifting baselines (Pauly 1995) and the 'presentist bias' (Zeller and Pauly 2018), and generally requires some form of reconstruction or re-estimation approach (Pauly 1998; Zeller *et al.* 2016). Catch data are among the easiest fisheries data types to collect, and are therefore of particular importance in developing countries and emerging economies, which often have limited resources for monitoring and scientific surveys (Kleisner *et al.* 2013). Data-limited stock assessment methods (Froese *et al.* 2017, 2018, 2020), for which catch data are a fundamental component, are often the only available method to assess the status of fish populations in data-deficient situations. Therefore, improving the comprehensiveness and resolution of historical catch time series for freshwater fisheries can be highly beneficial, and can directly contribute to better understanding the current status of stocks (Froese *et al.* 2017).

Kenya (Fig. 1) is classified as a lower- to middle-income country (United Nations 2019) with a rapidly growing population of over 50 million (The World Bank 2019) and an emerging and growing economy (https://en.wikipedia.org/wiki/Kenya). However, food and nutritional security issues, including widespread malnutrition and micronutrient deficiencies, remain a challenge in the country (Kimani-Murage *et al.* 2011; Comprehensive Africa Agriculture Development Programme 2013). Capture fisheries play a central role in Kenya's culture, economy and food supply chain, and were valued at US$440 million in 2018, with ~1.2 million people directly or indirectly employed in fisheries (Kimani *et al.* 2018). Compared with many other coastal countries around the world, Kenya's capture fisheries are unique in that most of total reported catches come from freshwater fisheries (Kimani *et al.* 2018).

Lake Victoria is the second largest lake in the world, but only 6% of it is within Kenya's borders (Fig. 1). Despite this limited area, the largely open-access fisheries in Lake Victoria dominate Kenya's reported catches (Kimani *et al.* 2018; Food and Agriculture Organization of the United Nations 2020*b*). From the 1950s to the 1970s, Lake Victoria supported diverse, multispecies fisheries, with native haplochromine cichlids and native tilapias accounting for a large portion of catches (Ogutu-Ohwayo 1990; Aura *et al.* 2020). However, two species deliberately introduced into the lake in the 1950s, the Nile perch (*Lates niloticus*) and the Nile tilapia (*Oreochromis niloticus*), as well as the native silver cyprinid (*Rastrineobola argentea*) have dominated fisheries since the 1980s (Irvine *et al.* 2019).

A multi-million dollar Nile perch export industry developed in the 1980s for marketing to highly developed and food-secure countries such as the US and those in the European Union (Cowx *et al.* 2003). Furthermore, a large fraction of reported silver cyprinid catches from Kenya's Lake Victoria waters has been converted to fishmeal for animal feed since the 1990s, thus directing protein and nutrients away from direct human food supply chains (Abila 2003). Consequently, the proportion of catch taken from Lake Victoria that is going to local food supply declined over time (Muyodi *et al.* 2010). The at-times higher prices being paid by fishmeal and export processing factories compared to local markets led to locally sourced fish, such as silver cyprinids (known locally as *Dagaa*) and Nile perch frames, becoming increasingly unaffordable for many locals (Abila 2003). This has provided an opening in the market for cheaper aquaculture-produced fish imports from China (Dijkstra 2019), and an explosion of local cage culture for Nile perch on Lake Victoria (Njiru *et al.* 2019).

Lake Turkana (Fig. 1) supports Kenya's second largest freshwater fishery, accounting for ~5% of reported freshwater catches (Kimani *et al.* 2018). Eight other lakes, dams and rivers are sporadically but not consistently included in nationally reported catch data back to 1950, accounting for ~1% of reported freshwater catches. These minor freshwater fisheries

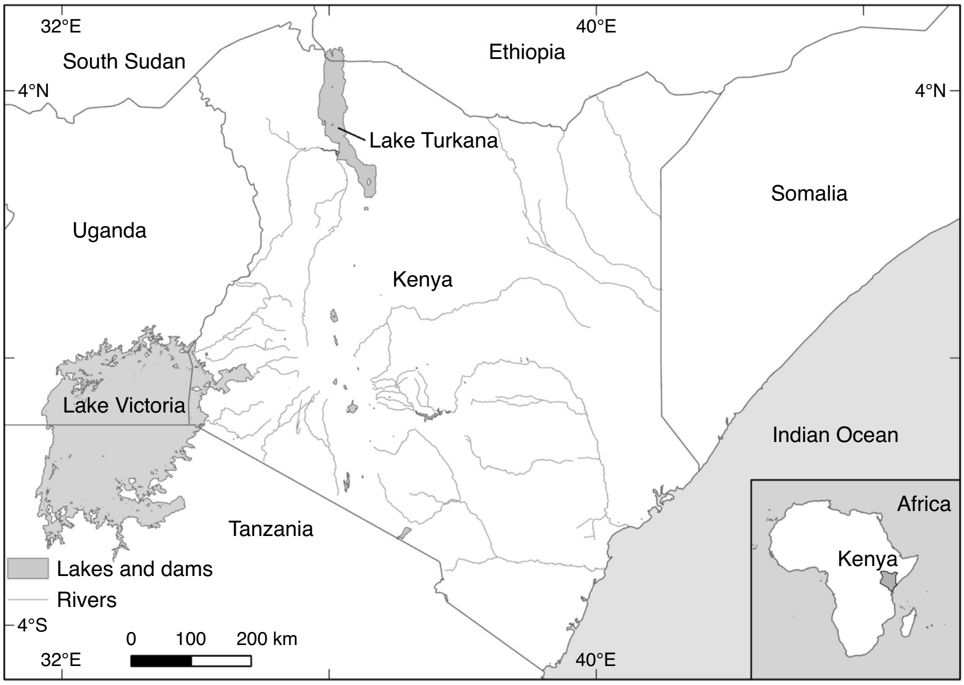

Fig. 1. Kenya and its freshwater bodies, highlighting Lakes Victoria and Turkana.

are primarily open access, with catches mostly consumed domestically (Kimani *et al.* 2018).

The collection of catch data in Kenya is challenging due to various factors, including the over 300 landing sites on Kenya's shores of Lake Victoria alone (Kimani *et al.* 2018), the dominance of small-scale fishing sectors and a large number of freshwater bodies with fisheries throughout the country (Cowx *et al.* 2003). In addition, fisheries are thought to contribute little to Kenya's official gross domestic product (GDP; ~0.5%) and are therefore not viewed as a national priority, leading to a lack of investment in monitoring and assessment nationwide (Tuda 2018). More recently, the government has outlined the improvement of stock assessments, the setting of management reference points and increasing the per-capita fish consumption from ~4.7 to 10 kg year^{-1} by 2030 as central goals of the Kenya Vision 2030 long-term development blueprint (Kimani *et al.* 2018; see https://vision2030.go.ke, accessed 3 March 2021). As such, freshwater fisheries may provide a substantial contribution towards meeting several of Kenya's SDG targets; however, social and economic development must be balanced against the long-term conservation and sustainability of resources. Therefore, blind pursuit of a 10 kg year^{-1} target without taking into account already overfished or threatened stocks is ill-advised. This makes the improvement and increased comprehensiveness of Kenya's freshwater catch data essential for supporting future management and food security challenges.

Kenya's marine fisheries data were reconstructed back to 1950 by Le Manach *et al.* (2016) and McAlpine (2019). The present study conceptually builds on this work for Kenya by reconstructing the freshwater catches in the country, disaggregated by major waterbodies, fishing sector, taxon and reporting status.

Materials and methods

We followed the well-documented and established catch reconstruction approach first applied for Pacific Islands marine fisheries in Zeller *et al.* (2006, 2007), described in Zeller *et al.* (2016) and applied globally for marine fisheries (Pauly and Zeller 2016*a*, 2016*b*). This approach uses the officially reported data as baselines, and complements these with estimates of unreported catches based on secondary data and sources, as well as consultation with in-country fisheries experts. Only landed (i.e. retained) catches for Kenya were addressed in this study, because discards from small-scale sectors, which dominate Kenya's freshwater fisheries, are thought to be generally negligible (Zeller *et al.* 2018).

Waterbody assignment

The number of waterbodies for which the State Department for Fisheries, Aquaculture and the Blue Economy (SDFA&BE; also known as the Kenya Fisheries Service, KeFS) has reported catches for has varied over time. The most recent reported catches are separated into 10 individual waterbodies, plus an aggregate category labelled 'Riverine' (Kenya Fisheries Service 2017). The number of waterbodies reported in the KeFS data declined to four before 1990, with additional catches assigned to an aggregate category labelled 'Other'. No information was included as to which individual waterbodies the 'Riverine' or 'Other' catches come from (Kenya National Bureau of Statistics 1972; Kenya Fisheries Service 2017). For the 10 waterbodies reported in the KeFS data either regularly or sporadically, we identified historical time periods with no official KeFS data records. For such periods, we were able to source anchor point data (*sensu* Zeller *et al.* 2016) from data sources that included

Table 1. Waterbodies included in the reconstruction of Kenya's freshwater fisheries catches, with the associated grouping category and county or province for which population data were used

Population data were not used for all waterbodies for all years; thus, only the years for which population data were used are listed. TRD, Tana River Delta. Sources: Kenya National Bureau of Statistics (1957, 1967, 1972, 1982, 1994, 2002, 2012, 2019)

Category	Waterbody	Population data years used	County or province
Lake Victoria	Lake Victoria	1989–2017	Nyanza province
Lakes, dams and TRD	Lake Turkana	1948	Northern Frontier province
		1962–99	Turkana and Marasabit counties
		2009	Turkana Central and Marasabit counties
	Lake Baringo	1948–99	Baringo county
		2009–17	Baringo and Baringo North counties
	Lake Naivasha	1948	Nakuru county
		1962	Naivasha county
		1969–2017	Nakuru county
	Tana River dams	1989–2017	Embu and Machakos counties
	Tana River delta	1948	Tana–Lamu county
		1962–99	Tana county
		2009–17	Tana delta county
	Turkwel dam	1948	Nyanza province
		1962–99	West Pokot county
	Lake Kanyaboli	1948–62	Nyanza province
		1969–2017	Siaya county
	Lake Kenyatta	1948	Tana–Lamu county
		1962–2017	Lamu county
	Lake Jipe, Lake Chala and others in Taita-Taveta county	1948–2017	Taita–Taveta county
Rivers	Sondu-Miriu River	1948–62	Central Nyanza county
		1969–89	Kisumu county
		1999–2017	Kisumu and Homa Bay counties
	Kuja River	1948–62	Nyanza province
	Athi-Sabaki River	1948–62	Kilifi county
	Malewa River	1948	Nakuru county
		1962	Naivasha county
		1969–89	Nakuru county
	Nzoia River	1948–62	Nyanza province
	Ewaso-Ngiro River and swamp	1948–62	Northern province

estimates of catch that were in secondary data but not in the official time series data records, including the taxonomic composition of catches and the number of licenced fishers (Tables S1–S8 of the Supplementary material).

We identified six freshwater bodies (Sondu-Miriu River, Kuja River, Athi-Sabaki River, Malewa River, Nzoia River and Ewaso-Ngiro River and swamp) with known fisheries from 1950 to 2017 that were not included in the official KeFS time series data, as confirmed by a detailed review of the secondary literature and collaboration with experts on Kenya's freshwater fisheries. We were able to identify a small range of data and information sources for specific years or sectors, which we treated as anchor point data (*sensu* Zeller *et al.* 2016) for these six waterbodies to conservatively approximate likely catches over time (Table S9 of the Supplementary material).

We retained the derived catch time series for each of the 16 waterbodies separately in the dataset (reconstructed data are available from the corresponding author). However, for ease of result presentation, we grouped the data here into three categories based on the quality and quantity of anchor points and baseline data available: (1) Lake Victoria; (2) Lakes, Dams and the Tana River Delta (TRD); and (3) Rivers (Table 1).

Lake Victoria

Lake Victoria had the most comprehensive and detailed data back to 1968 on total catches and taxonomic compositions, as well as on the number of licenced fishers. Data for the pre-1968 period were more limited (Table S1).

Lakes, dams and the Tana River Delta

In all, 11 waterbodies, or groups of waterbodies, were placed in this category (Table 1). Total catches and taxonomic compositions were available for most waterbodies in this category from 1992 to 2017. Some data were available back to 1967, but mainly as aggregate catch totals, and very limited information existed before 1967 (Tables S2–S8). We treated the TRD and Tana River dams as different waterbodies in this study because historical catch data were reported separately for each of these. Lake Jipe, Lake Chala and other waterbodies in Taita–Taveta County were only reported collectively in the KeFS data back to 1992 without differentiation between specific waterbodies within the county. Therefore, all the waterbodies in the Taita–Taveta County were grouped together in this study.

Rivers

The six waterbodies in this category (Table 1) were not included in any nationally reported data. Very limited information in the form of catch totals only was available from 1950 to 2017 (Table S9).

Reported catches

The KeFS is responsible for collecting and reporting fisheries data in Kenya, and we treated these data as the reported baseline for freshwater catches. We obtained catch data reported by the KeFS from various reports, as well as published and unpublished data provided by in-country collaborators for a range of anchor point years (Tables S1–S9). National freshwater catch data reported by the KeFS were compared with data reported by the FAO on behalf of Kenya (Food and Agriculture Organization of the United Nations 2020*b*). Data reported by the KeFS separates catch by several waterbodies and has a higher taxonomic resolution than data reported by the FAO, which also does not separate catch by waterbody. We accepted the KeFS reported catch data rather than the FAO data as the reported baseline data due to their greater spatial and taxonomic resolution. We chose the end year of 2017 because it was the most recent year for which catch data reported by the KeFS were available at the time of this study. The current FAO dataset (Food and Agriculture Organization of the United Nations 2020*b*) does include data for 2018, but as a preliminary FAO estimate (J. Geehan, FAO Fisheries Statistician, pers. comm.) and was not considered reliable enough.

Gap filling in reported baseline data

We used simple linear interpolations to fill in gaps of no catches for a given waterbody between years with reported catch anchor points for each given waterbody. We thus assumed continuation of fishing between years of reported data, rather than continuing the default pattern of having years with 'no reported data' be retained as effectively zero catches (Zeller *et al.* 2016). Alternative methods of catch estimation were used to fill in reported baseline gaps for waterbodies where anchor points did not exist for the start year (1950) or end year (2017) of our study, and there was no information to suggest that fisheries did not exist in these waterbodies in those years. Catches were estimated back to 1950, from the earliest anchor point, by assuming past catches changed at the rate of historical local population density change (persons km^{-2}) in the county or province in which the waterbody was located (Table 1). This approach assumed that changes in historical small-scale fisheries catches are directly related to local or regional human population trends over time, at least for the earliest periods where we assumed no overfishing occurred. We sourced population densities for each county or province from historical Kenyan censuses (Kenya National Bureau of Statistics 1957, 1972, 1982, 1994, 2002, 2012, 2019) and linearly interpolated between these years to produce an approximate time series of population density for each county or province. Where a waterbody spanned over more than one county, we derived the mean population density. Catches were estimated forward from the latest data anchor point to 2017 based on alternative fisheries information and trends in catch from geographically similar Kenyan waterbodies with catch anchor points available for 2017 (see the 'Methods' section of the Supplementary material for details). Estimating catches forward to 2017 was only required for waterbodies in the Rivers category.

To account for the taxonomic composition for years where we filled data gaps, we applied the taxonomic composition of catches from the nearest anchor point year available for each waterbody to catches preceding it. Where there were gaps in the taxonomic composition of catch between anchor points, we linearly interpolated the proportion of total catches for each taxonomic group between anchor points (see the 'Methods' section of the Supplementary material for details).

Quantifying fully unreported catch components

Fisher-household catches

We assumed that catches directly consumed in fisher-households by fishers and their families and were not sold or taken to markets were not part of the officially reported data structure, and represent a proxy for unmonitored and thus unreported subsistence fishing. We thus assumed that all reported data were derived from commercial catches. We estimated minimum unreported catches for fisher-households for nine waterbodies using anchor points for the number of licenced fishers, combined with consumption rates (Tables S1–S7), for Lake Victoria and all the waterbodies in the Lakes, Dams and TRD category, excluding Turkwel Dam (Table 1). To remain conservative in the absence of readily usable secondary information, and to avoid very high uncertainty around estimates, we did not specifically estimate take-home catch by licenced fisher-households for the various smaller River waterbodies or for Turkwel Dam. However, future research should derive such estimates, as well as estimate take-home catch from non-licenced subsistence fishers.

To estimate this unreported catch component, we first created a time series of the number of people in fisher-households. We did this by multiplying the number of licenced fishers, taken from anchor points of fishers for each waterbody (Tables S1–S7), by the average household size for each county or province, taken from historical Kenyan censuses (Kenya National Bureau of Statistics 1957, 1972, 1982, 1994, 2002, 2012, 2019).

Second, we developed a time series of annual fish consumption rates for people in fisher-households. This was based on a rate of 90 kg $person^{-1}$ $year^{-1}$ for people in fisher-households surrounding Lake Victoria in 1995 (Bokea and Ikiara 2000) and a rate of 73 kg $person^{-1}$ $year^{-1}$ for people in fisher-households surrounding Lake Turkana in 1982 (Kolding 1989). These were the only two annual fish consumption rates for people in fisher-households identified in the literature. To remain conservative in our estimations, we relied on the rate of 73 kg $person^{-1}$ $year^{-1}$ to estimate fish consumption rates in fisher-households for the waterbodies that had information for the number of licenced fishers available, except for Lake Victoria. These very high rates do not reflect the average fish consumption rates for the general population, and were only used here as a proxy to estimate unreported subsistence catches in the absence of wider data on general subsistence fishing by non-licenced fisher-households.

Per capita fish consumption in Kenyan fisher-households over the past 70 years likely decreased due to the increased availability of alternative food sources and the development of a cash-based economy (Ochieng and Maxon 1992; Geheb and Binns 1997), as well as increases in fish prices at local markets (Abila 2003). To account for this likely trend, we assumed that fish consumption rates in 1950 were 20% higher than in the respective anchor point year of 1995 for Lake Victoria (i.e. declining at a rate of 0.44% year^{-1} over the full 1950–2017 time period). We assumed that this rate of decline was the same for all other waterbodies, and applied it to the 1982 anchor point for the waterbodies other than Lake Victoria, but anchored to the 73 kg person^{-1} year^{-1} consumption rate in fisher-households used for the other waterbodies. Using this rate of decline, we derived an assumed consumption time series for fisher-households, which declined for Lake Victoria from 108 kg person^{-1} year^{-1} in 1950 to 81.2 kg person^{-1} year^{-1} in 2017, and decreased for the other waterbodies from 83.5 kg person^{-1} year^{-1} in 1950 to 62.5 kg person^{-1} year^{-1} in 2017.

Thereafter, we derived the time series of catches consumed in fisher-households (here serving as an estimation proxy for general overall subsistence catches) by multiplying the number of people in fisher-households by the annual fish consumption rates for each of the nine waterbodies from 1950 to 2017. We assumed that the taxonomic composition of fisher-household catches was the same as for reported catches. Fishing without licenses is a common practice in freshwater bodies throughout Kenya (Etiegni *et al.* 2017); therefore, our estimated fisher-household catches, based on the number of licenced fishers, are likely to be conservative estimates of overall freshwater subsistence catches. Future research needs to carefully fill this data gap by deriving estimates of non-commercial subsistence catches for all waterbodies in Kenya.

Bait catches

We also estimated the unreported bait catches for the Nile perch longline fishery (Cowx *et al.* 2003; Mkumbo and Mlaponi 2007). The Nile perch longline fisheries in Kenya and Tanzania are considered to be similar (P. Tuda, pers. obs., K. Obiero, pers. obs.). Therefore, we used the bait to hook ratio and a modified taxonomic composition of bait catch for Tanzania's Lake Victoria longline Nile perch fishery to estimate Kenya's bait catch (Mkumbo and Mlaponi 2007; see the 'Methods' section of the Supplementary material for details). We recognise that many Kenyan fishers operate in Tanzanian and Ugandan waters, but these are still deemed Kenyan catches because international 'flag-state' rules apply to catch data (Garibaldi 2012). However, because the native silver cyprinid *R. argentea* is not used as bait by the Kenyan Nile perch longline fishers (I. Cowx, pers. obs.), it was excluded from the taxonomic composition data taken from Mkumbo and Mlaponi (2007). Furthermore, since 2000, an increasing amount of bait used by Kenyan fishers consists of farmed catfish, which is not wild caught fish. Therefore, future research should carefully investigate the use of bait fish. Owing to a lack of more detailed information, and to remain conservative, we assumed that the Kenyan longline Nile perch fishery began in 1981 (i.e. bait catches were 0 in 1980), because this was the year when reported Nile perch catches first rapidly increased in Kenya's portion of Lake Victoria. Therefore, we estimated bait catches for the Kenyan Lake Victoria longline fishery for the period 1981–2017.

Unreported catches taken with illegal gear

We accounted for the largely unreported catches from widespread illegal, or unregulated, fishing known to occur on Lake Victoria (Lake Victoria Fisheries Service 1959; Cowx *et al.* 2003; Etiegni *et al.* 2017; Wanguche *et al.* 2021) as best as possible in the absence of more detailed information. These catches are here considered 'illegal' because they are largely taken using illegal fishing gear (Wanguche *et al.* 2021), such as gill-nets with a mesh size of less than 12.7 cm (Gichuru *et al.* 2019). We did this through a flat catch adjustment, by adding an additional 25% to all reported and reconstructed unreported catches for Lake Victoria for the period 1950–1982 (except for 1958; see the 'Methods' section of the Supplementary material for details) as assumed illegal gear catches (Coche and Balarin 1982). For 1983–2017, the 25% assumed illegal gear catch was added to all reported and reconstructed unreported catches, excluding Nile perch (Coche and Balarin 1982). We assumed that the taxonomic composition of these catches was the same as for the reported catches for Lake Victoria.

Unreported Nile perch catches from fishing with illegal gear accounted for an additional 20% of reported Nile perch catches from Kenya's portion of Lake Victoria in 2003 (Cowx *et al.* 2003) and 30% in 2017 (P. Tuda, pers. obs., I. Cowx, pers. obs.). Therefore, we conservatively assumed that the percentage of illegal Nile perch catches was 20% of reported catches from 1950 to 2003 and thereafter increased linearly to 30% by 2017. Our broad estimates of illegal gear catches should be treated with caution until more detailed estimates can be derived.

Assigning total reconstructed catches to fishing sectors

Both reported and estimated unreported catches were allocated to fishing sectors in line with sectoral definitions of the Sea Around Us (Zeller *et al.* 2016). Because only small-scale sectors have been identified for Kenya's freshwater fisheries, we constrained sectoral assignments of catches to either 'artisanal' (i.e. small-scale, mainly commercial) or 'subsistence' (i.e. small-scale, mainly non-commercial) fishing. We assigned all reported and gap-filled unreported baseline catches from Lake Victoria and waterbodies in the Lakes, Dams and TRD category, as well as the unreported bait catches entirely to the artisanal sector, implying most of these catches are destined for commercial sale (or export sale). Conversely, we allocated all estimated catches destined to fisher-households entirely to the subsistence sector, suggesting priority use for household consumption, community sharing or barter. Owing to a lack of information, we assumed that catches from waterbodies in the Rivers category and unregulated catches taken with illegal fishing gear from Lake Victoria were 50% for subsistence and 50% for artisanal purposes. We recognise that there is overlap between the artisanal and subsistence sectors in terms of commercial versus non-commercial use, based on fishers' catch volumes and values, as well as household need and opportunity over time and in space, and thus we consider our assignments to be an approximation.

A recreational freshwater sector also exists in Kenya, mainly for trout in high-altitude lakes, driven to a large extent by tourism (Kimani *et al.* 2018). However, because of a complete lack of information, we did not estimate this here.

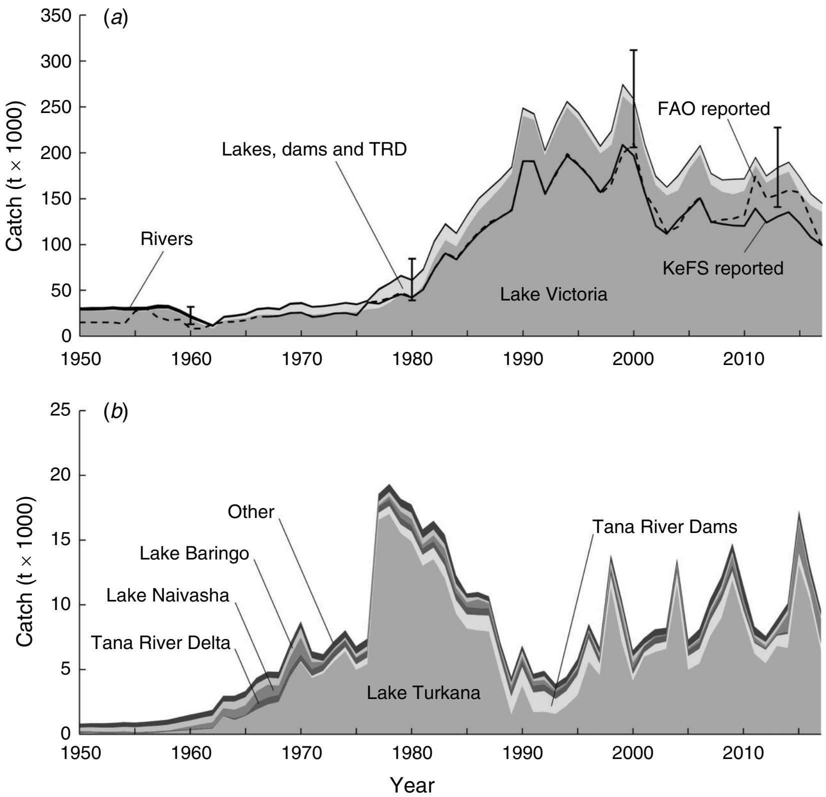

Fig. 2. (*a*) Total reconstructed freshwater catches for Kenya from 1950 to 2017 by major waterbody category. Catches as reported by the FAO on behalf of Kenya are overlaid as a dashed line, whereas the KeFS nationally reported catches are overlaid as a solid line. Data reliability (uncertainty) bounds are indicated as catch-weighted averages for the 1950–69, 1970–89, 1990–2009 and 2010–17 periods. (*b*) Total reconstructed freshwater catches for Kenya from 1950 to 2017 for individual waterbodies within the Lakes, Dams and TRD category.

Quantifying data reliability (uncertainty)

The reliability of, or confidence in, the various data and data sources used for the reconstruction was estimated using the scoring method described in Zeller *et al.* (2016) and previously applied to global marine catches (Pauly and Zeller 2016*a*, 2016*b*). This method was adapted from the Intergovernmental Panel on Climate Change when using multiple and differing sources of evidence (Mastrandrea *et al.* 2010) and represents a form of 'uncertainty' measure regarding the data and information sources used for estimation. We estimated data reliability scores and the associated percentage uncertainty bounds (Table S11) based on a qualitative evaluation of the trust in the secondary data and information sources used. This was done separately for each fishing sector in each waterbody in the three categories Lake Victoria, Lakes, Dams and TRD and Rivers for each of four time periods (1950–69, 1970–89, 1990–2009 and 2010–17). Total data reliability scores and the associated percentage uncertainty bounds were derived for each of the four time periods based on the catch-weighted score averages for each category and fishing sector.

Results

The total reconstructed freshwater catches in Kenya from 1950 to 2017 were 32% higher than the catches reported by the FAO on behalf of Kenya (Fig. 2*a*; Table S10). Catches varied between 12 000 and 40 000 tonnes (t, Mg) year^{-1} from 1950 to the mid-1970s, after which catches increased rapidly to a time series peak of ~270 000 t in 1999, driven by a large increase in catches from Lake Victoria (Fig. 2*a*; Table S10). After 2000, catches experienced a generally decreasing trend, declining to a low of ~145 000 t in 2017, driven by declines in catches from Lake Victoria.

The freshwater catch data reported nationally by the KeFS since 1967 matched closely with data reported by the FAO on behalf of Kenya from 1967 to 2008 (Fig. 2*a*). However, between 2008 and 2016, catches presented by the FAO on behalf of Kenya were on average 12% (i.e. ~21 000 t year^{-1}) higher than those reported nationally by the KeFS. For the last year of data available to us during the study (i.e. 2017), there was a close match between the KeFS- and FAO-reported data (Fig. 2*a*).

The reliability (data uncertainty) scores were poorest for the earlier decades (1950s and 1960s; Fig. 2*a*; Table S11), driven by the general paucity of data and information for all waterbodies from the early periods, resulting in estimated average uncertainty bounds of ±34% of total catch (Fig. 2*a*). The most recent decades, 1990–2017, had substantially better data and information sources, resulting in lower estimated uncertainty bounds of ±25% of total catch (Fig. 2*a*; Table S11).

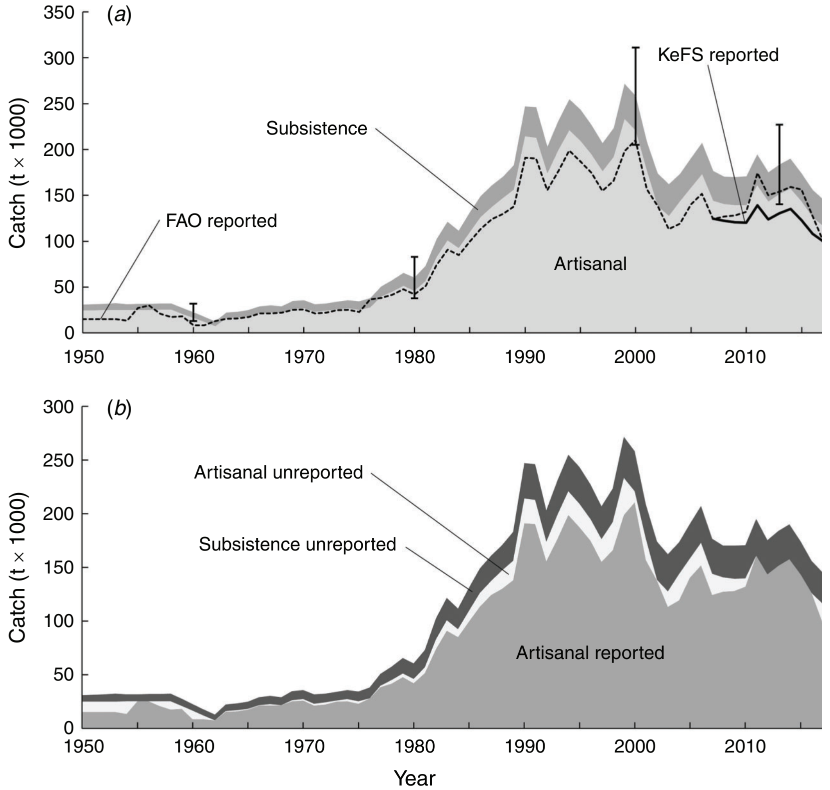

Fig. 3. (*a*) Total reconstructed freshwater catches for Kenya from 1950 to 2017 by fishing sector. Catches as reported by the FAO on behalf of Kenya are overlaid as a dashed line, whereas the KeFS nationally reported catches are overlaid as a solid line. Data reliability (uncertainty) bounds are indicated as catch-weighted averages for the 1950–69, 1970–89, 1990–2009 and 2010–17 periods. (*b*) Total reconstructed freshwater catches for Kenya from 1950 to 2017 by fishing sector and reporting status within each fishing sector.

Lake Victoria dominated Kenya's freshwater catches, accounting for 92% of total catches for 1950–2017, with the Lakes, Dams and TRD category accounting for 7% and the Rivers category comprising the remaining 1% (Fig. 2*a*; Table S10). Catches from the Lakes, Dams and TRD category, comprising 11 individual waterbodies (Table 1; Fig. 2*b*), increased from ~1000 t in 1950 to a time series maximum of ~20 000 t in 1978, after which they declined to 4500 t in 1992. Since 1992, catches from the Lakes, Dams and TRD category have fluctuated between 5000 and 17 000 t year^{-1}, but with a generally increasing trend (Fig. 2*b*; Table S10). Lake Turkana dominated catches in the Lakes, Dams and TRD category, accounting for 65% of total reconstructed catches and driving catch trends throughout the time series, whereas the Tana River fisheries (Tana River Dams and Tana River Delta) and the other waterbodies accounted for 20 and <5% of catches respectively (Fig. 2*b*). Reconstructed catches from the general Rivers category peaked in the mid-1950s at ~3400 t year^{-1} (Fig. 2*a*), driven by peaks in catches from the Sondu-Miriu, Nzoia and Kuja rivers (Table S10). Catches then declined throughout the remainder of the time series to just over 200 t in 2017 (Fig. 2*a*).

The artisanal fishing sector accounted for ~80% of total reconstructed freshwater catches in the country, whereas the subsistence sector accounted for 20% (Fig. 3*a*; Table S10). Most artisanal catches (91%) were deemed to have been reported (Fig. 3*b*). Overall, ~71% of the total unreported catches estimated here were from the subsistence sector (Fig. 3*b*).

In total, 26 taxa were identified and included in the total reconstructed catches, of which Nile perch *L. niloticus* (37%), silver cyprinid *R. argentea* (29%), Nile tilapia *O. niloticus* (8%) and other *Oreochromis* spp. (5%) accounted for the majority of catches (Fig. 4). From 1950 to 1980, catches were taxonomically more diverse, with other species from the genera *Oreochromis* (23%), *Haplochromis* (21%) and *Clarias* (9%) and silver cyprinid *R. argentea* (10%) making up the majority of catches. Since peaking in 1999 at ~150 000 t, catches of Nile perch have been declining, with 2017 catches less than one-third of peak levels; in contrast, catches of the silver cyprinid have increased steadily over the same period.

Discussion

The reconstruction for Kenya's freshwater catches suggests that total catches were 32% higher than the data reported by the FAO on behalf of Kenya from 1950 to 2017. This under-reporting was due to unmonitored waterbodies, incomplete time series for monitored waterbodies and the under-representation in the officially reported data of both catches taken with illegal gear and locally consumed catches from the non-commercial

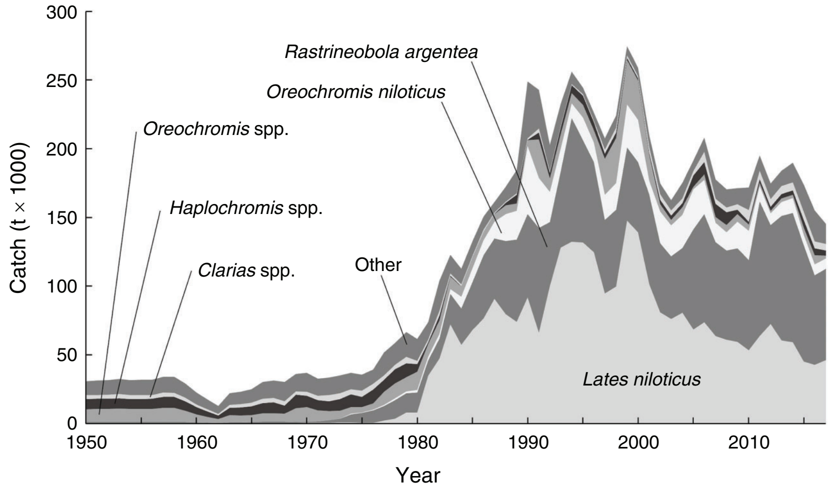

Fig. 4. Total reconstructed freshwater catches of Kenya from 1950 to 2017 by major taxa, with the 'Other' category including 20 additional taxa.

subsistence sector. Such an under-representation of monitored as well as unmonitored fisheries, as well as generally under-represented subsistence catches, is widespread in both freshwater (Cooke *et al.* 2016; Lynch *et al.* 2017) and marine (Zeller *et al.* 2015; Pauly and Zeller 2016*a*; Teh and Pauly 2018; Teh *et al.* 2020) catch statistics around the world and contributes to the socioeconomic undervaluation and marginalisation of small-scale fisheries (Pauly 1997, 2006). The proportion of unreported catches identified for Kenya here is concerning for the wider African freshwater fisheries data, given that Kenya received the highest confidence level in reported catch statistics during an audit of African freshwater fisheries (Welcomme and Lymer 2012). Furthermore, Fluet-Chouinard *et al.* (2018) suggested in their global approximation of freshwater catches that Kenya is among the few countries for which reported catch statistics seem to be larger than their broad estimates based on consumption surveys. However, because we used a detailed and comprehensive country-specific approach for reconstructing catches by individual waterbodies, we consider our findings to be reliable. The data shortfall identified in our study suggests that freshwater catches for local consumption may also be undervalued by management authorities and decision makers in Kenya, despite the crucial role such fisheries play in food and nutritional security in the country. Because these fish provide a vital source of nutrients and micronutrients for the poorest people in Kenya, fisheries and their catches in Kenya should be viewed and treated as a national human health asset (Vianna *et al.* 2020), and not only as a commercial commodity.

Catches from Lake Victoria dominated total freshwater catch tonnages in Kenya. After 1980, catches of the three main species from Lake Victoria were increasingly exported or converted to animal feed, and are represented fairly accurately in reported data (Cowx *et al.* 2003; P. Tuda, pers. obs.). Nevertheless, export and fishmeal catches do not contribute directly to national nutrition and can represent a net loss to national human health and food and nutritional security. However, the diversion of catches to fishmeal is not as large currently as in the earlier years, and increased market value has resulted in more fish being consumed locally (P. Mboya, pers. obs.). Furthermore, higher prices for export-oriented catches can contribute to better income streams for fishers. The decrease in Kenyan Nile perch catches has also been influenced by conflict-driven restrictions on Kenyan fishers to fish in Ugandan waters (Glaser *et al.* 2019); however, stock biomass of Nile perch in the Kenyan region of Lake Victoria has declined strongly due to intense overfishing, and requires fishing effort reductions of ~40% in order for fish stocks to recover (Gichuru *et al.* 2019).

Increasing domestic fish consumption

Increasing the national average per capita fish consumption from the current 4.7 to 10 kg year^{-1} by 2030 is a central goal of the Kenya Vision 2030 long-term development blueprint (Kimani *et al.* 2018). Reconstructed catches suggest that actual current consumption levels may be higher than reported data would suggest, given that most of the unreported catches are likely consumed locally. However, for average national per-capita consumption rates to reach 10 kg year^{-1}, total catch from the freshwater bodies in Kenya would have to increase from the reconstructed total of 145 000 t year^{-1} in 2017 to ~550 000 t year^{-1} by 2030. This approximate figure takes into account projected population growth (Obiero *et al.* 2019) and assumes that current total marine catches (McAlpine 2019) and aquaculture production, as well as fish imports and exports, remain at 2017 levels (Kenya Fisheries Service 2017).

It is unlikely that Lake Victoria and other freshwater systems in Kenya can support such an increase in required catches to accommodate a 10 kg year^{-1} fish consumption rate, given the 48% decline in total catches since 1999 (see Fig. 2) and the reported declines in fish stocks since 2014 (Aura *et al.* 2020). This decline in catches occurred despite increasing fishing effort (Lake Victoria Fisheries Organization 2017). Declining catches in the presence of increasing fishing effort are a strong signal of substantial declines in the abundance of the underlying fish stocks. Furthermore, these shortfalls are unlikely to be met by Lake Turkana's currently less-fished resources, because it has an estimated maximum sustainable yield of only 30 000 t year^{-1}

(Kimani *et al.* 2018). Fisheries on Lake Turkana are also driven by flooding events, which are now affected by dams on the Omo Gibe river system (I. Cowx, pers. obs.). Increasing the amount of affordable domestically caught freshwater fish that are available for local consumption is of high food and nutritional security importance. Securing a larger portion of domestically caught fish for local consumption could significantly increase fish availability for local consumption, but the higher prices paid for Nile perch in export markets (Abila 2003) makes this a challenging proposition.

Despite the potential utility of Kenya's freshwater resources and fisheries to address food security and rural poverty in Kenya, caution must be used when integrating goals into policy and management, because goals that blindly favour economic development may occur at the expense of ecological sustainability and thus become self-defeating (Spaiser *et al.* 2017). Given the current state of freshwater fisheries in Kenya and the demonstrated high level of overfishing in Lake Victoria (Gichuru *et al.* 2019), as well as the resulting absence for sustainable expansion or growth potential, policy makers should focus on more realistic consumption targets to avoid the risk of implementing policies that may continue to promote and exacerbate overfishing or damaging or unsustainable aquaculture practices. Important commercial stocks are already overfished in Lake Victoria (Gichuru *et al.* 2019), and the waterbody faces considerable pressures due to overfishing, pollution, eutrophication, farming operations, invasive weeds (water hyacinth) and illegal fishing (Muyodi *et al.* 2010). Thus, any management and policy decisions aiming to increase production through aquaculture or capture fisheries must be carefully considered in terms of their environmental and social impacts. Lake Victoria's commercial fisheries are currently operating below their optimum level as a result of highly excessive fishing pressure (fishing effort), which has led to suboptimal fish biomass (Gichuru *et al.* 2019). Rebuilding stock biomass through effectively implemented and enforced fishing effort restrictions is one avenue that could lead to higher catches from Lake Victoria in the longer term; however, effort reductions are likely to affect the livelihoods and food security of surrounding communities in the short to medium term. This calls for government-supported efforts to mitigate the negative social side effects of the urgently required fishing effort reductions, including alternative non-fishing and non-aquaculture livelihood developments and other support programs.

Simultaneously, post-harvest losses are very high around Lake Victoria, estimated to be ~20–40%, and represent a waste of resources (Gichuru *et al.* 2019). Improving preservation and processing capabilities for fishers and local markets may provide an avenue to reduce post-harvest losses and provide a greater local fish supply while reducing waste. Addressing wastage through post-harvest loss reduction is a win–win proposition to help mitigate the needed effort reductions to enable stock rebuilding. Finally, regular monitoring of fish stocks and the environment is strongly recommended to ensure future changes in abundance or conditions can be acted on quickly and effectively.

Recently increasing fish imports appear to be heavily augmenting domestic supply. However, the negative effects of recent increases in Chinese tilapia imports on Kenyan fisher's incomes and livelihoods (Dijkstra 2019) demonstrate that any increases in imports need to be carefully considered to ensure that negative local socioeconomic impacts are minimised. Domestic aquaculture production has increased in recent years and has the potential to be an additional future supplier of domestic fish, as well as supporting Kenyan livelihoods (Obiero *et al.* 2019), with a recent study of small waterbodies in 15 Kenyan counties suggesting aquaculture potential of 72 000 t (Kenya Marine and Fisheries Research Institute, Aquaculture Business Development Programme for Small Waterbodies 2020). However, increasing current production levels from 12 000 t $year^{-1}$ (Kenya Fisheries Service 2017) to a figure large enough to help support a target fish consumption rate of 10 kg $year^{-1}$ would require massive growth (Obiero *et al.* 2019). Furthermore, increasing aquaculture production would increase the dependence on fishmeal as feed, which is associated with a large range of food insecurity issues and environmental challenges, both in Kenya and globally (Abila 2003; Cashion *et al.* 2017; Edwards *et al.* 2019). In recent years, cage culture has increasingly become established in Lake Victoria as a promising venture to increase fish production, promote employment opportunities and enhance economic well-being (Musa *et al.* 2021). However, recent studies have shown that 45% of cages are located within 200 m of the shoreline, which is likely to cause conflict with other lake users. Other concerns related to cage culture include localised eutrophication from excess nutrients, the use of poor-quality feeds that exacerbate eutrophication due to incomplete utilisation, high stocking densities and lack of knowledge and expertise by local cage farmers (Njiru *et al.* 2019). This results in an urgent need to formulate and implement national and regional policies and regulations to reduce the environmental effects and improve the actual net food production potential of cage culture (Aura *et al.* 2018).

Kenya's domestic marine fisheries have the potential for future growth in offshore waters, but would require replacement of the current foreign fleet dominance in these fisheries (McAlpine 2019). Whether such an offshore expansion of domestic marine fisheries would benefit domestic fish supply is also highly questionable, because these fisheries target high-value large pelagic species, such as tuna and billfishes, which generally supply the international trade flow to high-income countries (e.g. in Asia and Europe; Campling 2012). Finally, it is also questionable whether consumption rates as high as proposed by Kenya are truly necessary or beneficial for human health (Vianna *et al.* 2020).

Future data improvements

The freshwater catch time series reported by the FAO on behalf of Kenya between 2008 and 2016 followed a different trend to the data reported nationally by the KeFS (see Fig. 2*a*). This period coincided with an expansion in reported aquaculture production in Kenya (Kenya Fisheries Service 2008, 2016). After consultation with Kenyan fisheries experts, as well as with the FAO Fisheries Statistician, it seems likely that the wild capture data reported by the FAO on behalf of Kenya during the period 2008–16 inappropriately included aquaculture production. Such reporting mix-ups between wild capture data and aquaculture production have also been observed historically in other countries (Welcomme 2011; Bartley *et al.* 2015). Therefore, the Kenyan government should request and resubmit a readjustment of these data to the FAO (Garibaldi 2012) to ensure that total freshwater wild capture fisheries catches and trends from 2008–16 are not misrepresented in the data the FAO presents on behalf of Kenya.

We generated a conservative estimate of Kenya's total freshwater catches that has reassessed the comprehensiveness of existing reported datasets by identifying and filling data gaps in time and space. Assumptions had to be made to estimate catches for periods without anchor points, most notably for waterbodies in the Rivers category due to the very limited information available. However, assumption-based estimates were, in most cases, only for small portions of each waterbody, such as the lower portions of a river (see the 'Methods' section of the Supplementary material for details). We treated all assumption-based estimates conservatively and considered these likely minimal estimates. Future research should focus on identifying additional data and information sources, including *in situ* fisher interviews to improve the accuracy of the various catch components identified in this study. Furthermore, future investigations, as well as official statistics by the Kenyan Government, should consider the fisheries for lungfish (*Protopterus anectens*), which currently may not be accounted for despite being an important fishery in Lake Victoria and the TRD. This likely gap in coverage is mainly due to these catches being taken mostly from wetland areas, and the catches of lungfish generally do not process through an official landing site (W. Nyingi, pers. obs.).

There were some waterbodies in Kenya that we could not include in the present study due to the absence of information, or that we likely did not cover adequately. Future investigations could start filling these gaps with on-the-ground research, potentially linked to food and nutrient security, agriculture, farming and livelihood investigations (see also Kenya Marine and Fisheries Research Institute, Aquaculture Business Development Programme for Small Waterbodies 2020). Furthermore, some recreational freshwater fishing is known to occur in Kenya (Kimani *et al.* 2018). However, we could not identify any catch estimates or readily useable secondary data to allow estimation. Illegal or unregulated fishing activities using illegal gear also occur in Kenyan waterbodies other than Lake Victoria, such as Lake Naivasha (Mutie *et al.* 2021), but were not addressed in this study because no such information was available at the time of data collection. The exclusion of these sources of unreported catches further supports the conservative nature of the unreported catches estimated here and calls for future targeted investigations of such unreported components.

The catch reconstruction undertaken in this study provides a more comprehensive accounting of Kenya's freshwater capture fisheries from 1950 to 2017, particularly when considered alongside the reconstructions of Kenya's marine fisheries by Le Manach *et al.* (2016) and McAlpine (2019). Both the present freshwater and separate marine studies demonstrate the need for improved accounting of catches in national and subsequently international statistics, particularly for the small-scale sectors. However, such improvements in accounting need to avoid or explicitly address any 'presentist bias' in the time series data (Zeller and Pauly 2018). This can help support future management decisions around domestic food security and livelihoods in Kenya.

Data availability

The data presented in this publication are available from the corresponding author.

Conflicts of interest

The authors declare that they have no conflicts of interest.

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