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174

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Front cover photograph shows tea growing in the headwaters of the Tana River in Kenya (*photo:* Matthew McCartney).

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Project

This work was undertaken as part of the Water Infrastructure Solutions from Ecosystem Services Underpinning Climate Resilient Policies and Programmes (WISE-UP to Climate) project. The project generated knowledge on how to implement mixed portfolios of built water infrastructure (e.g., dams, levees, irrigation channels) and 'natural infrastructure' (e.g., wetlands, floodplains, forests) that contribute to poverty reduction; water, energy and food security; biodiversity conservation; and climate resilience at a landscape scale. 'WISE-UP to Climate' aimed to demonstrate the application of optimal portfolios of built and natural infrastructure developed through dialogue with stakeholders and decision-makers at multiple levels (local to national) to identify and find consensus on trade-offs. The project also sought to link ecosystem services to water infrastructural development in the Volta River Basin (Ghana, principally, and also Burkina Faso) as well as the Tana River Basin in Kenya.

The project was led by the International Union for Conservation of Nature (IUCN) and involved the Council for Scientific and Industrial Research - Water Research Institute (CSIR-WRI); African Collaborative Centre for Earth System Science (ACCESS), University of Nairobi; International Water Management Institute (IWMI); Overseas Development Institute (ODI); University of Manchester; and the Basque Centre for Climate Change (BC3). This project was part of the International Climate Initiative. Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit (BMU) (Federal Ministry for the Environment, Nature Conservation and Nuclear Safety), Germany, supported this initiative on the basis of a decision adopted by the German Bundestag.

For further details about the project, visit: http://www.waterandnature.org/initiatives/wise-climate

Collaborators

International Water Management Institute (IWMI)

International Union for Conservation of Nature (IUCN), Switzerland

African Collaborative Centre for Earth System Science (ACCESS), University of Nairobi, Kenya

Basque Centre for Climate Change (BC3), Spain

Council for Scientific and Industrial Research – Water Research Institute (CSIR-WRI), Ghana

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Contents

Acronyms and Abbreviations

AFC	Annual fish catch
CC	Climate Change
GCM	Global Circulation Model
GDP	Gross Domestic Product
GWh	Gigawatt hours
HGF	High Grand Falls
KenGen	Kenya Electricity Generating Company
KES	Kenyan Shilling
KNBS	Kenya National Bureau of Statistics
MW	Megawatts
NCWSC	Nairobi City Water and Sewerage Company
NES	National Environment Secretariat
NI	Natural infrastructure
NWCT	Northern Water Collector Tunnel
NWF	Nairobi Water Fund
PPP	Purchasing Power Parity
RCP	Representative Concentration Pathways
SWAT	Soil and Water Assessment Tool
USD	United States Dollar
WLC	Water level change
WRMA	Water Resources Management Authority

Summary

A study was conducted to explore the synergies and trade-offs between built and natural infrastructure in the Tana River Basin. A simple framework for better understanding the interactions and co-dependencies between water-related built and natural infrastructure was developed. To evaluate the costs and benefits associated with the current built infrastructure, empirical relationships were determined quantifying the links between river flow and ecosystem services. Depending on rainfall, river flow and other factors, the benefits vary from year to year, but a conservative estimate of the average cumulative value of six key water-dependent services (i.e., floodplain grazing, riverbank gardening and recession agriculture, freshwater fisheries, marine and estuarine fisheries, coastal shrimp fisheries and beach nourishment) in the lower basin is USD 152 million per year. The large dams built in the basin have significantly increased overall financial returns by creating new revenue streams (i.e., hydropower and irrigation) and by reducing the adverse impacts of large floods. Overall, average annual revenue has increased to USD 298 million. Nonetheless, the dams have also reduced the benefits that accrue from moderate floods with the greatest losses in the agriculture sector. Although they benefit from increased flood protection, impoverished pastoralists and smallholder farmers lose the most revenue; on average, USD 9.5 million per year. To improve the effectiveness and durability of future development initiatives, policy-makers and decision-makers should: (i) recognize that natural infrastructure in the Tana River Basin represents a national asset, providing valuable services to people living both in, and outside, the basin; (ii) adopt an ecosystem services approach to make clear the synergies and trade-offs between different sectors in different development scenarios; (iii) ensure that environmental and other issues associated with human well-being, such as equity and social inclusion, are considered in decision-making; and (iv) plan and manage natural and built infrastructure in tandem.

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Introduction

Large dams, and other built water infrastructure, have long been a cornerstone of national economic growth and development (Grey and Sadoff 2007). In the face of climate change (CC), there is a broad consensus that, in many places, more is needed to manage water scarcity and, even where rainfall increases, greater variability (McCartney and Smakhtin 2010). However, built infrastructure, in particular large dams, remains highly contentious; in part because of the huge capital costs incurred and in part because of the difficulty of mitigating environmental and social impacts.

In common with many countries in Africa and despite significant economic progress in recent years, inadequate built infrastructure is widely perceived as a drag on economic and social development in Kenya (Oates and Marani 2017). As a result, large dams for hydropower and irrigation, as well as diversions for urban water supply, feature prominently in key policies and strategies intended to drive Kenya's future development and specifically the aims laid out in Vision 2030; the blueprint that guides the country's national development and ambition to be a middle-income economy by 2030. "Modernizing infrastructure" is a priority of the previous (2013-2017) and the current (2018-2022) Medium Term Plans, both of which seek to transform the national economy to one that is high growth, broad based, inclusive and sustainable (GoK 2013a, 2017).

CC is recognized as a threat to economic growth and national development, with droughts, floods and sea level rise being the most pressing climate hazards (GoK 2016). Over the last three decades, rapid warming of the Indian Ocean has resulted in increased convection and precipitation over the sea, thereby contributing to increased atmospheric subsidence over eastern Africa and, hence, decreased rainfall in Kenya during the period March to June (i.e., the long wet season) (Williams and Funk 2011). However, the results from ensembles of global circulation models (GCMs) suggest a reversal of these historic trends, so that East Africa will likely experience a wetter climate with more intense wet seasons, increases in heavy precipitation and less severe droughts by the end of the twenty-first century (Moise and Hudson 2008; Shongwe et al. 2011; Sood et al. 2017).

This study investigated the synergies and trade-offs between built (i.e., engineered) and natural (i.e., managed natural or semi-natural ecological systems) infrastructure for CC adaptation and sustainable development in the Tana River Basin. A recent study concluded that current development plans for the basin have positive but also potentially serious negative effects for various stakeholders, and called for more integrated planning to optimize water resources development and use within the basin. It also called for additional research to better understand the trade-offs associated with different development options (van Beukering and de Moel 2015).

Working with natural processes at a basin scale is a challenge. In contrast to built infrastructure, the evidence base for context-specific understanding of the interlinkages between natural infrastructure and hydrology is largely lacking. Limited quantitative understanding of the benefits natural infrastructure provides and the likely impacts of changing flow regime, resulting from either construction of built infrastructure or climate change, remains a key constraint to pragmatic approaches for incorporation of natural infrastructure in water resource planning and management (McCartney et al. 2013).

The ecosystem services approach clarifies the relationship between ecological processes and human well-being; and in this study, provided the basis for quantifying the interactions between natural and built infrastructure. Trade-off analyses are particularly relevant when considering policies and plans that affect the sustainable provision of benefits from multiple sectors. Based on a simple conceptualization of upstream and downstream services, the study: (i) quantified ecosystem services in relation to current climate, land cover/land use and land management, and flow regime; (ii) evaluated the impact of the existing dams on both flow and downstream ecosystem services; and (iii) determined preliminary economic values for many ecosystem services.

To ensure that the evidence produced in the study was appropriate for the realities of decision-making, an "action-learning" process was conducted. This comprised meetings every 6 months, with decision-makers and a range of stakeholders and stakeholder representatives, over the 3-year duration of the project. At the meetings, project methods and findings were presented, discussed and, to the extent possible, verified. Where appropriate, based on feedback received, approaches were modified and results presented in ways more amenable to the group. A forthcoming report will provide more details of this process (Dalton and Welling Forthcoming).

Natural Infrastructure and Interactions with Built Infrastructure

Natural infrastructure comprises features of the natural world (e.g., wetlands, forests, grasslands) that provide important benefits to people. These benefits are provisioning services such as food and water, regulating services such as flood and disease control, cultural services such as spiritual, recreational and cultural benefits, and supporting services such as nutrient cycling (Table 1).

In the past, the value of these ecosystem services went largely unrecognized in economic and financial decision making; typically overlooked or perceived simply as "free"/"public" goods. In recent years, there has been an increasing recognition that ecosystem services are valuable economically. Increasingly, the case is made to maintain and invest in them to ensure that they continue to sustain both human well-being and national economies (Kubiszewski et al. 2017).

In the context of water resources,the interactions between natural and built infrastructure occur via water-dependent ecosystem services. In this study, two broad types of services were recognized (Figure 1; Annex A): (i) *upstream services* - relate to the way natural infrastructure located upstream of built infrastructure, by affecting hydrological processes (e.g., runoff and groundwater recharge), influences the performance (and hence the benefits) derived from built infrastructure; and (ii) *downstream services* - relate to how built infrastructure, by affecting the timing and magnitude of water, sediment and nutrient fluxes, influences the benefits derived from downstream natural infrastructure (Table 2).

Upstream services were quantified directly in terms of the hydrological characteristics of sub-basins. Downstream services were quantified in terms of "benefit functions" which, in the context of water, are empirical relationships that quantify the link between river flow, water level or storage to the benefits that people derive from that water.

Benefit functions provide a mechanism for quantifying the impacts of altered flow regimes, caused by the presence and operation of built infrastructure. The impact of existing dams on the downstream benefits in the Tana River Basin was determined.

TABLE 1. Classification of different types of ecosystem services.

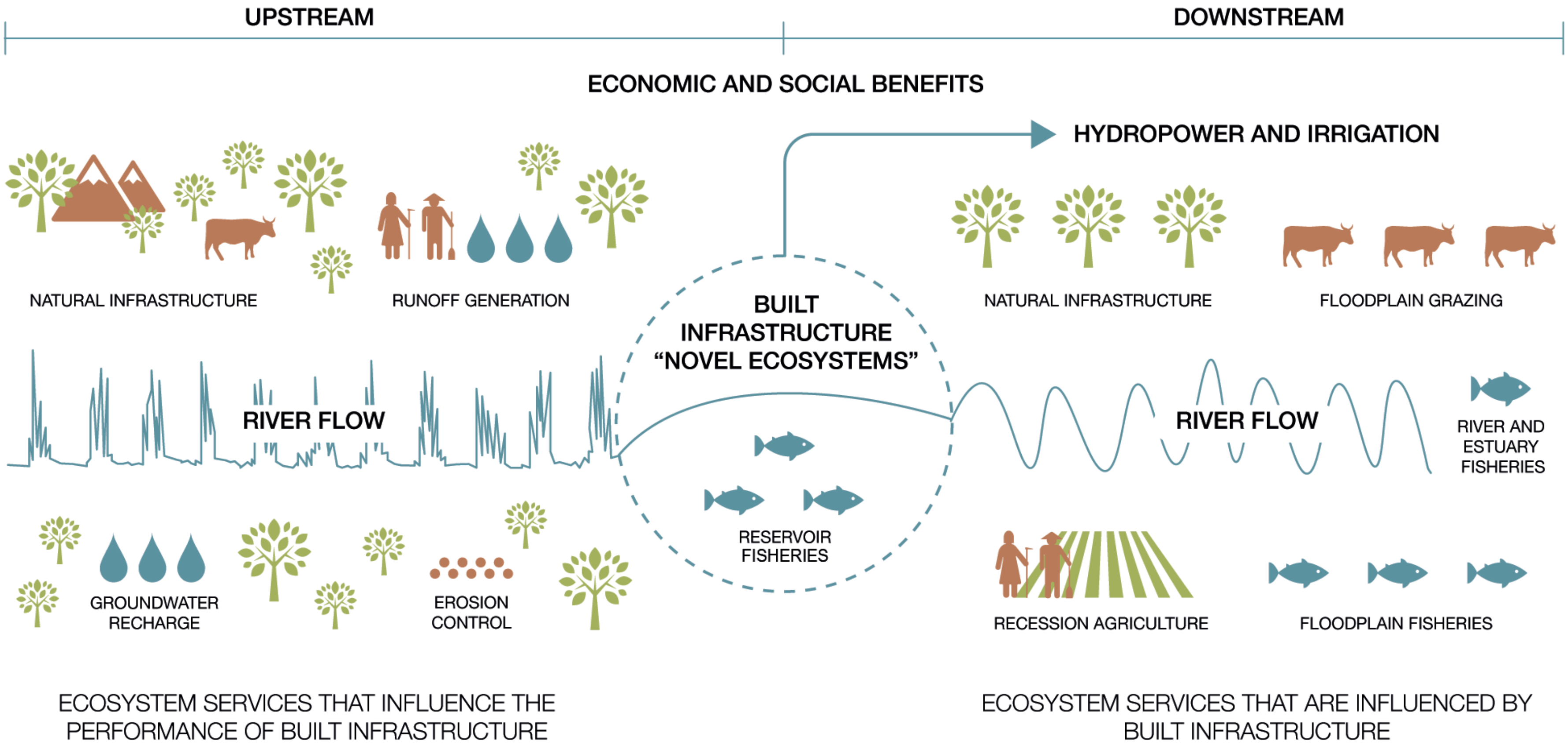
Provisioning services	The products obtained from ecosystems, including, for example, genetic resources, food and fiber, and freshwater.
Regulating services	The benefits obtained from the regulation of ecosystem processes, including, for example, the regulation of climate, water, and some human diseases.
Cultural services	The nonmaterial benefits people obtain from ecosystems through spiritual enrichment, cognitive development, reflection, recreation, and aesthetic experience, including, for example, knowledge systems, social relations, and aesthetic values.
Supporting services	Ecosystem services that are necessary for the production of all other ecosystem services. Some examples include biomass production, production of atmospheric oxygen, soil formation and retention, nutrient cycling, water cycling, and provisioning of habitat.

Source: MA 2005.

TABLE 2. Interaction between natural and built infrastructure.

	Description
Upstream services	Characteristics of the hydrological regime, affected by natural processes that are influenced, often in complex ways, by the biophysical characteristics, and hence functions, of the catchment upstream of built infrastructure. Typically, they affect the rainfall-runoff response of a catchment: splitting rainfall between event-based and longer-term runoff, and evaporation. This, in turn, determines the water yield of a catchment, extent of groundwater recharge,magnitude of natural flow regulation and sediment yield, all of which affect the technical performance of built infrastructure. The specific catchment characteristics that influence runoff and soil erosion are: vegetation, soil, geology, slope and catchment size (Chorley 1969). Land use and land cover, and hence land management practices, can also modify processes and provide a means by which landscapes can be managed to influence the upstream services and improve the performance of built infrastructure. For example, investments in afforestation, reforestation, riparian buffer strips and terracing affect both runoff and soil erosion that, in turn, affect the reliability, resilience and vulnerability of downstream dams.
Downstream services	A function of alteration of downstream flow and other fluxes which can significantly affect ecosystem services provided by natural infrastructure located downstream of built infrastructure. For example, the most common impact of a dam is increased flow regulation; a decrease in flood peaks and an increase in low flows. In addition, trapping of sediments in a reservoir and changes to the chemical composition of the water released downstream of a dam, result in complex alteration of downstream riparian ecosystems, affecting terrestrial and aquatic flora and fauna. This, in turn, affects ecosystem services such as freshwater and nearshore marine fisheries, floodplain grazing and flood-recession agriculture, as well as river and coastal geomorphology.

FIGURE 1. Conceptualization of the interaction between built and natural infrastructure in a basin.



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The Tana River Basin

The Tana River Basin, located in the southeastern part of Kenya, is one of six major river basins in the country (Figure 2). With an area of 95,000 km^2, it covers 17% of the country's land area and supports the livelihoods of some 6.5 million people, the majority of whom (5.3 million) live in the upper 17,000 km^2 of the basin (TNC 2015). The upper basin includes two of Kenya's 'water towers': the Aberdare Mountains and Mount Kenya. Mean annual discharge into the Indian Ocean is 5,175 million cubic meters (Mm^3).

The Tana River is the principal water source for Kenya's capital city, Nairobi, and, with an installed capacity of 547 megawatts (MW) in five hydropower schemes (built between 1968 and 1988), produces around 70% of the country's hydroelectricity, which in turn constitutes approximately 40% of Kenya's total generation (Baker et al. 2015). The total cultivated area in the basin is estimated to be approximately 1 million hectares (Mha), of which 68,700 ha is currently irrigated (Hoff et al. 2007), but with significant potential for further expansion. An estimated 288,600 ha of large-scale irrigation are planned by the year 2030 (GoK 2013b).

Many rural communities in the basin rely on river-dependent ecosystems for crop production, livestock keeping and fisheries (Baker et al. 2015). The Tana Basin is also the site of numerous conservation efforts, recreation and tourism activities, containing several national parks and reserves. However, socioeconomic and biophysical changes are increasing the pressure on the Tana River Basin ecosystems. Challenges that decision-makers face in the medium- and long-term relate to growing human population, increasing demands for water across all sectors, periodic droughts and floods, and CC (Oates and Marani 2017).

Several of the flagship projects identified in Kenya's Vision 2030 and in the National Water Master Plan 2030 lie in, or are dependent on, water transfers from the basin (GoK 2013b). For example, to meet the needs of Nairobi's growing population and industries, the Northern Water Collector Tunnel (NWCT) will transfer water from the upper catchment to Nairobi and its satellite towns. Further downstream, the Kenyan government is proposing to build a large dam – the High Grand Falls (HGF) Dam (storage capacity 5,000 Mm^3) – for hydropower (500-900 MW), irrigation (180,000 ha), water supply to the coastal town of Lamu, and for downstream flood protection (Oates and Marani 2017). Both projects are controversial.

Upstream Natural Infrastructure

Upstream ecosystem services are affected by land use and management practices, and therefore can be influenced by human agency. There is increasing awareness of the role that natural infrastructure can play in safeguarding the quantity and quality of downstream water resources, particularly in relation to city water supplies (Ozment et al. 2016). However, constraints remain in terms of quantifying impacts.

In the Tana River Basin, the Nairobi Water Fund (NWF) has established a funding mechanism for investing in upstream natural infrastructure, with part of the justification being reduced sediment to the downstream reservoirs. In this study, hydrological and soil retention services in the Upper Tana River Basin (Table 3) were quantified and the possible implications of CC for these services was determined.

FIGURE 2. Map of the Tana River Basin.

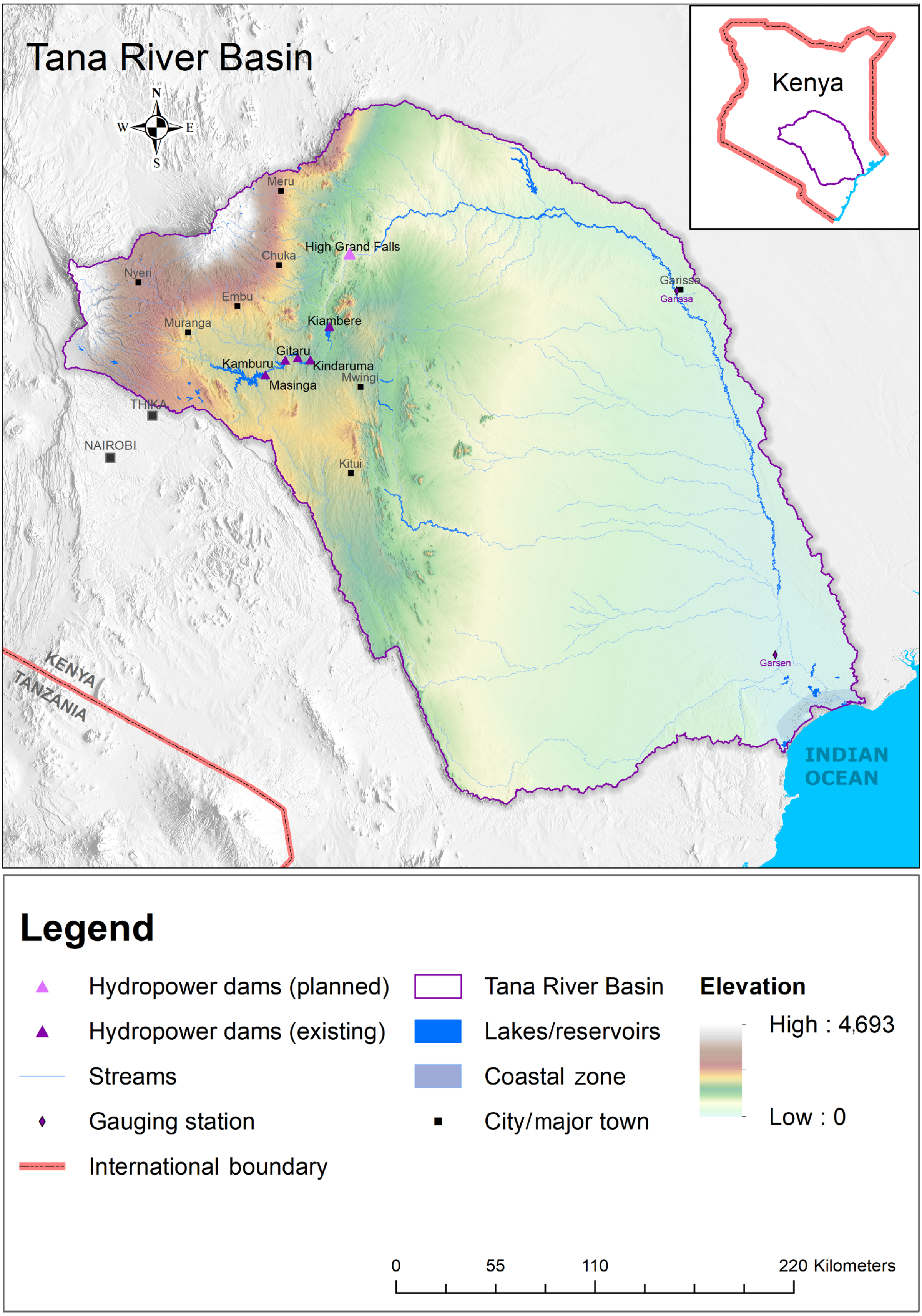


TABLE 3. Benefits from natural infrastructure located upstream of built infrastructure.

Benefit	Description
Water yield	The total water produced in a catchment that flows out of the catchment and is not evaporated. It is a function of the meteorological (i.e., rainfall, temperature, etc.) and physical (i.e., topography, land use and land cover) characteristics of the catchment. Water yield represents the total “useable” water available in the catchment. Changes in a catchment that affect annual average water yield will increase or decrease the total volume of water supply to downstream built infrastructure, including dams.
Baseflow	The portion of streamflow that comes from deep subsurface flow and delayed shallow subsurface flow. The baseflow depends upon the aquifer properties and amount of groundwater recharge that takes place within a catchment, which is in part determined by the biophysical characteristics of the catchment. A reservoir storage-yield relationship indicates the water yield that can be guaranteed for a human built reservoir of a given volume. This is a function of baseflow; the greater the baseflow, the smaller the reservoir needs to be in order to reliably provide a specified yield.
Flow regulation	The ratio of dry-season flow to total flow in a stream. Upstream of built dams, dry-season flow is made up of baseflow and water released from natural water storage (e.g., lakes, ponds and aquifers). The greater the natural flow regulation of catchments upstream of a dam, the less storage is required and the smaller the dam can be for a given reservoir yield.
Soil retention	Factors affecting the rate of soil erosion across a landscape include: rainfall (intensity and distribution), soil type (i.e., texture and structure), topography (i.e., slope), vegetation cover and land management. These affect runoff, the amount of soil washed from hillslopes and ultimately the destination of the sediment. Human ability to manage land cover and land practices provides the opportunity to enhance these processes for downstream benefits.

Hydrological Services

The Soil and Water Assessment Tool (SWAT) was used to quantify hydrological processes classified as upstream ecosystem services. This spatially distributed model was configured and calibrated for the current situation, and then used to determine the possible impact of CC from results obtained from an ensemble of 12 GCMs. Changes in the upstream ecosystem services were determined for two representative concentration pathways[1] (i.e., RCP 4.5 and RCP 8.5) (see Sood et al. 2017 for details).

Results were derived for hydrological characteristics comprising the upstream ecosystem services, three of which are presented here: water yield, baseflow and flow regulation (Table 3). Using the model, average annual values were obtained for a total of 368 sub-catchments for the period 1983-2011 (Figure 3) and summarized for each RCP, for two elevation zones (i.e., upper and lower) over three future 30-year time periods (i.e., 2020-2049, 2040-2069 and 2070-2099) (Table 4).

The results show considerable heterogeneity in the response to rainfall, with differences between the elevation zones. Currently, water yield and baseflow decline with altitude, but flow regulation is fairly uniform across the basin (Table 4). The results of the CC analyses confirm those of earlier studies, indicating an increase in rainfall at the end of the twenty-first century. They also indicate increases in both water yield and baseflow, with the greatest increases experienced under RCP 8.5 (Table 4). In addition, detailed analyses indicated large increases in the magnitude and frequency of floods, with change increasing over time to the end of the twenty-first century (Sood et al. 2017).

[1] Representative Concentration Pathways (RCPs) are time- and space-dependent trajectories of concentrations of greenhouse gases and pollutants resulting from human activities, including changes in land use. RCPs provide a quantitative description of concentrations of the climate change pollutants in the atmosphere over time, as well as their radiative forcing in 2100 (for example, RCP 4.5 achieves an overall impact of 4.5 watts per square meter by 2100). The word “representative” signifies that each RCP provides only one of many possible scenarios that would lead to the specific radiative forcing pathway. Radiative forcing is a measure of the additional energy taken up by the Earth system due to increases in climate change pollution (van Vuuren et al. 2011).

FIGURE 3. Spatial distribution of the annual average hydrological outputs from the SWAT model for the Tana River Basin for the baseline scenario. (a) water yield, (b) baseflow, and (c) flow regulation.

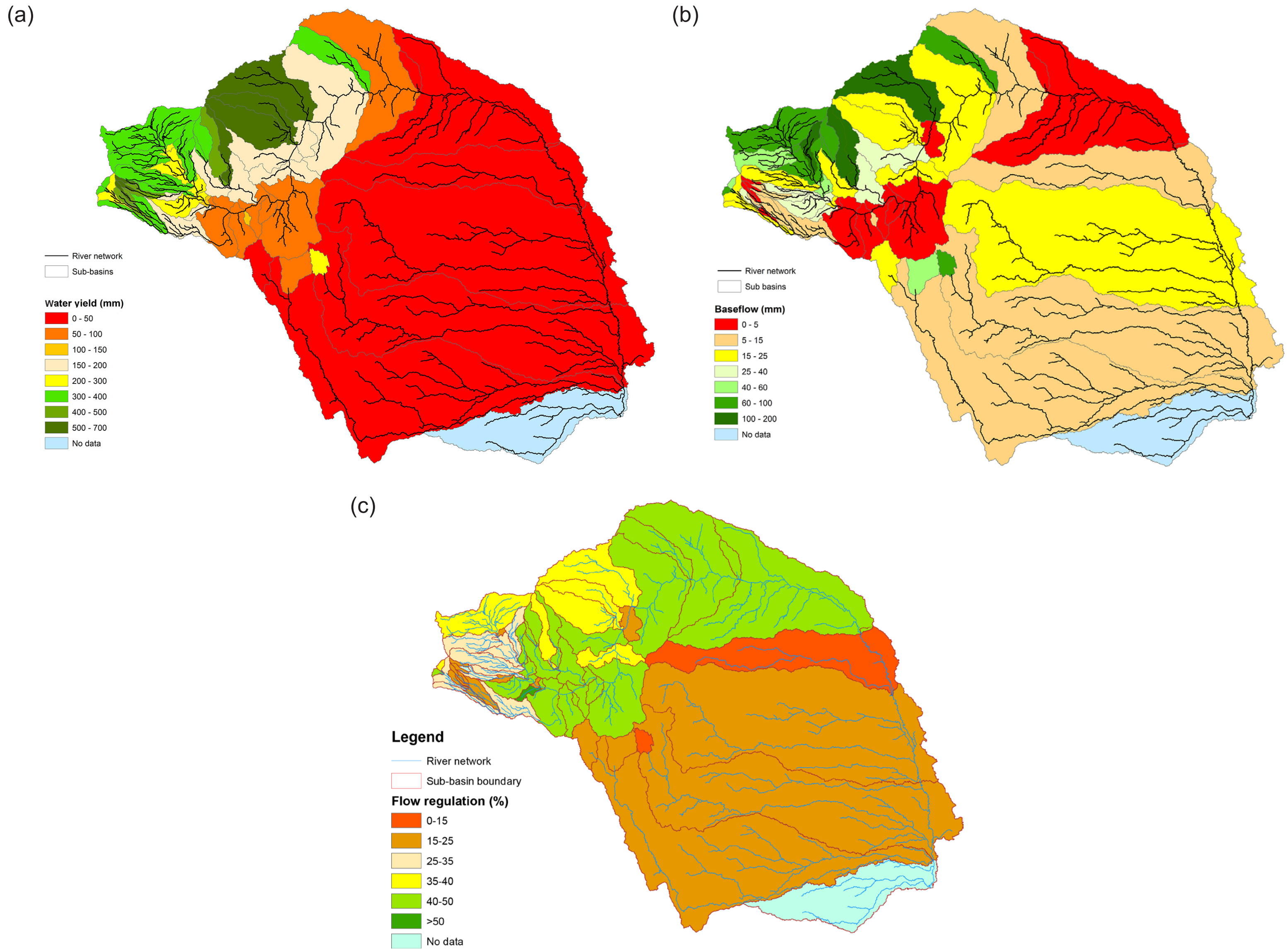


TABLE 4. Annual averages of hydrological variables and "upstream" ecosystem services in the three zones of the Tana River Basin for the current and future scenarios, under RCP 4.5 and RCP 8.5.

Elevation zone+	Current				2020-2049				2040-2069				2070-2099			
	Rainfall (mm)	Water yield (mm)	Baseflow (mm)	Flow regulation (%)	Rainfall (mm)	Water yield (mm)	Baseflow (mm)	Flow regulation (%)	Rainfall (mm)	Water yield (mm)	Baseflow (mm)	Flow regulation (%)	Rainfall (mm)	Water yield (mm)	Baseflow (mm)	Flow regulation (%)
					RCP 4.5											
Upper	915	222	43	37	991	327	79	35	1,019	349	88	35	1,090	402	105	31
Lower	476	18	4	41	535	42	13	35	563	55	20	34	590	76	33	34
Average	640	94	19	39	706	149	38	35	733	165	46	34	777	198	60	33
					RCP 8.5											
					1,018	348	85	35	1,039	357	88	35	1,270	545	147	31
					541	49	16	35	562	57	21	34	671	120	56	33
					719	161	42	35	740	169	46	34	895	279	90	32

Note: + Upper comprises the sub-catchments with an average altitude greater than 600 meters above sea level (masl), and Lower comprises sub-catchments with an average altitude less than 600 masl.

Soil Retention

In the upper catchments of the Tana River Basin, steep slopes and high population densities coupled with deforestation and intensive land use have resulted in increased soil erosion and, hence, riverine sediment loads (TNC 2015). Increased sediment loads are increasing the costs of water treatment for Nairobi and resulting in increased sedimentation in the downstream reservoirs. It is estimated that Masinga and Kamburu reservoirs have lost 10% and 15% of their capacity since they were commissioned in 1981 and 1983, respectively (WRMA 2011).

The NWF is predicated on the fact that improved land management in the upper catchment will reduce soil erosion and improve dry-season river flow, which in turn will cut the cost of water treatment for Nairobi, decrease build-up of sediment in the downstream reservoirs and improve hydropower generation. The business case for the fund postulated that a USD 10 million investment in targeted interventions (i.e., riparian management, agroforestry, terracing on steep hillslopes, reforestation, grass strips on farms and mitigation of road erosion) over 10 years would likely return USD 21.5 million over 30 years (TNC 2015).

One limitation of the study conducted by TNC (2015) is that it did not quantify the possible impacts of CC. In the current study, the possible impacts of CC on runoff, erosion and sediment fluxes in the Upper Tana Basin (i.e., upstream of the Masinga Reservoir) were determined. The analyses provided insight into how CC might influence the biophysical effectiveness of different land management practices implemented through the NWF (Simons et al. 2017). The same SWAT model that was developed for the NWF Business Case was used (Vogl et al. 2017) and the simulations were carried out for the Thika watershed; one of the main catchments draining into the Masinga Reservoir. Impacts on sediment yield were then up-scaled to the entire Upper Tana Basin using results from previous assessments that determined the relative contribution of the Thika watershed to the total input to the Masinga reservoir. The same CC scenarios were used as described above (Simons et al. 2017).

The results of the modelling indicate that CC is likely to have considerable impacts on flows and sediment, but the magnitude of change is very much dependent on the model projection (Simons et al. 2017). Different model projections indicate CC-induced changes in sediment yields (i.e., before proposed interventions) ranging from a 50% reduction to a 60% increase, relative to the current baseline. Inter-annual variability was found to increase in nearly all cases. The impacts of CC on the NWF portfolio of investments determined that, even under future climates, the interventions resulted in reduced runoff and soil erosion, causing considerable reductions in river sediment loads. Although there was a lot of variation among the projections, overall, the relative impact of the NWF investments under CC was similar to that predicted under the current climate; an approximate decrease of 40% in sediment yield from the Thika watershed to the end of the twenty-first century (Simons et al. 2017). Hence, targeted investments in natural infrastructure in the upper basin will not eliminate the problem but have the potential to reduce reservoir sedimentation under both existing and possible future climates (Figure 4).

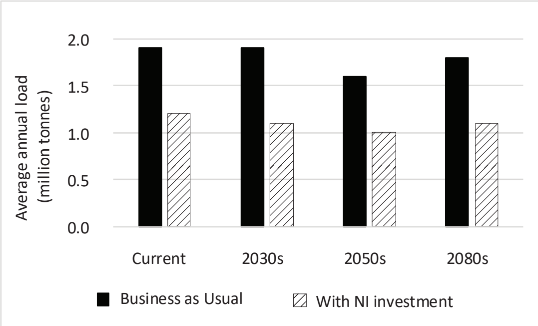
Built Infrastructure

Benefits

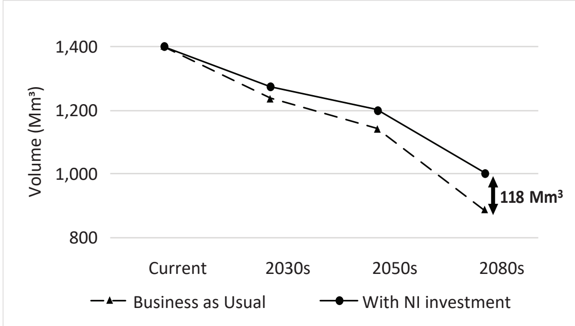
The built infrastructure, specifically the large dams, was constructed to generate benefits from hydropower, irrigation and flood control (Annex B). In addition, although not a primary reason the dams were built, increased fisheries are also a benefit, supporting the livelihoods of many hundreds of people (Table 5).

FIGURE 4. Impact of investments in natural infrastructure on: (a) sediment yields from the Thika/Chania catchment, and (b) water storage volume in the Masinga reservoir.

(a)



(b)



Source: Based on data presented in Simons et al. 2017.
Note: NI – Natural infrastructure.

The Impacts of Built Infrastructure (Dams) on Flows

The dams in the Tana River Basin regulate flows: decrease flood peaks and increase low flows. The extent to which they do so and hence the impact they have on the downstream benefits derived from natural infrastructure (see below) is dependent on both the total storage capacity of the reservoirs and the way the dams are operated. Total storage in the five large reservoirs on the main river is 2,331 Mm^3 (i.e., 45% of the mean annual discharge) (Table 6).

As a first step to determining the impact of the dams on downstream ecosystem services, records of historic flow were analyzed. Flow analyses were conducted at Garissa, the most downstream station for which reliable flow records – provided by the Kenya Water Resources Management Authority (WRMA) – were available. Data are also available closer to the Delta, at Garsen, but there are significant gaps in the time series and, because of transmission losses and regular overbank flooding, a lot of uncertainty about the relationship between flow at this station and flow at Garissa. Consequently, flow at Garissa was used to determine benefit functions for all downstream ecosystem services.

In its natural cycle, the Tana River experienced biannual floods with peaks in May and November. River flows in May (associated with the long rainy season from April to June) were generally higher and less variable than flows in November (associated with the short rainy season from October to November). The low flow periods corresponded to the end of the dry season in the upper catchment. The lowest river flows occurred during the period February to March and September to October (Figure 5).

Although the Kindaruma, Kamburu and Gitaru dams were constructed between 1968 and 1978, they had relatively little storage and produced little flow regulation. Construction of the Masinga and Kiambere dams between 1978 and 1988 resulted in much greater flow regulation at Garissa. Since 1989, the median flows in May has declined from 840 Mm^3 (313 m^3s^{-1}) to 681 Mm^3 (254 m^3s^{-1}). Median flows in October to December – including high flow periods - have increased by, on average, 50%. Flows in the dry season, January to March, have increased by, on average, 95% (Figure 5).

Flow duration

A flow duration curve shows the relationship between any discharge and the percentage of time that discharge is exceeded. Figure 6 summarizes the results of flow duration analyses conducted at Garissa for the two periods 1941-1979 and 1989-2013. The graphs illustrate the decrease in flood flows (Q10 and Q5) and the increase in low flows (Q95 to Q25) after dam construction.

TABLE 5. Benefits derived from built infrastructure.

Benefit	Description	Benefit
Electricity	Electricity generation is the primary purpose for the construction of dams in the Tana River Basin. All the Tana schemes are operated by the parastatal Kenya Electricity Generating Company Ltd (KenGen). Electricity is vital for broad national development, with a range of both direct and indirect benefits. Currently, Kenya has electrification rates below the average for sub-Saharan Africa, with an overall connection of just 56% (i.e., 78% and 39% for urban and rural areas, respectively) (World Bank 2017).	Although higher river flows enable greater electricity generation, the presence of water storage has largely decoupled hydropower from flow (Annex B). The firm energy generation target from the Tana schemes is 172 $GWhmonth^{-1}$ (i.e., 2,064 $GWhy^{-1}$). Over the years 2005 to 2015, average annual energy generation was 2,558 $GWhy^{-1}$, approximately 48% of all electricity generated by KenGen (Annex B).
Irrigation	Irrigation is viewed by the Kenyan government as critical for food security, national development and adaptation to CC. Based on data in the National Water Master Plan, formal irrigation in the Tana Basin is estimated to cover 68,700 ha from a potential of about 300,000 ha. Much of the existing irrigation is in the Upper catchment (e.g., for rice, fruit and tea), but much of that planned is in the lower basin to make use of flows released from the reservoirs. Currently, though there are plans for rehabilitation and significant extension, functioning formal irrigation in the lower basin is estimated to be less than 8,000 ha (Annex B).	Inter- and intra-annual differences in irrigation demand depend on variations in rainfall, irrigation efficiency and crops cultivated. The dams have increased dry-season flows in the Lower Tana Basin (see above), and although volumes abstracted for irrigation are not known, water availability is not currently a constraint for the existing irrigation schemes.
Reservoir fisheries	Fisheries is a secondary benefit of reservoirs that is often promoted by dam proponents as a benefit for local communities. The potential fisheries yield of reservoirs is a function of size, depth, availability of habitats and natural food for fish. Fluxes of organisms, detritus, nutrients and other materials into the reservoir strongly affect primary productivity (not least through impacts on turbidity) and hence food webs and fisheries productivity. Smaller, shallower reservoirs tend to be more productive than large and deep ones (Jackson and Marmulla 2001). Limiting annual water level fluctuation and drawdown rates in the reservoir tends to increase fisheries productivity (Bernacsek 1997).	Masinga, Kamburu and Kiambere reservoirs support 800 fishermen, many of whom sell the fish as far afield as Nairobi (Jumbe 2003). To quantify the benefits in relation to water management options, empirical relationships were derived for the Masinga and Kamburu reservoirs that linked annual fish catch to water level changes (Annex B). There were no fisheries data for the Kiambere reservoir.
Flood control	As well as benefits (discussed below), flooding in the Lower Tana Basin also has costs associated with destruction of infrastructure, damage to crops, loss of livestock and disruption to people's lives and livelihoods. In the Lower Tana Basin, flooding caused major displacement of people in 1997/1998, 2007/2008 and again in 2013 (Kiringu 2015), and led to large economic losses. By increasing flow regulation and attenuating flood peaks, the dams in the basin mitigate some of the adverse impacts of large floods.	A flood "cost" function was developed, which integrated the economic costs across all sectors for a range of flood frequencies. The impact of the dams on the costs of flooding was deduced based on the dam modified flood frequency regime.

TABLE 6. Characteristics of the hydropower dams on the main stem of the Tana River.

Dam	Year of commissioning	Catchment area (km²)	Storage (Mm³)		Installed generating capacity (MW)
			Live	Total	
Kindaruma	1968	9,807	7.5	16.0	44
Kamburu	1974	9,520	123.0	150.0	94
Gitara	1978	9,520	12.5	20.0	225
Masinga	1981	7,335	1,410.0	1,560.0	40
Kiambere	1988	11,975	485.0	585.0	144

Source: Adapted from Baker et al. 2015.

FIGURE 5. Flow at Garissa: Pre- and post-major dam construction in the middle basin.

Month	Median monthly flow (m^3s^{-1})	
	1941-1979	1989-2013
Jan	218	424
Feb	154	287
Mar	167	327
Apr	449	546
May	840	678
Jun	475	388
Jul	267	293
Aug	237	257
Sep	184	230
Oct	194	321
Nov	492	563
Dec	413	696

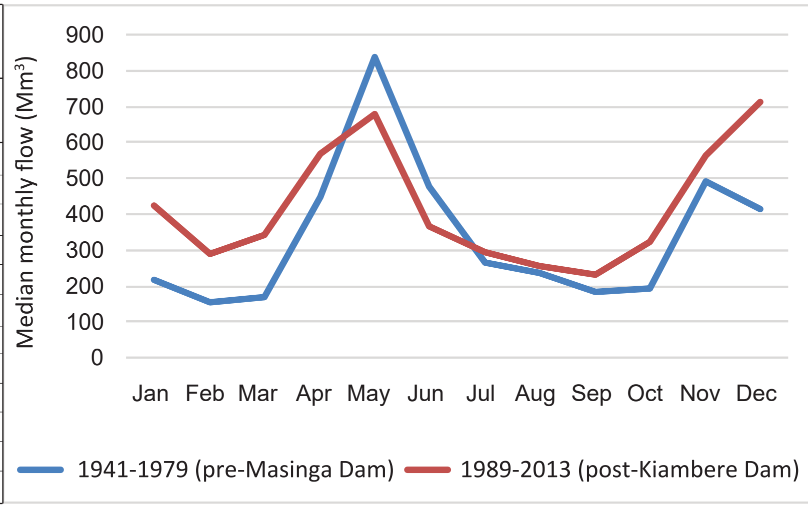
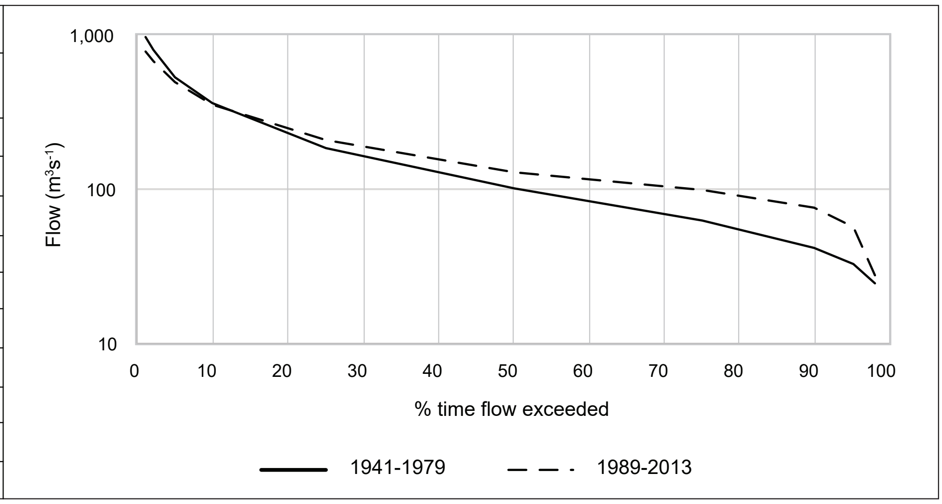


FIGURE 6. Comparison of flow duration curves at Garissa before and after construction of the dams.

Percentile	Flow (m^3s^{-1})	
	1941-1979	1989-2013
98	24.7	27.5
95	32.7	56.8
90	41.2	75.3
75	63.0	97.4
50	102.0	129.3
25	185.7	207.1
10	361.0	350.9
5	530.6	492.1
2	792.3	669.7
1	971.8	776.2

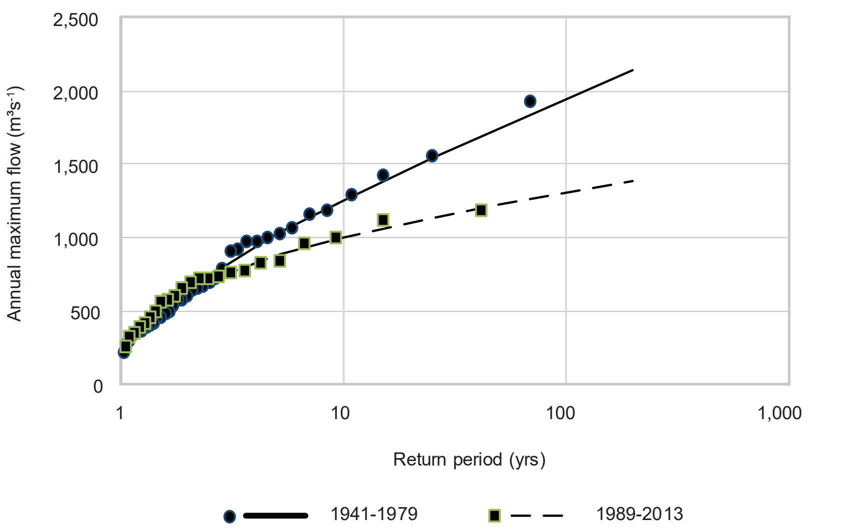


Flood frequency

At Garissa, annual maximum (flood) flows have been altered by the construction and operation of the dams. A statistical distribution (Pearson type 3) fitted to the series of annual maximum flows indicates a clear shift in floods between the two periods, 1941-1979 and 1989-2013 (Figure 7). Furthermore, there has been a change in the occurrence of maximum floods. Prior to 1979, 70% of annual maximum floods occurred during the period April to May. After 1989, only 40% of annual maximum floods occurred in these months and they were much more likely to occur in the period October to December. It is not only the change in magnitude but also the alteration of timing that could have significant impacts on the ecology and ecosystem services of the basin.

FIGURE 7. Comparison of flood frequency at Garissa before and after dam construction.

Return period, T (years)	Flood magnitude (m^3s^{-1})	
	1941-1979	1989-2013
1.1	272	347
1.3	419	430
1.5	510	552
1.8	607	622
2	658	656
5	1,022	875
10	1,256	997
25	1,541	1,133
30	1,596	1,158
50	1,747	1,224
100	1,946	1,308
200	2,141	1,388



Downstream Natural Infrastructure

Benefits

Downstream ecosystem services provide benefits for large numbers of people in the Lower Tana Basin. These services are directly dependent on river flow. Modifications of the flow by the dams has affected the benefits derived. It is likely that future built infrastructure (e.g., the HGF Dam) will affect flows further (van Beukering and de Moel 2015).

Benefit functions were derived for six downstream ecosystem services deemed most important for the livelihoods of significant numbers of people, and for which data were available to enable relationships to be determined. The benefit functions were classified into two groups:

- Benefits associated with flooding in the Lower Tana Basin: floodplain grazing, riverbank gardening and recession cultivation, and floodplain fisheries.
- Benefits associated with river discharge to the sea: nearshore coastal marine and estuarine fisheries, coastal shrimp fisheries, and beach nourishment.

In each case, multiple regression analyses were conducted to determine the relationship between a measure of the benefit and one or more flow characteristics (Table 7). Since all the ecosystem service benefits are a function of dynamic flow, they were all derived in relation to flows with specific return periods (i.e., 1.8, 2, 5, 10, 25 and 50 years) (see Annex C for details).

In the case of the benefits of flooding, the independent variable used was flood extent. Consequently, it was necessary to define a relationship between flows in the river and flood extent. High flows at Garissa generate floods both along the river between Garissa and Garsen and downstream of Garsen, in the delta. The active floodplain area between Garissa and Garsen is approximately 900 km^2 (Omengo et al. 2016) while it is about 400 km^2 in the delta (Leauthaud et al. 2013).

Relationships were derived between 30-day cumulative flow at Garissa and the flood extent. The areal extent of inundation has been determined – from satellite images - for several floods in the delta and between Garissa and Garsen (Leauthaud et al. 2013; Omengo at al. 2016). In both cases, strong correlations were found between the cumulative flow at Garissa and the flood extent (Figure 8).

TABLE 7. Ecosystem services derived from natural infrastructure downstream of the dams. Details of the benefit functions derived are presented in Annex C.

Ecosystem service	Description/location	Benefit function
	Benefits accruing from flooding in the Lower Tana	
Floodplain grazing	Pastoralism is a key livelihood activity in the Lower Tana Basin. During the dry season, both the floodplain between Garissa and Garsen and the delta provide grazing grounds for large herds of cattle, goats, sheep and camels. In 2009, according to the Tana River County census (which covers the river south of Garissa), 240,000 people were found to depend on livestock for their livelihoods (KNBS 2010). Furthermore, pastoralists from outside the basin, as far afield as the border with Somalia, come to graze livestock in the delta. Typically, livestock numbers grazing on the floodplain exceed 1.5 million during the dry season, and comprise a significant proportion of the national herds of cattle and sheep/goats (GoK 2015).	Relationship between flood extent and the number of cattle that can be grazed on the Tana floodplain: TH = 844,131 (FA = 0) TH = 1,015.4FA + 844,131 (FA > 0) Where: TH = number of grazing livestock FA = inundated area downstream of Garissa and in the delta (km^2)
Riverbank gardening and recession cultivation	About 115,000 people practice flood-recession and riverbank farming along the Tana River, which provides the only source of land in the region that is suitable for arable agriculture (IUCN 2003). This occurs primarily between Garissa and Garsen, but there is also some practiced in the Delta. Farmers practicing flood-recession agriculture benefit from both the floodwaters, which effectively irrigate their crops, and the deposition of fertilizing sediments.	Relationship between flood extent and area that can be cultivated on the Tana floodplain: Pre-dam construction CA = 3,000 (FA = 0) CA = 15FA + 3,000 (0 < FA ≤ 597) CA = 10,365 (FA > 597) Post-dam construction CA = 3,000 (FA = 0) CA = 15FA + 3,000 (0 < FA ≤ 491) CA = 10,365 (FA > 491) Where: CA = cultivated area (ha) FA = inundated area downstream of Garissa and in the delta (km²)

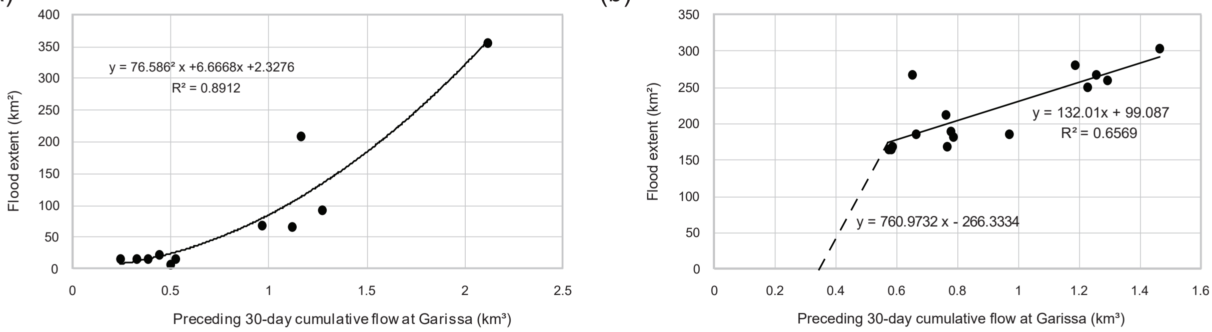
(Continued)

TABLE 7. Ecosystem services derived from natural infrastructure downstream of the dams. Details of the benefit functions derived are presented in Annex C. (Continued)

Ecosystem service	Description/location	Benefit function
Floodplain and delta freshwater fisheries	In the Tana River Basin, floodplain wetlands, lakes, and other aquatic habitat support large freshwater fisheries. Overbank flooding of the floodplain and delta is necessary to ensure that freshwater habitat (particularly in the form of oxbow lakes (i.e., Shkababo, Kongola and Bilisa) is maintained (Leauthaud et al. 2013). The total freshwater catch (primarily Tilapia, *Clarias spp* and *Protopterus spp*) is estimated to be up to 500 ty^{-1} based on the river's catchment area (Welcomme 1985). However, the National Environment Secretariat (NES) presents freshwater catch data for the Tana River District, which indicates catches ranging from 59 to 705 ty^{-1} in the years 1979 to 1983 (NES 1985).	Relationship between flood extent in the delta and freshwater capture fisheries in the Lower Tana River: $RFC = 0.0033DFA^2 + 0.3414\ DFA + 40$ Where: RFC = annual river fish catch (tonnes) DFA = delta flooded area (km^2)
	Benefits accruing from river discharge into the sea	
Marine and estuarine fisheries (excluding shrimp)	The Tana River flows into the northern end of the Ungwana Bay, which supports one of East Africa's major fisheries. Small-scale inshore fisheries are the mainstay of over 3,000 artisanal fishers in the bay (Munga et al. 2012). Many factors, both biophysical and socioeconomic, affect fish catches in nearshore coastal waters. There is often a positive correlation between river runoff (particularly wet-season runoff) and coastal catches. This is attributable to land-based nutrient input into the sea via river or coastal rainfall leaching, which effectively fertilizes the coastal water thereby providing food for fish (Hoguane and Armando 2015).	Relationship between annual flow at Garissa and nearshore marine fisheries (excluding shrimp) in Ungwana Bay: $UBC = 0.1195Q_A + 342.07$ ($R^2 = 0.40$) Where: UBC = annual Ungwana Bay catch (tonnes), excluding shrimp Q_A = total annual flow at Garissa (Mm^3)
Shrimp fisheries	As a consequence of nutrient input from the Tana and Athi rivers, the Ungwana Bay is a very productive shrimp ground. Unsustainable trawling was a threat to the shrimp fisheries in the early 2000s and led to a trawl ban in 2006. Subsequently, artisanal catches have recovered, but remain low (Munga et al. 2012).	Relationship between flow at Garissa and shrimp catch in Ungwana Bay: $SC = 0.002924\ Q_{(A\text{-}J)} + 0.113382952Q_F + 21.80516$ Where: SC = annual shrimp catch (t) $Q_{(A\text{-}J)}$ = total wet-season (April to June) flow at Garissa (Mm^3) Q_F = total dry-season (February) flow at Garissa (Mm^3)
Beach nourishment (prevention of beach erosion) in an area of high tourism	In contrast to the upper catchment where elevated river sediment loads are a problem (see above), in the lower basin, river sediment loads enhance benefits both from the floodplain and the coast. Beach nourishment (i.e., the supply of sediment to beaches) is a critical ecosystem service in the lower basin. The Kenya coast is an area of outstanding natural beauty and a globally important tourist destination. The Tana River supports fluvial sediment input to the Ungwana Bay, which, through longshore drift, supplies sand to the beaches and reduces coastal erosion.	Relationship between flow at Garissa and sediment washed out to sea: Long wet season (March to June): $SSC = 3.0715Q_{Ga}$ Short wet season (October to December): $SSC = 10.04754Q_{Ga}$ ($Q_{Ga} \leq 1{,}536.96$) $SSC = 4.2327Q_{Ga} + 889.49$ ($Q_{Ga} > 1{,}536.96$) Dry season (July to September and January to February) $SSC = 2.0432Q_{Ga}$ Where: SSC = mean monthly sediment concentration (mgl^{-1}) Q_{Ga} = mean monthly flow at Garissa (m^3s^{-1})

FIGURE 8. Derived relationship between 30-day cumulative flow at Garissa and downstream flood extent: (a) between Garissa and Garsen; and (b) in the Tana Delta. No flooding is assumed for cumulative flows below 0.35 km^3.

(a) (b)



Economic Analyses

There is a long history of determining the monetary value of benefits from built water resource infrastructure. In contrast, techniques for valuing the benefits derived from natural infrastructure are fewer in number, much less widely applied and much more controversial. Nevertheless, valuing the benefits that accrue from natural infrastructure is important for a number of reasons:

- It provides the basis for a solid economic justification for investing in natural infrastructure in budgetary planning and management.
- It can contribute to a greater understanding of social and equity issues pertaining to changes wrought by built infrastructure.
- It provides a basis for evaluating: (i) trade-offs in allocating water between competing uses; (ii) the impacts of built infrastructure on natural infrastructure; and (iii) alternative development pathways.

In the current study, we valued the key benefits accruing from both built and natural infrastructure. All values were corrected to United States dollars using a purchasing power parity (PPP) exchange rate for 2015.

Built Infrastructure

Only the direct monetary value of hydropower was estimated; no allowance was made for the multiplier effects generated for the wider economy. For irrigation, data were only available to estimate the value of annual average production (Annex B). For both (hydropower and irrigation), benefits are dependent on an assured water supply. The construction of the dams largely guarantees these supplies for current levels of development, and therefore effectively decouples production from flow variability. This was confirmed for hydropower, where only a weak correlation was found between annual hydroelectricity generation and annual flow (Figure B1, Annex B). Hence, benefit functions were not derived for either hydropower or irrigation, but instead annual average production and monetary values were estimated. In contrast, fisheries production in reservoirs is partially contingent on water level changes and hence dam operation. Therefore, benefit functions were derived for reservoir fisheries that linked potential productivity to water level changes in the Masinga and Kamburu reservoirs (Annex B). Estimated mean annual values are presented in Table 8.

TABLE 8. Estimated mean annual value of direct benefits from the hydropower dams built on the main stem of the Tana River.

	Average annual value (USD millions)
Hydroelectricity generation	128
Existing irrigation schemes in the Lower Tana	9.3
Reservoir fisheries (Masinga and Kamburu)	2.0

Natural Infrastructure

Valuing the ecosystem services provided by natural infrastructure is dependent on identifying both the environmental linkages which maintain a particular service and the economic linkages that realize the monetary value of that service.

Upstream ecosystem services: In the Tana River Basin, the benefits of upstream ecosystem services accrued from the built infrastructure (i.e., water supply to Nairobi, hydropower generation, irrigation and reservoir fisheries). Ideally, to avoid overvaluing the ecosystem services, a valuation analysis would be determined from “production functions” for each benefit (i.e., a relationship describing how each benefit is derived from the separate upstream ecosystem services, as well as all the other inputs required to generate it). However, the lack of available data on how each upstream service relates explicitly to the benefits meant that this was not possible.

In the business case developed by the NWF, a different approach was adopted: the services were effectively bundled together and a suite of computer models were used to determine the differences in the value of benefits arising from alternative packages of specific investments in natural infrastructure in the upper basin. The investments comprised portfolios of activities across the three watersheds draining into the downstream dams, including: (i) riparian management, such as vegetation buffers along riverbanks; (ii) agroforestry; (iii) terracing of hill slopes on steep farmland; (iv) reforestation of degraded lands and forest edges; (v) grass strips in farms; and (vi) road erosion mitigation.

The business case study concluded that reduced soil loss, reduced suspended sediment and increased dry-season river flow arising from a USD 10 million investment in natural infrastructure would generate USD 21.5 million in benefits over a period of 30 years; a net present value of USD 5.9 million (TNC 2015). These are benefits accruing to primarily the Kenya Electricity Generating Company (KenGen) (the leading electric power generation company in Kenya), the Nairobi City Water and Sewerage Company (NCWSC) (which provides clean water and sewerage services to the residents of Nairobi County), and both small- and large-scale farmers in the upper catchment (Table 9).

Downstream ecosystem services*:* Secondary data on economic values were obtained from both government and non-government sources, and combined with the benefit functions to enable values to be attached to flows with different return periods: 1.8, 2, 5, 10, 25 and 50 years (Annex C). In all cases, it was assumed that communities have the capacity to exploit additional opportunities arising from larger floods. Thus, for example, all additional grazing created by larger floods will be utilized either by local communities or by pastoralists moving into the area from elsewhere.

TABLE 9. Cumulative benefits across different benefit streams/stakeholders.

	Present value (USD millions)
Benefits	
Upstream farmers (reduced erosion/nutrient loss from fields)	12
NCWSC (reduced water treatment and sludge disposal)	3.4
KenGen (increased hydropower generation)	6.2
Costs	
Investment in portfolios of interventions	-7.1[+]
Additional (maintenance costs)	-8.5*
Net present value	5.9

Source: Modified from TNC 2015.

Notes: [+] Net present value is less than USD 10 million because the investment is spent over 10 years and hence 'discounted'.

* Additional costs predominantly for upstream farmers.

The exception was flood-recession agriculture, for which it was assumed that no additional benefit could be gained from land flooded with return periods greater than 5 years, since the local population is unlikely to have the capacity to utilize less frequently flooded land.

For livestock, the total output value was determined based on the value of livestock products (i.e., milk, offtakes [meat and hides] and manure) and a range of benefits that are important for pastoralist communities: credit access, self-insurance and risk pooling (Annex C). For other benefits (i.e., recession agriculture, floodplain fisheries, marine fisheries, shrimp fisheries), monetary values were derived from market values of products. Again, there were insufficient data to derive production functions, so "gross" values or "output economic value" (i.e., excluding production/capital costs) were determined.

Although potentially highly valuable, insufficient data exist to enable an estimate of the value of the beach nourishment service. In any case, studies indicate that despite the dams, annual sediment fluxes into Ungwana Bay have not changed significantly (Annex C). Therefore, it was anticipated that the corresponding economic values have not changed drastically.

Using the benefit functions and economic values deduced for different benefits, it was possible to translate the impact of the main-stem dams on floods into an estimate of the economic consequences for benefits derived from floods of different magnitude. The results indicate that the impact of the dams varies considerably for floods with different return periods (Table 10).

Flood "Cost" Function

As well as benefits, flooding also has negative impacts, and incurs costs associated with the destruction of infrastructure, damage to crops, loss of livestock and disruption to people's livelihoods. In the Lower Tana Basin, flooding is a recurrent problem. Major displacement of people occurred in 1997/1998, 2007/2008 and again in 2013 (Kiringu 2015). The economic costs from El Niño-induced flooding in 1997/1998 (approximately a 35-year return period event) was estimated to be USD 29.1 million (corrected to 2015). One of the main justifications for building the HGF Dam is additional flood control.

In order to incorporate the costs of flooding into the analyses, a flood "cost" function was developed (Annex D). Costs were related to loss of livestock and crops, damage to livestock watering points and transport routes, damage to other transport and communication networks, and damage to built water resource infrastructure. By attenuating flood flows, the dams significantly mitigate the economic costs of flooding (Table 11).

TABLE 10. Summary of the monetary value of benefits derived from downstream natural infrastructure (downstream ecosystem services) in the Tana River Basin.

	Value (USD millions, 2015)						
Return period, T (years)	Flood extent (km^2)	Floodplain grazing	Recession agriculture	Floodplain fisheries	Marine fisheries	Shrimp fisheries	Total
			Pre-dam construction				
1.8	321	137.5	15.6	0.35	2.03	0.26	156
2	350	141.0	16.5	0.38	2.11	0.27	160
5	597	170.5	23.9	0.66	2.68	0.38	198
10	800	194.7	23.9	0.89	3.06	0.46	223
25	1,095	229.9	23.9	1.22	3.52	0.57	259
50	1,252	259.1	23.9	1.50	3.89	0.67	289
MAF+	399	146.9	18.0	0.44	2.22	0.35	168
			Post-dam construction				
1.8	335	139.2	16.1	0.36	2.24	0.31	158
2	353	141.3	16.6	0.38	2.30	0.33	161
5	491	157.8	20.7	0.54	2.75	0.47	182
10	587	169.3	20.7	0.65	3.01	0.61	194
25	709	183.8	20.7	0.78	3.30	0.81	209
50	802	194.9	20.7	0.89	3.50	0.97	221
MAF	381	144.6	17.8	0.41	2.40	0.36	166

Note: + MAF - Mean annual flood (T = 2.2 years).

TABLE 11. Comparison of pre- and post-dam flood-induced economic losses for the Lower Tana Basin.

Return period, T (years)	Pre-dam (1941-1979)		Post-dam (1989-2013)		Avoided flood losses (USD millions)
	Flood extent (km^2)	Economic losses (USD millions)	Flood extent (km^2)	Economic losses (USD millions)	
1.8	321	0	335	0	-
2	350	0	353	0	-
5	597	-9.4	491	-0.2	9.2
10	800	-42.6	587	-8.3	34.3
25	1,095	-127.0	709	-25.2	101.7
50	1,252	-229.6	802	-43.0	186.5

Overall Economic Value of Flooding in the Lower Tana Basin Before and After Dam Construction

The net economic value of the Tana River dams for floods was determined by summing benefits derived from grazing, flood-recession agriculture and fisheries (floodplain and coastal), and by comparing it with flood-induced economic losses, before and after dam construction (Table 12). The results indicate the following:

- Overall, the potential economic benefits of flooding outweigh the economic costs that are incurred due to floods.
- The dams built in the basin slightly reduce the net economic benefits for more frequent floods (i.e., T < 10 years).
- Although the benefits of flooding are reduced by the presence of dams, by reducing the costs associated with less frequent floods, the dams result in significant net economic gains.

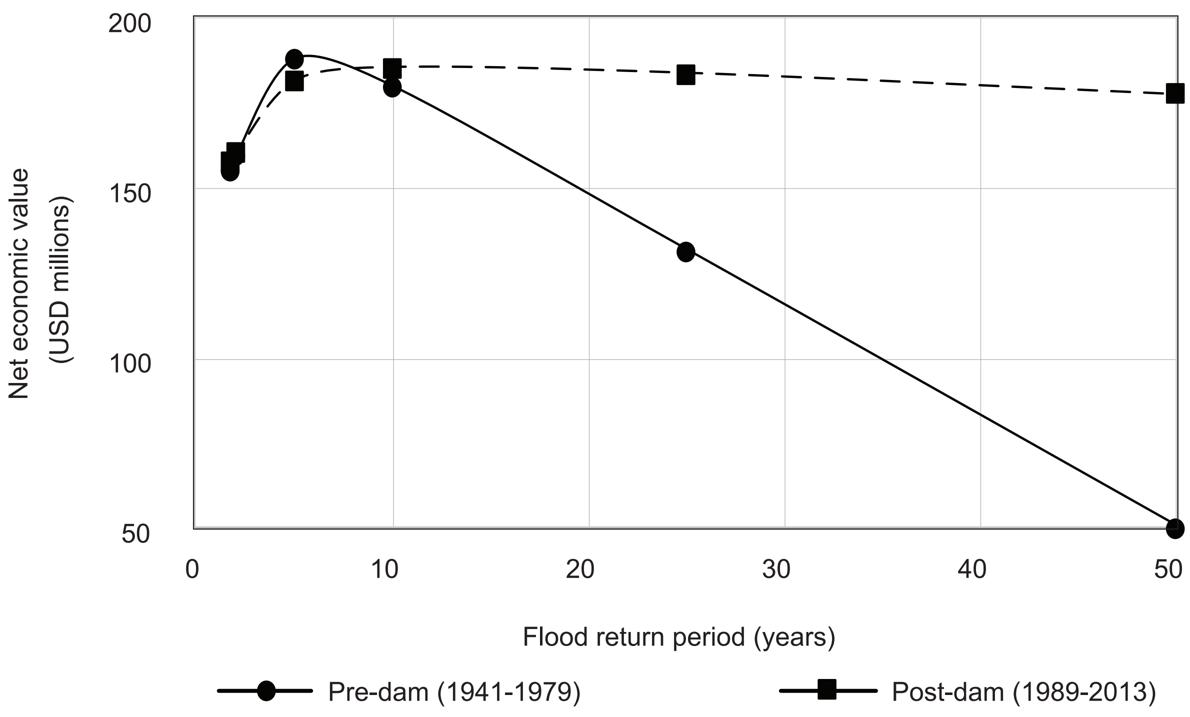
Consequently, in relation to flooding, the net impact of the existing dams in the Tana Basin is positive (Figure 9). No economic losses have been included for lost labor, and disruption to and loss of lives, which would significantly add to flood losses. Hence, the estimated economic benefit of the dams is conservative.

TABLE 12. Comparison of flood-induced economic benefits and losses in the Lower Tana Basin, with and without the dams.

Return period, T (years)	Pre-dam (1941-1979) Flood extent (km^2)	Economic losses (USD millions)	Economic benefits (USD millions)+	Net benefit (USD millions)	Post-dam (1989-2013) Flood extent (km^2)	Economic losses (USD millions)	Economic benefits (USD millions)+	Net benefit (USD millions)	Variation after dam construction (USD millions)
1.8	321	0	155.8	155.8	335	0	160.4	160.4	4.6
2	350	0	160.3	160.3	353	0	163.0	163.0	2.8
5	597	9.4	198.1	188.7	491	0.2	183.8	183.6	-5.2
10	800	42.6	223.0	180.4	587	8.3	195.5	187.2	6.8
25	1,095	127.0	259.2	132.2	709	25.2	210.6	185.4	53.2
50	1,252	229.6	289.1	59.5	802	43.0	222.0	179.0	119.5

Note: + Floodplain grazing, flood-recession agriculture, floodplain and delta fisheries, marine fisheries and shrimp fisheries.

FIGURE 9. Estimated net economic value of floods in the Lower Tana Basin before and after dam construction.



Overall Economic Impact of the Tana Dams

To determine the overall impact of the five main-stem dams in the basin, average annual values were deduced for the pre- and post-dam periods (Table 13). Agriculture is the most negatively impacted sector. The changes in flood frequency caused by the dams have had negative consequences on the average annual revenue generated by livestock and crops – USD -6.4 and USD -3.2 million, respectively. However, the agriculture sector also benefits from a significant reduction of flood risk, for floods with return periods greater than 10 years. So, the net result is a much smaller reduction for crops and positive for livestock. Marine fisheries, including shrimp, also gain slightly from the presence of the dams. Revenue from floodplain fisheries diminish.

The dams also enable significant new revenue streams from hydroelectricity generation, irrigation and reservoir fisheries. In purely monetary terms, these greatly outweigh the relatively smaller losses in other sectors (Figure 10). However, the individuals who lose and benefit are different. The livelihoods of many tens of thousands of people – most of whom do not have access to electricity – are adversely impacted by the annual loss of revenue from livestock and fisheries.

TABLE 13. Estimated value of average annual benefits derived from the built infrastructure (dams) and natural infrastructure in the Lower Tana Basin before and after dam construction.

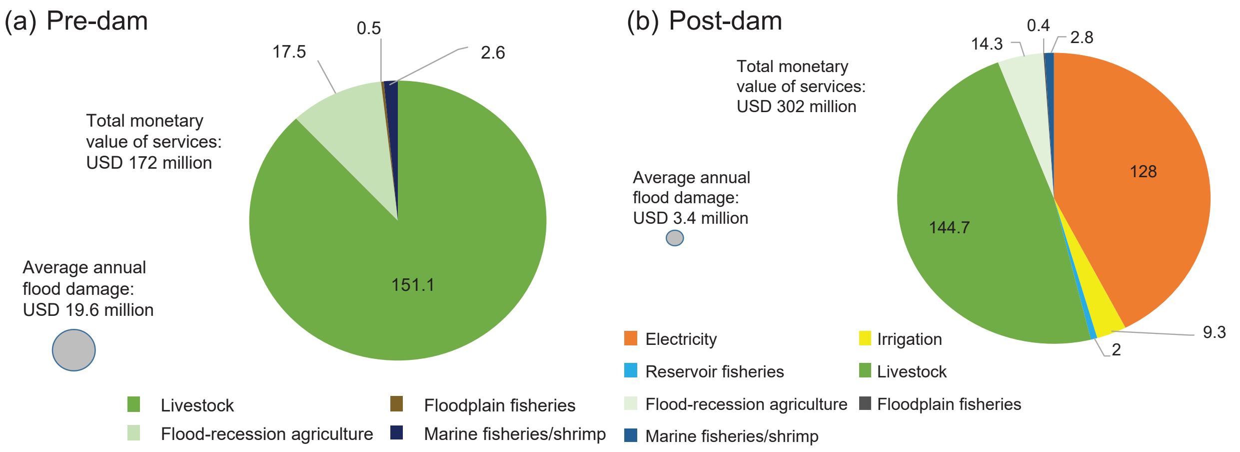
	Estimated annual economic output value (USD millions, 2015)		Estimated variation after dam construction (USD millions, 2015)	Estimated net impact variation* (USD million, 2015)
	Pre-dam	Post-dam		
Direct dam benefits				
Hydroelectricity	0	128	128	128
Irrigation	0	9.3	9.3	11.3
Reservoir fisheries	0	2.0	2.0	2.0
Total		139.3	139.3	141.3
Type 2 ecosystem service benefits				
Livestock	151.1	144.7	-6.4	3.21
Flood-recession agriculture	17.5	14.3	-3.2	-0.6
Floodplain fisheries	0.47	0.4	-0.07	-0.07
Marine fisheries	2.3	2.4	0.1	0.1
Shrimp fisheries	0.31	0.39	0.08	0.08
Total type 2	171.7	162.2	-9.5	2.72
Overall total	171.7	301.5	129.9	144
Disservices				
Economic losses due to flooding**	-19.6	-3.4	16.1	1.6
Net benefits	152.1	298.1	146	

Notes:

* The net impact redistributes the avoided flood damage to the beneficiaries, here livestock (61%) and agriculture (29%), in the same proportion as these activities are impacted by floods (see Annex D, Table D1). The remaining damage is considered as the damage to the transport, communication and water infrastructure sectors (10%). Avoided losses in agriculture are distributed among irrigation (44%) and flood-recession agriculture (56%) based on their respective land uses.

** This considers damage to transport, communications and water facilities.

FIGURE 10. Comparison of the monetary benefits and costs: (a) before dam construction, and (b) after dam construction.



Discussion

This study has highlighted that the benefits people derive from the Tana River Basin are dependent on complex dynamic interactions between natural and built infrastructure. Upstream ecosystem services contribute to the benefits derived from built infrastructure. They are rarely considered explicitly, but both the NWF and this study have highlighted their significant economic value, now and in the future. Quantifying the downstream ecosystem services in relation to floods of different magnitude has provided a better understanding of the dynamic nature of benefits and the impacts of upstream built infrastructure.

Several limitations to the study are acknowledged:

- Upstream ecosystem services are modified by land cover and land management practices; both forestry and agricultural management practices alter runoff and sediment fluxes. Beyond the broad level analyses conducted in the NWF study, there has been no detailed analyses exploring the role of these modifying influences.
- Throughout the basin, but particularly in the more arid lower basin, many rural livelihoods are founded on the integrated use of a wide range of flow-dependent ecosystem services. Although this study has found that the overall economic impact of the dams is positive, they do have distributional impacts that need to be carefully considered. Future studies need to focus on more disaggregated economic analyses - who gains and who loses - particularly in the context of further likely changes to the flow regime arising from both more built infrastructure and CC.
- The analyses presented, though focused on the most tangible downstream services, are only a partial representation of the total flow-related ecosystem services and benefits in the basin. A more comprehensive assessment of the value of the benefits from the natural infrastructure would require: (i) inclusion of non-use values of ecosystem services, option values or non-consumptive values such as cultural services; and (ii) expanding

the range of services and processes dependent on river flow (e.g., mangrove habitats, riverine forest, etc.).

- For each ecosystem service, a direct flow dependency has been derived. The focus was on flooding, because it supports the predominant livelihood benefits in the lower basin. No allowance was made for indirect processes pertaining to more complex ecological functions, even where they are linked to water flows (including low flows). For example, the relationship between soil fertility and silt deposition in the case of land-based floodplain services. This would require much greater in-depth understanding of these ecological processes as well as the economic interrelationships.

Notwithstanding these limitations, the study has provided a useful first step in quantifying the interrelationships between built and natural infrastructure in the Tana River Basin. It provides a perspective for better understanding and integrating the water-related benefits generated by natural infrastructure into economic analyses and water resource planning.

The Tana River is one of several rivers in Eastern Africa which is projected to have increased but more variable flow in the second half of this century (Nakaegawa et al. 2012). This study has indicated that increases in upstream ecosystem services (water yield, baseflow and groundwater recharge) can also be anticipated in the future (Sood et al. 2017), and planned land management interventions in the upper catchment, intended to reduce downstream sediment loads, are likely to be worthwhile investments even in the face of extreme CC (Simons et al. 2017). Hence, in the absence of other major changes, investment in upstream ecosystem services should broadly improve the future performance of built infrastructure, enabling greater flexibility in operations and potentially providing opportunities for dam management to enhance downstream ecosystem services.

Investment in, and protection of, natural infrastructure is consistent with the Paris Agreement, which argues for the protection of livelihoods and ecosystems as well as improving the effectiveness and durability of adaptation actions. It also calls for greater resilience of socioeconomic and ecological systems to be brought about through economic diversification and sustainable management of natural resources (UNFCCC 2015). Importantly, it is also consistent with Kenya's own National Climate Change Action Plan, which acknowledges the imperative of resilient ecosystems for enhancing the resilience of populations vulnerable to climate shocks (GoK 2013c).

Conclusions

This study considered hydrological, ecological and economic processes in order to estimate a value for flow-related ecosystem services. It provided quantitative insights into the links between flow and the benefits derived from both built and natural infrastructure. The results are a first step in better understanding the trade-offs associated with different development options and the possible impacts of CC. The results provide initial perspectives not just on the monetary values of a number of ecosystem services but also, importantly, on aspects of equity and social inclusion, which should also be considered in decision-making.

Natural infrastructure in the Tana River Basin represents a national asset providing direct benefits to hundreds of thousands of people in the basin and indirect benefits to many more outside the basin boundaries. In the upper basin, natural infrastructure contributes to the performance of existing built infrastructure. By regulating upstream river flows and reducing soil erosion – biophysical effects that can be enhanced by targeted land management practices – the water storage/yields of downstream reservoirs are preserved, thereby enhancing long-term hydropower and irrigation benefits. In the lower basin, benefits from natural infrastructure accrue primarily to poor subsistence smallholder farmers and pastoralists. Depending on rainfall, river flow and other factors (including social), the benefits vary from year to year, but a conservative estimate of the average cumulative value of six key water-dependent services in the lower basin is USD 152 million annually.

The large dams that have been built have significantly increased overall financial returns by creating new revenue streams (i.e., hydropower and irrigation), and by reducing the adverse impacts of large-scale flooding. Overall, average annual revenue is increased to USD 298 million. However, they have also reduced the benefits that accrue from flooding, with the greatest losses in the agriculture sector. Although they benefit from increased flood protection, those who lose the most revenue as a consequence of the dams are the impoverished pastoralists and smallholder farmers in the lower basin.

A significant proportion of the population in the basin is extremely susceptible to climate-related events. The projected overall increase in river flow presents opportunities for increasing total benefits, though great dexterity will be needed to successfully manage the anticipated increased variability in flows. Without doubt, the operation of current built infrastructure will play a central role in adapting to a hotter, wetter but more variable climate.

In combination, built and natural infrastructure should be seen as critical elements of a strategy for the basin to adapt to CC. Balancing the costs and benefits of flooding across different stakeholders/sectors will require that the future focus of dam operation and management goes beyond simply maximizing hydropower revenue. Planning and managing mixed *portfolios* of natural and built infrastructure in tandem enables benefits to be optimized across stakeholders. It minimizes risks of maladaptation and is more likely to improve resilience and human security.

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Annex A. Benefits from Natural and Built Infrastructure

WISE-UP TO CLIMATE

Upstream natural infrastructure

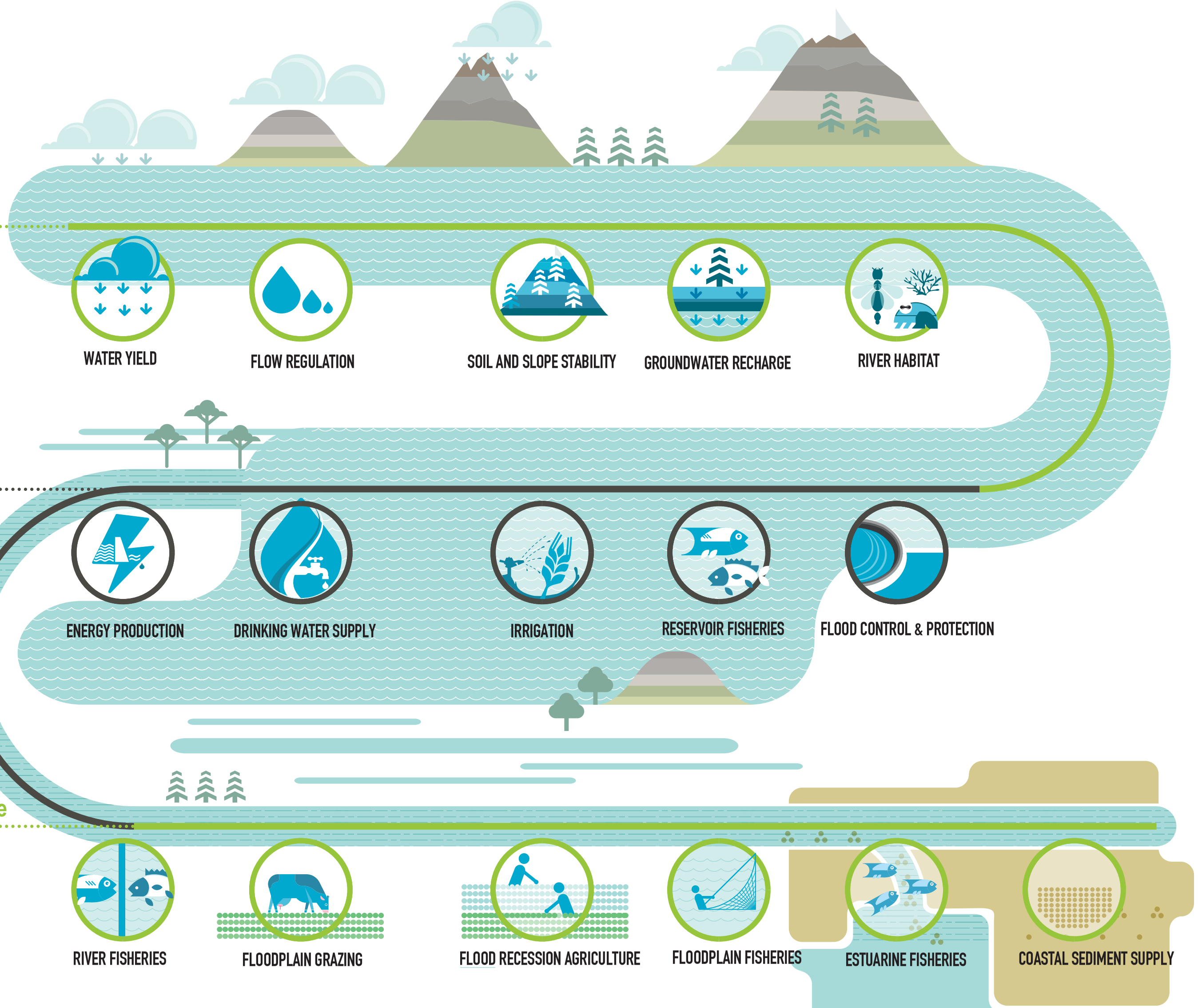
Natural infrastructure in the headwaters of river basins can affect the performance of downstream built infrastructure designed to manage water resources. The condition of natural systems that help collect, store, clean and convey water and sediment through infiltration, groundwater recharge, erosion control, etc can modify hydrological processes, affecting the volume and timing of water runoff and fluxes of sediment and nutrients. In turn, this can affect the ecological condition of rivers and reservoirs, with implications on water supply provision, electricity generation, flood protection and biodiversity.

Built infrastructure

Built infrastructure allows societies to better cope with the natural variability of rivers, making water available when it would not be under natural conditions. However, it can also modify natural river flows significantly, disrupting freshwater habitat, biodiversity, ecosystem services, and downstream natural infrastructure functions. Careful planning and management of built infrastructure can minimize the losses and maximize the benefits accruing from both built and natural infrastructure.

Downstream natural infrastructure

Downstream river flows can be affected by the presence and operation of built infrastructure. This impacts the environmental and social benefits gained from flooding such as fisheries, fertile land for livestock grazing and flood recession farming. The way built infrastructure is designed and operated can affect the water/sediment/nutrient fluxes in river systems.



Annex B. Quantifying and Valuing Benefits from Built Infrastructure

Hydroelectricity

The large dams on the Tana River were built primarily for the purpose of electricity generation. KenGen published annual reports and financial statements (2008-2015) providing information on the units of electricity generated and sold, the source of electricity and the revenue generated from those sales for the period 2005 to 2015 (Table B1).

Each report includes a breakdown of power generated and sold at each KenGen power station. In addition, for the past 4 years (2012-2015), total revenue is disaggregated by the source of electricity generation (i.e., hydro, geothermal, thermal and wind), enabling the revenue from individual schemes to be estimated. These data indicate that revenue per unit of hydroelectricity (i.e., gigawatt hours [GWh]) varied between 0.72 and 0.78 of the average revenue generated across all sources of electricity generation. Prior to 2012, only total revenue is published, so the revenue specific to hydropower can only be estimated based on the average ratio of hydropower revenue to total revenue estimated for the years 2012 to 2015 (i.e., 0.74). Tax paid by KenGen varied considerably from year to year. In some years, the company paid up to 50%, but it received substantial tax "credits" in other years. Overall, between 2007 and 2015, the tax paid seems to have been about 2%. This was ignored in calculations.

Annual electricity generated and revenue from the five main schemes in the basin vary from year to year, but average revenue was USD 128 million (assuming a PPP exchange rate of 44.28) over the most recent 5 years (i.e., 2011-2015). This is the estimated direct monetary value of electricity, making no allowance for secondary benefits. As a consequence of the water storage, there is only a weak correlation between the electricity generated and annual discharge (Figure B1).

TABLE B1. Hydroelectricity generated and revenue for the main-stem hydropower schemes in the Tana River Basin.

Year	Hydroelectricity generated (GWh)	Revenue (USD millions)	Annual flow at Garissa (Mm^3)[+]
2005	2,291	69.7*	1,362.5
2006	2,406	72.9*	1,656.2
2007	2,820	113.5*	2,684.8
2008	2,885	115.9*	1,983.7
2009	1,713	83.1*	1,296.6
2010	1,429	72.4*	1,907.9
2011	2,505	121.2*	N/A
2012	2,414	116.9	N/A
2013	3,137	138.9	N/A
2014	2,643	133.6	N/A
2015	2,092	129.0	N/A

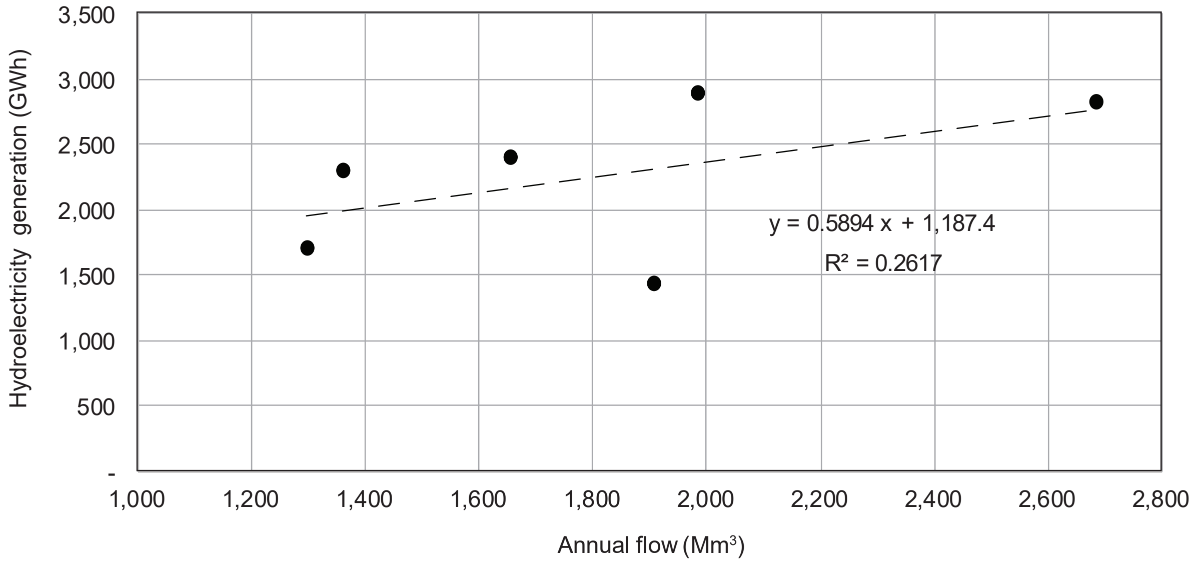
Source: KenGen annual reports 2008-2015 (KenGen 2008, 2009, 2010, 2011, 2012, 2013, 2014, 2015).

Notes:

* Estimated from total KenGen revenue based on the average ratio of hydropower revenue to total revenue (2011 to 2015).

[+] The financial year in Kenya is from July 1 to June 30 the following year. Therefore, annual flows are computed for these months (i.e., 2005 is July 1, 2004 to June 30, 2005).

FIGURE B1. Relationship between annual flow (June-July) and annual hydroelectricity generated by the five main-stem schemes in the Tana River Basin.



Irrigation

Based on data in the National Water Master Plan, formal irrigation in the Tana Basin is estimated to cover an area of 68,700 ha from a potential of 205,000 ha (Hoff et al. 2007). Irrigators include large commercial farms (e.g., Del Monte, Kakuzi), public schemes (e.g., Mwea, Bura, Hola) and community-based smallholder schemes (Hoff et al. 2007). Much of the irrigation is in the upper catchment (e.g., for rice, fruit and tea). The extent of functioning irrigation in the lower catchment is unclear. Several public schemes have been initiated but, for a variety of reasons, have largely failed (Table B2).

The extent of smallholder and private irrigation in the lower basin is unknown, but believed to be limited. The current total area that is actually irrigated is almost certainly less than 8,000 ha. Revenue from irrigation systems is highly variable and dependent on many factors, including the crops cultivated and yields. However, based on an estimated average revenue of USD 0.15 m^{-3} of diverted irrigation water and an average water requirement of 7,777 m^3 ha^{-1} (Hoff et al. 2007), this equates to USD 1,167 ha^{-1} or an estimated maximum total value of approximately USD 9.3 million for irrigation in the lower basin.

Reservoir Fisheries

Fish productivity in reservoirs depends on depth, surface area, water inflow, residence time, connectivity with upstream habitats, availability of habitat and water quality (Bernacsek 1984). Typically, changes in water level results in periodic exposure and flooding of the shallow littoral zone, which affects the fisheries of the reservoir. During flooding, many fish species migrate to the recently flooded areas to feed and breed: newly inundated areas act as a nursery ground for many fish species. During periods of drawdown, fish become concentrated in the deeper waters, but often many breeding fish and juveniles are left stranded in pools, just as on a natural floodplain (Bernacsek 1984).

There are over 800 fishermen and 400 fishing boats on the reservoirs of the Tana River (Table B3). On the Masinga reservoir, more than 400 fishermen use gill nets and longlines. The fish catch is composed of predominantly tilapiine fishes, common carps, and a few *Barbus* sp. and *Labeo* sp. Fish are sold in Nairobi and other towns closer to the reservoirs. Between 2010 and 2014, average annual catch in the "Tana River dams" varied from 583 to 1,024 tonnes (t), with an average value of KES 84,318 t^{-1} (Table B4).

TABLE B2. Existing formal irrigation schemes in the Lower Tana Basin.

Scheme	Date	Planned (ha)	Actual (ha)	Comment
Bura	1988	6,700	2,500	Cotton cultivation. Largely collapsed in 1989. Some maize grown, but maybe less than 2,500 ha.
Hola		4,161	900	Failed due to unreliability of supply.
Tana Delta		12,000	1,300	Rehabilitated. Rice and maize cultivation.

TABLE B3. A summary of reservoir characteristics and fish catch in the reservoirs of the Tana River.

Reservoir	Year of closure	Altitude (masl)	Storage volume (Mm^3)	Depth (m)	Surface area (km^2)	Generating capacity (MW)	Fisheries	Annual production (ty^{-1})
Kindaruma	1968	780	18	13	2.6	140	No*	0
Kamburu	1975	1,006	146	50	15.0	94	Yes	163 (45-215)
Gitaru	1978	924	20	20	3.1	145	No*	0
Masinga	1981	1,056	1,560	48	125.0	40	Yes	960 (400-1,200)
Kiambere	1988	700	595	65	25.0	140	Yes	468

Source: Adapted from Jumbe 2003.

Note: * Good stocks of fish have been reported to exist in Kindaruma and Gitaru reservoirs, but the presence of a large number of crocodiles has prevented regular fishing in these reservoirs.

TABLE B4. Fisheries from reservoirs in the Tana River (2010-2014).

Year	Production (tonnes)	Value (KES millions)	KES t^{-1}	USD (2015) t^{-1*}
2010	583	37.39	64,136	1,448.41
2011	732	53.78	73,471	1,659.24
2012	967	81.61	84,394	1,905.92
2013	705	73.02	103,580	2,339.21
2014	1,024	98.31	96,007	2,168.18
Average	802	68.82	84,318	1,904.20

Source: GoK 2015.

Note: * Exchange rate = 44.28 (purchasing power parity for private consumption in 2015).

A study of fisheries in the Masinga and Kamburu reservoirs (Jumbe 2003) found that:

- changing reservoir water levels has an adverse impact on fish catch, with catches of tilapiine fish generally higher when water levels were high; and
- common carp catch was generally correlated with water inflow.

Regression analyses of total annual fish catch for both the Masinga and Kamburu reservoirs showed only a very weak correlation with: (i) mean annual water level (masl); (ii) May water level (masl); and (iii) total annual inflow (Mm^3). Although still weak, the best correlation – and the characteristic that can be managed – was with the annual amplitude of water level change (i.e., difference between the maximum and minimum water levels).

To derive a benefit function, the following assumptions were made:

- Broadly, a water-level system that mimics the flood and ebb of the natural flood pulse, and for which changes are not too rapid, is best for reservoir fisheries.

- Water level changes up to 2-4 m benefit fish production, but greater changes than this reduce fish production (Bernacsek 1984).

Relationships were developed for the Masinga and Kamburu reservoirs. In both cases, annual fish catch (AFC) was related to annual maximum water level change (WLC). A large number of factors affect fish catch and there is a lot of scatter in the data. Consequently, in both cases, the relationship was based on observed data, but points were chosen subjectively to provide an estimate of maximum possible fish production for water level change (Figure B2; Table B5).

Based on the time series of end-of-month water levels (1981-2015), return periods were determined (assuming a Pearson type 3 statistical distribution) for the annual amplitude of water level change in both reservoirs. This enabled an estimate of variation in the value of reservoir fisheries under conditions created by dam operation over the past 35 years (Table B6).

FIGURE B2. Annual maximum fish production for varying water level changes (maximum to minimum) in (a) Masinga, and (b) Kamburu reservoirs.

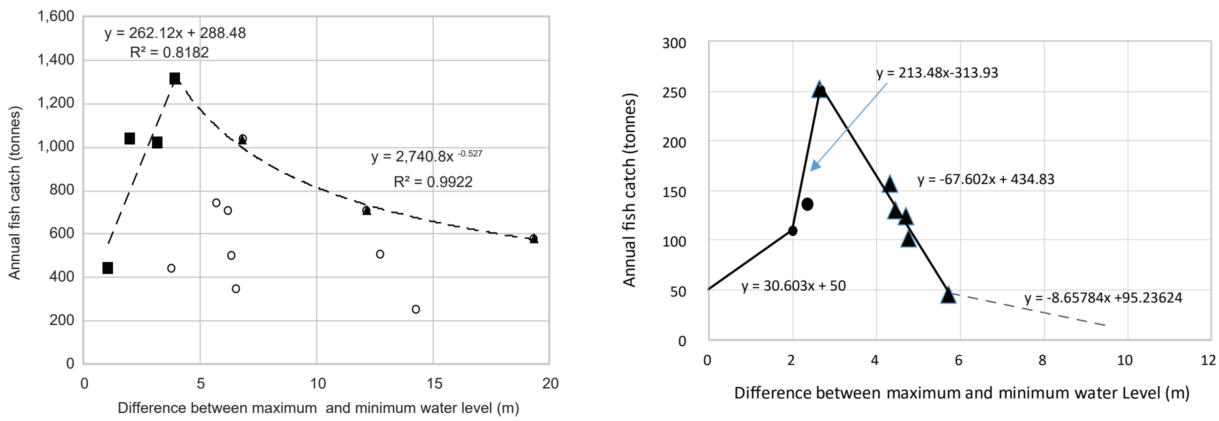


TABLE B5. Relationship between annual fish catch (AFC) (metric tons) and maximum water level change (WLC) (meters) in the Masinga and Kamburu reservoirs.

Reservoir	Range of water level change (WLC) (m)	Equation
Masinga	0 to 3.91	AFC = 261.12 WLC + 288.48
	> 3.91	AFC = 2,740.8 $WLC^{-0.527}$
Kamburu	0 to 1.99	AFC = 30.603 WLC + 50
	1.99 to 2.65	AFC = 213.48 WLC - 313.93
	2.65 to 5.71	AFC = -67.602 WLC + 434.83
	5.71 to 11	AFC = -8.65784 WLC + 95.23624
	> 11	AFC = 0

TABLE B6. Estimate of the annual production (tonnes) and value (USD, 2015) for reservoir fisheries in Masinga and Kamburu reservoirs under the dam operating regime from 1981 to 2015.

Return period, T (years)	Masinga Reservoir			Kamburu Reservoir			Total	
	Water level change (m)	Annual fish catch (tonnes)	Value (USD, 2015)	Water level change (m)	Annual fish catch (tonnes)	Value (USD, 2015)	Annual fish catch (tonnes)	Value (USD, 2015)
1.8	6.73	1,003	1,910,848	3.99	165	314,380	1,169	2,225,228
2	7.48	949	1,807,357	4.29	145	275,761	1,094	2,083,118
5	12.88	713	1,357,264	6.37	40	76,331	753	1,433,596
10	16.57	624	1,188,522	7.66	29	55,064	653	1,243,586
25	21.00	551	1,049,012	9.19	16	29,840	567	1,078,852
50	24.21	511	973,251	10.27	6	12,035	517	985,286
Mean annual	8.59	882	1,608,257	4.61	123	234,569	1,006	1,914,825

Annex C. Quantifying and Valuing Benefits from Downstream Natural Infrastructure

Floodplain Grazing

Pastoralism is a key livelihood activity in the Lower Tana Basin. A significant proportion of the Tana River County population (240,075 in the 2009 census) depends on livestock for their livelihoods. A recent survey found that the county is 79% food insecure, with incidence of poverty at 62% (ALMRP 2004). For many households, wealth is primarily defined by the number and type of livestock owned.

During the dry season, both the floodplain between Garissa and Garsen and the delta provide grazing grounds for large livestock herds. Pastoralists from outside the county, and as far afield as the border with Somalia, come to graze livestock during the dry season. The contribution of the riverine grazing becomes even more critical during periods of severe drought.

A recent survey found that rural communities in Tana and Garissa counties are unanimous that the impacts of drought are more profound than any other environmental shocks. Livestock death and emaciation represent the greatest threat to disposable wealth. The 2011 drought was widely recognized as having been the most severe in recent times. Drought-related livestock mortality levels varied widely, but in the surveyed communities, this ranged from 40-95% depending on species (Anonymous 2010). There is widespread perception that droughts are increasing in frequency and duration (Anonymous 2010).

Table C1 shows the distribution of grazing livestock in the Tana River County between 2009 and 2014. These include livestock kept by households and institutions (e.g., schools and prisons). Comparison with total numbers of livestock across the whole of Kenya indicates that, between 2009 and 2014, cattle in Tana River County represented between 3% and 4.5% of the total national herd. Similarly, goats and sheep comprised between 1.8% and 3.6% of the national total. It is assumed that the vast majority of these livestock will graze on the floodplains between Garissa and Garsen and in the delta.

To determine the benefit function, the following three key assumptions were made:

- All the animals reported depend on the floodplain and the delta for grazing.
- The animals reported include the influx of animals that have been moved to the river grazing areas from outside the Tana River County and were present during the census.
- The census captured the maximum number of grazing animals in Tana River County.
- The importance of floods for grazing is independent of when it occurs in the year (i.e., short or long rainy season).

TABLE C1. Distribution of grazing livestock in the Tana River County recorded between 2009 and 2014.

	2009	2010	2011	2012	2013	2014
Cattle (beef)	268,894	381,000	376,000	518,562	586,489	607,190
Goats/sheep	756,802	685,000	700,000	807,751	926,696	1,019,000
Camels	48,882	73,000	64,000	58,614	64,268	61,992
Total	1,074,578	1,139,000	1,140,000	1,384,927	1,577,453	1,688,182

Sources: Otundo 2010; GoK 2015.

A strong linear relationship was found between the total number of grazing livestock and the total flood extent across the floodplain and in the delta (Figure C1; Table C2).

The direct use value of the livestock on the floodplain was estimated in terms of livestock products (meat, manure and milk). Other direct benefits for livestock owners in relation to credit access, self-insurance and risk pooling were determined (Table C3). A weighted average gives a value of KES 5,204 (USD 118 in 2015) per head of livestock. Using this value in conjunction with flood return periods, the impact of the operating regime of dams on the value of livestock grazing in the lower basin was estimated (Table C4).

These analyses indicate that the dams result in a slight increase in floodplain grazing in relation to smaller more frequent floods, but result in a significant decrease in the value of livestock for floods with return periods greater than 2 years (Table C4). Thus, for a flood with a return period of 5 years, the economic loss is approximately USD 13 million; and for a flood with a return period of 25 years, the loss is more than USD 46 million. Overall, the expected annual value[2] of livestock grazing prior to dam construction was estimated to be around USD 151.1 million, but was approximately USD 144.7 million after dam construction (Table 13).

FIGURE C1. Relationship between the flooded area and number of grazing livestock in the Tana River County.

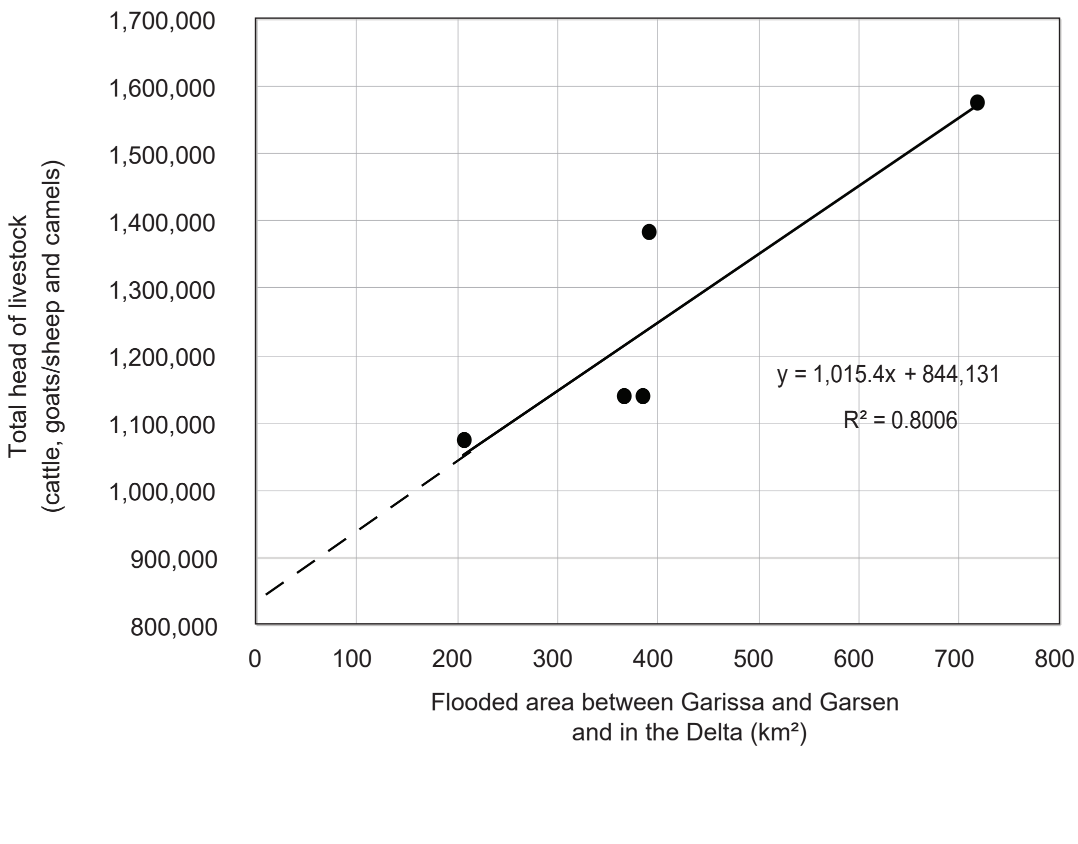


TABLE C2. Inferred relationship between the total number of grazing livestock (TH) and the flooded area (FA) (km²).

Equation	
TH = 844,131	FA = 0
TH = 1,015.4FA + 844,131	FA > 0

[2] The expected annual value takes into account the exceedance probability of the floods.

TABLE C3. Direct use value of livestock that graze on the Tana floodplain.

	Value per head	
	KES	USD (2015)[+]
Cattle	8,692	196
Goats and sheep	2,666	60
Camels	10,386	235

Note: [+] Exchange rate = 44.28 (PPP for private consumption in 2015).

TABLE C4. The potential annual value of livestock that grazed in the Lower Tana Basin (between Garissa and Garsen and in the Delta) for the pre- (1942-1979) and post-dam (1989-2013) flood regimes. All values are expressed in USD (2015).

Return period, T (years)	Total flood extent (km²)		Total head of livestock		Value (USD 2015)		Variation after dam construction (USD 2015)
	Pre-dams	Post-dams	Pre-dams	Post-dams	Pre-dams	Post-dams	
1.8	321	335	1,170,074	1,184,290	137,525,322	139,196,208	1,670,886
2	350	353	1,199,521	1,202,567	140,986,392	141,344,406	358,013
5	597	491	1,450,325	1,342,692	170,464,785	157,814,078	-12,650,707
10	800	587	1,656,451	1,440,171	194,691,923	169,271,329	-25,420,594
25	1,095	709	1,955,994	1,564,050	229,898,883	183,831,519	-46,067,364
50	1,340	802	2,204,767	1,658,482	259,138,561	194,930,638	-64,207,922

Riverbank Gardens and Flood-recession Cultivation

About 115,000 people practice flood-recession and riverbank farming in the Lower Tana Basin (IUCN 2003). This occurs primarily between Garissa and Garsen, but there is also some farming in the delta. The principal crops grown in the Tana River County (which covers the river south of Garissa and the delta) are maize, rice, cowpea, green gram and banana (GoK 2015). Other crops are grown over smaller areas. On average, 15,136 ha were cultivated in the Tana River County over the years 2012-2014, and the total value of crops was approximately USD 30 million y^{-1} (Table C5) with an average value of USD 1,943 ha^{-1}. A proportion of the crops (i.e., most likely some of the millet, maize and sorghum) will be under rainfed cultivation and grown upslope of the floodplain. Much of the rice is probably grown in the formal irrigation schemes.

To derive a benefit function, the following assumptions were made:

- Three-thousand hectares (3,000 ha) (30 km^2) of riverbank gardens downstream of Garissa are utilized, and although these may be irrigated, they are independent of flow.
- In any given year, only 15% of the total flooded area is actively used for flood-recession agriculture.
- No benefit is gained from land flooded with return periods greater than 5 years, since this is too infrequent for people to utilize.
- Flooding in the months from October to December brings no agricultural benefits. In fact, flooding in October destroys planted crops before harvesting. This loss is effectively incorporated into the flood "cost" function (Annex D).

TABLE C5. Average production and value of different crops grown in Tana River County over 3 years (2012-2014).

Crop	Area (ha)	Production (tonnes)	Value		
			KES	USD 2015	USD ha^{-1}
Sorghum	184	64	2,628,137	59,353	406
Millet[+]	19	9	585,450	13,222	561
Rice	1,526	6,961	397,703,830	8,981,568	5,704
Maize	8,047	8,754	286,488,318	6,469,926	790
Cowpea*	1,491	1,091	10,357,310	233,905	157
Green gram**	1,841	959	71,955,000	1,625,000	881
Cassava	156	1,846	36,909,077	833,538	4,694
Tomato	172	7,107	179,916,667	4,942,833	24,134
Kale	80	1,077	18,633,333	420,807	6,214
Banana	1,534	15,891	273,203,333	6,169,904	4,024
Beans	18	7	414,540	9,362	511
Sweet potatoes	68	846	24,381,952	550,631	7,703
Total	15,136	44,612	1,303,176, 947	30,310,049	

Source: GoK 2015.
Notes: [+] Two years of data only (2012-2013).
* Value given per hectare in Kiprop et al. 2015.
** Value given on the website - http://kilimo.biz/crops/cereals/green-grams/

Based on these assumptions, the relationship between flooded area and floodplain cultivation (i.e., riverbank gardening and flood-recession agriculture) was inferred (Figure C2; Table C6). This suggests that in the post-dam period, the maximum area of floodplain cultivation is 10,365 ha (i.e., approximately 68% of the average total cultivated area in Tana River County). The relative value of floodplain agriculture determined for floods with different return periods was estimated (Table C7).

Floodplain Fisheries

Floodplain wetlands, lakes, and other aquatic habitat support large fisheries (Welcomme 1985). By mobilizing nutrients and creating aquatic habitat, flooding is the most important aspect and the most biologically productive feature of many river ecosystems. In unmodified floodplains, primary production is often much higher than in permanent water bodies, and fish yields and production are strongly related to the extent and duration of floods (Junk et al. 1989).

In the Tana River, overbank flooding of the floodplain is necessary to ensure that freshwater habitat (particularly oxbow lakes [i.e., Shkababo, Kongola and Bilisa]) and pools) is maintained (Leauthaud et al. 2013). The total freshwater catch (primarily Tilapia, *Clarias spp* and *Protopterus spp*) is estimated to be up to 500 ty^{-1} based on the river's catchment area (Welcomme 1985). However, the National Environment Secretariat presented freshwater catch data for the Tana River District that indicates catches ranging from 59 to 705 ty^{-1} in the years 1979 to 1983 (NES 1985). More recently, the Economic Review of Agriculture presented data on freshwater fish catch for Tana River County (which, in theory, includes the floodplain and the delta) of between 362 t (in 2010) and 39 t (in 2012) (GoK 2015). The Kenya National Bureau of Statistics (KNBS) (KNBS 2013) presented the quantity and value of fish landed from 2008 to 2012 based on data from the Fisheries Department (Table C8). As can be seen in Table C8, in years of overlap, there is inconsistency between the data presented in the different reports.

FIGURE C2. Inferred relationship between 30-day cumulative flows at Garissa and riverbank and flood-recession agriculture on the Lower Tana floodplain before and after dam construction.

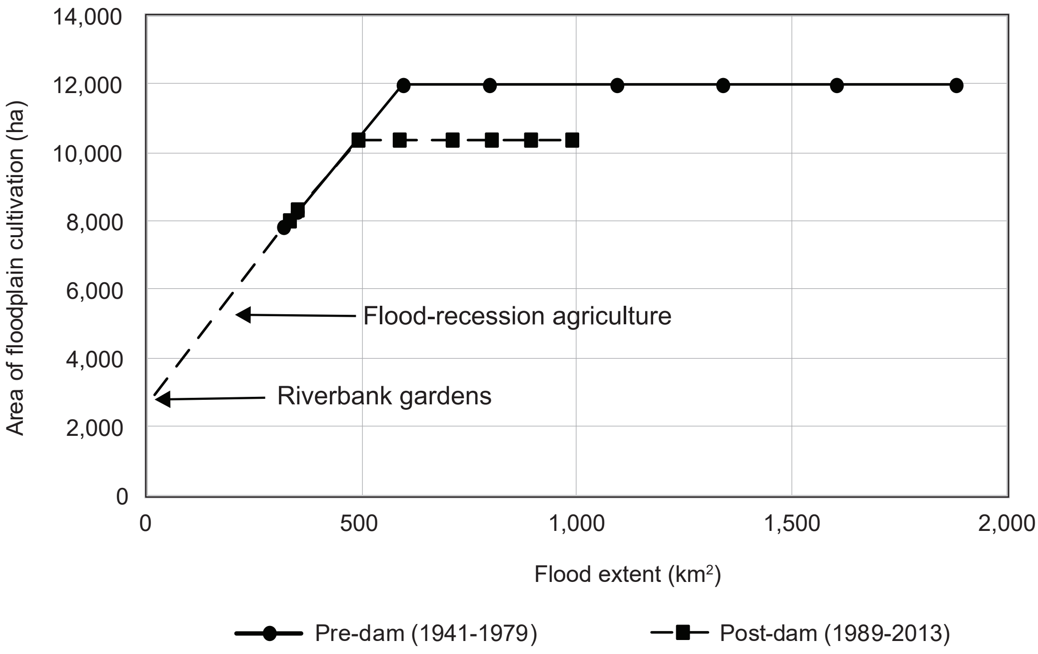


TABLE C6. Inferred relationship between flooded area (km²) and floodplain cultivation for the pre- and post-dam periods.

Pre-dam construction	CA = 3,000	FA = 0
	CA = 15FA + 3,000	0 < FA ≤ 597
	CA = 11,955	FA > 597
Post-dam construction	CA = 3,000	FA = 0
	CA = 15FA + 3,000	0 < FA ≤ 491
	CA = 10,365	FA > 491

Note: CA = cultivated area (ha); FA = flooded area (km^2).

A report on ecosystem services in the Tana Basin presented a relationship between the previous years' average annual water height at Garissa (a surrogate for flow) and annual fish catch in Tana River County based on five data points between 1999 and 2006. These are presented graphically but unfortunately not in a table, so it is not possible to determine for which years the catch data are attributed. Consequently, these data were not used in this study. Nevertheless, they indicate a catch of between 300 ty^{-1} and 520 ty^{-1} (van Beukering and de Moel 2015).

Overall, the annual fish catches reported are low, just 1.5 to 17.6 $kgha^{-1}y^{-1}$, which compares to typical figures for fully exploited African floodplains of 54.7 ± 36.5 $kgha^{-1}y^{-1}$ (Welcomme 1985). Catch statistics from rivers are frequently of low quality because of difficulties inherent in collecting data from fisheries that operate from numerous locations dispersed along the length of a river. For this reason, statistics tend to significantly under-represent the total fisheries catch.

Analyses of the data indicated only a weak correlation between fisheries yield and flood extent. The best results were obtained using the estimated flood extent of the delta (as opposed to the total of the floodplain and the delta) and the fisheries data from the Economic Review of

TABLE C7. Estimated extent and value of riverbank gardening and flood-recession cultivation on the Lower Tana floodplain for floods with different return periods (T).

Return period, T (years)	Flood extent (km^2)		Riverbank gardens (ha)	Flood-recession cultivation (ha)		Total (ha)		Value of floodplain cultivation (USD 2015)		Variation after dam construction (USD 2015)
	Pre-dams	Post-dams		Pre- dams	Post-dams	Pre-dams	Post- dams	Pre-dams	Post-dams	
1.8	321	335	3,000	4,815	5,025	7,815	8,025	15,644,904	16,065,304	420,400
2	350	353	3,000	5,250	5,295	8,250	8,295	16,515,733	16,605,819	90,086
5	597	491	3,000	8,955	7,365	11,955	10,365	23,932,799	20,749,767	-3,183,032
10	800	587	3,000	8,955	7,365	11,955	10,365	23,932,799	20,749,767	-3,183,032
25	1,095	709	3,000	8,955	7,365	11,955	10,365	23,932,799	20,749,767	-3,183,032
50	1,340	802	3,000	8,955	7,365	11,955	10,365	23,932,799	20,749,767	-3,183,032

TABLE C8. Tana River freshwater fisheries (excluding the reservoir fisheries).

	Annual fisheries catch (tonnes)[+]	Flood extent of delta (km^2)	$kgha^{-1}$[ł]
1979	71.8[+]	317	2.3
1980	59.4[+]		
1981	289.7[+]		
1982	478.2[+]	272	17.6
1983	705.5[+]	412	17.1
2008	89*	325	2.7
2009	95*	170	5.6
2010	362[‡]/107*		
2011	53[‡]/97*	261	2.0
2012	39[‡]/490*	264	1.5
2013	46[‡]		
2014	47[‡]		

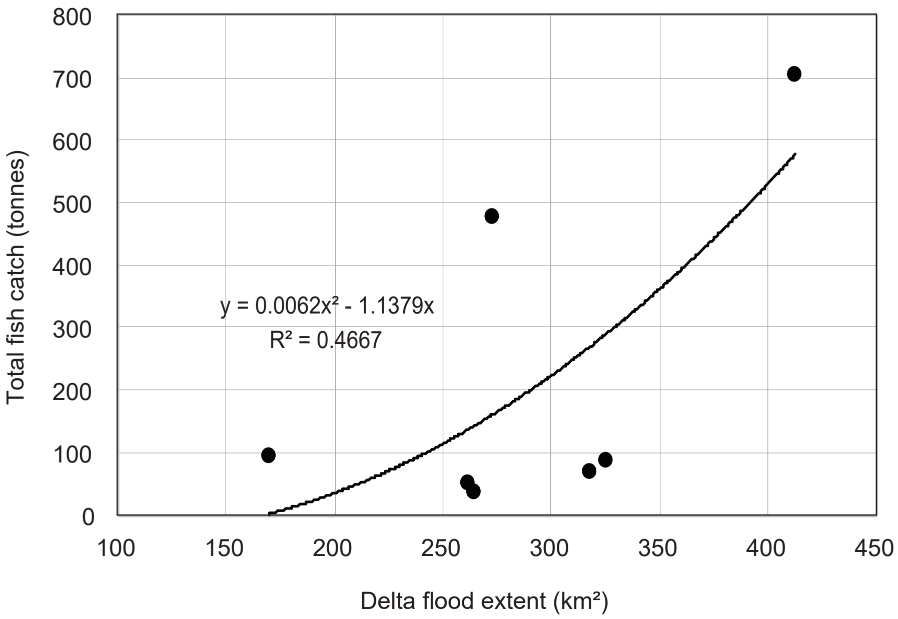
Notes:[+] Data from NES 1985; * Data from KNBS 2013; [‡] Data from GoK 2015; [ł] Using data from GoK 2015, where this contrasts with KNBS 2013.

Agriculture, where these data contrasted with those of the KNBS (Figure C3). This makes sense, if it is assumed that the majority of the fisheries are located in the delta with only relatively small catches in the river upstream of Garsen.

To determine the benefit function, the following three key assumptions were made:

- The reported fish catch is predominantly from the delta, and though some fish are caught upstream of the delta, these largely go unrecorded.
- The three highest points represent realistic upper limits of the catch from the delta, and in other years, there has been significant underreporting of the total catch.
- The minimum annual catch is 40 t and this will occur, from the river, even if there is no flooding.

FIGURE C3. Relationship between flood extent (km^2) in the delta and annual fish catch (tonnes) reported.



Based on these assumptions, Figure C4 presents the benefit function for floodplain fisheries. No allowance was made for when the flood occurs in the year.

Based on data presented in the Economic Review of Agriculture (GoK 2015), the delta fisheries of the Tana River are estimated to have a value of KES 70,391 per tonne (i.e., USD 1,590 per tonne). Using this value, in conjunction with the flood frequencies before and after the dam construction, it is possible to compute the impact of the dams on the value of fisheries (Table C9). This illustrates that for more frequent floods, the dams result in a very slight increase in the value of fisheries, but the dams cause a decrease in value for floods with a return period of greater than 2 years (Table C9). Thus, for a flood with a return period of 5 years, the dam operating regime reduces the potential value of the fisheries from USD 656,580 to USD 535,756 (i.e., a reduction of 18.5%). Similarly, for a flood with a return period of 10 years, the potential value of the fisheries is reduced from USD 887,098 to USD 645,451 (i.e., a reduction of 27.2%). The expected annual value of floodplain fisheries declines from about USD 0.47 million to about USD 0.4 million after the dam construction (i.e., a reduction of 15% in floodplain fisheries livelihoods).

FIGURE C4. Annual maximum fish catch in relation to flood extent in the delta.

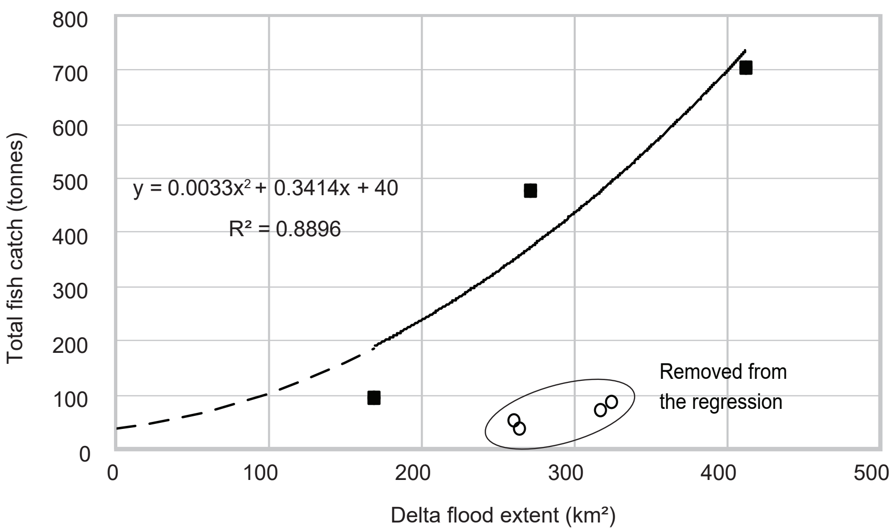


TABLE C9. The potential annual value of delta fisheries for the pre- (1941-1979) and post-dam (1989-2013) flood regimes with all values expressed in USD 2015.

Return period, T (years)	Flood extent (km²)		Maximum potential fish catch (tonnes)		Value (USD 2015)		Variation after dam construction (USD 2015)
	Pre-dam	Post-dam	Pre-dam	Post-dam	Pre-dam	Post-dam	
1.8	233	239	220	229	349,752	364,060	14,308
2	246	247	240	242	381,547	384,727	3,180
5	336	300	413	337	656,580	535,756	-120.823
10	396	333	558	406	887,098	645,451	-241,647
25	470	370	769	492	1,222,542	782,172	-440,369
50	524	396	946	558	1,503,933	887,098	-616,835

Marine and Estuarine Fisheries

Many factors, biophysical and socioeconomic, affect fish catches in nearshore coastal waters. There is often a positive correlation between river runoff (particularly wet-season runoff) and coastal catches. This is attributable to land-based nutrient input into the sea that effectively fertilizes the coastal water, thereby providing food for fish. For example, total annual catch off the coast of Mozambique is positively correlated with total annual runoff of the Zambezi River (Hoguane and Armando 2015).

The Tana River flows into the northern end of the Ungwana Bay, which supports one of East Africa's major fisheries. The other major river flowing into the bay is the Athi-Sabaki River, which enters at the southern end. Fulanda et al. (2011) presented 20 years (1985-2005) of data on marine fisheries in the Ungwana Bay. Additional marine fish catch data (2010-2014) for Tana River County are presented in the Economic Review of Agriculture (GoK 2015). It is not stated, but it is assumed that these data represent fish landed along the coast of the County, which incorporates approximately half the Ungwana Bay. However, the data presented in the Economic Review of Agriculture (GoK 2015) are inconsistent with data presented in KNBS (KNBS 2013), which are also supposedly total marine catch for Tana River County (Table C10). As with freshwater fisheries, marine catch data are often of poor quality. Given the uncertainty in the data for years after 2005, the analyses focused exclusively on the data published in Fulanda et al. (2011) to develop the benefit function for marine fisheries.

TABLE C10. Ungwana Bay marine fisheries (1985-2014).

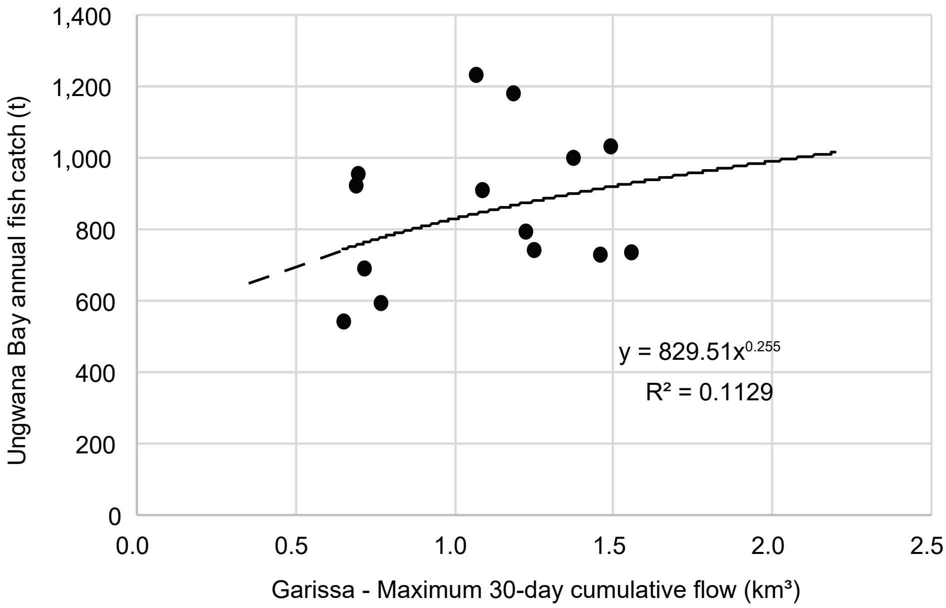
Year	Total annual catch (tonnes)*	Fishing effort (boat days)	Kg/boat/day	Garissa annual flow (Mm^3)
1985	704	34,000	20.7	4,085
1986	688	36,800	18.7	4,190
1987	910	38,400	23.7	2,512
1988	909	39,200	23.2	5,134
1989	512	38,200	13.4	6,284
1990	736	36,600	20.1	7,046
1991	957	38,600	24.8	4,127
1992	625	39,800	15.7	3,716
1993	921	48,200	19.1	4,705
1994	1,029	49,000	21.0	5,727
1995	1,234	51,000	24.2	5,538
1996	1,080	47,800	22.6	m
1997	724	43,600	16.6	m
1998	519	49,000	10.6	9,692
1999	593	52,920	11.2	3,347
2000	542	38,200	14.2	1,808
2001	776	40,200	19.3	m
2002	729	44,200	16.5	5,236
2003	998	62,400	16.0	m
2004	1,179	67,000	17.6	4,879
2005	1,249	65,400	19.1	m
2006	m	m	m	5,896
2007	m	m	m	6,266
2008	55[†]	m	m	4,427
2009	40[†]	m	m	3,238
2010	358[+]/54[†]	m	m	5,597
2011	790[+]/62[†]	m	m	m
2012	743[+]/73[†]	m	m	m
2013	803[+]	m	m	m
2014	383[+]	m	m	m

Notes: * Data 1985-2005 from Fulanda et al. 2011; [†] 2008-2012 fish catch from KNBS (2013); [+] Economic Review of Agriculture (GoK 2015).
m = missing

The regression analyses conducted initially indicated that neither total annual artisanal fish catch nor annual fishing effort (in terms of kilograms/boat/day) in the Ungwana Bay are positively correlated with Tana River flow measured at Garissa. Analyses with the maximum 30-day cumulative flows at Garissa indicate only a very weak correlation with wet-season flows (Figure C5).

The regression results are sensitive to outliers. For the analyses with annual flow, outliers in 1989, 1990 and 1998 significantly affect the regression results. If these are removed, total annual fish catch is positively correlated with total annual flow at Garissa (Figure C6).

FIGURE C5. Regression relationship between total annual fish catch in the Ungwana Bay and annual maximum 30-day cumulative flows at Garissa.



The benefit function derived for near-coast total annual fish catch is as follows:

$$UBC = 0.1195Q_A + 342.07 \ (R^2 = 0.40)$$

Where: UBC = annual Ungwana Bay catch (t) and Q_A = total annual flow at Garissa (Mm^3)

This equation indicates that only fish catches greater than 342 t are influenced by the total annual flow at Garissa. It is likely that this means the hydropower dams will not affect the coastal fishery much, but irrigation (with actual water consumption) might affect it slightly.

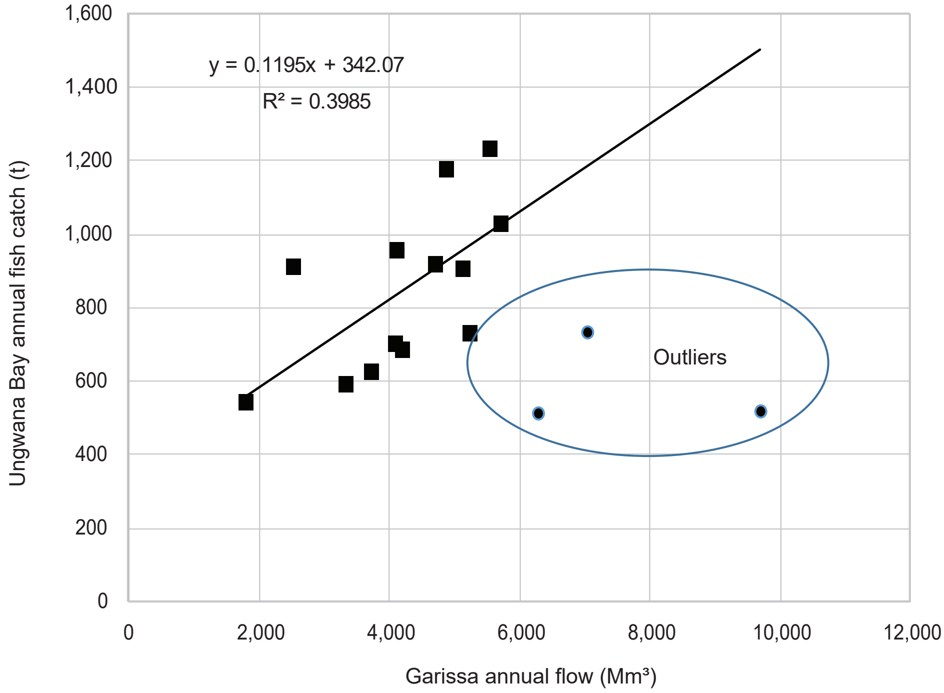
Fulanda et al. (2011) presented fish catch data by species. For shrimps, between 1985 and 2005, the artisanal catch varied from 34 to 105 ty^{-1}. To test the assumption that the annual fish catch would be a function of flow characteristics in both the wet and dry season (Munga et al. 2012), multiple regression analyses were conducted. The highest coefficient of determination (R^2) was achieved when combining both wet- and dry-season flow:

$$SC = 0.002924\ Q_{(A\text{-}J)} + 0.113382952Q_F + 21.80516 \quad R^2 = 0.67$$

Where: SC = annual shrimp catch (t), $Q_{(A\text{-}J)}$ = total wet-season (April-June) flow at Garissa (Mm^3), and Q_F = total dry-season (February) flow at Garissa (Mm^3).

Surprisingly, the annual shrimp catch was not inversely correlated with dry-season flow. Rather, both higher wet- and dry-season flows result in greater shrimp catches.

FIGURE C6. Regression relationship between total annual artisanal fish catch in the Ungwana Bay and total annual flow at Garissa. The three outliers are removed from the regression analysis.



The average value of marine fisheries over the period 2010-2014 was KES 107,262 (USD 2,422) per tonne of fish. Return periods were determined for the total annual flow at Garissa for the pre-dam (1941-1979) and post-dam (1989-2013) periods. In conjunction with the equations above for the annual catch at Ungwana Bay, this enabled an estimate of the potential value of marine fisheries (excluding shrimp) for the period before and after dam construction (Table C11). The results indicate the following:

- Annual flows were slightly higher in the period after dam construction.
- Because of the higher flows, the annual mean increased slightly from 4,824 Mm^3 to 5,230 Mm^3, resulting in a small increase in the value of mean annual marine fisheries from USD 1.97 million to USD 2.00 million.

It is not clear why the annual flow regime is different in the pre- and post-dam periods. The expectation would be for a slight decrease as a consequence of increased abstractions for irrigation and additional evaporation from the reservoirs. The fact that flows are higher must reflect higher average rainfall in the 18 years for which data are available after construction of the dam compared to the 36 years before dam construction.

Using data from KNBS (KNBS 2013), the average value of crustaceans (predominantly shrimp) in Tana County over the period 2012-2014 was KES 289,183 per tonne. This equates to USD 6,531 (2015) using the PPP of 44.28. Potential shrimp catch is correlated to flow, both in the period April to June and in February. Therefore, to evaluate the impact of the dams on potential shrimp catch, it was necessary to determine the impact on flows in both periods (Table C12). The results indicate that dams have benefited shrimp production.

TABLE C11. The potential annual value of marine fisheries (excluding shrimp) for the pre- (1941-1979) and post-dam (1989-2013) flow regimes with all values expressed in USD 2015.

Return period	Pre-dam (1941-1979)			Post-dam (1989-2013)			Variation after dam construction (USD 2015)
	Annual flow at Garissa (Mm^3)	Annual fish catch (t)	Value (USD 2015)	Annual flow at Garissa (Mm^3)	Annual fish catch (t)	Value (USD 2015)	
1.8	4,151	838	2,029,636	4,859	923	2,235,506	205,870
2	4,424	871	2,109,562	5,098	951	2,303,322	193,760
5	6,411	1,108	2,683,576	6,648	1,136	2,751,392	67,816
10	7,708	1,263	3,058,986	7,537	1,243	3,010,546	-48,440
25	9,306	1,454	3,521,588	8,546	1,363	3,301,186	-220,402
50	10,463	1,592	3,855,824	9,232	1,445	3,499,790	-356,034

TABLE C12. The potential annual value of shrimp for the pre- (1941-1979) and post-dam (1989-2013) flow regimes with all values expressed in USD 2015.

Return period	Pre-dam (1941-1979)				Post-dam (1989-2013)				Variation after dam construction (USD 2015)
	April-June flow at Garissa (Mm^3)	February flow at Garissa (Mm^3)	Annual shrimp catch (t)	Value (USD 2015)	April-June flow at Garissa (Mm^3)	February flow at Garissa (Mm^3)	Annual shrimp catch (t)	Value (USD 2015)	
1.8	1,751	117	40	261,240	1,479	193	48	313,488	52,248
2	1,898	129	42	274,302	1,592	208	50	326,550	52,248
5	2,898	244	58	378,798	2,370	385	72	470,232	91,434
10	3,499	340	71	463,701	2,848	555	93	607,383	143,682
25	4,205	476	88	574,728	3,414	811	124	809,844	235,116
50	4,698	585	102	666,162	3,813	1,026	149	973,119	306,957
Mean annual	2,028	177	48	312,168	1,706	302	61	398,341	60,960

Beach Nourishment (Coastal Sediment Supply)

Rivers supply 95% of sediment entering the oceans. When sediment reaches the coast, it is entrained by longshore drift and littoral cells until it is accreted on beaches. A balanced sediment budget means that, over time, equal amounts of sediment are transported to and from a beach; annual losses are offset by annual gains, and the beach remains relatively stable. However, an imbalance in sediment gained or lost during the year destabilizes the beach and causes changes in its shape and/or position.

Human activities that affect the discharge of rivers and alter sediment fluxes can have significant impacts on the amount of sediment a river transports to the coast. For example, deforestation and agriculture as well as urbanization can increase erosion and hence sediment provision to a river. Conversely, removal of water for irrigation reduces river flow and typically reduces a river's sediment carrying capacity. The building of dams has significantly reduced the coastal sediment yield of many rivers, as sediment is trapped behind the dams.

The effect of changing sediment fluxes reaching the coast is context specific. There are examples where the coastal sediment supply has increased and accretion of the shoreline is evident (e.g., the Yellow River). However, anthropogenic impacts most commonly lead to erosion. For example, changes within the Volta River, in particular, the construction of the Akosombo Dam, have led to coastal erosion; between 1.5 and 2 m of the 560 km Ghana coastline is lost annually (Appeaning Addo 2009).

The Kenya coast is an area of outstanding natural beauty and a globally important tourist destination. In total, it is estimated that the tourism industry in Kenya (dominated by visitors to the coastal beaches and game reserves) contributes approximately 10% of gross domestic product (GDP). In 2006, tourism generated USD 803 million (Wikipedia). Coastal erosion has been reported at various places along the Kenyan coastline (Omuombo et al. 2013).

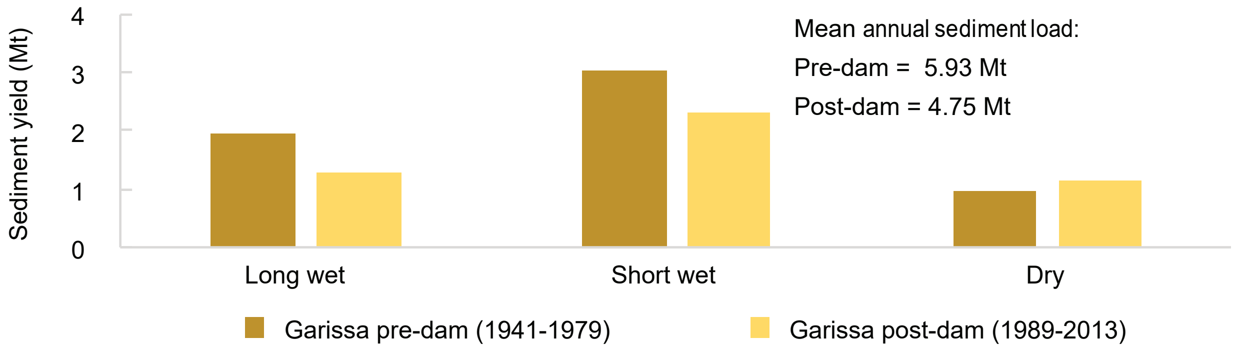
Fluvial input to the Ungwana Bay is dominated by the Athi-Sabaki River in the south and the Tana River in the north. Land-use change, irrigation and, in particular, the construction of dams in the basin would be expected to have modified coastal sediment fluxes. However, recent analyses of the sediment yield of the Lower Tana concluded that dam construction has, rather unexpectedly, not greatly affected the annual sediment flux (Geeraert et al. 2015). It was hypothesized that autogenic processes, namely riverbed dynamics and bank erosion downstream of the dams, mobilized large quantities of sediment stored in the alluvial plain and this was compensating for sediment trapped in the dams (Geeraert et al. 2015).

A more recent study, conducted for this study, included a simulation of flow and sediment yield before and after dam construction (Vercruysse 2017). The findings broadly concur with the previous findings, but provide additional insights into the impacts of the dams constructed in the Tana. In summary:

- The construction of the dams has modified the flow regime at Garissa, and has altered the sediment regime with a much more even distribution of sediment yield through the year (i.e., wet-season sediment yield decreases and dry-season yield increases) (Figure C7).
- The construction of the dams has resulted in a total reduction of 25% in the average annual sediment load at Garissa.
- Of the sediment load transported at Garissa, 30-60% is deposited in the Lower Tana (i.e., in the river channel and on the floodplain) before it reaches Garsen. This remains the case even after dam construction.
- The construction of the dams has resulted in a small increase in sediment yield at Garsen throughout the year, and hence a 11% increase in the average annual sediment load being washed out to sea (Figure C8).

Based on the analyses of Vercruysse (2017), sediment rating curves were developed, linking suspended sediment concentration to mean monthly flow at Garissa in the three seasons (long wet, short and dry seasons). For each season, the rating curve comprises two equations (Table C13; Figure C9). There are no available data to enable an estimate of the value of the sediment transport in the river. However, as noted above, the tourism value of the beaches is high.

FIGURE C7. Sediment yield at Garissa in the long wet (March to May), short wet (October to November) and dry (June to September and December to February) seasons before and after dam construction.



Note: Mt = Million tonnes.

FIGURE C8. Sediment yield at Garsen in the long wet (March to May), short wet (October to November) and dry (June to September and December to February) seasons before and after dam construction.

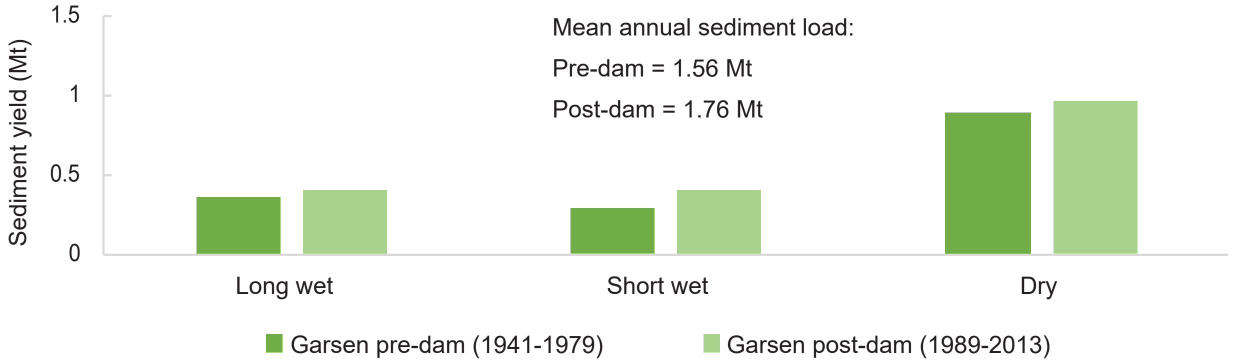
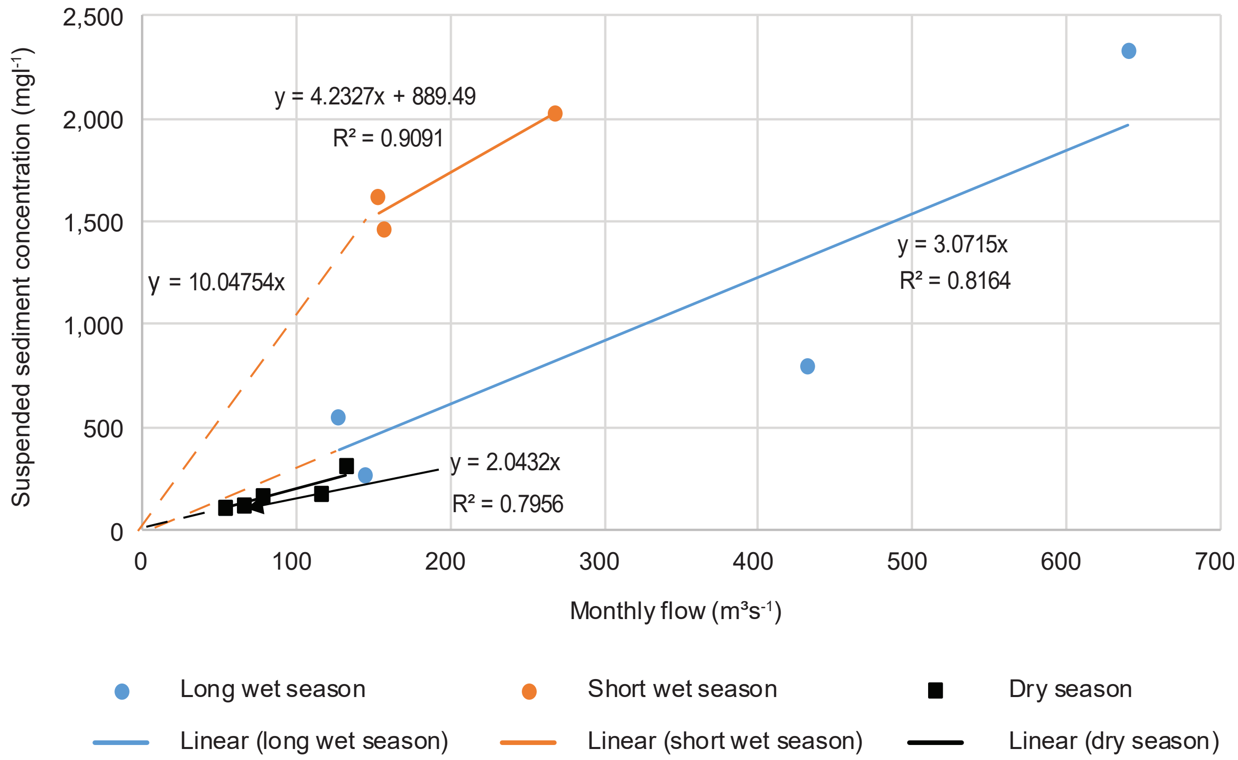


TABLE C13. Relationship between mean monthly suspended sediment concentration and mean monthly flow at Garissa.

	Months	Rating equation	
Long wet season	March to June	$SSC = 3.0715\ Q_{Ga}$	
Short wet season	October to December	$SSC = 10.04754\ Q_{Ga}$	$(Q_{Ga} \leq 1{,}536.96)$
		$SSC = 4.2327\ Q_{Ga} + 889.49$	$(Q_{Ga} > 1{,}536.96)$
Dry season	July to September and January to February	$SSC = 2.0432\ Q_{Ga}$	

Note: Q_{Ga} = Mean flow at Garissa (m^3s^{-1}); SSC = mean monthly sediment concentration (mgl^{-1}).

FIGURE C9. Regression equations between suspended sediment concentration and flow at Garissa in three seasons: long wet (March to June), short wet (October to December) and dry (July to September and January to February).



Annex D. Estimating Flood "Costs"

As well as benefits, flooding in the Tana Basin also has costs associated with infrastructure destruction and livelihood disruption. One of the main justifications for the construction of the HGF Dam is flood control. To incorporate the costs of flooding into the analyses, a flood cost function was developed.

Although flooding is recognized as a major risk in the Lower Tana Basin, there is little information on the economic costs of flooding. The one event for which economic costs are available is the El Niño event of 1997/1998, which caused the worst flooding since the early 1960s.

El Niño events typically affect the whole country and usually cause increased rainfall in the period October to December. In 1997/1998, despite warnings from the meteorological department, the country was ill-prepared and high rainfall did a lot of damage. Nationally, the phenomenon affected 300,000 families and approximately 300 people drowned. There was also an upsurge of vector-borne and waterborne diseases (i.e., cholera, malaria, Rift Valley fever, typhoid and dysentery).

Both Garissa and Tana River districts were among the eight most adversely affected districts in the country (Karanja et al. 2001). Approximately 50,000 people were displaced from refugee camps in the North Eastern Province (predominantly Garissa District), and 25,000 people were displaced in Tana River District (Karanja et al. 2001).

In addition to huge human suffering, the floods resulted in large economic losses. The total cost of flood-related damage to agriculture and infrastructure was estimated to be approximately USD 1 billion. This excludes losses due to the disruption of transport routes, estimated to be an additional USD 1.5 to USD 2.1 billion (Karanja et al 2001).

The El Niño flood event of 1997/1998 was caused primarily by high rainfall in the lower part of the basin; 925 mm between October and December 1997 (cf. the long-term average annual rainfall of about 300 mm), but was exacerbated by high flows from upstream. The maximum daily flow at Garissa (December 2, 1997) was 1,192.1 m^3s^{-1} and peak monthly flow was 2.20 km^3. Based on the flood frequency analyses for the post-dam period (1989-2013), these flows have a return period of approximately 30-40 years. An independent analysis of the event estimated a 35-year return period (Dilley et al. 2005).

Large numbers of sheep and goats died in the Garissa and Tana River districts. In addition, for larger animals (cattle/camels), less directly affected by flooding, mortality and morbidity increased dramatically as a result of diseases such as foot rot and pneumonia (Dilley et al. 2005). In addition, about 1,200 ha of bananas, tomatoes and vegetables were washed away in Garissa District, and 100% of bananas, mangoes, rice, maize and pulses were destroyed in the Tana River District (Otiende 2009). Table C1 presents an estimate of direct economic losses at the national level and specifically in the North Eastern Province. Assuming that losses in the North Eastern Province were predominantly in the Tana Basin, the direct El Niño-induced losses in the Lower Tana Basin were approximately USD (2015) 29 million.

There are no data available for flood events with other return periods. Therefore, a flood cost curve was developed based on the following assumptions:

- Flood events with a return period less than 2 years cause no economic losses.
- People are used to, and largely adapted to, flood events with a return period of 5 to 10 years. Furthermore, built infrastructure is largely designed to cope with these events. Hence, economic losses increase with increasing return period, but the losses are relatively small (i.e., < USD 4 million).
- Neither people nor built infrastructure cope well with flood events with return periods in excess of 10 years, and flood costs rise rapidly with increasing return periods up to 50 years.

- Beyond return periods of 50 years, the rate of increase in economic losses reduces, simply because a lot of the possible damage has been done.

Figure D1 presents the curve derived based on these assumptions. Converting the return periods to flood extent enables the derivation of a relationship between losses and flood extent (Figure D2), which was used to determine the impact of the dams on flood-induced economic losses for floods with different return periods (Table D2).

TABLE D1. Direct economic losses* resulting from flooding in the El Niño event of 1997/1998.

Sector	Comment	Estimated national losses (USD millions)	Estimated costs in the North Eastern Province (USD millions)
Agriculture	Loss of livestock	186.79	15.60
	Loss of crops	199.93	8.42
	Damage to livestock watering points	3.45	1.72
	Damage to livestock routes to markets	0.78	0.39
Transport and communications	Several bridges and an estimated 100,000 km of rural and urban roads were destroyed	1,102	1.06
Water resources	Destruction of small earth dams, increased sedimentation in rivers, and destruction of property and water supply facilities	14.59	1.91+
Total		1,507	29.10

Source: Karanja et al. 2001, but corrected to 2015 values.

Notes: * No indirect losses included (e.g., from the disruption to transport or labor lost due to illness).
+ Cost of rehabilitating water supply facilities.

FIGURE D1. Derived relationship between return period of floods at Garissa (post-dam construction) and economic losses in the Lower Tana Basin.

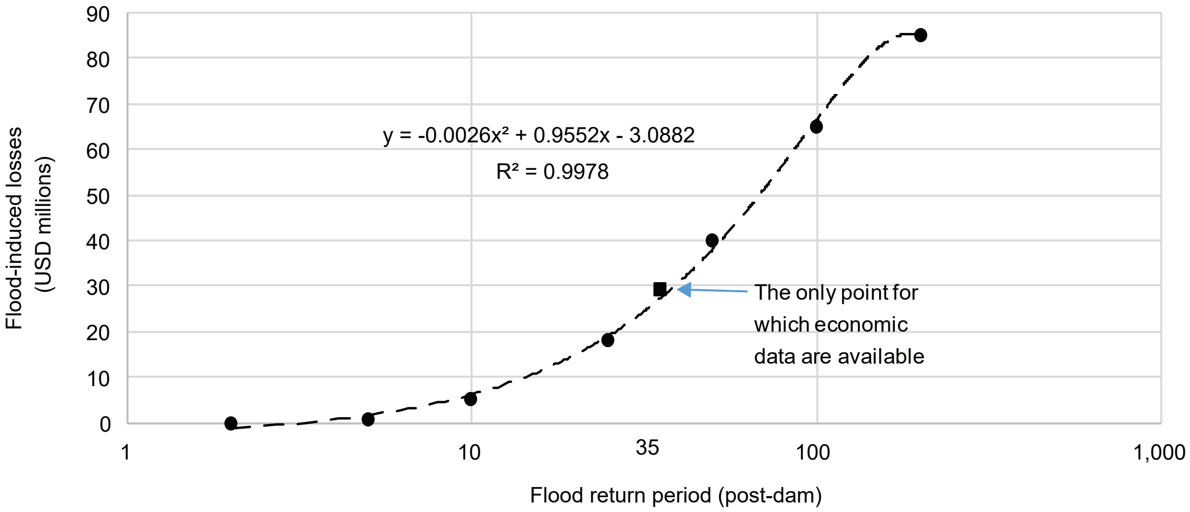


FIGURE D2. Derived relationship between flood extent and flood losses.

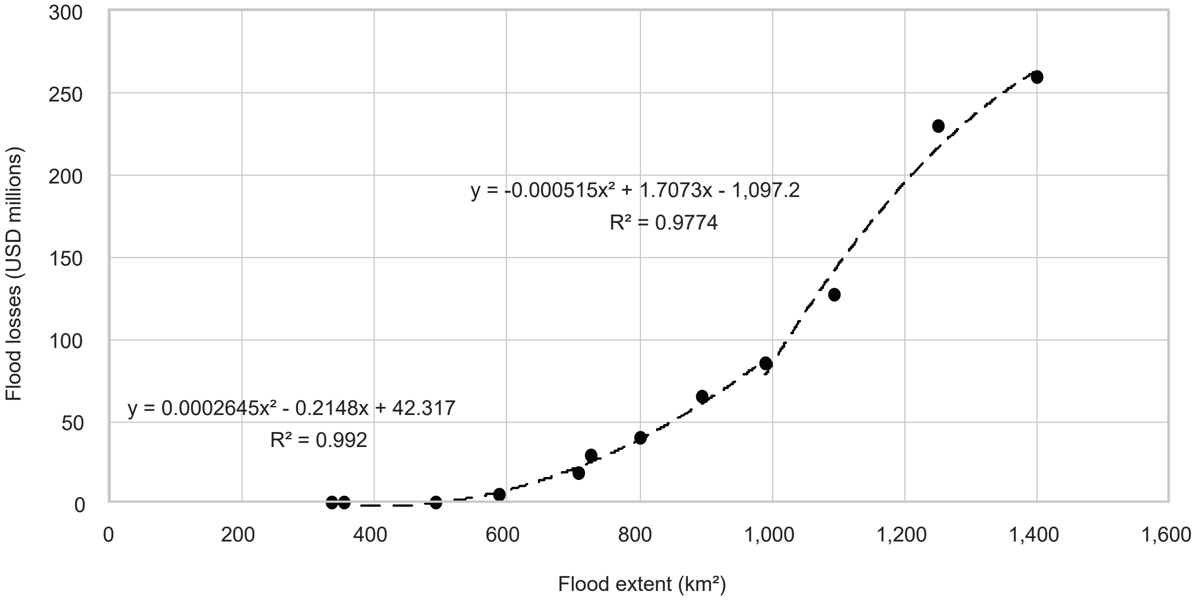


TABLE D2. Comparison of pre- and post-dam flood-induced economic losses for the Lower Tana Basin.

Return period, T (years)	Pre-dam (1941-1979)		Post-dam (1989-2013)		Avoided flood losses (USD millions)
	Flood extent (km²)	Economic losses (USD millions)	Flood extent (km²)	Economic losses (USD millions)	
1.8	321	0	335	0	-
2	350	0	353	0	-
5	597	9.4	491	0.2	9.2
10	800	42.6	587	8.3	34.3
25	1,095	127.0	709	25.2	101.7
50	1,252	229.6	802	43.0	186.5

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