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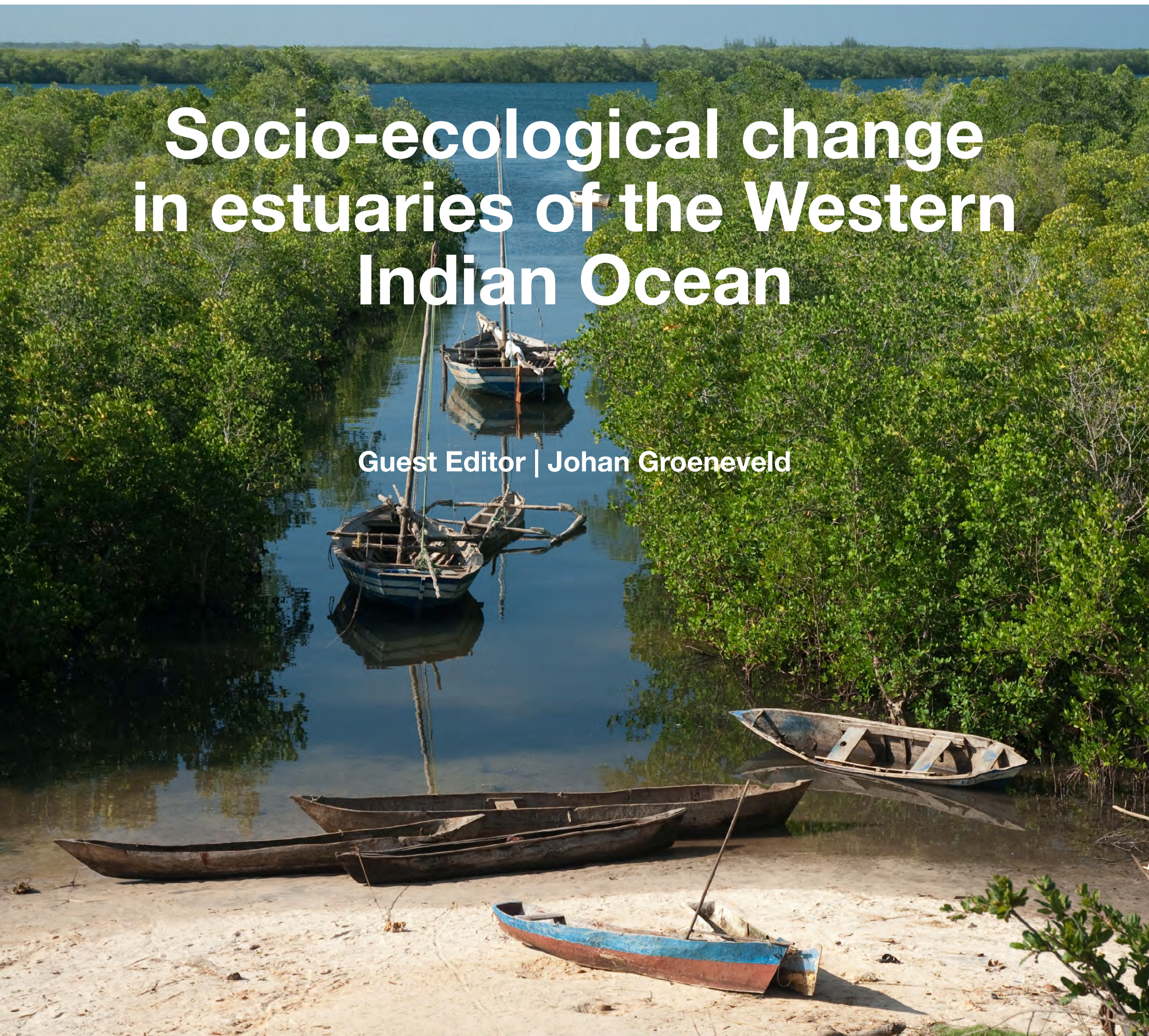

Socio-ecological change in estuaries of the Western Indian Ocean

Guest Editor | Johan Groeneveld

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Cover image: The Rovuma Estuary creeks near Quionga in Mozambique. © José Paula, 2007

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Socio-ecological change in estuaries of the Western Indian Ocean

Estuaries are critical habitats with high biological productivity and an abundance of natural goods and services; features that for millennia have attracted human settlements along the Western Indian Ocean (WIO) coast. Flexible socio-ecological systems evolved around them, with livelihood strategies and natural replenishment of ecosystems achieving a dynamic equilibrium which lasted well into the second half of the 20th Century. The most recent decades have seen high human population growth and urbanization in sub-Saharan Africa, extreme climatic events, political upheaval, and migrations towards coastal areas and beyond. The demand for natural resources has increased exponentially, in some cases beyond the capacity of ecosystems to supply. Loss of function and the reduced capacity to produce essential goods and services are then inevitable outcomes. A key challenge of the 21st Century is to find workable solutions that will maintain well-functioning and productive ecosystems, under challenging circumstances of ever greater demands and a declining natural resource base exacerbated by climate change.

This Special Issue of the Western Indian Ocean Journal of Marine Science is based on the research undertaken by the Estuarize-WIO Project (2016-2019) funded by the Marine Science for Management (MASMA) Program of the Western Indian Ocean Marine Science Association (WIOMSA). Estuarize-WIO adopted a regionalized trans-disciplinary approach from the onset, focusing on three typical estuarine systems across a broad latitudinal gradient in the WIO region – the Bons Sinais Estuary in Mozambique, Ruvu Estuary in Tanzania and Tana Estuary in Kenya. These estuaries form part of socio-ecological systems that are threatened by disruption of freshwater flow (upstream abstraction), local exploitation patterns (increasing societal needs) and climate change effects (sea-level rise and extreme climatic events).

In accordance with a trans-disciplinary approach, the 9 papers of the Special Issue address a range of interlinked biophysical, natural resource use and socio-economic aspects, along a transitional gradient from sparsely populated rural- to denser urbanized communities (Groeneveld *et al.*, 2021a). Four papers from the Bons Sinais Estuary describe the residual circulation of the estuary with implications for larval dispersal and fisheries (Hoguane *et al.*, 2021); household dependence on fish-based farming systems (Francisco et al., 2021); decadal change in land use / land cover (LULC) and habitat loss associated with rapid urbanization (Furaca *et al.*, 2021); and low-trophic-level estuarine fisheries using unselective fine-mesh gears (Mugabe *et al.*, 2021). One paper from the Ruvu Estuary explores seasonal-to-decadal changes in LULC and estuarine fisheries, which includes an occasional fishery for invasive fresh-water prawns (Groeneveld *et al.*, 2021b). Two papers from the Tana Estuary compare livelihood strategies at coastal and upstream communities based on household surveys and remote sensing of LULC (Mwamlavya *et al.*, 2021); and describe diverse and well-organized estuarine fisheries (Manyenze *et al.*, 2021). The final paper of the Special Issue relies on a systems-oriented approach to demonstrate that human-induced processes affect WIO estuaries and dependent livelihoods more deeply than inherent physical differences (Santos *et al.*, 2021).

The Special Issue further contributes biodiversity information in the form of species lists compiled for fisheries; and provides the metadata of datasets used during research undertaken for this publication (Santos et al., 2021). A key conclusion of the Special Issue is that research, management and governance will benefit from greater regional cooperation, given the similarities of estuarine systems along 2000 km of tropical coastline in the WIO, and the different levels of disturbance resulting from anthropogenic activities in upstream catchment basins and estuaries.

Johan GROENEVELD
Guest Editor

Estuarize-WIO: A socio-ecological assessment of small-scale fisheries in estuaries of the Western Indian Ocean

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Abstract

Estuaries provide unique ecosystem goods and services and have been focal points for human settlement and resource use throughout recorded history. In the Western Indian Ocean (WIO) region, the effects of human population growth, rapid economic development and climate change on estuaries threaten their ecological functioning and the sustainability of estuary-dependent livelihoods. Governance systems are ill-equipped to deal with the mounting challenges. Long-term datasets that describe estuary-scale trends are scarce, and socio-ecological interactions that support sustainable use of resources are incompletely understood. To address these gaps, the Estuarize-WIO project (2016-2019) compiled datasets on biophysical, ecological, socio-economic and fisheries aspects of selected estuaries in Mozambique (Bons Sinais), Tanzania (Ruvu) and Kenya (Tana), analysed trends per estuary, and used a socio-ecological systems (SES) framework to integrate information from multiple sources at local and regional levels. The introductory paper of this Special Issue of the Western Indian Ocean Journal of Marine Science provides regional context and reviews the relevant literature available for WIO estuaries. In succeeding papers, estuarine circulation is inferred from hydrological measurements, seasonal and decadal trends in land cover and land use are investigated using remote sensing images, household surveys are used to investigate socio-economic circumstances and resource use, and long-term catch survey data and field samples are used to describe small-scale fisheries. In the synthesis paper, a SES framework is constructed to investigate linkages and feedback loops in individual estuaries. A regionally comparative analysis accross the WIO region was conducted, and recommendations were made for future research and governance. The methodological approach developed for Estuarize-WIO is well-suited to research of data poor systems with limited accessibility and research infrastructure.

Keywords: eastern Africa, estuary-dependent livelihoods, climate change, natural resources, population growth, satellite

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Background

Estuaries as dynamic, transitional ecosystems are defined variously (Whitfield and Elliott, 2011) but are generally partially enclosed coastal water bodies where rivers reach the sea, and where sea and freshwater mix to provide high levels of nutrients in the water column and sediments (Elliott and Whitfield, 2011; Wolanski *et al.*, 2019). Estuaries are among the most productive natural habitats in the world and sustain plant and animal communities capable of wide-ranging salt tolerance, enrich nearshore marine ecosystems by exporting sediments, nutrients and organic matter, and connect and support the functioning of many different habitats. Estuaries have been focal points of human settlement and resource use throughout history (Lotze *et al.*, 2006), because they provide unique goods and services on which the social and economic prosperity of coastal communities rely.

Typical ecosystem goods and services derived from estuaries in the Western Indian Ocean (WIO) have been described by McNally *et al.* (2016) for the Wami Estuary in Tanzania and Hamerlynck *et al.* (2010) for the Lower Tana Delta in Kenya, with the relative scale and importance of goods and services differing across estuaries. Ecosystem goods and services fall into four broad categories: provisioning (capacity to create biomass and produce food, raw materials and energy resources); regulating (essential ecological processes and life support systems); supporting (space for plants and animals, thus conserving biodiversity); and cultural (contributions to human well-being) (Millennium Ecosystem Assessment, 2005). Estuarine goods and services are important at spatially different scales – locally for food security, coastline stabilization and economic activity; regionally as a conduit of terrigenous matter to marine environments and as nurseries for marine fish and crustaceans; and globally as a carbon sink in wetlands and dense mangrove forests (Bosire *et al.*, 2016).

Estuaries are one of the coastal areas most at risk from human activities in the WIO region (Diop *et al.*, 2016). They are affected by localized overexploitation and degradation of coastal habitats, are vulnerable to reduced freshwater inflow resulting from upstream damming and land cover change in catchments, and to sea level rise and the increasing frequency of droughts, floods and storms brought by climate change (Kitheka and Mavuti, 2016; Mwaguni *et al.*, 2016; Shagude, 2016; Wagner and Sallema-Mtui, 2016; Duvail *et al.*, 2012, 2017). The recent 'Regional State of the Coast Report for the Western Indian Ocean' (UNEP-Nairobi Convention and WIOMSA, 2015) showed that the demand for ecosystem goods and services in the WIO continues to increase, while the capacity of ecosystems to service these demands remain relatively constant or decrease if they become degraded. Coastal areas of the WIO have seen rapid human population growth over the past decades (UN-Habitat, 2014; Celliers and Ntombela, 2015), with coastal towns and cities often strategically placed along the banks of estuaries to benefit from their natural resources and shelter, which gave rise to economic hubs with industrial ports for shipping (e.g., Durban in South Africa, Maputo, Beira and Quelimane in Mozambique, Dar-es-Salaam in Tanzania, and Mombasa in Kenya) (Jackson, 2015).

Most estuaries of the WIO form complex land- and seascapes consisting of interacting terrestrial, coastal and marine ecosystems with high biological productivity. They are multi-user and multi-functional areas of high socio-economic value for local communities (Terer *et al.*, 2004) and have maintained exceptional goods and service values (Scheren *et al.*, 2016). Traditional livelihood activities are fishing and hand-collection of invertebrates (van der Elst *et al.*, 2005; Groeneveld, 2015), harvesting of mangroves for fuelwood and construction materials, floodplain agriculture of multiple crops (rice, maize, beans, vegetables), banana and mango plantations, cattle herding on communal rangelands, hunting and gathering of forest products (Hamerlynck *et al.*, 2010; Bosire *et al.*, 2016). Diversified livelihood strategies based on fish-based farming systems are typical along the edges of WIO estuaries (Hamerlynck *et al.*, 2020). Rights of access to key resources to different user groups were historically regulated through complementary and mutually beneficial exploitation strategies which were flexible to cope with seasonal and interannual variability in resource abundance (Terer *et al.*, 2004; Duvail *et al.*, 2012). Even so, Katikiro *et al.* (2014) suggested that social structures may be weakening, based on a shift from collective communal fisheries to individual and private fishing groups observed in fishing villages in Tanzania.

Governance of coastal resource-use in the WIO region (including in estuaries) relies partially on community-based management (CBM; Maina *et al.*, 2011; McClanahan *et al.*, 2016; Cockerill and Hagerman, 2020). Basic policy drivers are participation and co-management, adapting to local socio-ecological conditions, and use of economic and social incentives (McClanahan *et al.*, 2009). Although practical, CBM have faced criticism relating to knowledge, participation, and representation, partially rooted in historical legacies and international agendas of donor agencies (Cockerill and Hagerman, 2020). Examples of CBM are Beach Management Units (BMUs) for small-scale fisheries (Oluoch and Obura, 2008; Kanyange *et al.*, 2014) which have been partially successful, but are afflicted by inadequate resources, low efficiency and enforcement and jurisdictional squabbles. Closure of previously fished areas (called *tengefu*) to enhance their recovery and increase local benefits are also used in Kenya (Mangora *et al.*, 2014; McClanahan *et al.*, 2016).

In estuarine systems, CBM is geared towards resolving local socio-ecological issues of resource exploitation, but the functioning of estuarine ecosystems remain particularly vulnerable to freshwater input originating from catchment areas, over which CBM has little control (see Fulford *et al.*, 2020). Land-based sources of pollution and other activities that cause the degradation of coastal and marine environments (including estuaries) may induce impacts beyond national boundaries and can only be addressed at national or regional levels (van der Elst *et al.*, 2009). In the WIO, existing and potential land-based impacts were highlighted in a Transboundary Diagnostic Analysis (TDA or decision support tool; UNEP-Nairobi Convention Secretariat, 2009a), which formed the basis for the development of a Strategic Action Programme (SAP; UNEP-Nairobi Convention Secretariat, 2009b). The SAP sets out the policy, legal and institutional reforms and investments required to address the issues identified by the TDA. Many of the land-based (or upstream) threats to estuaries remain unresolved and are challenging when juxtaposed with the prioritization of natural resources for economic and infrastructure development – for example, abstraction of freshwater for consumption, energy generation and agriculture.

The growth of towns around WIO estuaries play an important role in the socio-economic dynamics of development, but the use of natural resources around them is also affected by the political dynamics of stability and conflict (Büscher and Mathys, 2019). Long-standing conflicts exist between ethnic groups that compete for land use, and between local communities and external investors intent on large-scale land and water use for commercial ventures (Duvail *et al.*, 2012; Smalley and Corbera, 2012; Kipkemoi *et al.*, 2017). The influence of the Covid-19 pandemic on the socio-economic stability of communities living around WIO estuaries remains to be determined.

Ostrom (2009) provided a general framework for analysing sustainability of socio-ecological systems (SES), in which a dynamic balance between users (e.g. coastal communities, society, economy) and a natural system that provides resources (estuarine ecosystems in the present case) can be achieved through constant adaptation and natural biophysical resilience. SES are complex and explicitly linked in two-way feedback relationships that are often self-reinforcing or self-moderating (Adger, 2000; Redman *et al.*, 2004; Berkes *et al.*, 2014). SES frameworks are appropriate for assessing coupled human and natural systems in estuaries, where multiple interdependent natural resources are exploited in a limited area according to their spatio-temporal availability.

The complex interplay of the natural ecosystem goods and services and the derived societal benefits make WIO estuaries good candidates for implementing natural capital accounting (NCA) systems that monitor and report on ecosystem change and use (Hein *et al.*, 2020). The country-level NCA reporting standards derived for the United Nations Sustainable Development Goals 2030 Agenda could consider, for example, that focussing on estuarine SES would address several of the 17 goals including no poverty, zero hunger, clean water, climate action, life below water and life on land (www.sds.un.org/goals).

The Estuarize-WIO project (2016-2019) was funded by the MASMA programme of the Western Indian Ocean Marine Science Association (WIOMSA; www.wiomsa.org) to compile datasets on biophysical, ecological, socio-economic and fisheries aspects of selected estuaries in the WIO, and integrate the information using a SES framework (Fig. 1). The project relied on existing data and limited field sampling to fill data gaps and validate earlier data. Estuarize-WIO focussed on estuaries at a regional level, transcended political boundaries and relied on a multidisciplinary approach.

The objectives of Estuarize-WIO were to:

1. Describe and understand the estuarine biophysical environment, ecological function and natural capital, with a focus on seasonal and long-term change in land cover and land use;
2. Define human user groups, socio-economic and cultural settings, and the reliance of livelihood activities on estuarine resources for food security and employment;

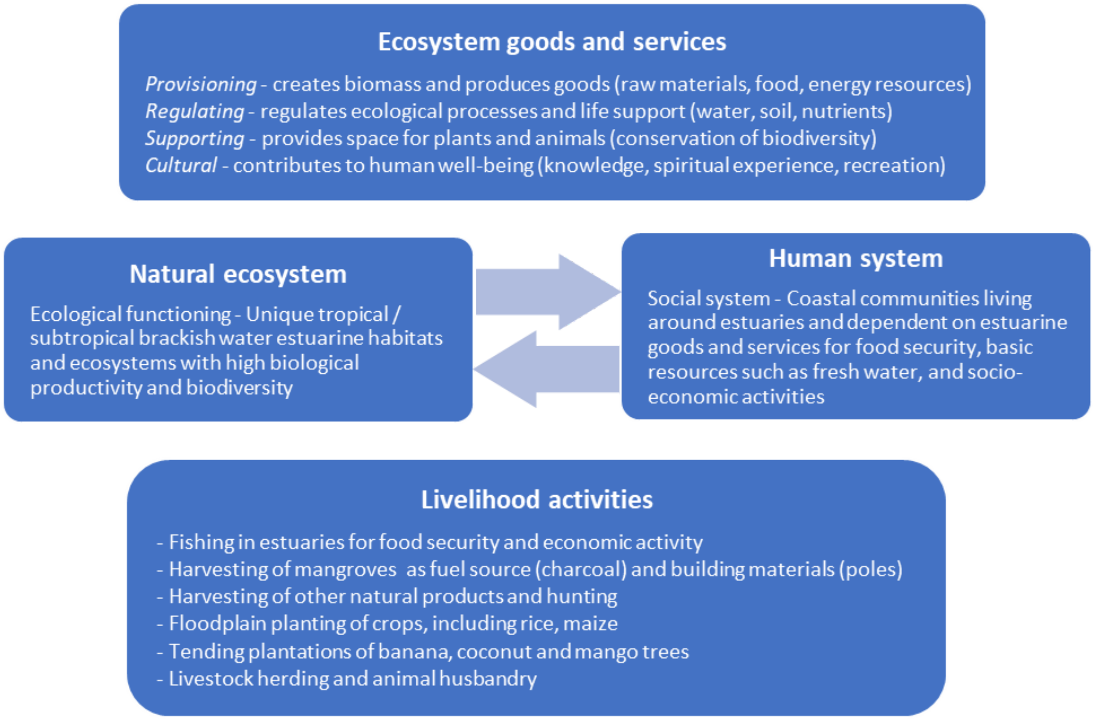

Figure 1. Simplified Socio Ecological Systems (SES) concept (Ostrom, 2009) showing key interactions between social and ecological systems in Western Indian Ocean estuaries (McNally *et al.*, 2016).

3. Investigate small-scale fisheries as a key component of SES around WIO estuaries; and
4. Identify essential links and feedback loops in SES that facilitate long-term sustainability of resource use and the conservation of critical habitats.

Description of 'WIO estuaries'

Rivers that discharge into the WIO often have steep headwater gradients, naturally carry high sediment loads, and meet the ocean on flat coastal plains, where they form fan-shaped deltaic systems (Duvail *et al.*, 2017). The deltas form when sediment deposits are reshaped over time by compaction, dewatering and renewed sedimentation by successive flood deposits. Major fan-shaped deltas in the WIO region are the Zambezi, Rufiji and Tana deltas, and many other smaller deltaic systems discharge into Maputo Bay (Incomati, Maputo) and further to the north (Ruvuma, Ruvu, Athi-Sabaki). As elsewhere, these WIO systems support the majority of coastal wetlands, are associated with important coastal marine fisheries (Day *et al.*, 2019) and are highly susceptible to sea level rise due to near sea-level topography and high rates of subsidence (Day and Rybczk, 2019).

The climate in the WIO ranges from subtropical to tropical, and precipitation is dominated by a seasonal monsoon regime. Rainfall and flow characteristics of WIO estuaries are highly seasonal. Summer rainfall occurs in southern and central Mozambique, peaking above 200 mm/month in December to March, followed by dry conditions of 15 to 60 mm/month between June and October (https://worldweather.wmo.int/en). Heavy extended rainfall occurs in March to May in northern Mozambique, Tanzania, Kenya and southern Somalia, before the southeast (SE) monsoon, and short rains occur in the same region in October to December during the northeast (NE) monsoon (McClanahan, 1988). The alternating dry and wet periods result in high seasonal variability in runoff and sediment transport. By latitude, annual rainfall decreases northwards from Mozambique (530-1140 mm per year) to Somalia (250-375 mm) and as a result there are larger and more numerous estuaries in the southern part of the WIO, particularly in southern Mozambique (Taylor *et al.*, 2003). Some southern African rivers have catchment basins that extend far to the west, such as the Zambezi which originates in Angola, thus receiving inflow from different climate zones.

Most deltaic estuaries of the WIO are river dominated during periods of high rainfall, but tidal and wave processes are more important during droughts. The tidal range is 2-4 m (mesotidal), and strong tidal currents (> 2 m/s) influence headwaters far upstream in some estuaries (Scheren *et al.*, 2016). Mangrove forests are critical habitats in the region, covering an estimated 1 million ha, mostly in Mozambique, Tanzania, Kenya and Madagascar (Bosire *et al.*, 2016). Nine mangrove species occur along the banks of estuaries and in coastal depressions across the region, and they extend upstream to the limit of seawater intrusion. Typical threats to mangrove ecosystems are overharvesting for fuel and construction materials, clearing and conversion to other land uses, pollution and sedimentation, pest infestations, and excessive flood damage (Bandeira and Balidy, 2016; Lugendo, 2015; Bosire *et al.*, 2016). Sea-level rise and associated beach erosion are emerging threats to mangroves because their inland retreat may be limited by change in land use. Wetlands are common habitats around WIO estuaries, because of low topography and restricted freshwater drainage, and they are replenished by seasonal rainfall or floods.

Traditional use systems in the deltas and floodplains of the WIO are adapted to seasonal floods and dry periods, with fishing taking place during the floods, planting of rice and other crops during flood recession and grazing by livestock afterwards (Duvail *et al.*, 2017; Hamerlynck *et al.*, 2020). Tidal rice and other crops are cultivated on floodplains, on different levels adapted to flooding frequency, height, duration and groundwater level (Hamerlynck *et al.*, 2010). Human population densities in deltas between Somalia and central Mozambique (incl. Zambezi delta) range between 25 and 249 inhabitants/km^2, well below the world average of around 500 inhabitants/km^2 (Overeem and Syvitski, 2009). Densities are higher around deltas in southern Mozambique and Madagascar (250-999 inhabitants/km^2). Urbanization (formal development of towns, cities and growth of informal settlements) along the banks of estuaries is a common sight.

Selection of estuaries for study by Estuarize-WIO

Three estuarine systems located in Mozambique, Tanzania and Kenya were chosen for the Estuarize-WIO project (Fig. 2), based on the following criteria:

- Broad geographical coverage in the WIO (i.e., estuaries in different countries) and similar estuary size
- Presence of small-scale fisheries and dependent communities adjacent to the estuary
- Proximity to a research station (or fisheries office) as collaborating entity, and existing data on fisheries, socio-economic or cultural settings available, or easy to obtain
- Field sampling logistically possible in a secure environment

Bons Sinais Estuary in Mozambique

Geographical setting

The Bons Sinais ("good signs") Estuary is located along the central Mozambique coast in Zambézia Province (Fig. 2). It originates at the confluence of the Cuacua and Licuar Rivers (17°54'S; 36°49' E), is about 30 km long and 2.5 km wide at its mouth, and discharges into the WIO at 18°01'S; 36°58' E, near the northern end of the Sofala Bank (Hoguane *et al.*, 2021). The Bons Sinais was historically connected to the Zambezi River via the Cuacua tributary and was navigable until it silted up *circa* 1820 (Newitt, 1995). The construction of the Kariba (1955) and Cahora Bassa dams (1974) in the upper Zambezi River reduced downstream flow and flood peaks, disconnecting the Cuacua from the Zambezi (Beilfuss and Santos, 2001). During intense flooding, the upstream connection with the Zambezi River is occasionally reconnected, channelling flood waters via the Cuacua into the Bons Sinais. The climate along the central Mozambique coastline is influenced by a sub-tropical anticyclone system, southeast trade winds, and the southern extremity of the East African monsoon system (Sætre and da Silva, 1984). Rainfall averages 1140 mm per annum, of which ~80 % falls between November and April.

Ecosystems and socio-ecological importance

The Bons Sinais Estuary is linked to extensive freshwater wetlands and tidal creeks, and is fringed with dense mangrove forests, dominated by the white mangrove *Avicennia marina*. It is an important breeding and nursery ground for many fish and crustaceans, of which some species recruit to highly productive fishing grounds on the Sofala Bank, including a large bottom-trawl fishery targeting penaeid prawns. Small-scale fishers operate in the estuary and Sofala Bank coastal waters using dugout canoes and other small boats, and a variety of fishing gear (Hoguane and Armando, 2015; Mugabe *et al.*, 2021). Catches are predominantly sold at local markets. Other activities are floodplain agriculture (particularly maize and rice), mangrove harvesting for fuelwood, charcoal-making and poles for construction, artisanal salt-making and mariculture of shrimps at a commercial farm on the south bank of the estuary. Remnants of large industrial coconut palm plantations surround the estuary on slightly higher ground, but many of the trees are dead or have been affected by outbreaks of coconut lethal yellowing disease since the late 1990s (Bonnot *et al.*, 2010).

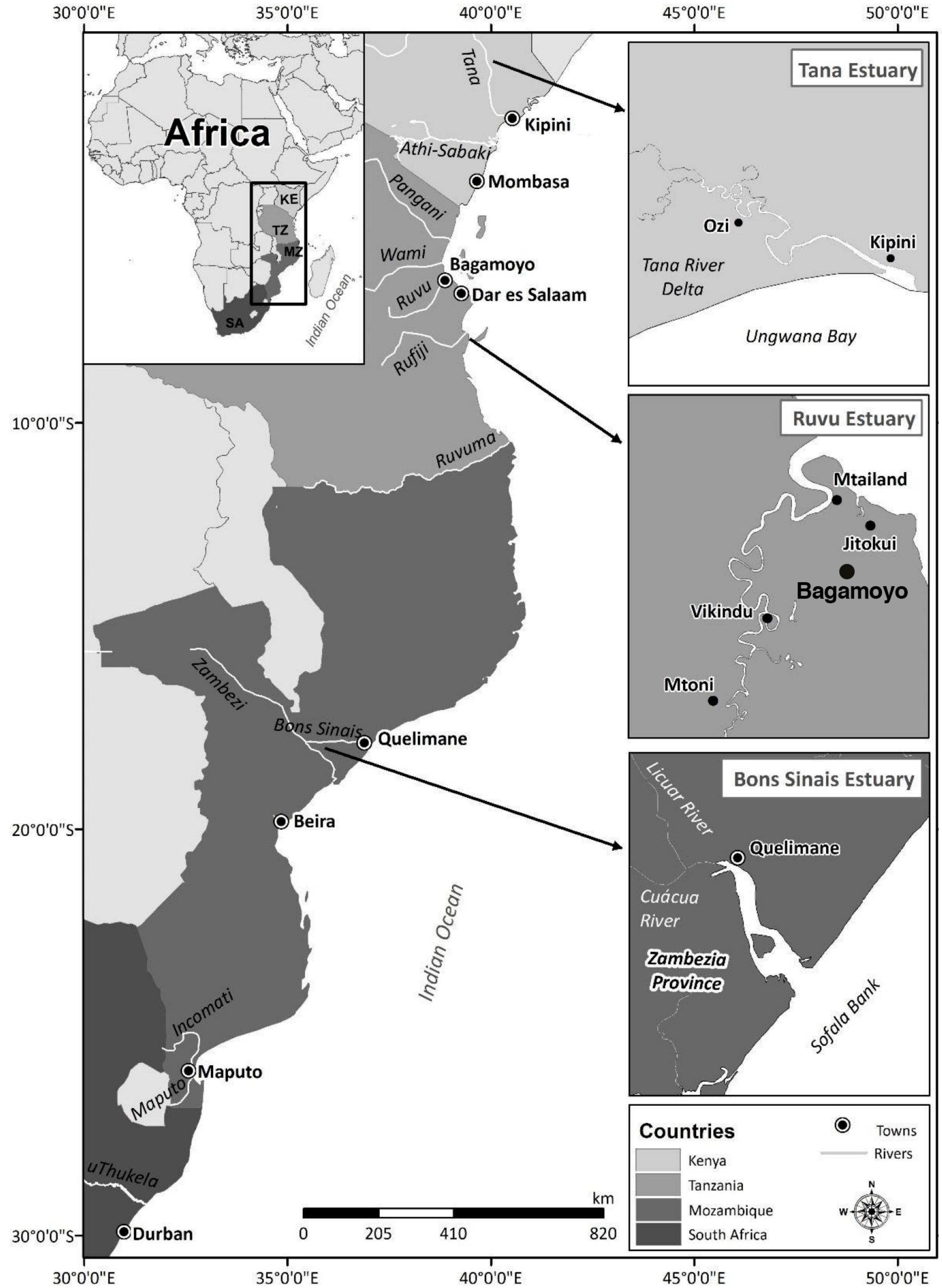

Figure 2. Estuarize-WIO study area in the Western Indian Ocean region, showing towns and estuaries mentioned in the text: Tana Estuary in Kenya (top right panel); Ruvu Estuary in Tanzania (middle) and Bons Sinais Estuary in central Mozambique (bottom).

Key drivers of socio-ecological change

The city of Quelimane is located on the northern bank of the estuary, some 25 km from its mouth, with a seaport located adjacent to the city. Quelimane originated as a Swahili trade centre in the pre-colonial era and became a Portuguese colonial town in 1761, forming a hub for trading and transport by sea or land. Quelimane grew rapidly after the Mozambican civil war between 1977 and 1992 when up to 3 million people were displaced from inland areas to the coast, and from rural to urban areas (Wilson, 1994). Quelimane is the sixth most-populous city in Mozambique (pop. ~400 000 in 2020; www.populationstat.com) and is the administrative capital of Zambézia Province.

Rapid urbanization (growth of human population, expansion of built environment) accompanied by increased demand on local resources to provide space, water, food, fuelwood, transport and raw materials for construction and economic activity have been key drivers of socio-ecological change over the past three decades. Much of the new construction took place on low-lying land after clearing of mangroves or landfilling, making the city prone to flooding. Sectoral changes in livelihood opportunities during the rural-urban transformation are reported by Francisco *et al.*, (2021). Changes in land use and land cover around the Bons Sinais Estuary, caused by the conversion of estuarine wetlands to agricultural lands, affect critical habitats and ecological functioning on which crucial ecosystem goods (fish, wood) and services (protection against floods, storms) in the region rely (Furaca *et al.*, 2021).

Ruvu Estuary in Tanzania

Geographical setting

The Ruvu River (~ 12 000 km^2 catchment basin; JICA, 2013) originates in the Uluguru Mountains in Tanzania and flows north-eastwards for some 316 km before it terminates in a meandering medium-sized estuary, 5 km north of Bagamoyo Town (Fig. 2). The Ruvu Estuary discharges into the WIO at 6°38'S; 38°87'E on the mainland side of the Zanzibar Channel (Shagude *et al.*, 2003). It is a major source of siliciclastic sediments which strongly influences the nearshore sea bottom morphology and sediment composition. Using satellite imagery from 1986 to 2000, Shagude *et al.* (2003) showed rapid accretion at the estuary mouth, with the coastline progressing northwards and a developing delta over the nearshore shelf area. Peak freshwater discharge through the estuary occurs in April and May, coinciding with the main rainy season between March and May in the catchment basin (GLOWS-FIU, 2014), with a smaller discharge peak in November to January.

Ecosystems and socio-ecological importance

The Ruvu Estuary is fringed by dense mangrove forests (including species of *Sonneratia*, *Rhizophora*, *Avicennia*, *Ceriops*, *Bruguiera*, *Heritiera*), extending from the estuary mouth to some 10-12 km upstream, where a gradual transition from mangroves to palms indicate mainly freshwater conditions throughout the year (GLOWS-FIU, 2014). Most communities in the Bagamoyo District rely on a combination of fishing and farming for food and a cash income (Mkama *et al.*, 2010; Mbwambo *et al.*, 2012). Farmers have adapted their farming strategies to cope with increasing variability in climate conditions (Mbwambo *et al.*, 2012). Subsistence rice farming takes place in the meanders of the upper estuary. Most fishing takes place in coastal and nearshore waters, using a variety of small craft and gear types (Jiddawi and Ohman, 2002; GLOWS-FIU, 2014). Landings at Bagamoyo fish market comprise of multiple fish species caught on coral reefs, sandy and muddy sea bottom, and pelagic habitats (Semesi *et al.*, 1998; GLOWS-FIU, 2014). The coastal waters of Bagamoyo constitute important penaeid prawn bottom trawling grounds (Teikwa and Mgaya, 2003). Fisheries in the bay supply local needs, as well as the Dar-es-Salaam fish market, with fresh fish, and inland markets with smoked and fried fish. Fisheries in the enclosed part of the Ruvu Estuary are not well-described, but catches include marine catfish *Arius africanus,* milkfish *Chanos chanos* (GLOWS-FIU, 2014) and more recently, invasive giant freshwater prawn *Macrobrachium rosenbergii* (Kuguru *et al.*, 2019). Molluscs and crabs are collected in or close to mangrove stands.

Key drivers of socio-ecological change

In contrast to the Bons Sinais Estuary, where Quelimane is built on the banks of the estuary and within the estuarine functional zone, the built-up area of Bagamoyo Town is located approximately 5 km to the south of the Ruvu Estuary, beyond its functional zone. Bagamoyo is a historical trading and cultural centre and formerly (1885-1916) the capital of German colonies in East Africa. The historical German stone town and 8th Century Kaole ruins just south of Bagamoyo are easily reached on all-weather roads from Dar-es-Salaam, some 80 km away. Over the past two decades, the town has become an important cultural, beach and conference tourist hub, which has created both economic and development opportunities, while adding new complexity to key economic and social challenges. The population of Bagamoyo is highly mixed because of migration and settlement of different ethnic groups, and a new university campus in the town. Traditional leadership plays only a minor role under the current administrative setup.

Key drivers of socio-ecological change around the lower Ruvu Estuary are mangrove clearing for construction of commercial salt pans, mangrove harvesting for charcoal and construction, and tourism development. The high market demand for fish is an important driver of local economic activity, but agricultural activity appears to be largely at a subsistence level along the lower estuary, with low value crops. Upstream water abstraction for domestic use and economic development in Dar-es-Salaam and irrigation of agricultural lands has reduced flow volumes in the estuary. Industrial effluents and untreated sewage associated with urbanization have reduced water quality, which is categorized as 'moderately polluted' on the River Pollution Index (Alphayo and Sharma, 2018). Decadal trends in freshwater flow, land use / land cover and reliance on fishing in the Ruvu Estuary are demonstrated in Groeneveld *et al.* (2021).

Tana Estuary in Kenya

Geographical setting

The Tana is the longest river in Kenya (~1100 km long) and the largest supplier of fresh water into Ungwana Bay on the north coast of Kenya (Kitheka and Mavuti, 2016). The Tana Delta and Estuary receives runoff from a medium-sized basin comprising the Central Kenya Highlands, particularly the southern slopes of Mount Kenya and eastern slopes of the Aberdares mountain ranges (Maingi and Marsh, 2002). The catchment basin is seasonally flushed during the transitions between the NE and SE monsoons, in March to June and October to January, respectively (Kitheka and Mavuti, 2016). The Tana Delta comprises of four estuaries of which the northern-most one covered in this study (hereafter called Tana Estuary; Fig. 2) has been channelled to form the main river mouth into Ungwana Bay (Scheren *et al.*, 2016). Kipini Town is located on the northern bank of the estuary where it discharges into Ungwana Bay, in an area with low population density of 9 persons/km^2 (Tana Delta Sub-County; Government of Kenya, 2019). Erosion of the beach and dunes adjacent to the estuary mouth has collapsed built infrastructure, including a hotel (pers. obs. JCG).

Ecosystems and socio-ecological importance

The Tana Estuary comprises of a mosaic of coastal wetlands, including marine, brackish and freshwater intertidal areas, sandy beaches, grasslands and coastal forests. The main channel meanders through 22 km^2 of mangroves (mainly *Avicennia marina*, *Heritiera littoralis* and *Rhizophora mucronata*), forming highly productive and functionally interconnected ecosystems (Kitheka *et al.*, 2005). Livelihood activities around the Tana Estuary are organized according to the availability of arable land, adequate fresh water supply, access rights, cultural institutions, and social and demographic dynamics (Smalley and Corbera, 2012). Key activities are floodplain agriculture, fishing in the bay, estuary and freshwater wetlands, and livestock herding on communal rangeland (Hamerlynck *et al.*, 2010). Small-scale businesses to supply basic needs are centralized in Kipini Town – including a burgeoning telecommunications sector. Despite its abundant natural attractions, a potential tourism industry is stymied by security concerns in the nearby border area with Somalia, occasional agro-pastoral conflicts between Orma and Pokomo communities (Musyoka, 2019) or political instability (Kirchner, 2013).

The fisheries and biodiversity of Ungwana Bay have been extensively studied, including analysis of prawn bottom trawl catches (Munga *et al.*, 2013; Swaleh *et al.*, 2015), artisanal and commercial fisheries (Fulanda *et al.*, 2011; Munga *et al.*, 2014a, 2014b), socio-economics (Odhiambo-Ochiewo *et al.*, 2016) and biodiversity of ecosystems (Samoilys *et al.*, 2011). Fewer studies have focussed on fisheries and estuarine ecosystems in the enclosed part of the Tana Estuary, although Dzoga *et al.* (2018, 2019, 2020) found that the ecological vulnerability to climate variability of small-scale fishing communities differed among coastal sites in Ungwana Bay and the lower Tana Estuary.

Key drivers of socio-ecological change

Socio-ecological changes around the Tana Estuary are attributed to several factors, both upstream and locally around the estuary. Upstream construction of hydroelectric power (HP) plants and dams, and changes in land cover / land use practices driven by agriculture development affect the quantity and quality of fresh water entering the estuary and duration and timing of flooding events (Duvail *et al.*, 2017). Specific impacts of upstream water extraction include increased turbidity, sedimentation, and changes in beach morphology (Kitheka and Mavuti, 2016). Disrupted seasonal cycles and scarcity of fresh water affect floodplain farming and fishing. Local over-exploitation of estuarine resources has reduced the surface area and longevity of flood-supported swamp forests, wetlands and mangroves, and diminished the abundance and diversity of fish. Climate change is projected to bring a drier climate with increasing variability in seasonal rainfall, increasing the pressure on traditional SES (Duvail *et al.*, 2017).

Mwamlavya *et al.* (2021) demonstrates spatio-temporal trends in natural resource-use in the Lower Tana River Delta, based on household surveys and remote sensing of land cover and land use patterns, whereas

Manyenze *et al.* (2021) describes a highly organized and structured small-scale fishery suited to different estuarine habitats in the Tana Estuary. Santos *et al.* (2021) links social, ecological and economic values to provide a holistic rendition of the SES of the Tana Estuary, for comparison with the other estuaries addressed in this Special Issue.

Project framework, research strategy and data sources

The Estuarize-WIO Project was structured into four inter-linked work packages (WP1 to WP4). WP1 described the estuarine environment, WP2 the livelihoods and socio-economic circumstances of estuary-dependent communities, and WP3 the small-scale fisheries (Fig. 3). WPs 1 – 3 provided the information inputs to WP4, where socio-ecological modelling of linkages and feed-back loops in SES was undertaken, to evaluate vulnerability, adaptation and resilience. Planning and coordination at project and WP level took place at regional workshops, but the implementation of research projects was decentralized and undertaken by partner institutes (or research nodes) in each country.

Estuarize-WIO relied heavily on pre-existing datasets collected routinely by government departments (fisheries catch assessments, population census data) and on open-source data available from the internet (satellite images downloaded from the US National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA) or multi-composite images obtained from Google Earth®). Data gaps were addressed by undertaking limited field sampling, in a multidisciplinary way for WP1 – WP3 combined. The combination of historical and newly collected data allowed for a broader analysis of time series information, combined with more detailed spatial or seasonal analyses based on new data. Six Masters students undertook supervised projects to address specific data gaps identified by Estuarize-WIO. Scientific capacity-building was therefore explicitly incorporated in the research framework.

For WP1, the information to describe estuarine habitats and anthropogenic influences were obtained from open-source Landsat and Sentinel 2 satellite images depicting changes in land cover and land use (Furaca *et al.*, 2021; Mwamlavya *et al.*, 2021; Groeneveld *et al.*, 2021). Ground-truthing was based on geo-located photographs taken during field trips and Google Earth (https://www.google.com/earth/). Instream salinity, water temperature and depth profiles were measured with a CTD deployed from a boat during field trips (Hoguane *et al.*, 2021), and data were augmented by information obtained from reports of earlier studies

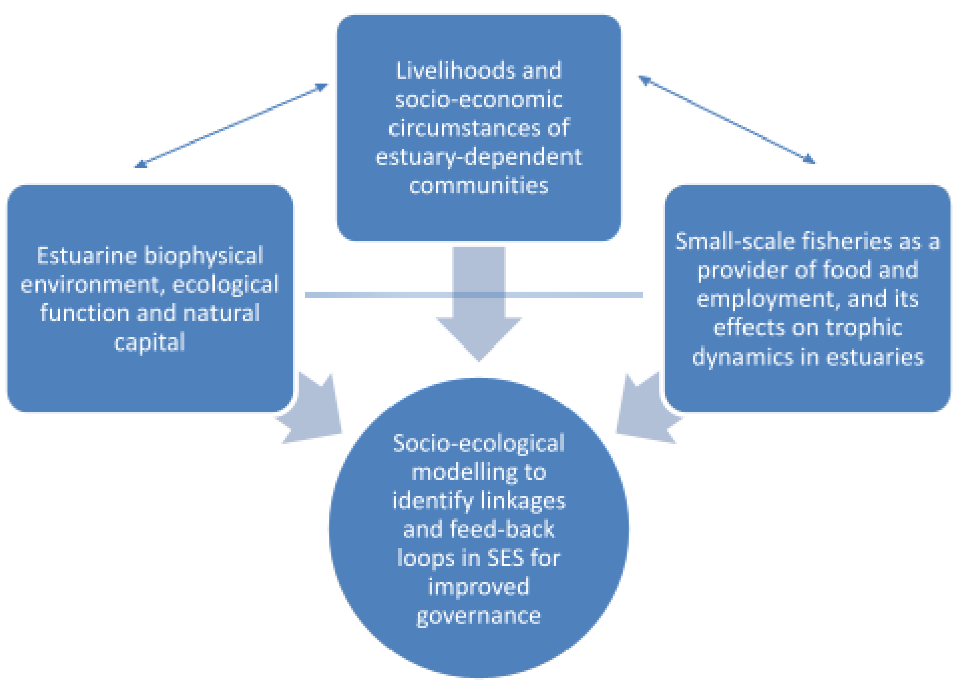

Figure 3. Relationships between Estuarize-WIO Work Packages (WP) for different disciplines, feeding into a socio-ecological system (SES) modelling framework.

(GLOWS-FIU, 2014; Hoguane *et al.*, 2020) and hydrological records of precipitation and flow volumes.

For household surveys (WP2) existing census data were used as a guide to spatially stratify sampling and determine the required sample sizes. Household surveys provided information on livelihood activities and use of natural resources around estuaries (Francisco *et al.*, 2021), which could be cross-matched with land cover and land use practices obtained from satellite images (Furaca *et al.*, 2021; Mwamlavya *et al.*, 2021).

The objectives of WP3 were to describe estuarine fisheries in the WIO and assess their ecological footprint. Historical data of fishing effort and landings were obtained from respective government fisheries departments but were often not available to species level because of catch aggregation in groups, or were collected in an inconsistent way (Groeneveld *et al.*, 2014). Estuarize-WIO therefore undertook additional sampling to improve data on species and size composition of catches, boats and gear used, and to determine gear selectivity (Kuguru *et al.*, 2019; Manyenze *et al.*, 2021; Mugabe *et al.*, 2021; Groeneveld *et al.*, 2021).

Integration of Estuarize-WIO research papers into a Special Issue

The study of SES in estuarine environments is not a new field in the WIO region (see Hamerlynck *et al.*, 2010; Blythe, 2014; Blythe *et al.*, 2014; Dzoga *et al.*, 2018). Nevertheless, most published information has dealt with basin-scale impacts of economic development and agriculture on flow regimes and water resource management, downstream socio-economic effects of altered freshwater flows, or ecosystems effects in nearshore marine environments (papers in Diop *et al.*, 2016; Fennessy *et al.*, 2016; Duvail *et al.*, 2017). Far fewer studies have relied on a multidisciplinary approach to individual estuaries, to provide finer detail on interlinked biophysical, natural resource and socio-economic aspects. The Special Issue addressed this knowledge gap, by contributing a collection of nine papers from the Estuarize-WIO Project.

Four papers on the Bons Sinais Estuary relied on oceanographic and fisheries data collected by the School of Marine and Coastal Sciences (Eduardo Mondlane University, Quelimane) over the past decade (Hoguane *et al.*, 2020). Hoguane *et al.* (2021) modelled residual circulation in the estuary, demonstrating potential influences on the dispersal of fish and crustacean larvae. Francisco *et al.* (2021) undertook a household survey to confirm the relative importance of the Bons Sinais Estuary to local livelihoods in urban (near Quelimane) and rural (along the coast and upstream of the town) areas. Furaca *et al.* (2021) used remote sensing data to assess the change in land cover and land use around the estuary over the past three decades (1991-2018), a period of rapid population growth and urbanization. Small-scale fisheries in the estuary are a crucial source of food security and employment, and a key component of the socio-ecological dynamics in both rural and urban settings. Mugabe *et al.* (2021) described the fishing gears used and composition of catches and compared the catch composition and size selectivity of chicocota nets (fine-mesh mosquito nets, illegal but not enforced) to beach seine nets (legal gear with fine-mesh panels).

For the Ruvu Estuary, information obtained from Landsat and Sentinel-2 satellite images were used to assess seasonal and historical trends in land cover and land use. Instream physical measurements (CTD data) collected by TAFIRI during a 2018 field trip was augmented with similar CTD data collected in 2013 by the GLOWS-FIU project (GLOWS-FIU, 2014). Fisheries datasets sourced from online data portals, government and private institutions and the literature, (GLOWS-FIU, 2014; Yona, 2017; Kuguru *et al.*, 2019) were compiled and a simple socio-ecological analysis undertaken (Groeneveld *et al.*, 2021). The diversity of catches by locality (estuary and bay) were contrasted, and a nascent fishery for invasive giant freshwater prawns described (Kuguru *et al.*, 2019).

For the Tana Estuary, household survey data and spatially explicit Sentinel-2 satellite images of land cover and land use were cross-matched to investigate spatio-temporal trends in livelihood strategies (Mwamlavya *et al.*, 2021). Land cover and land use were strongly seasonal, and coastal and upstream communities relied on different combinations of ecosystem goods and services. Small-scale fisheries formed a key component of livelihoods at all sampled sites. Manyenze *et al.*, (2021) compared gear-use, species and size composition of landings between the estuary mouth (full-time fishers in the lower estuary and Ungwana Bay) and the mid and upper estuary (part-time fishers using more traditional gear).

In the summary paper of this Special Issue, a SES approach was used to illustrate linkages and feed-back loops between estuarine ecological functioning and the use of the natural resources by local communities, within a typical WIO socio-economic and cultural setting (Santos *et al.*, 2021). The SES models were constructed for each estuary individually, highlighting the differences between them, and were compared regionally within the WIO. Trends were generalised across the region. The paper concludes that the methodological approach developed for Estuarize-WIO is well-suited to research of data poor systems with limited accessibility and research infrastructure.

The meta-data of all the information used during Estuarize-WIO is provided as an appendix to the Estuarize-WIO Special Issue (Santos et. al., 2021), to encourage its use for further studies on estuaries in the WIO region.

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The residual circulation profile of the Bons Sinais Estuary in central Mozambique - potential implications for larval dispersal and fisheries

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Abstract

The residual circulation in estuaries determines the net exchange of water, heat, salt, fine sediments and drifting biological organisms between estuarine and nearshore marine waters. The Bons Sinais Estuary in central Mozambique is ~ 30 km long with the city of Quelimane and an industrial port on the northern bank of its upper reaches. To investigate residual circulation in the estuary, seasonal (wet, dry and transition season) CTD profiling data were collected at 11 fixed stations between the upper estuary and mouth, and vertical current profiles were measured over a full tidal cycle at a fixed mid-estuary station. Strong longitudinal gradients in salinity and density indicated that the estuary was river-dominated during the wet season and tide-dominated during the dry season, but the water column remained partially mixed. Tidally averaged vertical profiles from the mid-estuary station revealed: uniform vertical temperatures, warmest during the wet season; depth-stratified salinity during the wet season, but uniform profiles during the dry and transition seasons with highest salinity during the dry season when the density was also highest. The density was uniform and somewhat lower in the transition season, and in the wet season the density was even lower, but stratified. The vertical velocity profile showed a classical two-layer circulation model, with downstream flow intensifying at the surface, and upstream flow at the bottom, during the wet and transitory seasons, when freshwater discharges into the estuary. The flow velocities obtained from a calibrated Hansen and Rattray model fitted the observed data well, confirming that a simplified modelling approach is adequate to describe the residual flow of the Bons Sinais Estuary. The residual circulation model provides insights useful for fisheries research and predicting the spread of water-borne pollutants in the estuary.

Keywords: estuarine circulation, tidal asymmetry, tidal straining, gravitational circulation, net flow, larvae transport

Introduction

Understanding the residual circulation in estuaries is important because it determines the net exchange of water, heat, salt, biological propagules and the spread of chemical pollutants (Kjerfve *et al.* 1981; Li, 1997). Residual flow in estuaries is typically downstream in surface layers and upstream in deeper more saline layers near the bottom, because of the density gradient between fresh and salt water (Hansen and Rattray, 1965). Many fish and crustacean species have adapted to using tides and residual currents to move between nearshore shelf habitats and estuarine environments during different life history stages to spawn, shelter or feed (Potter *et al.*, 1990; Churchill *et al.*, 1999; Whitfield, 1999; Lozano and Houde, 2013; Potter *et al.*, 2015). Residual flow is also important for the transport of fine sediments. Whereas near-bottom flow in rivers and upper estuaries brings fluvial sediments downstream (Dyer, 1995), it also imports marine sediments into lower estuaries, sometimes resulting in the siltation of navigation channels or harbours (McSweeney *et al.*, 2016; Xiao *et al.*, 2018).

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The classical theory of two-layer estuary circulation, where pressure longitudinal gradient balances stress divergence (Cheng *et al.*, 2011) was developed by Hansen and Rattray (1965), after earlier studies by Pritchard (1956). The classical theory remains valid and continues to be applied despite advances in hydrodynamic modelling (Chatwin, 1976; Prandle, 1985; Geyer and MacCready, 2014). Priya *et al.* (2012) argued that the classical model applies better to mixed or partially mixed estuaries. The main advantage of the simple classical model is the provision of an analytical solution which is easy to interpret for management decisions (Guillou *et al.*, 2000; Savenije *et al.*, 2007).

The Bons Sinais Estuary in central Mozambique (Fig. 1) has high ecological and socio-economic importance. It discharges onto the shallow Sofala Bank which supports the richest prawn and small pelagic fisheries in the Western Indian Ocean (Mazzilli, 2015; Mugabe *et al.* 2021). It plays a vital role as nursery and breeding grounds for coastal fish and crustaceans, especially for shallow water prawns which form the mainstay of coastal fisheries in the region.

The city of Quelimane, capital of Zambézia Province with a population of ~ 400 000 in 2020 (www.populationstat.com) and a harbour for sea-going vessels is located in the upper reaches of the estuary (Fig. 1). Local inhabitants rely heavily on the ecosystem goods and services provided by the estuary, including fish, mangrove wood for fuel and construction, and floodplains for planting rice and other crops or for salt production or aquaculture (Mazzilli, 2015; Francisco *et al.* 2021). These activities encroach on the estuarine functional zone and contribute to pollution, siltation and the degradation of ecologically important habitats (Furaca *et al.* 2021). An understanding of the estuary circulation pattern is therefore crucial for developing deeper insights and management strategies.

There are several studies on the hydrodynamics of the Bons Sinais Estuary. Among these, Hoguane *et al.* (2020) applied a simple tidal (longitudinal) model to describe the main hydrodynamic features of the estuary, Mocuba (2010) mapped sewage pollutants using biochemical oxygen demand as an indicator, Nataniel (2010) and Paulo (2012) studied nutrient flux in mangroves and the estuary and Mazzilli (2015) developed a framework for rapid assessment of the hydrodynamics of data-poor estuaries. Most species caught by fisheries on the Sofala Bank are of the *Engraulidae*, *Clupeidae*, *Sergestidae* and *Penaeidae* families, live in the region of freshwater influence and are short-lived (1–2 years), recruiting to fisheries within the first year of their life (Hoguane and Armando, 2015), emphasizing the importance of estuarine habitats on fish production.

The approach adopted in this study was to apply a simple model to represent the residual circulation in the Bons Sinais Estuary, to reduce the degrees of freedom and modelling effort required while still capturing the key controlling factors. Direct measurements of currents and the classical theory of Hansen and Rattray (1965) were combined with an analytical solution (MacCready and Geyer, 2010; Geyer and MacCready, 2014) to model residual flow, temperature and salinity flux at a fixed position in the estuary. The fundamental mechanisms governing the transport and exchange of materials in the estuary were inferred and related to the transport of fish and crustacean larvae, an important factor in sustaining local fisheries and food security.

Materials and Methods

Study area

The geographical setting, ecosystems and socio-ecological importance of the Bons Sinais Estuary were summarized by Groeneveld *et al.* (2021). In brief, the estuary is shallow and funnel-shaped, about 30 km long with a maximum width of 2.5 km near the mouth (Mazzilli, 2015). It extends from the junction of the Cuacua and Licuar tributaries and drains into the Mozambique Channel over the northern Sofala Bank (17° 54' S, 36° 49' E; Fig. 1). The Cuacua River was once connected to the Zambezi River – as a part of the Zambezi Delta – and it was navigable until it silted up circa 1820 (Newitt, 1995). Following the construction of the Kariba (1955) and Cahora Bassa (1974) dams in the upper reaches of the Zambezi River, downstream flow and flood peaks were reduced, with several rivers (including Cuacua) becoming disconnected from the main branch of the Zambezi (Beilfuss and Santos, 2001).

The climate along the central Mozambique coast is influenced by a sub-tropical anticyclonic system, southeast trade winds, and the southern extremity of the East African monsoon system (Sætre and Jorge da Silva, 1984). The average wind speed varies between 3 and 5 m s^{-1}, with higher values in summer, from September to January (Hoguane, 1999; Rodrigues *et al.*, 2000). Rainfall averages 1140 mm per annum of which ~ 80 % falls between November and April, and the average annual evaporation is estimated at 1650 mm, exceeding rainfall by about 500 mm (Hoguane, 1999; Muchangos, 1999). Daily air temperature varies from around 25 °C in winter and 28 °C in summer, and atmospheric pressure from 1005 to 1020 kPa in winter and 1000 to 1010 kPa in summer (Hoguane, 1999; Muchangos, 1999).

The estuary receives an average of 500–840 $m^3 s^{-1}$ of freshwater per year from the Cuacua and Licuar tributaries (Mazzilli, 2015). The estuary is fringed by dense mangrove vegetation dominated by *Avicennia marina* (white mangrove) and is linked to extensive freshwater wetlands and tidal creeks that contribute to the mass transport of water to the mangroves. The tides are semi-diurnal, with average amplitudes of 1.2 m and 3.8 m for neap and spring tides respectively and a maximum spring tide of 4.5 m (INAHINA, 2012). Water masses over the Sofala Bank are characterized by low salinity (<26) and high temperature near the estuary mouth; a salinity of 34.8 to 35.5 in open sea water; and high salinity of 35.5 to 37 over the southern Sofala Bank (Sætre and Jorge da Silva, 1984; Gammelsrød and Hoguane, 1995; Nehama *et al.*, 2015).

Data

Temperature, salinity and depth were measured with a Valeport CTD instrument, and flow velocity with a Seaguard RCM (Recording Current Meter). The CTD data were collected at 11 fixed stations in the estuary (Fig. 1). The sampling was conducted during dry (18 July 2011) and wet (22 February 2012) seasons, from a boat equipped with a GPS navigation system and echo-sounder for depth recording. The survey started at the beginning of the flood cycle, proceeding upstream from the estuary mouth. The CTD data were used to determine the longitudinal density profile using Matlab-software.

The vertical velocity profile at station 6 (see Fig. 1) was measured every 0.5 h over a 13 h period, which covered a full tidal cycle between two low tides. The recording frequency was once every 10 seconds, for 10 minutes at each 1 m depth interval between the surface and bottom (0.5 m offset from surface or bottom observed). To determine the residual currents, average currents over a tidal cycle were calculated. Profiles were obtained for the dry- (30 November 2012), wet- (6 March 2013) and transition seasons (28 April 2013).

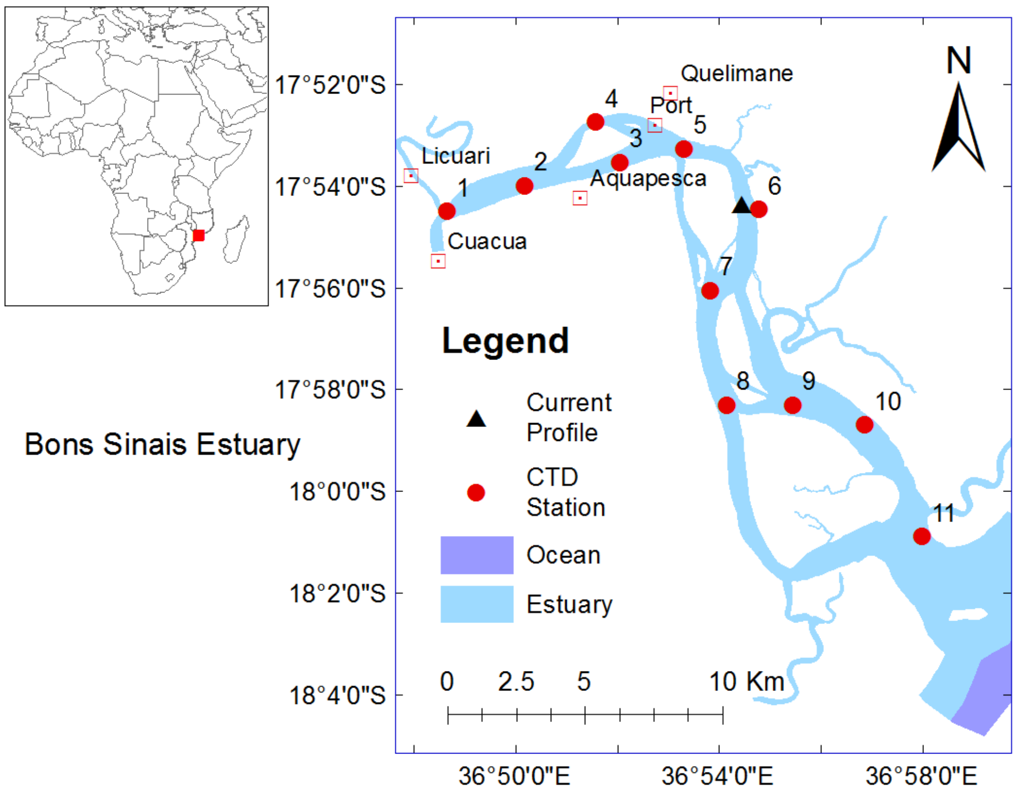

Figure 1. The study area and the location of sampling stations, denoted by red circles. The black triangle at Station 6 is where water current velocities were measured.

Circulation model

The analytical solution of Hansen and Rattray (1965) was used to determine the residual currents. The basic equations (MacCreary and Geyer, 2010; Geyer and MacCready, 2014) consisted of the Reynolds-averaged equations for salinity and along-channel momentum, in hydrostatic form and subject to the Boussinesq approximation. The momentum advection and Coriolis forces were excluded and only the along-channel gradients were considered. Thus, the equations were as follows:

$$\frac{\partial S}{\partial t} + u\frac{\partial S}{\partial x} = \frac{\partial}{\partial z}\left(k\frac{\partial S}{\partial z}\right) \qquad [1]$$

$$\frac{1}{\rho}\frac{\partial p}{\partial x} = \frac{\partial}{\partial z}\left(A\frac{\partial u}{\partial z}\right) \qquad [2]$$

Where S is the salinity, x (m) is along-channel distance, measured from the estuary's head, z (m) is the water level in the water column measured from the surface, and negative downwards, ρ (kg m^{-3}) is the water density, p (N m^{-2}) is the pressure obtained from the hydrostatic equation, k is the eddy diffusion coefficient (constant at 0.006 $m^2 s^{-1}$; Hoguane *et al.*, 2020), u (m s^{-1}) is the along-channel velocity, and A is the eddy viscosity. By tidally and width averaging all the variables and assuming a constant longitudinal salinity gradient and constant tidally averaged eddy viscosity, the vertical profile of the subtidal along-channel velocity without wind effects was obtained as follows (MacCreary and Geyer, 2010; Geyer and MacCready, 2014):

$$U = U_r(1.5 - 1.5\zeta^2) + U_g(1 - 9\zeta^2 - 8\zeta^3) \qquad [3]$$

Where U (m s^{-1}) is the observed velocity with depth, positive for upstream velocity (flood), U_r (m s^{-1}) is the residual velocity, U_g (m s^{-1}) is the gravitational velocity, $\zeta = \frac{z}{h}$ is the normalized depth, and h (m) is the local depth. The equation [3] was calibrated by regression analysis using the observed velocity, to estimate U_r and U_g.

Results

Longitudinal variation in water temperature, salinity and density

The observed longitudinal temperature profile during the dry season (Fig. 2a) showed slightly cooler water (21 °C) input from the ocean and warmer water (22.4 – 22.6 °C) at the surface in mid-estuary, but the water column appeared to be thermally mixed (left panel in Fig. 2a). Surface and bottom salinity did not differ (middle panel in Fig. 2a), but a strong longitudinal gradient was visible, with salinity decreasing from 29 at the mouth to 23 in the upper estuary. Similarly, density was not stratified by depth, but decreased longitudinally from 1020 kg m^{-3} near the estuary mouth to 1015 kg m^{-3} in the upper estuary (right panel in Fig. 2a), with a gradient of about 0.2 kg m^{-3} km^{-1}.

During the wet season (Fig. 2b) water temperature was higher in the upper estuary than near the mouth (left panel in Fig. 2b) but the water column was thermally mixed. Salinity increased from 12 in the upper reaches to 22 at the estuary mouth (middle panel in Fig. 2b) indicating freshwater input. The water column was partially mixed, suggesting that freshwater input was not sufficient to oppose the strong tidal mixing, with little vertical stratification observed. The density (right panel in Fig. 2b) profile displayed a similar pattern to salinity, by increasing from 1005 kg m^{-3} in the upper estuary to 1012 kg m^{-3} near the mouth with a gradient of ~ 0.3kg m^{-3} km^{-1}.

Tidally averaged vertical profiles

Tidally averaged temperature, salinity, density and velocity profiles measured at Station 6 during the dry- (30 November 2012), wet- (6 March 2013) and transition seasons (28 April 2013) showed uniform temperature irrespective of depth during all three seasons (Fig. 3). Salinity was uniform irrespective of depth during the dry and intermediate seasons, but depth-stratified during the wet season, with higher salinity near the bottom. The tidally averaged density profiles were uniform during the dry and transition seasons, with higher density during November ~ 1022 kg m^{-3}, dry season, marine influence) and with lower density during April ~ 1014 kg m^{-3}, transition season, freshwater influence). The density profile was lowest and stratified during the wet season (March 1000 - 1009 kg m^{-3}).

The velocity profile showed a classical two-layer circulation model, with downstream (ebb) net flow at the surface and upstream (flood) net flow at the bottom. During the wet season, the residual flood currents were ~ 0.14 m s^{-1} upstream in the bottom layer and ~ 0.25 m s^{-1} downstream in the surface layer. The intensification of downstream flow at the surface is attributed to enhanced river discharge into the estuary. During the dry season, there was seldom much residual current (<0.05 m s^{-1}) reflecting a strong tidal influence. During the transition season, the residual flood currents reached 0.24 m s^{-1} near the bottom and the ebb current reached ~ 0.30 m s^{-1} near the surface.

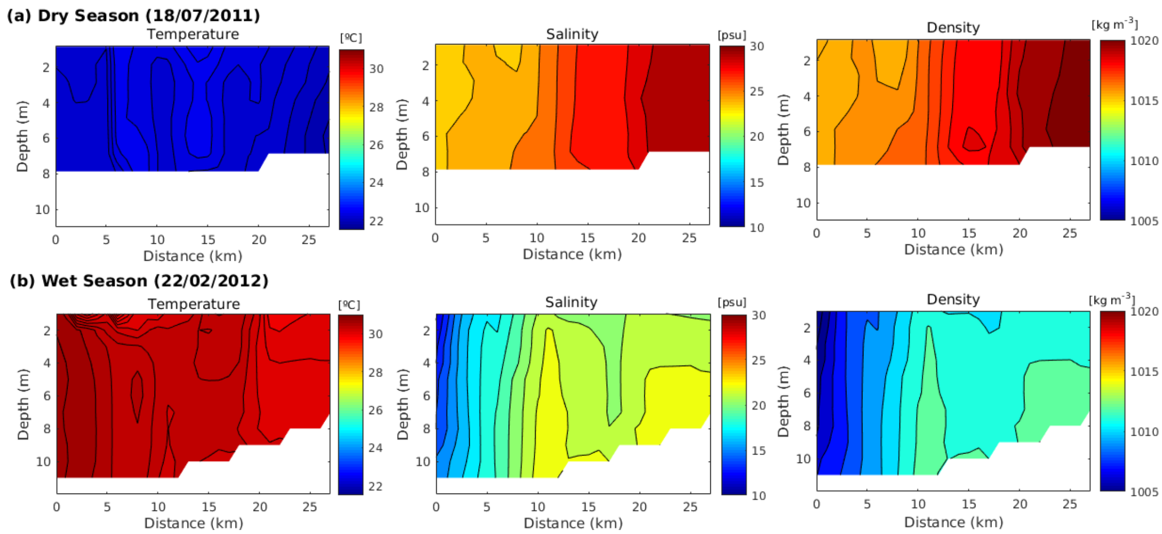

Figure 2. Longitudinal distribution of water temperature, salinity and density in the Bons Sinais Estuary during: (a) dry season (measured 18 July 2011) and (b) wet season (measured 22 February 2012). The estuary mouth is to the right of each panel.

Residual flow applying Hansen and Rattray equations

The modelled flow velocities fitted the observed data well with high coefficient of goodness of fit (r^2) (Table 1) confirming that the simplified model described the residual flow of the estuary well. During the dry season, the small residual- (U_r = 0.04 m s^{-1}) and gravitational flows (U_g = 0.03 m s^{-1}; Table 1) reflected reduced freshwater input and a tidally dominated estuary state, with net seawards flow attributed to freshwater stored in upper estuary wetlands or ground water sources. During the wet season, the residual- (~ 0.05 m s^{-1}) and gravitational flow (~ 0.19 m s^{-1}; Table 1) increased during ebb tide, because of increased longitudinal density and salinity gradients. During the transition season, residual flow decreased (0.02 m s^{-1}) during ebb tide but gravitational flow increased to 0.30 m s^{-1}, possibly because of freshwater drainage from wetland reservoirs filled up during the wet season.

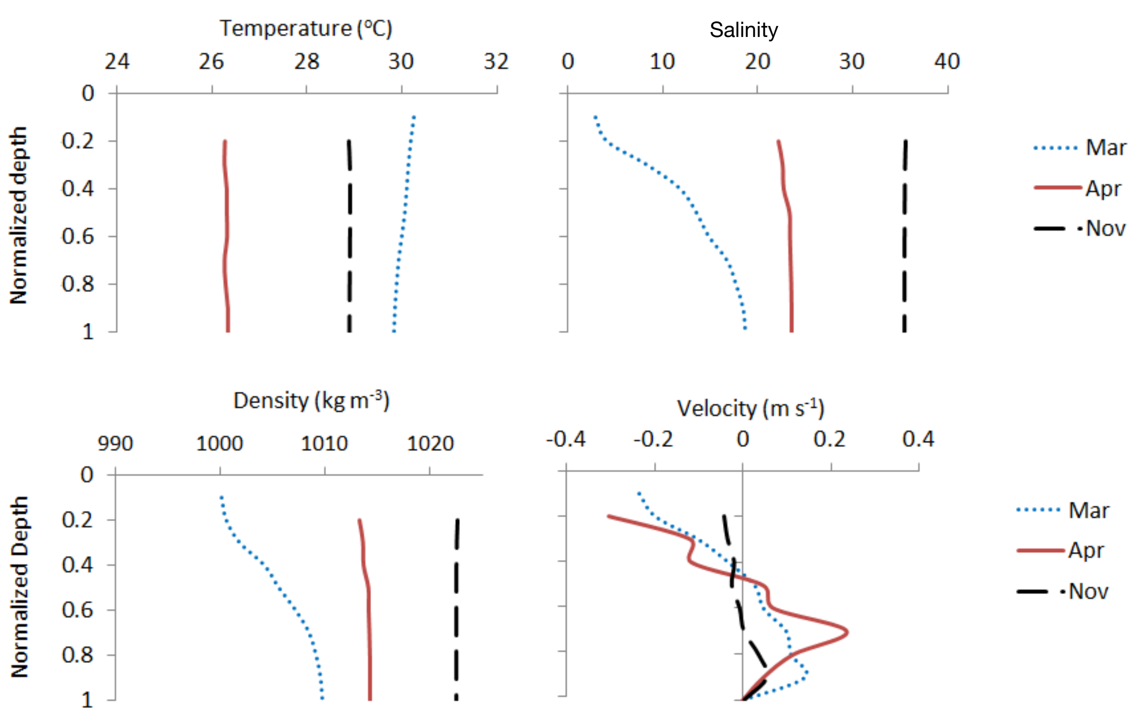

Figure 3. Tidally averaged temperature, salinity, density and velocity profiles with normalized depth, measured at Station 6 during the dry (30 November 2012), wet (6 March 2013) and transition (28 April 2013) seasons.

Table 1. Estimates of residual flow (U_r) and gravitational flow (Ug) based on the fit of the Hansen and Rattray model to the current velocity data collected at Station 6; where SS is the sum of squared differences from the mean, MS is mean square, F is F-Test, P-value is the level of statistical significance, and r^2 is the goodness of fit coefficient.

Period	Coefficients			SS	MS	F	P	r^2 (%)
	Const (m/s)	Ur (m/s)	Ug (m/s)					
Dry season (Nov)	0.02	-0.04	-0.03	0.006	0.003	9.5	0.014	76
Wet season (Mar)	0.02	-0.05	-0.19	0.143	0.071	101.7	0.000	97
Transition (Apr)	0.34	-0.02	-0.30	0.178	0.089	26.3	0.001	90

Simulated vertical flow velocities (U) were decomposed into components for residual velocity (U_r) and gravitational velocity (U_g) (Fig. 4; Equation 3). Strong gradients in vertical velocity profiles were apparent during the wet and transition seasons, when the surface layer was dominated by seaward flow and the bottom layer by upstream flow. The vertical profile during the dry season showed minimal residual flow.

Discussion

Observed vertical profiles of temperature, salinity and velocity

The empirical data and model outputs confirmed a change-over from a well-mixed water column during the dry season to a stratified water column during the wet season (see also Mazzilli, 2015). Nevertheless, throughout most of the year, the vertical profile remained mixed to partially mixed, thus justifying

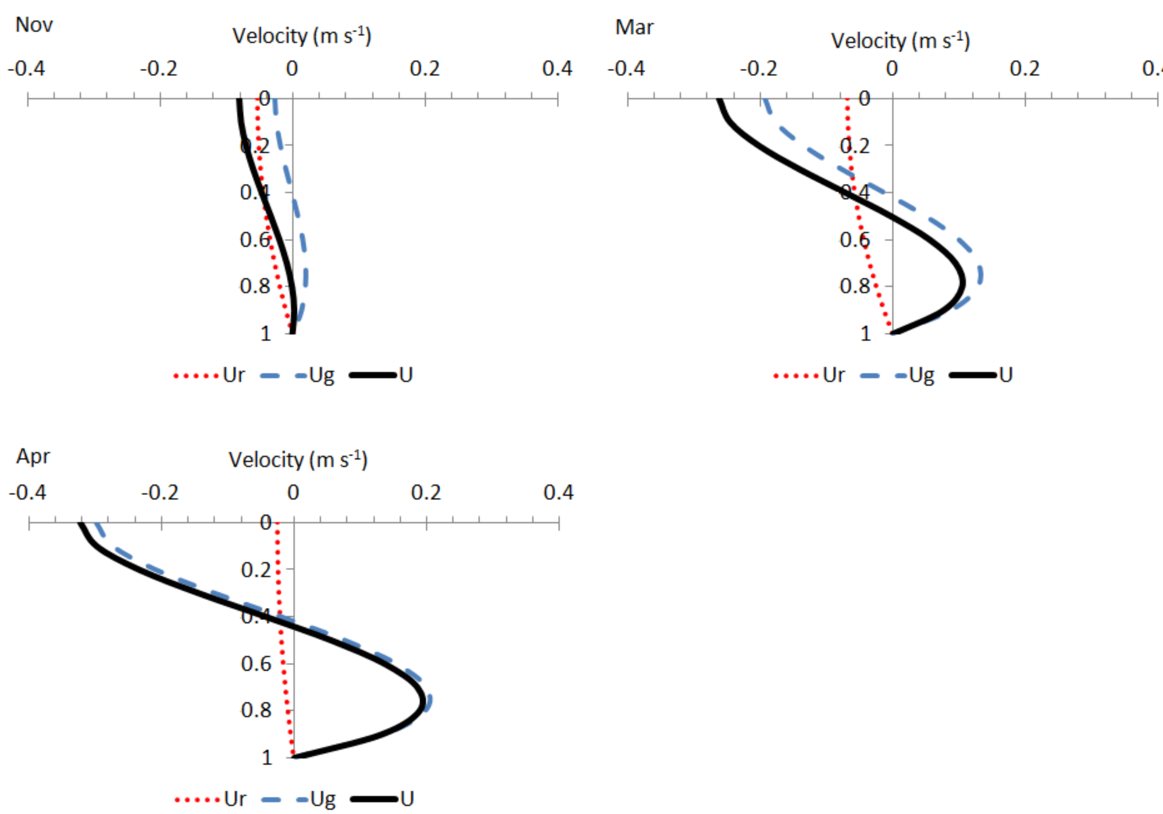

Figure 4. Simulation of the vertical flow velocity. The curves represent tidally averaged flow velocities with normalized depth, assuming constant longitudinal salinity and eddy viscosity. U_r is residual flow; Ug is gravitational flow; U is the sum of U_r and Ug. Nov = dry season; Mar = wet season; Apr = transition season.

the application of a Hansen and Rattray (1965) model (Priya *et al.*, 2012). The residual velocity at Station 6 was dominated by freshwater input during the wet and transitional seasons and tidal flow during the dry season. The finding agrees with Bernardes and Miranda (2001) who found major forcing agents to be the longitudinal density gradient and the river flow (with wind effect excluded) in mixed to partially mixed estuaries. The weak residual flow during the dry season can be explained by tidal straining (Burchard *et al.*, 2014; Geyer and MacCready, 2014). Several authors have shown that estuarine residual circulation weakens when tidal importance increases (Li, 1997; Shiraki and Yanagi, 2007; Cheng *et al.*, 2011) as is the case in the Bons Sinais Estuary, where the tidal amplitude reaches ~ 4 m during spring tide.

Comparison between the observed and modelled vertical velocity profiles

The modelled velocity profiles compared well with the observed data for the dry- (Fig. 5a) and wet seasons (Fig. 5b) but underestimated the maximum velocities during the transition season (Fig. 5c). An increased run-off during the April transition season, shortly after the rainy season can be explained by precipitation from more remote catchment areas reaching the estuary. The run-off increases the water level at the estuary head, causing a pressure force because of the surface tilt which drives surface water seawards hence increasing observed surface maximum velocities compared to modelled maxima. This increases the upstream pressure force in the lower layer (and increases the bottom velocity above model estimates) because of the increased density gradient. This effect is clearly seen when comparing the observed and modelled vertical velocities between seasons (Fig. 5 a-c). The prominent velocity peaks during the transition season is potentially exacerbated by freshwater drainage from wetland reservoirs filled up during the rainy season. Geyer and MacCready (2014), among others, suggested that U_g is directly proportional to the density (or salinity) gradient, indicating that the salinity at the head of the estuary was lower in April than in March. Furthermore, the depth of the modelled zero-velocity estimate (a measure of the depth of the boundary between the directional surface and bottom layers) reproduced the observed values well during all three seasons (Fig. 5), allowing for management applications in which dispersal patterns can be associated with vertical positioning in the water column.

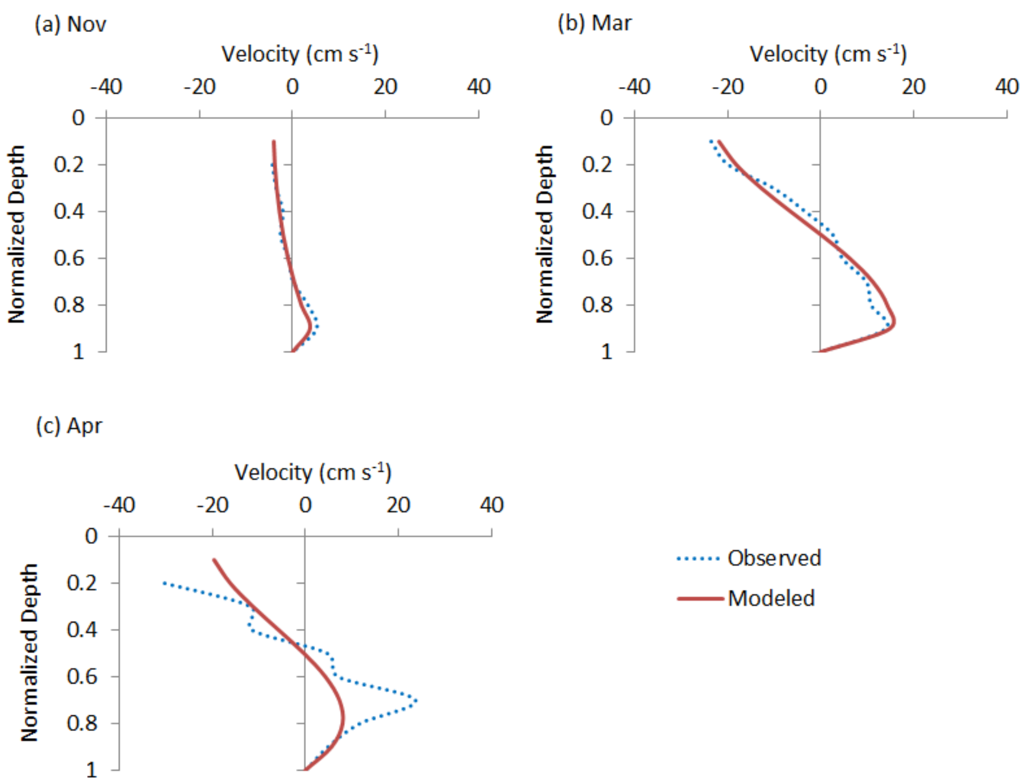

Figure 5. Comparison of the modelled and observed current profiles for a) the dry season (November) b) the wet season (March), and c) the transition season (April). Model-estimated zero-velocities compare well with the observed data in all three seasons.

Model evaluation

The model performance was evaluated by comparison between the observed and modelled result (Fig. 6). The model represented observations well with high goodness of fit ($0.90 < r^2 < 0.97$) for the wet and transition season, but a weaker fit to dry season data ($r^2 = 0.76$) because the latter observations overlapped with a neap tide - i.e. the model had to be fitted to narrow range of observed velocity data.

The residual circulation model developed here may contribute to understanding larval distribution patterns in the Bons Sinais Estuary. Most fish and crustacean larvae can position themselves in the water column to facilitate directional transport by currents - distribution patterns are therefore likely to match residual currents at different depths (Epifanio, 1988; Thiebault *et al.*, 1992; Lazarri *et al.*, 1993; Katz *et al.*, 1994; Garrison, 1999; Robins *et al.*, 2013; Teodósio and Garel, 2015). For example, in this study, seaward transport would be associated with high river runoff and landward transport with low runoff seasons, which matches with the life cycle of penaeid prawns. Female prawns spawn in coastal waters during the dry season with larvae entering the estuary during a period of weak and tidally-driven estuarine circulation (Gammelsrød, 1992). The estuary is a productive and sheltered nursery area where larvae grow into juveniles, before returning to offshore mudbanks – facilitated by a seawards residual flow during the wet season.

In conclusion, the classical two-layer Hansen and Rattray model provided a simple analytical tool which succeeded in quantifying fundamental residual circulation in a way that makes model simulations of dispersal and connectivity easier to interpret. Model simulations can provide a tool for predicting the outcomes of environmental and fisheries management decisions. The location of the estuary adjacent to the important Sofala Bank fishing grounds makes it a spatially well-placed location for *in situ* studies of changes in estuary circulation and its effects on the distribution and recruitment of estuary-dependent fish and prawns.

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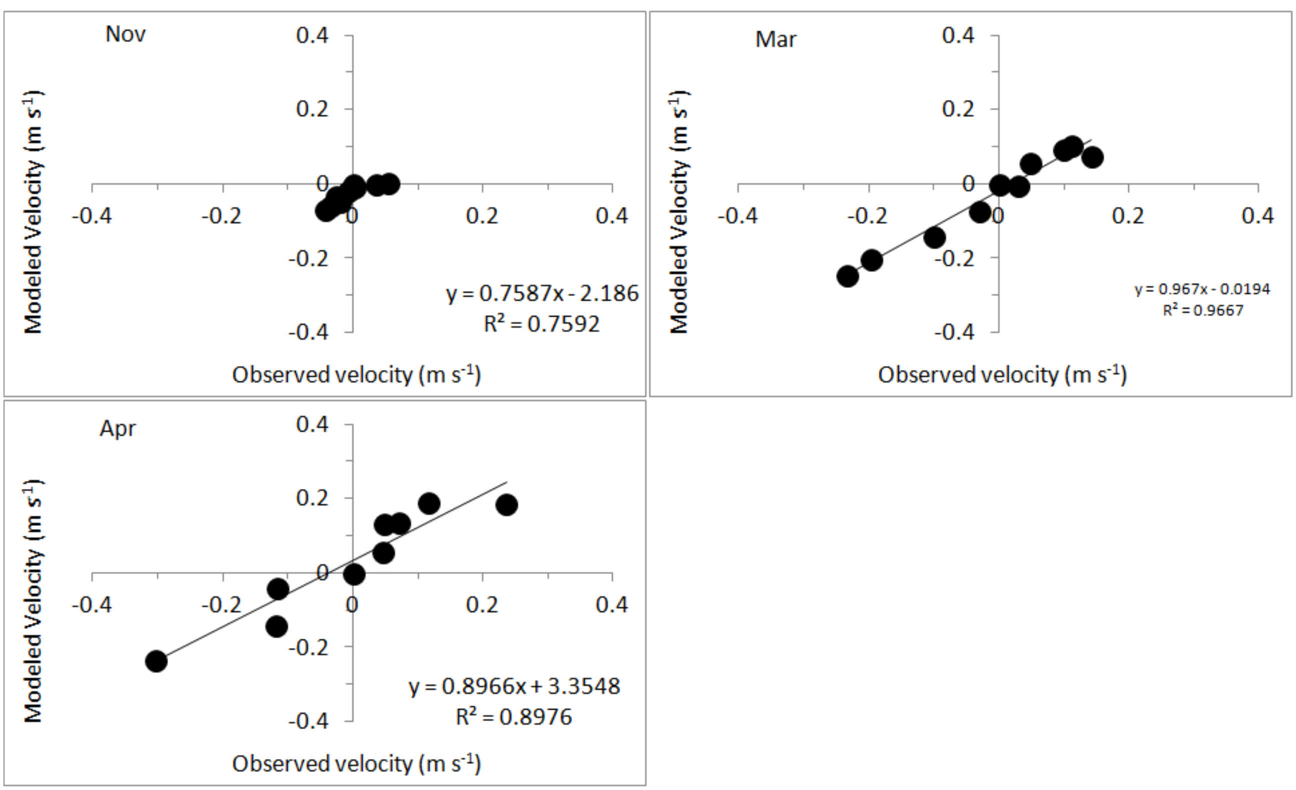

Figure 6. Model performance gauged by comparison of observed and modelled flow, as estimated by the Hansen and Rattray approach and measured at Station 6.

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Household dependence on fish-based farming systems in the Bons Sinais Estuary in Mozambique

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Abstract

Households in estuarine deltas of the Western Indian Ocean depend on small-scale fishing, farming in flood-recession and adjacent areas, and mangrove forest products for food security, energy and an income in so-called deltaic fish-based farming (FBF) systems. It was hypothesized that the relative importance of household activities would depend on location along the Bons Sinais Estuary in Mozambique, diversifying in peri-urban settings. Semi-structured interviews were undertaken at five sites, including rural sites near the estuary mouth and upstream, and peri-urban settings near Quelimane city. Fishing contributed the most to FBF livelihoods (54 %) followed by farming (15 %), small business operators (14 %), collection and use of mangrove products (6 %) and other activities such as wage-earning or formal employment (10 %). The highest diversity of activities was at a peri-urban site, Chuabo Dembe, which differed from all other sites in Cluster and Principal Components Analyses. Fishing dominated activities at four of five sites, with the highest preponderance near the estuary mouth. Women played an important role in generating household income, mainly through farming and operating small businesses in peri-urban areas. The education level declined in rural settings. Overexploitation and degradation of natural ecosystems to provide for an increasing urban population around Quelimane threaten estuarine functioning, making deltaic FBF systems vulnerable. Rural development programmes should focus on improving education levels and the efficiency of food production, processing and distribution systems.

Keywords: rural-urban linkage, rural development, urban expansion, agriculture, fishing, mangrove, charcoal

Introduction

Hamerlynck *et al.* (2020) defined fish-based farming (FBF) systems along the edges of Africa's water bodies as "mixed fishing / farming households that derive from 30 to 50 % of their income from fisheries." The basic economic unit of FBF systems is the household (or even the extended family) with some individuals focussing more on fisheries, while others predominantly farm. It includes both genders – with women contributing to farming and sometimes to fishing in shallow waters from the shore. The inclusion of livestock keeping, hunting and gathering of forest products and occasionally wage-earning makes FBF systems flexible and increases resilience and adaptive capacity of households during periods of change (Blythe, 2014; Blythe *et al.*, 2014; Hamerlynck *et al.*, 2020).

FBF systems occur in a wide range of climatic zones and ecosystems in sub-Saharan Africa, including marine (sandy coasts, coral reefs), fresh water (lakes and floodplains) and brackish water (estuarine) subsystems (Hamerlynck *et al.*, 2020). They support an estimated 22 million fisher-farmers, of which about half live in extreme poverty (Hamerlynck *et al.*, 2020). In the Western Indian Ocean (WIO), FBF systems in estuarine deltas (termed deltaic fish-based farming systems) are characterised by brackish water habitats, use of mangroves forest products and a high diversity of fish and crustacean species in catches (often juvenile or small individuals). Deltaic FBF systems occur, *inter alia*, in the Bons Sinais Estuary in Mozambique (Furaca *et al.*, 2021; Mugabe *et al.*, 2021), Tana Estuary in Kenya (Manyenze *et al.*, 2021; Mwamlavya *et al.*, 2021) and Ruvu Estuary in Tanzania (Groeneveld *et al.*, 2021a; 2021b). System-associated farming activities include tree crops (coconut, banana, mangos, various fruits and palms), maize and root crops such as cassava (Hamerlynck *et al.*, 2010; 2020) and tidal or mangrove

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rice cultivation, which relies on river floods and tidal bore to passively irrigate rice paddies (Hamerlynck *et al.*, 2020; Mwamlavya *et al.*, 2021). Harvesting of mangroves (forest products) for use as poles for building and charcoal for energy production form an integral part of deltaic FBF systems and is ubiquitous in WIO estuaries (Okello *et al.*, 2019).

Studies in the WIO region have highlighted several threats to ecosystem health and associated livelihoods around estuaries (papers in Diop *et al.*, 2016). Key among these are reduced freshwater input from upstream catchments (Duvail *et al.*, 2017) and change in land use and land cover (both upstream and in the estuarine zone) to accommodate the needs of growing human populations (Mwaguni *et al.*, 2016; Furaca *et al.*, 2021). These threats are exacerbated by overexploitation of estuarine habitats (mangrove cutting and clearing) and fish resources (Bosire *et al.*, 2016; Diop *et al.*, 2016) and increased climatic variability. At the estuary level, interventions are often hampered by low education levels of fisher-farmers, a lack of exchange between traditional and technical knowledge, and a limited understanding of ecological baselines and socio-cultural context (Hamerlynck *et al.*, 2020; Mwamlavya *et al.*, 2021). Full household livelihood spectra have rarely been assessed for deltaic FBF systems in WIO estuaries.

It was hypothesized that the relative importance of livelihood activities of deltaic FBF systems along the Bons Sinais Estuary in Mozambique would change along its length (i.e., linearly); and that activities would diversify in peri-urban areas around Quelimane city. Household surveys were used to investigate the demography and relative contributions of key livelihood activities of communities in rural and peri-urban settings along the estuary. We provide benchmark information for co-management approaches to maintain ecosystem health and flexible livelihood portfolios, within an existing socio-cultural context.

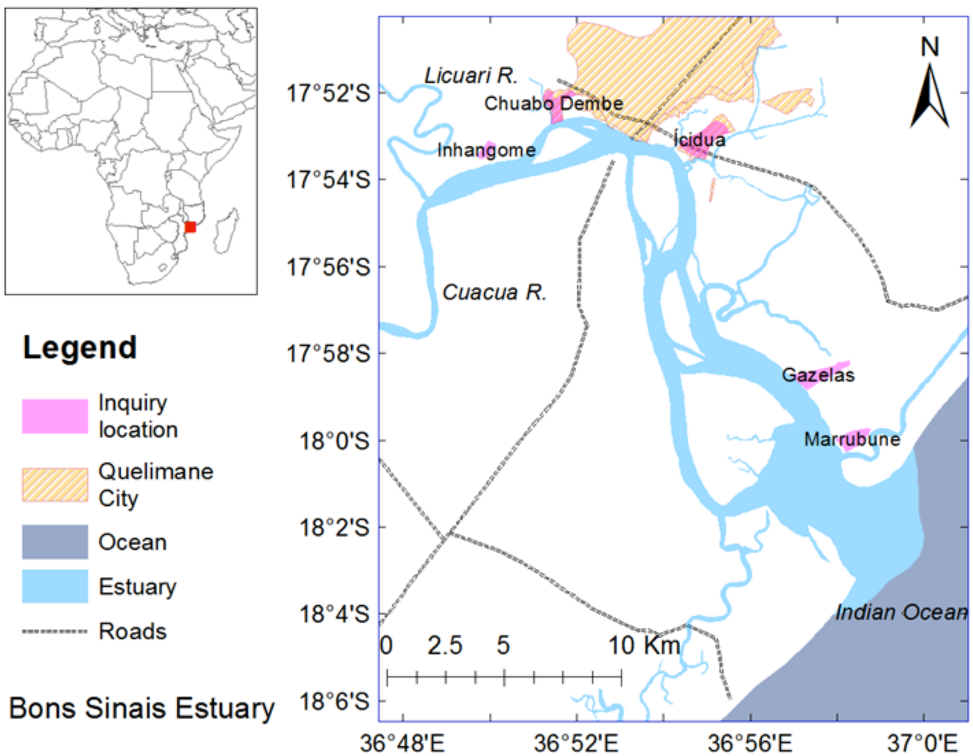

Figure 1. Location of sampling sites at Bons Sinais Estuary, showing Marrubune and Gazelas (rural areas near the coast), Icidua and Chuabo Dembe (peri-urban areas around Quelimane city) and Inhangome (rural area at the estuary head).

Materials and methods

The Bons Sinais Estuary discharges into the WIO at 18°01' S; 36°58' E and extends ~30 km inland to the city of Quelimane where a seaport is located (Fig. 1). The geographical setting, history of settlement, ecosystems and socio-ecological importance of the estuary have been summarized by Groeneveld *et al.* (2021a). Quelimane is the administrative capital of

Zambézia Province, with average population growth rate of 2.6 % per year (INE, 2007; 2017) and a population of ~400,000 in 2020 (www.populationstat.com). The estuary is surrounded by a mosaic of cultivated croplands and tree plantations, wetlands, mangroves and intertidal mudflats and built-up areas (Furaca *et al.*, 2021). Five villages between the mouth and upper estuary were sampled (Fig. 1): Marrubune and Gazelas in a rural area near the estuary mouth; Icidua and Chuabo Dembe in peri-urban locations near Quelimane city; and Inhangome in a rural area at the head of the estuary.

Semi-structured interview questionnaires at household level were conducted, applying a purposive-random sampling method to select households (Deng *et al.*, 2017). Interviews were conducted face-to-face with household heads or another household member, to collect qualitative and quantitative information on household demographics and livelihood activities. A standard questionnaire form is shown in Appendix 1.

Data were aggregated by site and activity and normalized to express activities as a proportion of households per site that participated in each activity. Household members frequently participated in more than one activity, and therefore proportional participation across activities often summed to >1.0 per site. The prevalence of each activity per site was first explored visually using a shadeplot of the data matrix (rows as activities, columns as sites). Data were further analysed using PRIMER 7 (Plymouth Routines in Marine Ecological Research) and selected procedures (see Anderson *et al.*, 2008). A hierarchical agglomerative clustering using a Euclidean Distance similarity resemblance matrix with group-average linking of clusters was used to construct a dendrogram. Permutation based on similarity profiles (using the procedure SIMPROF) was

Table 1. Number of households and sample size per site for this study. The demographic profile of households is presented as percentages, based on interviews of household heads. For the Religion (%) category, Other includes local beliefs and non-responses. For the Education (%) category, "<" indicates that the specified education level was not completed.

Category and Level	Combined	Marrubune	Gazelas	Icidua	C. Dembe	Inhangome
All households (number)	4834	1118	750	1816	850	300
Sample size (numbers)	182	28	36	37	39	42
Sample size (%)	3.8	2.5	4.8	2.1	4.6	14.0
Gender (% male)	76	89	61	78	51	88
Marital status (% married)	79	96	74	62	69	95
Age group (% per category)						
16-25	31	25	17	41	40	21
26-35	30	21	47	22	20	29
36-45	18	25	17	11	13	19
46-55	10	4	6	11	20	5
>55	7		14		8	10
No response	4	25		16		17
Religion (%)						
Christian	62	11	74	49	79	86
Muslim	24	86	4	24	10	7
Other	9		22	8	10	7
Education (%)						
< Primary school	45	61	70	38	33	38
Primary school	25		26	24	36	31
< Secondary school	12	11		8	8	26
Secondary school	8	7		22	3	5
<Tertiary certificate	2			3	8	
No response	8	21	4	5	13	

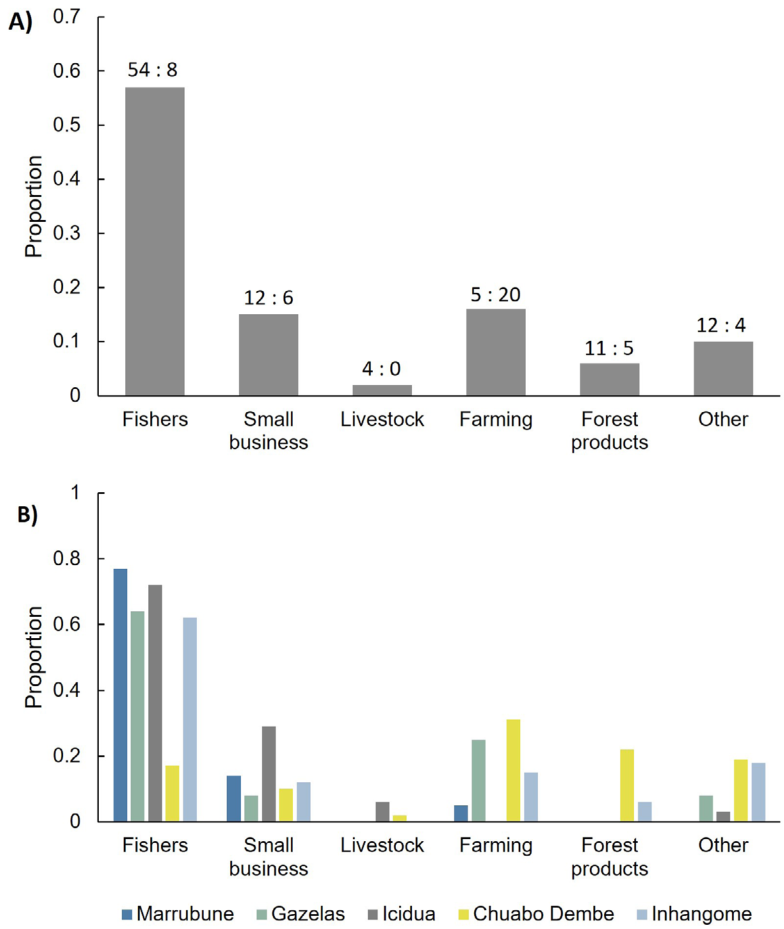

Figure 2. (a) Proportion of all interviewed household heads that answered affirmative per livelihood activity at Bons Sinais Estuary for all data combined. The percentages of men and women, respectively, that answered affirmative per activity are shown above the bars (% Men : % Women). (b) Proportion of all interviewed household heads that answered affirmative per livelihood activity at Marrubune, Gazelas, Icidua, Chuabo Dembe and Inhangome.

used to test for multivariate structure in the data at dendrogram nodes and significance levels were taken as <5 %. Principal Components Analysis (PCA) was used on the original normalised data using Euclidean distance as the underlying dissimilarity to ordinate sites according to the range of activities noted per site along two PCA axes. Activities were presented along vectors, vector lengths denoting the proportional importance of individual activities within and among sites.

Results

Demographic analysis

Interviews covered 182 households in five villages, representing an average of 3.8 % of households per village (Table 1). Men made up 76 % of all interviewees and the bulk of interviewees at Marrubune, Gazelas, Icidua and Inhangome, but equal numbers of men and women were interviewed at Chuabo Dembe (Table 1). Overall, 79 % of interviewees were married, and the rest were either single, widowed or divorced. Some 63 % of interviewees were younger than 36 y old and only 6 % were older than 55 y. The age structure of interviewees approximated the proportional demography of Quelimane in 2017 (INE, 2017): 44 % between 20-30 y, 19 % between 30-50 y and 7 % older than 50 y. Dominant religions were Christianity and Islam, with a large Muslim community at Marrubune (86 %) but mainly Christians at Inhangome, Chuabo Dembe and Gazelas. Literacy was low; of all interviewees, 45 % had not complete primary school education, 8% had completed a secondary school education, and only 2 % attended college. Literacy was lowest at rural sites, with 61 % (Marrubune) and 70 % (Gazelas) of interviewees not completing primary school (Table 1). There was no significant difference in the level of education of men and women.

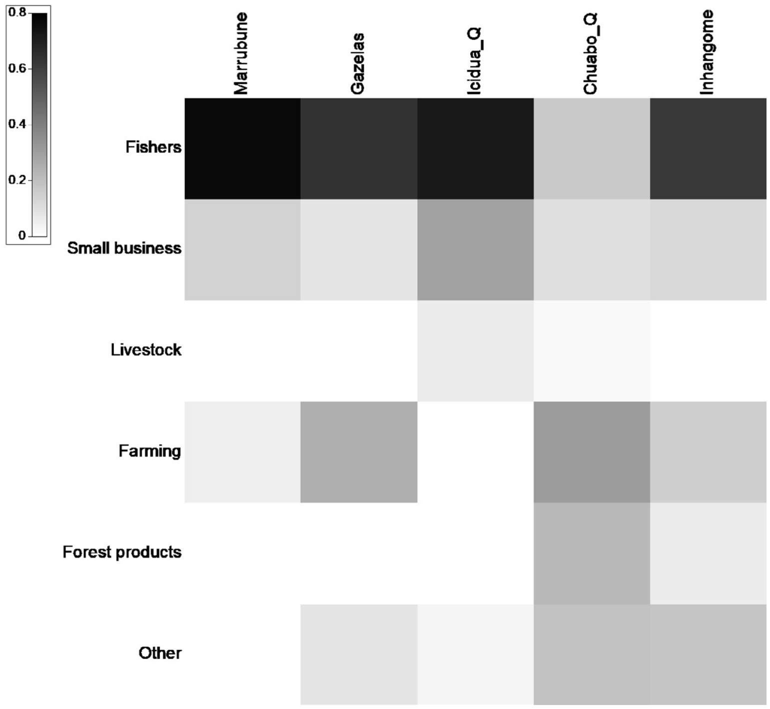

Figure 3. The prevalence of activities per site as the proportion of affirmative answers by interviewed household heads. Grey shading to black depict a high scale of activity and grey to white depict fewer or no instances of a particular activity at a sampling site.

Livelihood analysis

For all interviews combined, fishing contributed the most to livelihoods (54 %) followed by agriculture (15 %), small business operators (14 %), forest product collectors / dealers (6 %) and 'other' activities (10 %) (Fig. 2a). By gender, men focussed on fishing (54 %) whereas women participated mainly in agricultural activities (20 % overall). Few women participated in fishing (8 %). Both genders contributed to diverse livelihood activities at a lesser scale, with 6 % of women interviewees contributing as small business operators, 5 % as forest product dealers and 4 % undertaking other activities. Men contributed to small business (12 %), forest products (11 %), other activities (12 %) and livestock keeping (4 %) – the latter was only done by men.

Fishing dominated at Marrubune (77 %) and Icidua (72 %), Gazelas (64 %) and Inhangome (62 %) (Fig. 2b). Farming was important at Chuabo Dembe (31 %), Gazelas (25 %) and Inhangome (15 %). A broader spectrum of activities occurred at Chuabo Dembe; apart from farming (31 %), forest product dealers (22 %; mainly mangrove products), fishing (17 %) and small business enterprises (10 %) were important. A large proportion of 'other' activities (19 %) such as civil servants and college or shop employees was consistent with the location of a university college at this peri-urban site. Small business operators consistently made up 10 to 14 % of livelihood activities across sites (no sample at Gazelas).

The shadeplot showed the high importance of fishing at all sites, except Chuabo Dembe (Fig. 3). The plot further showed a greater diversity of activities at Chuabo Dembe than at any of the other sites. In the cluster analysis, Chuabo Dembe differed significantly ($p < 0.05$ at the node) from the other four sites (Fig. 4). Although not significant, the dendrogram clustered Gazelas and Inhangome (two rural sites relying on fishing and farming) as opposed to Icidua and Marrubune (two sites dominated by fishing). In the PCA, the first two principal components represented 96.1 % of cumulative variation. The ordination showed the overriding importance of fishing at Marrubune, and of farming and fishing combined at Gazelas and Inhangome (Fig. 5). Based on the range of activities, Chuabo Dembe was highly dissimilar to the other four sites, which grouped closer together. The grouping indicated a suite of fish-based farming systems, in which the relative importance of activities differed between sites.

Relative contributions of livelihood activities to household income

Fishing contributed most to household income at Marrubune (71 %), Gazelas (49 %) and Icidua (Fig. 6). Icidua is a peri-urban site, and where most fish

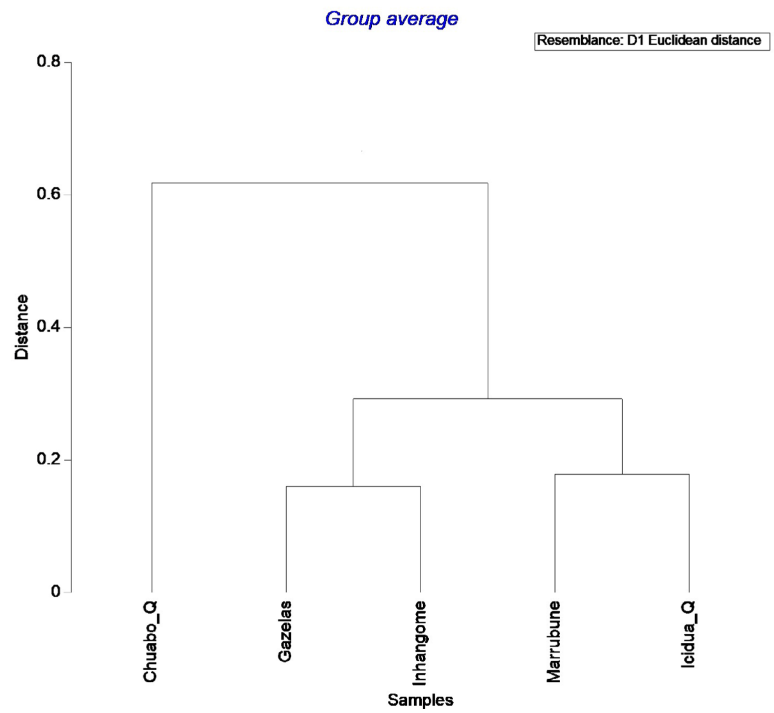

Figure 4. Dendrogram based on similarity profiles (using the procedure SIMPROF and Euclidean Distance) to test for multivariate structure in the data. Chuabo Dembe differed significantly ($p < 0.05$ at the node) from the other four sites.

intended for sale in Quelimane city is landed. Farming contributed most to household incomes at Chuabo Dembe (27 %) and Inhangome (32 %). The lower contribution of fishing to income at Inhangome (32 % relative to 62 % of household effort spent on fishing; Fig. 2b) is potentially due to captured fish being used for household consumption, rather than sold at markets. Operating small businesses contributed 18 % to household income at Marrubune, 17 % at Incidua and 12 % at Chuabo Dembe (Fig. 6). Contributions from 'other' sources were much larger at Chuabo Dembe (22 %) than at other sites, supporting a hypothesis of higher diversity of livelihood activities.

Discussion

The study aimed to determine the relative importance of livelihood activities in households that rely on FBF systems in rural and peri-urban settings around the Bons Sinais Estuary, based on a small dataset of 182 questionnaires directed at household heads, most of whom were men. The small and gender-biased dataset restricted the analyses that could be performed, but even so, clear trends emerged. Livelihood activities were dominated by fishing at most sites, but were diversified to include farming, collection and trade of mangrove poles and charcoal and small business enterprises. Unaite (2017) also found that 64 % of

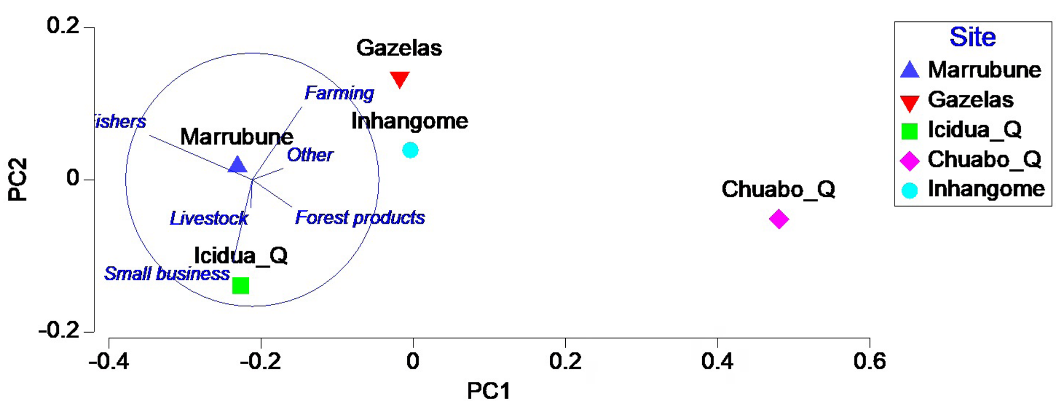

Figure 5. Principal Components Analysis (PCA) based on original normalised data using Euclidean distance to ordinate sites according to the range of activities along two PCA axes. Activities were presented along vectors, with vector lengths denoting the proportional importance of individual activities within and among sites.

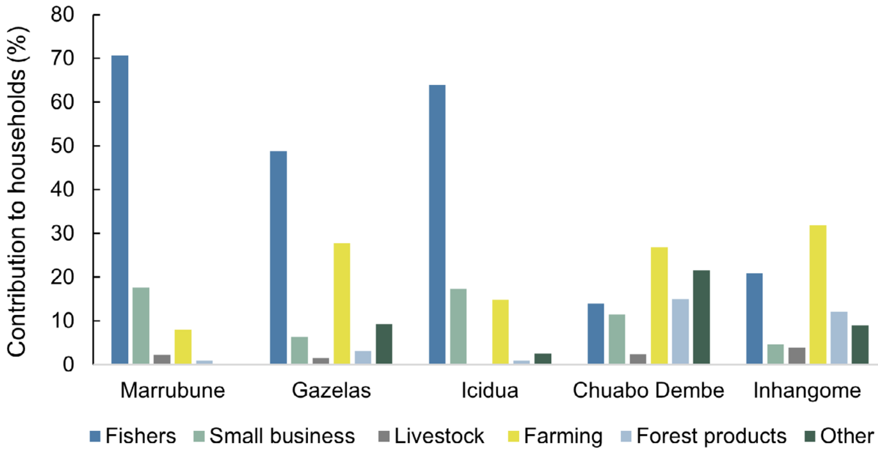

Figure 6. Relative contributions of livelihood activities to household incomes at the Bons Sinais Estuary at Marrubune, Gazelas, Icidua, Chuabo Dembe and Inhangome sampling sites.

households around the Bons Sinais Estuary included fishermen. The relative importance of household activities was further influenced by location along the estuary, reflecting the availability of specific resources and peri-urban concentration of markets. An emerging small business sector and higher percentage of paid employment (other activities) were evident at the peri-urban Chuabo Dembe site. Both initial hypotheses of this study (variability of the deltaic FBF system along the length of estuary; and rural/urban influence) were therefore accepted.

The mixed rural-urban form of living observed around Quelimane is common to many African towns and cities (Agergaard and Ortenbjerg, 2017; Agergaard *et al*., 2019) and elsewhere in the developing world (Sati *et al*., 2017; Shan *et al*., 2017). The inhabitants of newly urbanized areas are sometimes drawn back to rural livelihoods when unemployed, to supplement their income (Chibvongodze, 2013). Even so, the diversification of livelihoods at rural/urban edges can contribute to poverty eradication, better education and increased resilience of households (Drakakis-Smith *et al*., 1995; Cunguara *et al*., 2011; Potts, 2013; Thuo, 2013). Diversification forms an essential part of rural transformation and small-town development (Agergaard and Ortenbjerg, 2017; Agergaard *et al*., 2019).

Literacy declined at sites further from Quelimane (i.e., Marrubune and Gazelas), explained by the increasing distance to schools and a tertiary education college located at Chuabo Dembe. Fishing dominated livelihoods at Marrubune, leaving little time for further education at Quelimane, some 25 km away. Interestingly, literacy of farmers was similar to those engaged in small business and civil servants, though low, and the literacy of men and women did not differ. The Mozambique government has adopted education policies which includes adult literacy, the ability of people to make best use of the diversified income opportunities in a competitive market, and to improve their livelihood (INE, 2017; UNESCO, 2021).

At Chuabo Dembe, women were engaged with production and sale of charcoal and poles from mangroves. Women in rural Mozambique make a significant contribution to all stages of charcoal production which contrasts with much of the existing literature on charcoal in sub-Saharan Africa (Jones *et al*., 2016). Charcoal had different uses in livelihood strategies, including as an energy source and providing some financial autonomy for women, enabled by the informal nature of local regulations (Jones *et al*., 2016). The demands for agricultural products and charcoal are likely to increase as Quelimane city grows, thus continuing the important role of women in the local economies. Porsani *et al*. (2020) suggested that a gendered livelihood approach may give better insights to local culture in Mozambique, and hence increasing the number of women interviewed is likely to enhance inferences on livelihood strategies.

At present, rural and peri-urban forms of livelihood coexist around the Bons Sinais Estuary and are inter-dependent, strengthened by the demand for fresh food and energy from charcoal, and by marketing opportunities offered to farmers and fishers (see Allen, 2003; Allen *et al*., 2014; Kuusaana and Eledi, 2015). Whereas the mutually dependent system can prevail in theory, human population growth coupled with an ever-increasing demand for natural resources makes it ecologically unsustainable over a longer term.

Changing land use and land cover around the estuary over the past 27 years have indicated the degradation of wetland habitats (Furaca *et al.*, 2021) and estuarine fish and crustacean resources are heavily exploited for human consumption (Mugabe *et al.*, 2021). An additional concern is that rural livelihoods will remain a poverty trap, with few opportunities for education or alternative livelihoods, thus aggravating inequalities between rural and urban households (McMichael, 2000; Kuddus *et al.*, 2020).

Several authors (de la Masselière *et al.*, 2020; Gebre and Gebremedhin, 2019) have argued for sustainable urban-livelihood linkages that convey mutual benefits to rural and urban households. This would require support for rural development, such as improving food production systems to attain efficiency on land and water usage; introduction of innovative agriculture practices and energy production; and improvement of transportation infrastructure. In addition, there is a need for urban development planning (Deng *et al.*, 2017) – to prevent encroaching into low-lying areas prone to flooding. A key presumption of the above is that the capacity of rural households to contribute to innovation and the operation of more complex production systems will be enhanced by raising the level of education.

In conclusion, the Bons Sinais Estuary provides a good example of a deltaic FBF subsystem, with the relative importance of livelihood activities depending on location in the estuary, and diversification occurring in peri-urban areas near Quelimane. Women played an important role in generating household income, particularly through farming and dealing in forest products. The level of education declined further from urban areas, reducing opportunities of rural households. Degradation of natural ecosystems and overexploitation of living resources – to support growing human populations – threaten estuarine functioning, and hence dependent livelihoods. A programme for improved peri-urban planning, innovation of farming systems to increase efficient food production, and renewal of food production, processing and transport infrastructure is recommended. Improved education of rural communities is crucial, to enable them to participate effectively and harness benefits from the rural-urban linkage.

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Appendix

Questionnaire ID

The questionnaire form.

ESTUARIZE-WIO - Work Package 2

QUESTIONNAIRE – Bons Sinais estuary

Date	Time started interview	Time completed interview	Interviewer's name
____________	____________	____________	____________

Section A: Basic identification of estuary

Qi. What's the name of the village? ______________________

Qii. What's the name of the ward? ______________________

Section A: Respondent Socio-economic characteristics

Demographic information (Provide information on Household heads or representative ONLY)

Q1. What is your name? ______________________

Q2. Sex of respondent
a) Male b) Female ☐

Q3. Marital status of respondent
a) Married b) Divorced c) Widowed d) Not married ☐

Q4. How old are you? (Years) ______________________

Q5. Gender of household head
a) Male b) Females

Q6. What is the household head tribe? ______________________

Q7. What is the highest level of education of household head? ☐
a) Not complete Primary
b) Complete Primary High School
c) Complete College certificate
d) Not complete College Certificate
e) Bachelor's Degree
f) Master's Degree
g) Doctoral Degree (PhD)
h) Professional Course (JD, MD)
i) Prefer not to answer

Q7a. Does the household head have a household elsewhere besides the one in this village? ☐
a) Yes b) No

Q8. If yes where is this other household located? ____________________

Q9. Where was the household head born? ☐

a) This village
b) Another village in the ward/Location
c) Another ward in this district/county
d) Another district/county Specify ____________________
e) Another region

Q10. If not born in this village, when did the household head move to this village? ____________________

Q11. What is your monthly household income level? ____________________

Q12. What is the size of the household head? ____________________

Q13. What is your religion? ☐

a) Christian
b) Muslim
c) Others: ____________________

Q14. How many years have you been living in the Bons Sinais estuary? ____________________

Q15. What is your main occupation? (only one answer)

a) Fisher
b) Small business trader
c) Livestock keeper
d) Agricultural farmer
e) Forest product dealer
f) Other Specify ____________________

Q16. What other economic activity are you involved in? (only one answer) ☐

a) Fisher
b) Small business trader
c) Livestock keeper
d) Agricultural farmer
e) Forest product dealer
f) Other Specify ____________________

Q17. What are the economic activities that are carried out in this village?

S/N	Economic activities	Tick activities in your village
a)	Fishing	
b)	Small business trading	
c)	Livestock keeping	
d)	Agricultural farming	
e)	Forest product harvesting and trading	
f)	____________________	

Section B: Socio-economic activities and cultural practices

Q18. Please rank the main cultural economic/productive activities that sustain your household

S/N	Income generating activity	Percentage of income from activity	Rank
a)	Agriculture	________	____
b)	Fishing	________	____
c)	Forest (Timber, poles, firewood etc)	________	____
d)	Non-timber	________	____
e)	Salt making	________	____
f)	Livestock	________	____
g)	Business	________	____
h)	Other Specify ________	________	____

Q19. Provide the proportion of income (cash-sell by your households from the following

Source of income per month	Percent
Fishing	____
Crops (including associated products, e.g., beer)	____
Livestock (including all products eg meat, milk, skin, eggs etc)	____
Non timber forests products (poles, firewood, charcoal, palms, wild meat, live animals birds, wild food plants, medicinal plants, honey, mushrooms, reeds, grasses)	____
Timber product (income from sale of logs, timber or working in timber related activities)	____
Business income (not related to own-production of arable produce or livestock or harvested resources)	____
Pensions & remittances (all incomes from friends, relatives)	____
Salt making	____
Salary or wage (from formal employment)	____
Other casual (cash or in kind earning)	____

Q20. How much do you generate from each or any of the following economic activities per season (specify the season i.e. month, two months etc)

S/N	Activity	Output/ Production (Unit measure)	Amount consumed (Unit measure)	Amount sold	Unit price	Cost per season
a)	Agriculture	____	____	____	____	____
b)	Fishing	____	____	____	____	____
c)	Wood and Wood procuts (Mbao, Mkaa, Kuni, Fito	____	____	____	____	____
d)	Salt making	____	____	____	____	____
e)	Livestock	____	____	____	____	____
f)	Other Businesses	____	____	____	____	____

Unit measure: (1) Kg (2) Bags (3) Baskets (4) Number of fish pieces

Q21. Please give details on your livestock keeping.

Type of livestock	How many now	If you have to sell now, what is the average price
Chickens		
Goats		
Cattle (local)		
Cattle (dairy)		
Milk (litre) per day		
Duck		
Pigs		
Sheep		

Exploring urbanization and critical habitat loss through land cover change around the Bons Sinais Estuary, Mozambique

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Abstract

Estuaries supply direct and indirect multi-sectoral opportunities including for transport, natural resource use and climate protection. These provisions support livelihoods and contribute to social and economic development. The Bons Sinais Estuary in Zambézia Province, central Mozambique, is adjacent to the provincial administrative capital Quelimane, some 25 km from the coast. The rapid growth of Quelimane has increased the demand for natural resources from the estuary, including space, food, fuelwood, transport and raw materials for construction and economic activities. Expansion of the built environment has extended into low-lying lands, mostly within the critical estuarine functional zone with inevitable consequences, such as damage to natural habitats and flooding of occupied areas during rainy seasons. The aim of this study was to analyse three decades of change (1991 – 2018) in land use and land cover (LU/LC) in the Bons Sinais Estuary, focussing on the growth of Quelimane city and the transformation of estuarine and surrounding habitats. The method relied on open-access satellite images and a LU/LC change analysis to quantify the spatio-temporal changes brought about by economic development and related human activities. A combination of low-intensity fieldwork and satellite-derived data (Landsat-5, sensor: Thematic Mapper and Landsat-8; sensors: Operational Land Imager, Thermal Infra-Red Scanner) was used to generate LU/LC information classified according to the features: mangrove trees; wetlands; estuary intertidal areas; built-up area; cultivated trees; and cultivated land. From 1991 onwards, there was an overall increase in cultivated crops (66 %), development (79 %) (including rural human settlements) and intertidal mudflats (12 %) with a concomitant decline in critical wetlands (16 %) and mangroves (12 %). The study predicts a worsening of the impacts on the estuarine ecosystem with further growth of Quelimane city. To reverse the negative trend on estuary health, the recommendation is for management interventions that promote sustainable LU, and urban development plans that consider ecosystem conservation and active restoration.

Keywords: estuary land cover, urban expansion planning, mangroves, wetlands, human activities

Introduction

Estuaries are vulnerable to human pressure because they are easily accessible, have high diversity (species, habitats, natural resources) and have high utility for a broad range of human-related activities. Estuaries provide opportunities for transport (ports and shipping), harvesting of natural resources (fish and wood), flood-recession agriculture and protection against climate – all of which support local livelihoods and contribute to social and economic development (Barbier *et al.*, 2011; Calvão *et al.*, 2013; Khan and Kumar, 2009). Unplanned urbanization around estuaries can lead to natural habitat fragmentation, degradation and habitat loss (e.g., Alberti, 2005; Branoff, 2018; Davis, 2005; Grimm *et al.*, 2008; Lai *et al.*, 2015; McDonald, 2008; McKinney, 2006; Thanh *et al.*, 2004; Yi *et al.*, 2018; Zapata *et al.*, 2018;) and eventually to socio-economic decline (Jiboye *et al.*, 2019; Miah *et al.*, 2010; Rasyid *et al.*, 2016).

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The Bons Sinais Estuary in central Mozambique (Zambézia Province) is about 30 km long with the provincial administrative capital Quelimane located on its northern bank, some 25 km from the estuary mouth. The estuary has been popular in the recent literature, including accompanying studies in this Special Issue on estuarine hydrodynamics (Hoguane *et al.*, 2020; 2021), small-scale fisheries (Costa *et al.,* 2020; Mugabe *et al.*, 2021) and adaptation of associated livelihoods in rural and urban space (Blythe, 2014; Blythe *et al.*, 2014; Francisco *et al.*, 2021). The geographic setting, ecosystems and socio-ecological importance of the estuary have been summarised by Groeneveld *et al.*, 2021). The city of Quelimane grew rapidly during and after the Mozambican civil war (1977-1992) when up to 3 million people were displaced mainly from rural inland areas to the more densely populated coast (Wilson, 1994). Quelimane recorded an average annual growth rate of 4.5 % per year, increasing from 104,000 inhabitants in 1991 to 415,000 in 2020 (www.populationstat.com).

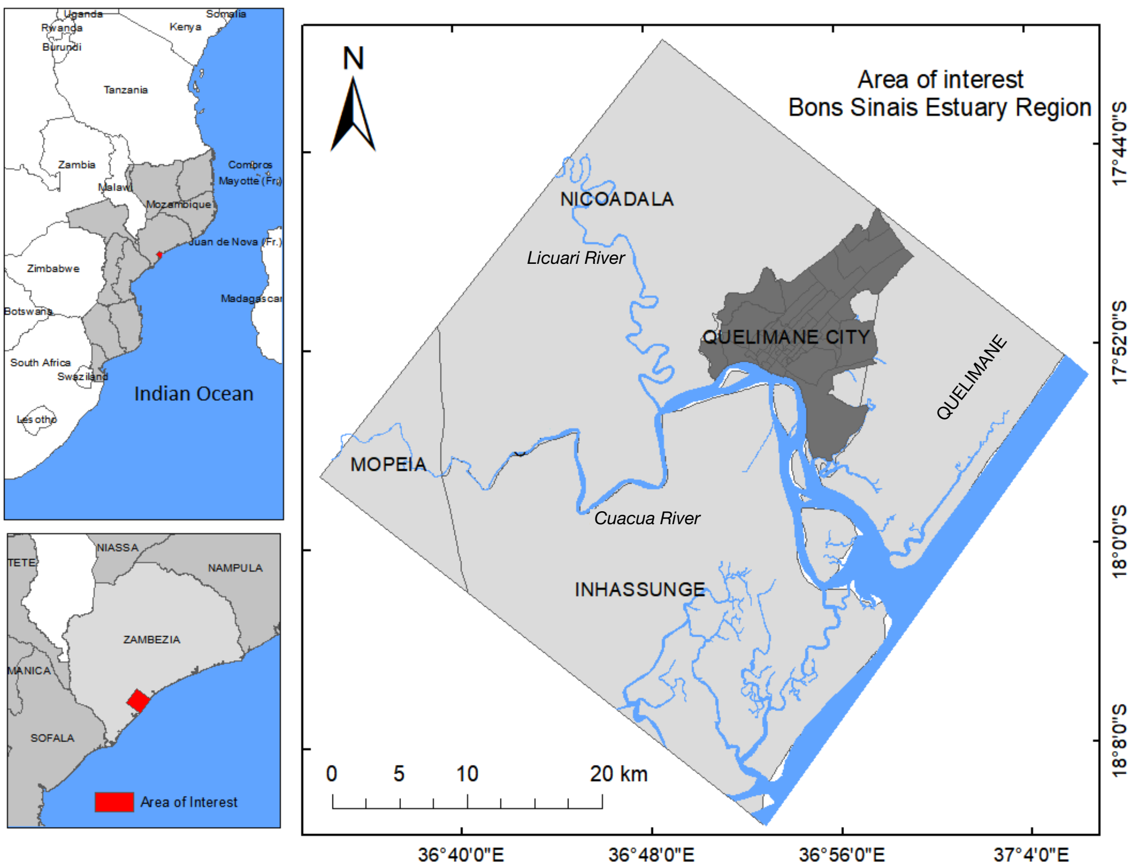


Figure 1. Location of the Bons Sinais Estuary relative to Quelimane city and adjoining districts.

The growth of Quelimane increased the demand for natural resources from the Bons Sinais Estuary, including space, fresh water, food, fuelwood, transport and raw materials for construction and economic activities. Expansion of the built environment extended into low-lying land, often within the estuarine functional zone, with predictable outcomes – damaged natural habitats and suburbs prone to flooding during rainy seasons (Mazzilli, 2015; Unaite, 2017). Urbanization is recognised as a primary driver of environmental degradation, including land use change (Hahs *et al.*, 2009), reduced water quality and pollution (Awaleh *et al.,* 2015; Seto *et al.*, 2013), modification of habitats, plant and animal communities, and biodiversity loss (Branoff, 2018; Yi *et al.*, 2018; Zapata *et al.*, 2018). The main livelihoods associated with the estuary are fishing and agriculture, collection and sale of firewood (from mangroves), small businesses trading fish and fish products and agriculture products (Blythe *et al.*, 2014; Unaite, 2017). Furthermore, the estuary provides nutrients that nourish adjacent coastal marine ecosystems and nurseries (Hoguane and Armando, 2015) and the dense mangrove forests are an important carbon sink and mitigation against climate change (Amade *et al.*, 2019).

Remote sensing and GIS techniques are often applied to detect change in LU and LC by season or over longer time frames (Mallupattu and Reddy, 2013; Berlanga-Robles and Ruiz-Luna, 2002; Hudak and Wessman, 1998; Ngondo *et al*., 2021). Analysis of satellite images is a cost-effective means of mapping physiognomic habitats, including mangroves, wetlands, sand and seagrass beds and coastline morphology (Dittrich *et al*., 2020; Dymond *et al*., 2019; Marzialetti *et al*., 2019). They can also be used to trace socio-economic and socio-anthropological effects and changes in coastal communities, such as the spatial and structural spread of urban areas and agriculture over time. Analyses of LU/LC can also contribute to the planning and management of land and water resources (Mallupattu and Reddy, 2013; Asselman and Middelkoop, 1995).

The aims of this study were to analyse decadal change (1991 – 2018) in LU and LC in the Bons Sinais Estuary, including the growth of Quelimane city and the transformation of estuarine and surrounding habitats. The study relied on open-access satellite images and a LU/LC change analysis to quantify the spatio-temporal changes brought about by economic development and related human activities (settlement, building, agriculture, commerce). The findings are intended to raise awareness of the implications of unplanned development in sensitive ecosystems, and the need for appropriate urban development plans to sustain the multiple goods and services on which settlements rely.

Materials and methods

Study area

The Bons Sinais Estuary extends from the confluence of the Licuári and Cuácua Rivers, with the Cuácua being the larger tributary into the estuary. The Licuári and Cuácua have a highly seasonal, torrential flow regime, with high flows for 3-4 months and low to nil flows for the remainder of the year (Barbieri *et al*., 2019; Inguane *et al*., 2014). Gauged flow data were available for the smaller Licuári tributary (basin size 3,775 km^2) during the peak wet season (January-April) measured 35 km northeast of Quelimane, ranging between 10 and 50 $m^3.s^{-1}$ (Mazzilli, 2015). Upstream pollution levels are considered negligible because of few known pollution sources. The estuary is approximately 30 km long, extending over four administrative areas: Quelimane City and the districts of Quelimane, Inhassunge and Nicoadala (Fig. 1). For this study, the area of interest (AOI) was taken as the estuarine area below 10 m amsl. The estuarine functional zone was characterised by mangroves, wetlands, mixed-forests, mudflats, agricultural land and developed areas. The area has high ecological and socio-economic diversity and supports riparian habitats connected to the water body, essentially the historical floodplain.

Datasets

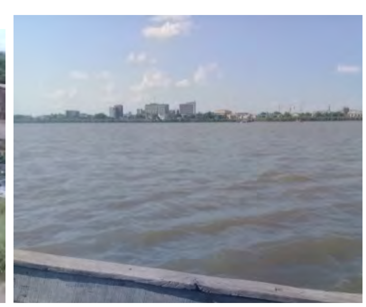
A combination of fieldwork and satellite-derived data from Landsat-5/TM (sensor: Thematic Mapper) and Landsat-8/OLI-TIRS (sensors: Operational Land Imager-Thermal Infra-Red Scanner) imagery (National Aeronautics and Space Administration (NASA)/ United States Geological Survey (USGS)) was used to generate accurate LU/LC information. Six geo-referenced Landsat images (1991 to 2018) were obtained via the USGS Data Access platform (https://earthexplorer.usgs.gov) at approximately five-year intervals. Images were selected between May and August of each study year to benefit from the lowest interference by cloud cover and standardise surface reflectance (depicted by sun elevation and azimuth) across the different classes. Selected images had a cloud cover of <10 % over the AOI (Table 1).

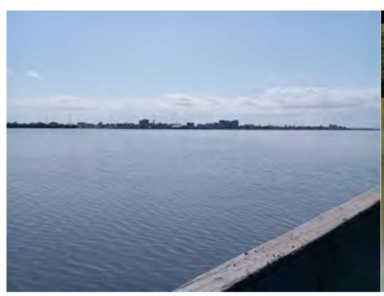
The images were Level 1 products (unprocessed, full resolution, georeferenced instrument data but with radiometric and geometric calibration) presented by

Table 1. Characteristics of satellite images used for LU/LC change detection in the Bons Sinais Estuary.

Date	Sensor ID	Cloud cover (%)	Sun elevation (º)	Sun azimuth (º)
1991-06-14	TM	0.00	34.43	44.34
1998-07-03	TM	1.00	36.48	42.31
2003-08-18	TM	2.00	42.95	51.86
2008-05-11	TM	8.00	43.05	42.69
2013-06-26	OLI-TIRS	0.01	40.03	36.43
2018-06-24	OLI-TIRS	8.90	39.62	36.98

Table 2. Land use and land cover classification classes applied in the study.

Classes	Description
Coastal bare	Substrates (usually sand) within the coastal intertidal zone (beach) that are denuded of vegetation and may be redistributed due to tidal action.  
Cultivated crops	Subsistence agricultural areas that are managed to produce harvested crops; mainly rice, maze and cassava. Crops also exist in-between fallow areas.  
Cultivated trees	Characterised by planted vegetation (orchards/plantations) that are not croplands; including coconut trees, banana, oranges, mango, etc.  
Developed	Includes medium density formal developments (Quelimane town and suburbs) and low density-informal development (sparsely distributed informal rural settlements).  

Classes	Description
Intertidal mudflats	Areas of non-vegetated, natural cover that is subject to seasonal and tidal ponding, soil saturation, or flooding in the functional zone of the Bons Sinais Estuary.  
Mangroves	Forested wetland areas and floodplain forests, influenced by tides and dominated by densely or sparsely distributed mangroves, dominated by *Avicennia marina*.  
Water	All areas of water, generally estuarine (i.e. a partially enclosed water body where salt water is measurably diluted with fresh water).  
Wetland	Wetlands, marshes or areas where the soil or substrate is periodically saturated, fed by rain or river water, and which may or may not be associated with vegetation (other than mangroves) but is not tidally influenced.  

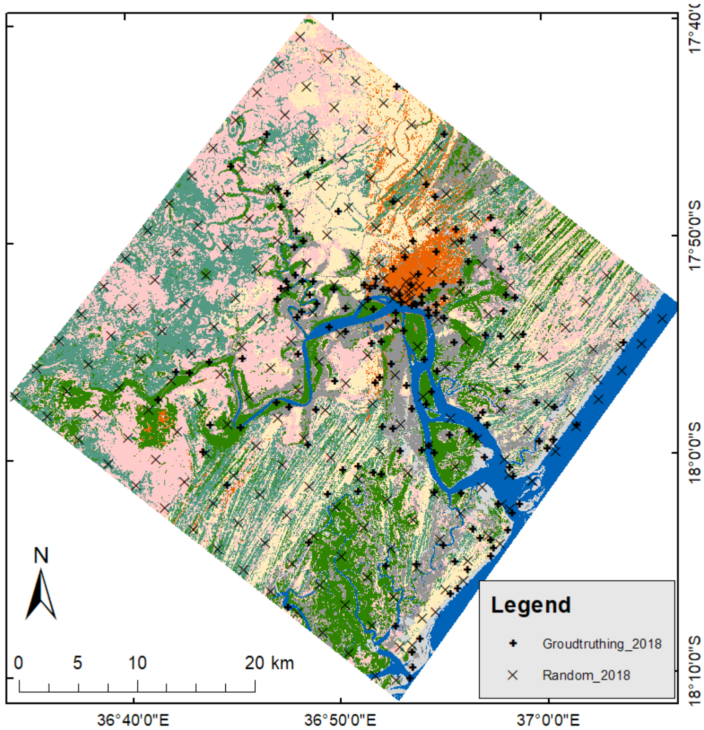


Figure 2. Location of the ground truthing and randomly selected validation points.

a 16-bit Digital Number (DN) for each OLI band, with a 30 m spatial resolution across sensors. The path and row, as used by the Worldwide Reference System (WRS), was 166 and 72 for the six images, respectively.

Image pre-processing

Radiometric calibration (RC) was performed by converting digital numbers (DN) to surface reflectance values to accurately compare different images and the thematic maps of LU/LC changes. The RC eliminates the differences in solar zenith angles associated with the time and date of acquisitions. The RC was performed by converting the original DN on each pixel into Top of Atmospheric (TOA) reflectance ($\rho\lambda$). The TOA reflectance for each spectral band was calculated using Equation 1:

$$\rho\lambda = \frac{(M_\rho * Q_{cal} + A_\rho)}{\sin(\theta)} \quad [1]$$

where M_ρ is reflectance multiplicative scaling factor, A_ρ is reflectance additive scaling factor, θ is sun elevation angle and Q_{cal} is DN.

Training data, LU/LC classification

True composite bands were used for each image, with Band 1 Visible (0.450 - 0.520 µm), Band 2 Visible (0.520 - 0.600 µm), Band 3 Visible (0.630 - 0.690 µm) and Band 4 Near-Infrared (0.760 - 0.900 µm) for Landsat-5 set, and Band 2 Visible (0.450 - 0.510 µm), Band 3 Visible (0.530 - 0.590 µm), Band 4 Visible (0.640 - 0.670 µm) and Band 5 Near-Infrared (0.850 - 0.880 µm) for the Landsat-8 set. A four-band combination was used to identify the LU/LC features for the AOI using a supervised classification algorithm. The training samples sites were selected randomly within the AOI, based on similarities in the spectral characteristics of the Landsat images combined with existing local knowledge and Google Earth imagery. A total of eight LU/LC classes were identified as follows: coastal bare; cultivated crops; cultivated trees; developed; intertidal mudflats; mangroves; water; and wetlands (Table 2).

Post-classification validation and change detection

After sufficient training samples were collected, the eight LU/LC classes in each time stamp were pre-validated. Evaluation of collected signatures was conducted through exploratory analysis of histograms and through observation of the level of association of the training samples. The validation of LU/LC classes was carried out through a combination of ground truthing points (160 field photos) used for training and a random sample of 220 points validated using Google Earth imagery from the year 2018. The most recent 2018 LU/LC image (Fig. 2) captured the main estuarine LU/LC features that included mangrove trees, freshwater

Table 3. Overall accuracy estimate given by combined ground truthing and random selected validation points for 2018.

	Water	Coastal Barrier	Mangrove	Intertidal Mudflat	Wetland	Developed	Cultivated trees	Cultivated crops	Total	User Accuracy
Water	32	1	0	0	0	0	0	0	33	0.97
Coastal Barrier	1	22	0	3	1	0	0	0	27	0.81
Mangrove	0	0	52		3	1	8	0	64	0.81
Intertidal Mudflat	1	0	1	31	6	7	0	0	46	0.67
Wetland	0	0	0	3	56		1	6	66	0.85
Developed	0	0	0	0	2	29	1	2	34	0.85
Cultivated trees	0	0	3	0	7	2	49	6	67	0.73
Cultivated crops	0	1	1	1	6	0	1	34	44	0.77
Total	34	24	57	38	81	39	60	48	381	
Producer Accuracy	0.94	0.92	0.91	0.82	0.69	0.74	0.82	0.71		0.80

wetlands, built-up areas, cultivated trees, and cultivated land. The number and location of the validation points were selected to ensure adequate reference data from field observation and Google Earth images in the interpretation of the main LU/LC features.

The accuracy assessment of the processed satellite images, through the combined ground truthing and random selected validation points (Table 3), determined a kappa coefficient of 77 % for overall assessment. The producer's accuracy (i.e., false negatives or errors of omissions) varied from 0.69 to 0.94, with the lowest accuracy in wetlands, and the user's accuracy (i.e., false positives or errors of commission) varied from 0.76 to 0.97, with the lowest accuracy for intertidal mudflats.

The recorded signature files created from training samples were then applied to detect changes in LU/LC in the Bons Sinais Estuary using a Maximum Likelihood Classifier (MLC). The MLC is widely used for thematic map production since it reduces the data redundancy that is common in remotely sensed estimations, where only a pixel with the maximum likelihood is classified into the corresponding class (Fan *et al.*, 2007; Manandhar *et al.*, 2009; Tan *et al.*, 2010).

In the post-classification procedure, the time series was combined for detecting LU/LC changes over the 27-year period. Change detection in LU/LC compared the area of each class between time stamps and then overall for the period 1991-2018. Continuous change was evaluated using the Continuous Change Detection and Classification (CCDC) algorithm.

Results

Major land use/land cover categories

The total area of the AOI was 1,516 km². Figure 3 and Table 4 show the allocation of this land into the major land cover categories for the Bons Sinais Estuary from 1991-2018. Wetlands constituted the major land cover at 25.4-31.3 % (average, 27.8 %) of the area, over the study period. This was followed by cultivated trees ranging from 19.5 % to 26.2 % of total overall cover, but which showed a steady decrease in cover from 1991. Mangrove forests, ranging from 15.7-17.1 % over the AOI, did not change notably overall but did show a decline in cover over time. Cultivated crops, which are used mainly for subsistence agriculture, showed a steady increase from 10 % to 16.5 %, averaging 13 % of the total area from 1991-2018. Developed land, representing urban development and rural human settlements, increased from 1.8 % to 3.2 %, averaging 2.4 % coverage throughout the study period.

In 1991, Quelimane City (indicated by white arrow), was a small, sparsely occupied urban area (Fig. 3a). At that time, wetlands (to the north and west), and mangroves (to the south and east), dominated the area. Cultivated trees, dominated by coconut palm trees, appeared as 'strips' running NE-SW, interspersed by narrow bands

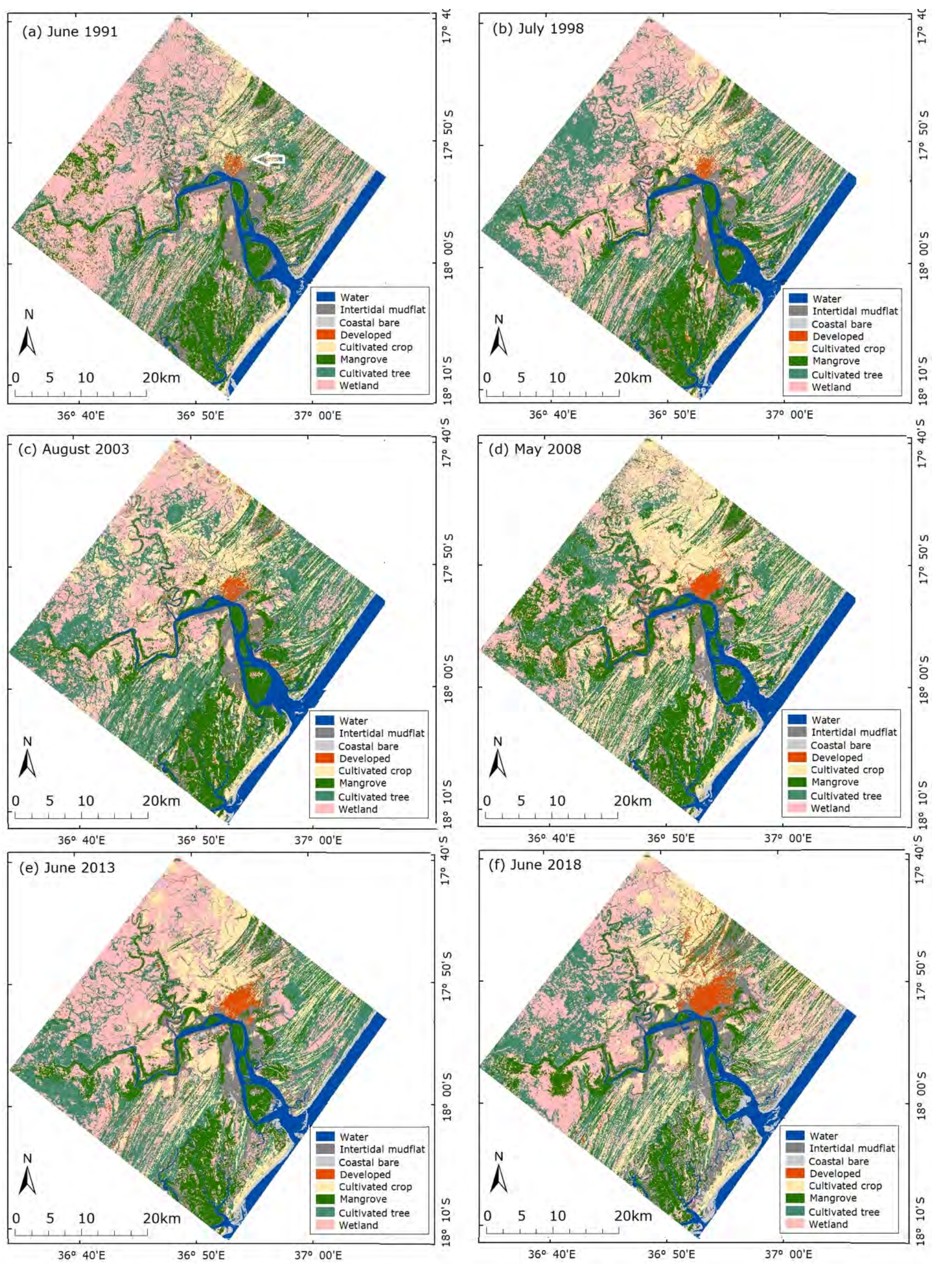


Figure 3. LU/LC in the Bons Sinais Estuary in (a) June 1991, (b) July 1998, (c) August 2003, (d) May 2008, (e) June 2013 and (f) June 2018. Quelimane City is indicated by the white arrow in (a).

of cultivated land in the western and southern side of the study area. By 1998 (Fig. 3b), densification of Quelimane City had begun with new, patchy human settlements noticeable north and west of Quelimane City. This was a clear indication of the expansion of the city. Extensive areas of cultivated crops, interspersed by wetlands, dominated the northern and western side of Quelimane. Areas of cultivated trees diminished in favour of cultivated land (croplands). Mangroves continued to dominate along the estuary and in the southern part of the study area. In 2003 (Fig. 3c). Villages continued to spread northwards, from Quelimane, and few, but less dense settlements were scattered in the northern margin of the estuary, near the mouth. The reduction in cultivated trees was replaced by cultivated croplands. Wetlands and cultivated land still dominated the northern and western part of the study area. In 2008 (Fig. 3d), Quelimane expanded, becoming denser but also new scattered patches of small villages appeared in the northern, north-eastern, eastern and south-eastern areas of the AOI. Areas under agricultural crops surpassed wetland extents. Cultivated trees were hardly noticeable in the remote sensing assessment, having been replaced by

Table 4. Major LU/LC categories in the Bons Sinais Estuary during the 1991 – 2018 period.

Categories	1991		1998		2003		2008		2013		2018		1991-2018	
	Area [km²]	[%]	Area [km²]	[%]	Area [km²]	[%]	Area [km²]	[%]	Area [km²]	[%]	Area [km²]	[%]	Area [km²]	[%]
Coastal Bare	27	1.8	22	1.5	20	1.3	28	1.8	35	2.3	56	3.7	29.0	107.4
Cultivated Crop	151	9.9	160	10.6	200	13.2	207	13.7	213	14.1	251	16.5	100.0	66.2
Cultivated Tree	356	23.5	382	25.2	397	26.2	355	23.4	336	22.1	296	19.5	60.1	-16.9
Developed	27	1.8	31	2.1	34	2.2	38	2.5	42	2.7	48	3.2	21.3	78.9
Intertidal Mudflat	115	7.6	118	7.8	121	8.0	122	8.1	125	8.3	129	8.5	13.6	11.8
Mangrove	260	17.1	259	17.1	253	16.7	246	16.2	238	15.7	228	15.0	-32.0	-22.3
Wetland	475	31.3	438	28.9	384	25.4	413	27.2	419	27.7	400	26.4	-75.5	-15.9
Water	106	7.0	106	7.0	107	7.0	107	7.1	109	7.2	109	7.2	3.7	3.5
Total	1,516	100.0	1,516	100.0	1,516	100.0	1,516	100.0	1,516	100.0	1,516	100.0		

cultivated land. In 2013 (Fig. 3e), Quelimane expanded and densified, including adjacent settlements and the appearance of new villages. There was a clear use of wetlands by villages for crop production in the northern and north-eastern parts of the AOI. Cultivated crops dominated the northern and southern parts of the study area and in the areas earlier occupied by cultivated trees, with a noticeable reduction in mangroves. In 2018 (Fig. 3f), Quelimane City continued to expand and was a prominent, developed area accompanied by further reduced natural wetland areas, particularly in the northern, eastern and south-eastern parts of the area. Cultivated land was the dominant LU, over cultivated tree areas and further reduced mangrove cover.

Changes in LU/LC

Over three decades (1991-2018) there was an overall increase in cultivated crop, development and intertidal mudflat categories, with a decline in wetlands, mangrove and cultivated tree areas (Fig. 4). Figure 5 presents the changes in the LU/LC main categories using sets of inter-annual comparisons. Except for the first interval (1991-1998), all were changes over five-year spans, compared with the overall change (1991-2018).

Cultivated trees showed the largest decrease of all classes, from 356 km² in 1991 (23.5 % of surface cover in the AOI) to 296 km² in 2018 (19.5 %) (Table 4). The average reduction rate was 2.2 km² per year, with a 16.9 % decline in coverage over the 27-year period. Notable declines occurred in 2003-2008 (-42 km²) and in 2013-2018 (-40 km²), corresponding to 10.6 % and 11.9 % reduction rates, respectively. Wetlands declined from 475 km² in 1991 (31.3 % of surface cover) to 400 km² in 2018 (26.4 %) (Table 4). The overall decrease of 75 km² corresponded to a reduction rate of 2.8 km² per year, and a 15.8 % decline in coverage over 27 years. Major

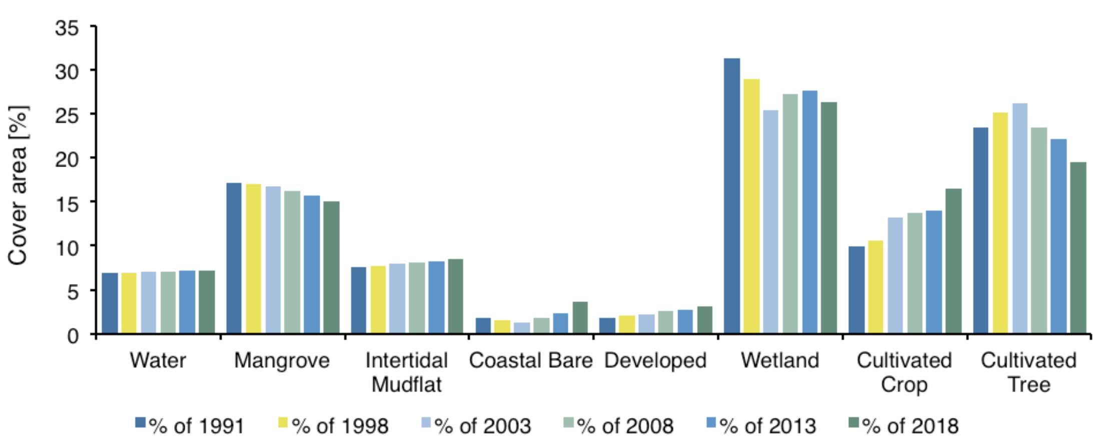


Figure 4. Temporal trends in the major LU/LC categories in the Bons Sinais Estuary between 1991 and 2018.

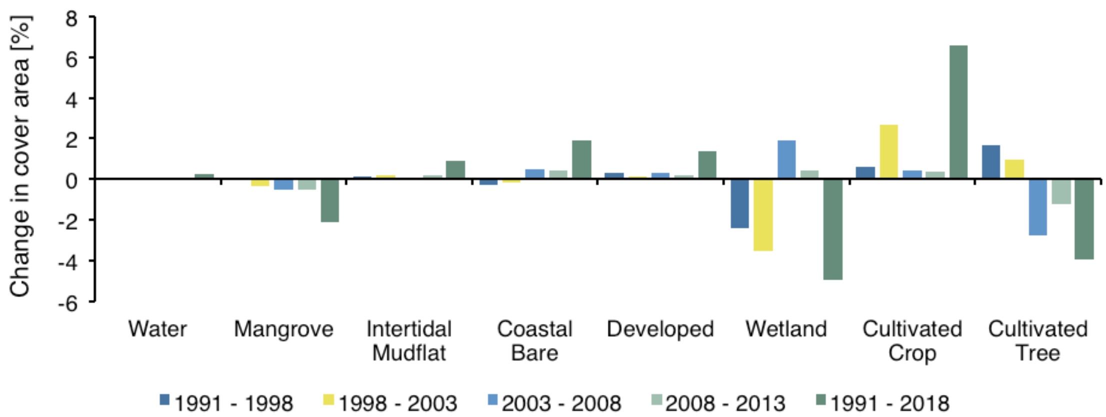


Figure 5. Changes in major categories of LU/LC in the Bons Sinais Estuary between 1991 and 2018.

reductions in wetlands were observed in early years, between 1991-1998 (-37 km²) and 1998-2008 (-54 km²), corresponding to 7.8 % and 12.3 % reductions, respectively. However, for the periods 1998-2008 and 2008-2013, small increases in wetlands of 7.6 % and 1.5% were noted. Mangroves declined from 260 km² in 1991 (17.1 % of surface cover) to 228 km² in 2018 (15 %). The average reduction rate was 1.2 km² per year or 12.3 % over the 27-year period.

Coastal bare land registered the highest increase of all classes, from 27 km² in 1991 (1.8 % of surface cover) to 56 km² in 2019 (3.7 %). The average increase rate was 1.1 km² per year, corresponding to an overall increase of 107.4 % over 27 years. Developed areas increased from 27 km² in 1991 (1.8 % of surface cover) to 48 km² in 2018 (3.2 %), an increase rate of 0.8 km² per year or 78.9 % over 27 years. Cultivated crops increased steadily from 151 km² in 1991 (9.9 % of surface cover) to 251 km² in 2018 (16.5 %). The rate of increase was 3.7 km² per year or 66.2 % over 27 years. The greatest increase (25 %) took place in 1998-2003. Intertidal mudflats increased from 115 km² in 1991 to 129 km² in 2018, an increase rate of 0.5 km² per year or 11.8 % over the study period.

Discussion

LU/LC changes

The study indicated a clear increasing trend in certain LU/LC categories around the Bons Sinais Estuary, such as cultivated crops (66 %), development (79 %) (including urban and rural human settlements), intertidal mudflats (1 2%) and coastal bare ground (107 %) from 1991 to 2018. Importantly, there was a concomitant effect on natural habitats, some being critical ecosystems, through an evident trend in reduced mangrove areas and wetlands. Although cultivated trees declined through time, they would have initially replaced natural coastal habitats. The results showed an anomalous increase in wetlands through the years 2008 to 2013. However, this was attributed to heavy rains observed in the years 2012-2013 (Fig. 6) and consequent flooding into low-lying habitats.

Most of the changes observed for the Bons Sinais Estuary may be attributed to human related activities. Notably, wetlands have been converted into agricultural farms and rural human settlements. Furthermore, mangroves, apart from being depleted for firewood, charcoal production and building material, have been converted into salt pans and aquaculture ponds (Unaite, 2017), or have been cleared and converted into human settlements (Fig. 7).

The increase in the area required for habitation and agricultural land, and the increased pressure on mangrove resources are attributed to the population growth observed in the Bons Sinais area during the last two decades (2000-2020). According to the National Statistics (INE, 2007; INE, 2017), the population of Quelimane city was 193,343 in 2007, increasing by 2.5 % per year over the next 10 years to 259,293 inhabitants in 2017.

The reduction in the cultivated trees was attributed to the disappearance of coconut palm plantations. Cultivated coconuts dominated the category 'cultivated trees' up until 1998, whereafter lethal yellowing disease resulted in mass mortalities of coconut palm trees in Zambézia province (Bila *et al.*, 2015). Lethal yellowing is a phytoplasma disease spread by the plant hopper *Haplaxius crudus* in global tropical environments and infects many palm species including commercially important coconut and date plantations. The incidence in East Africa is still puzzling as the

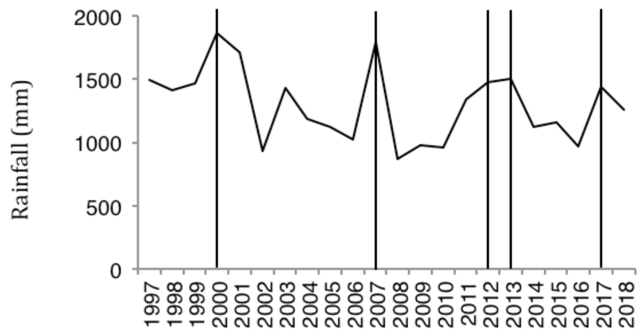


Figure 6. Total annual rainfall recorded at the Meteorological Station in Quelimane. The vertical lines indicate the periods of occurrence of heavy rain and flooding.

plant hopper is not native there (Brown *et al.*, 2006; Howard, 1992). The local population has initiated an extensive re-planting effort of alternate fruit trees such as mango, orange and banana. However, these efforts had not yet completely replaced the previous extent of coconut palm trees.

The small observed increase in intertidal mudflats, despite the movement of people and their settlements into these areas, was attributed to increased inundation – potentially because of sea-level rise. Several studies have shown evidence of sea level rise attributed to melting ice in polar regions and to thermal expansion of sea water due to global warming (Holgate *et al.*, 2013; PSMSL, 2020; Schneider, 1989). Mozambique is not an exception. Based on historical Monthly Mean Sea Level data (1961-2015), Maueua and Canhanga (2018) estimated that the sea level on the Mozambique coast has risen by 0.9-1.8 mm per year. Brown *et al.* (2011) used the global DIVA (Dynamic Interactive Vulnerability Assessment) model to estimate that African sea levels will rise from 0.17 m in 1995 to 1.26 m in 2100. Concerningly, Mozambique is predicted to be heavily impacted by such rises. The Bons Sinais Estuary and Quelimane city are both in a low-lying area (mostly <5 m amsl) and are likely to be heavily impacted by sea-level rise.

Possible impacts of the observed LU/LC changes

The reduction of coastal wetlands and mangroves are of major concern, given their important role in flood and storm mitigation (Blankespoor *et al.*, 2017; Leon *et al.*, 2018; Menéndez *et al.*, 2020; Sheng and Zou, 2017; Song *et al.*, 2014) and provision of goods and services on which the livelihoods of many local people entirely depend (Carugati *et al.*, 2018; Shapiro *et al.*, 2015). The destruction of these important habitats will exacerbate the effects of sea storms and flooding, predicted to increase as the climate changes. These factors are likely to worsen poverty levels, especially of

Figure 7. Aerial photo showing part of Quelimane City where mangroves and intertidal mudflats were cleared for human construction in 2014. Source: Silvermoz.com, obtained from Unaite (2017).

low-income groups. Mangroves are important nursery grounds for many fauna, including for those harvested by fishers (e.g. Ayub, 2010; Hatcher *et al.*, 1989; Loneragan, 1999) and their continued degradation is likely to result in reduced fisheries production (Malik *et al.*, 2017) with implications for livelihoods.

Proposed management strategies

Local livelihoods are strongly dependent on fisheries and fish products, which in turn depend on healthy natural ecosystems. Anthropogenic impacts on estuarine ecosystems are predicted to increase along with population growth, necessitating sustainable land use and urban planning strategies to ameliorate the potentially disastrous effects of lost critical habitats. Several studies (e.g. Basconi *et at.*, 2020; Martin, 2017; Matzek *et al.*, 2021; Lai *et al.*, 2015) have reiterated the importance of restoration and conservation strategies to reverse the downwards trends in estuarine goods and services. Mangroves in Mozambique are protected by law (Barbosa *et al.*, 2001) under the Forests and Land Legislation Act which envisages community participation in the protection of natural resources. The act was revised in 1998, stipulating that all mangroves are subject to partial protection, prohibiting development within 100 m inland from the upper tidal limit, and calling for communities to participate in the protection of natural resources (including mangroves) including conflict resolution. Even so, mangroves are still heavily exploited by coastal communities dependent on their wood for fuel and building, and law enforcement remains weak (Nicolau *et al.*, 2017). The need for restoration and conservation of estuarine ecosystems, including mangrove habitats, have never been greater. To be successful, strategies must involve local communities and promote alternative livelihoods, such as 'smart agriculture practices' that increase the yield and the efficiency of water and land use (Bach and Mauser, 2018; Kimaro, 2019). Effective law enforcement through capacitation and knowledge transfer to government departments are additional lines of defence for the protection of critical estuarine habitats.

Conclusion

In conclusion, the reduction in mangrove and other wetland habitats of the Bons Sinais Estuary over the past 27 years resulted mainly from accelerated urban development (often unplanned) and increased exploitation of estuarine resources by a growing population, as indicated by increases in areas under development and cultivated crops. The reduction in areas covered by cultivated trees stemmed from mass coconut palm mortalities caused by lethal yellowing disease in plantations. An increase in intertidal mudflats was tentatively attributed to climate-driven sea-level rise.

The study predicts a worsening of the anthropogenic impacts on the estuarine ecosystem with further growth of Quelimane city. To reverse the negative trend on estuary health, the recommendation is for management interventions that promote sustainable LU, and urban development plans that consider ecosystem conservation and active restoration. The present study contributes to the understanding of past and present changes in LU/LC in the Bons Sinais Estuary, including the socio-economic and ecological implications thereof.

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Small-scale fisheries of the Bons Sinais Estuary in Mozambique with emphasis on utilization of unselective gear

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Abstract

Small-scale fisheries in estuaries of the Western Indian Ocean form a key component of socio-ecological systems (SES) and food security, yet they remain poorly understood. This study describes the estuarine fisheries of the Bons Sinais Estuary in Mozambique based on fisheries and biological data collected by monitors between 2007 and 2016. Multiple gears were used, including beach seines (78 % of sampled fish), chicocota nets (12 %), gillnets (5 %), and hook and line (4 %). Landings were dominated by small pelagic fishes (Engraulidae 29 %, Pristigasteridae 16 %, Clupeidae 11 %) and prawns (Penaeidae 29 %). Monthly averaged fishing effort, landings and catch per unit effort of beach seine and chicocota nets peaked during the dry season, in April and July to October. The proportion of penaeid prawns in landings increased moderately at the end of the wet season, between January and March. The species and size composition selected by beach seine and chicocota nets overlapped, with chicocota nets also retaining marginally smaller individuals. Both gears exploited low trophic level species near the base of the food web, with low trophic values of 2.8 for chicocota and 3.0 for beach seine nets. The small-scale fishery in the Bons Sinais Estuary followed a 'balanced harvest' approach in which unselective fishing gear is used to exploit a mix of species and sizes proportional to natural productivity and relative abundance.

Keywords: chicocota net, balanced harvest, multi-gear fishery, multi-species fishery, estuarine fisheries, trophic dynamics

Introduction

Small-scale fisheries contribute 75-80 % of the total landings of marine species in Mozambique (Jacquet *et al.*, 2010; Doherty *et al.*, 2015) and are critically important to coastal communities for food security, nutrition, livelihoods and employment (Benkenstein, 2013; Blythe, 2014; Blythe *et al.*, 2014). Monitoring of small-scale fisheries is logistically complex because landing sites are scattered over large geographical areas and fishing is often informal, using multiple gear types to catch a mix of species. In the absence of accurate quantitative data (Cardinale *et al.*, 2014), a reconstruction of marine catches estimated that landings were 6.2 times greater than indicated by official statistics, and that the numbers of small-scale fishers had quadrupled over the last four decades (Jacquet *et al.*, 2010).

Most fisheries research in the Western Indian Ocean (WIO) region has focussed on coastal waters over the shelf, for example fisheries on Sofala Bank in Mozambique (Mualeque and Santos, 2011; Hoguane and Armando, 2015), Ungwana Bay in Kenya (Fulanda *et al.*, 2011; Munga *et al.*, 2013, 2014a) and Thukela Bank in eastern South Africa (Turpie and Lamberth, 2010). In

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contrast, estuarine fisheries have received scant attention (Kuguru *et al*., 2019; Costa *et al*., 2020; Dzoga *et al*., 2020; Manyenze *et al*., 2021). Estuarine fisheries are unique from several perspectives: they are influenced by a highly dynamic salinity gradient; affected by daily tides and seasonal freshwater runoff; rely on marine, brackish and freshwater species; include juveniles of many species in nursery habitats; and contribute to livelihoods that rely on fish-based farming systems (Blaber, 2013; Blythe *et al*., 2014; Hamerlynck *et al*., 2020; Mwamlavya *et al*., 2021). The flexibility of estuarine socio-ecological systems (SES) that include fisheries strengthens the capacity of communities to adapt to fluctuations in resource availability (Hamerlynck *et al*., 2010, 2020; Blythe, 2014; Blythe *et al*., 2014).

Fishing gear used in WIO estuaries are diverse and largely made locally from natural forest products or low-cost synthetic materials (Samoilys *et al*., 2011). Dugout canoes and larger planked canoes are typical fishing craft, but fishing areas in estuaries are often accessible by foot. Larger dhows and motorized boats are primarily used in bays or offshore fishing grounds. Fishing gear comprises of beach seine nets, gillnets, hook-and-line and traditional gear such as self-made traps, sticks and spears (Jiddawi and Öhman, 2002; Samoilys *et al*., 2011; Wilson, 2012; Munga *et al*., 2014b; Manyenze *et al*., 2021) and so-called 'chicocota' nets (described below; Costa *et al*., 2020), although utilization of these gear differ among estuaries. Fine-mesh mosquito netting (< 3 mm mesh size) originally distributed to combat malaria in developing countries are used as cod-ends in seine and chicocota nets or are deployed in other ways (Short *et al*., 2018; Jones and Unsworth, 2019). Beach seine and chicocota nets contribute the greatest percentage to landings of small-scale fishers in the Bons Sinais Estuary in central Mozambique (IIP, 2018).

Beach seines have been present in Mozambique since the 1940s and are a widespread and popular gear for catching small pelagic and demersal fishes and crustaceans for local markets (Wilson, 2012). They typically have a head rope of 100 – 225 m long, are deployed by a paddled canoe and hauled back to the beach by teams of up to 14 fishers. Mesh sizes range from 63 mm in the wings to 12 mm in the central panels and they are mounted with or without a 3 mm mosquito net in the cod-end. Mini-beach seines are about half the size of standard nets, are faster to deploy with a smaller crew and are less expensive. Beach seines are considered a destructive gear in several WIO countries, and their use is prohibited in some areas (McClanahan and Mangi, 2001). Compliance with a minimum mesh size of 38 mm (set at a central government level) has been as low as 10 % of inspected nets in Mozambique (Wilson, 2012), because of the perception of fishers that compliance would drastically reduce catch volumes (Darkey and Turatsinze, 2014). Local management measures such as voluntary closed seasons apply in some districts but are not consistently enforced.

Chicocota nets are made of old shrimp trawl nets with a cone-shaped cod-end of fine-mesh mosquito net (Short *et al*., 2018; Costa *et al*., 2020). The top of the net is kept afloat by buoys or recycled empty plastic bottles, flip flops or pieces of Styrofoam, and the bottom is weighted down with pieces of rock or other anchors. Chicocota nets are fixed gear set in the middle of estuary channels and anchored to stakes or vegetation on estuary banks. Net sizes vary depending on space available in estuary channels and the investment capacity of fishers but can be as large as shrimp trawl gear. Fisher dependency on chicocota nets is high in some areas - up to 100 % of gear deployed at sites in Beira, central Mozambique (Darkey and Turatsinze, 2014). As with beach seines, chicocota nets with small mesh sizes capture juveniles of many species, potentially reducing adult cohorts of target stocks. The use of chicocota nets is illegal in Mozambique, although the ban is not enforced and they are commonly used in estuaries (IIP, 2018).

The aims of this study were to: describe the estuarine fisheries of the Bons Sinais Estuary in Mozambique based on fisheries and biological data collected by monitors between 2007 and 2016; estimate the species and size selectivity of the most-used gears (beach seine and chicocota nets); and infer the harvest strategy adopted by estuarine fishers based on the trophic levels exploited, seasonal trends and location in the estuary.

Materials and methods

Study area

The Bons Sinais Estuary discharges into the Southwest Indian Ocean at 18°01' S; 36°58' E and extends ~ 30 km inland to the city of Quelimane where a seaport is located (Fig. 1). The geographical setting, history of settlement, ecosystems and socio-ecological importance of the estuary were summarized by Groeneveld *et al.* (2021). Hoguane *et al.* (2020; 2021) described estuarine circulation patterns, and Furaca *et al.* (2021) used remote sensing maps to infer changes in land use and land cover adjacent to the estuary over the past 27 years, including the growth of Quelimane city and its intrusion into the estuarine functional zone.

Data handling

Fisheries data were extracted from the IIP's PescART database (see IIP, 2006; Vølstad *et al.*, 2014) at two geographical scales; by district and landing site. Aggregated statistics on fishing effort, catch and catch per unit effort (CPUE) were available for Quelimane district (northern bank of the estuary) for the 2007 – 2015 period. Fisheries and biological data of key fish and crustacean species were extracted for four landing sites between the estuary mouth and upper reaches for the 2008 – 2016 period. The four sites were Marrubune (at the estuary mouth where the channel has broadened); Gazelas (lower estuary); Icidua (upper estuary in an urban area of Quelimane); and Chuabo Dembe (upper estuary where the channel has narrowed). The Icidua and Chuabo Dembe landing sites were located within the Quelimane district, but Marrubune and Gazelas were outside the district, but also on the northern bank of the estuary.

Routine sampling of landing sites by IIP monitors took place every month during the fishing season (April-December), on fixed sampling days according to the IIP sampling plan (two days per month per landing site) covering all gear types used. Chicocota nets were first recognized by IIP and sampled as a unique fishing gear after 2011. Fishing effort was determined by counting the number of gears in use during each outing and expressed as the number of active gears (i.e., number of beach seine hauls or chicocota nets sampled per outing). Landings were sorted and identified to species level based on Fischer *et al.* (1990) and weighed by species and gear type. Random samples of 13 commercially important species were selected and the total length (TL ± 1 cm) of specimens measured, with maximum sample size of 100 individuals/species. The selected species have been prioritized for data collection by IIP based on their perceived importance to small-scale fisheries in the region and account for more than 70 % of recorded landings (Daniel Oliveira pers. com., IIP – Zambezia).

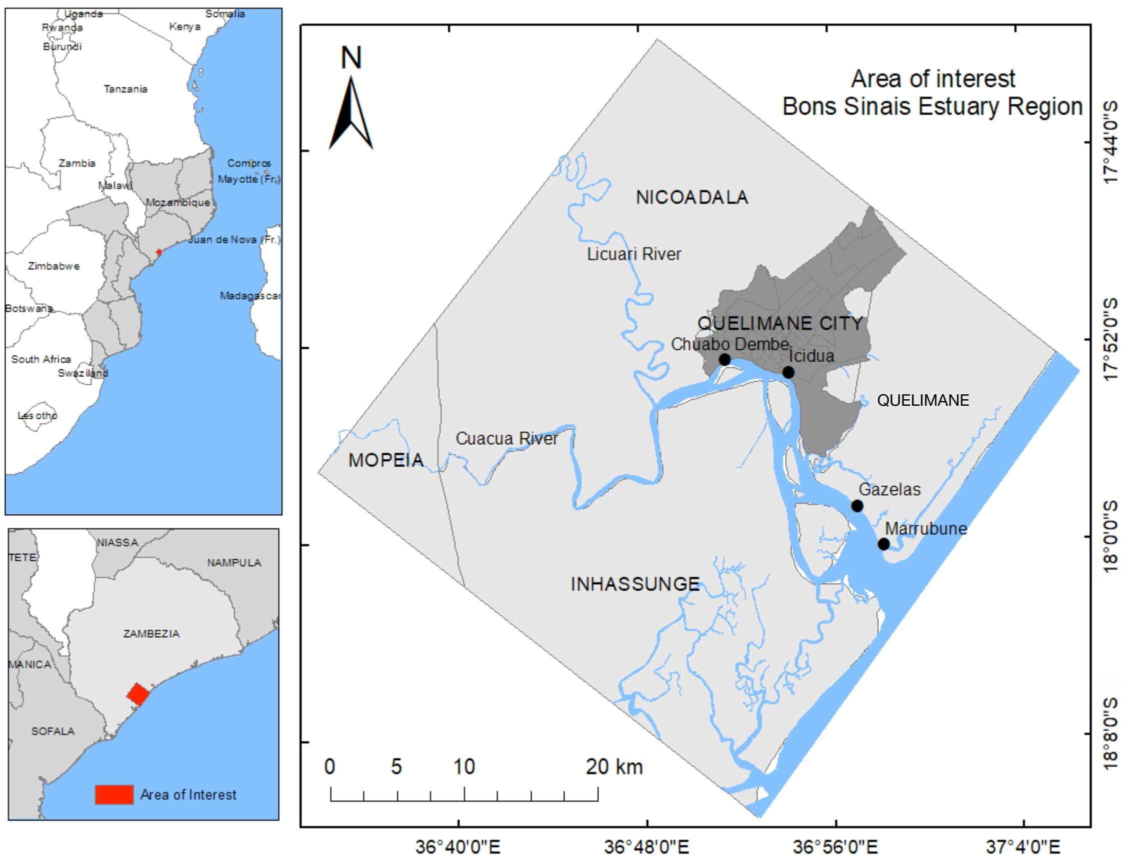

Figure 1. The Bons Sinais Estuary along the central Mozambique coast showing the locations of the four landing sites of Quelimane District sampled.

Table 1. Sampling effort measured as the numbers of fish and prawns measured per landing site and gear type.

	Marrubune	Gazelas	Icidua	Chuabo Dembe	All
Beach Seines	*1697*	2323	1790	1744	*7554*
Chicocota		75	217	847	1139
Gillnet (mono)	81	96	95	230	502
Handline	56	183	20	98	357
Seine Net	29	21	22		72
Longline	1	26		13	40
All	1864	2724	2144	2932	9664

Data were cleaned by removing anomalous records with clearly incorrect or mismatched species names or length measurements. Penaeid prawns were grouped as a single category to eliminate species identification errors of small juveniles. Records with length measurements smaller than 2 cm and larger than 20 cm were considered outliers and removed for three small pelagic fish species (*Hilsa kelee*, *Thryssa vitrirostris*, *Pellona ditchela*) and penaeid prawns (*Penaeus* spp.) prior to length-based analysis.

Data were stratified by landing site as described above, gear type and season. Gear types considered were beach seines, chicocota nets, monofilament gillnets, handline, longline and other seine nets (Table 1). No data were available for traps or other traditional gears such as spears or sharpened sticks – although they are used in the estuary (pers. obs.). Two seasons were considered: a dry season between April and October with average monthly precipitation of < 75 mm; and a wet season between November and March with average monthly precipitation of 75 – 250 mm. Freshwater inflow from rainfall in distant catchment areas was not considered because the historical connection with the Zambezi River (which fed into the upper Bons Sinais Estuary via smaller channels) had been lost after construction of large dams in the upper Zambezi catchment area (Beilfuss and dos Santos, 2001).

Relative abundance was calculated by dividing the number of individuals per species by the sum of individuals of all species combined per landing site. The length composition of small pelagic fishes and penaeid prawns caught by beach seine and chicocota nets at each landing site were compared using 1 cm length categories, and mean lengths were compared using one-way ANOVA followed by post hoc Tukey HSD tests.

Selectivity analysis

Chicocota nets caught a broader range of sizes than beach seines and were assumed to sample the fish assemblage unselectively. The selection curve of beach seines was therefore calculated relative to the size distribution recovered from chicocota nets. Similar fishing power, fishing effort and sampling effort between gears was not assumed (Millar and Fryer, 1999), and therefore the two profiles were compared in relative units, where $f_l=n_l/\sum n$ is the fraction of individuals of length l (total length, cm) in one gear. The ratio f_{BS}/f_{CC} (where BS refers to beach seine and CC to chicocota nets) was calculated for each length class and re-scaled to a maximum ratio of 0.999. Beta-regression of fractional data requires input values in the range]0,1[. The logistic retention curve was calculated using a logit link and the maximum likelihood method with the package betareg in R (Zeileis *et al.*, 2010) and the data and script are shown in Appendix 1. In addition to the l_{50}, the l_{25} and l_{75} points on the curve were determined to define the selection range of beach seine nets.

The trophic level of the catch in a given gear was calculated as $TLc = \sum n_{il}.w_{il}.TL_i / \sum n_{il}.w_{il}$, where w_{il} is the weight of species i at length l, and TL_i is the trophic level of that species (Trites, 2001). The trophic level of the gear g itself is defined as $TLg = 1 + TLc$. Local or regional data on weight-length relationships (Kaka *et al.*, 2019; Costa *et al.*, 2020) and diet composition (Blaber, 1979; Mavuti *et al.*, 2004; de Abreu *et al.*, 2017; Mwijage *et al.*, 2017) of the four main species in the catch were utilized. An average TL_i was utilized per species because no clear ontogenic shifts in diet were specified in the studies above, or these were obscured by spatial differences. *Thryssa vitrirostris*, however, showed a trend towards high piscivory in the size ranges observed, but this ontogenic change was not

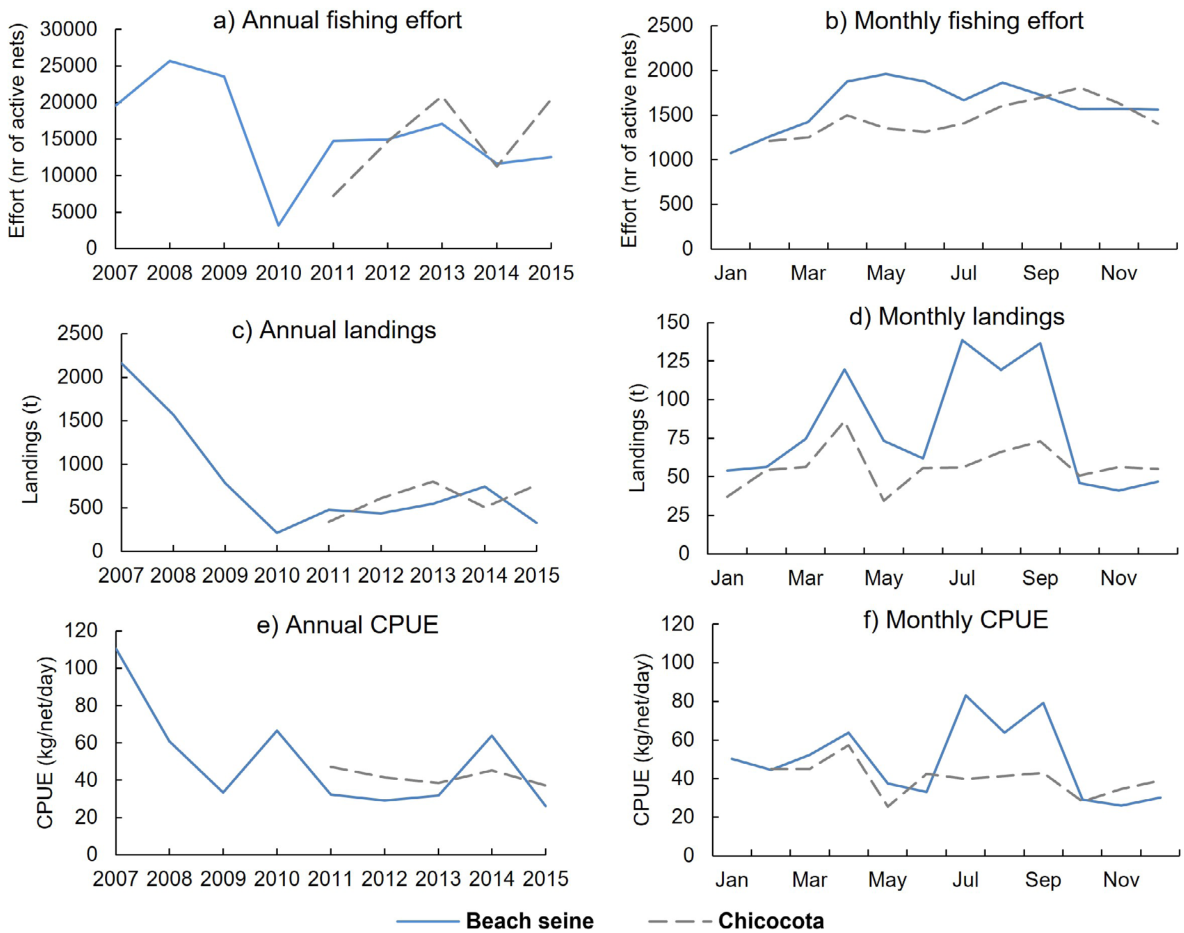

Figure 2. Trends in fishing effort (numbers of active nets observed), landings (tonnes) and CPUE (kg/net/day) for beach seine (line) and chicocota nets (dashed line) in the Quelimane District (central Mozambique) based on the PescART database compiled by the National Institute of Fisheries Research of Mozambique (IIP). Monthly values are averages for the period between 2007 and 2015.

accounted for. The trophic levels for *H. kelee* and *Penaeus* spp. were set at 2.5, for *P. ditchela* at 3.0 and for *T. vitrirostris* at 3.5. (Appendix 1).

Results

Effort, landings and CPUE

Data on fishing effort (number of active nets) and landings (tons) made by beach seines in Quelimane district were available on the IIP's PescArt database for the 2007 – 2015 period, but data for chicocota nets were restricted to 2011 – 2015 (Fig. 2a). Beach seine effort peaked at >25 000 active nets per year in 2007 to 2009 but decreased to ~ 15 000 per year between 2011 and 2015. Chicocota effort increased steeply from 7 000 active sets in 2011 to 20 000 in 2013, when it exceeded beach seine effort.

The average monthly fishing effort for both gear types was lowest between January and March (Fig. 2b). Beach seine effort increased to 1 500 to 2 000 hauls per month between April and December. Chicocota effort first peaked at 1 500 sets in April and then increased steadily to a maximum number of 1 800 sets in October.

Beach seine landings for Quelimane district declined from >2 000 t in 2007 to <750 t per year between 2011 and 2015 (Fig. 2c). Chicocota landings fluctuated between 350 t and 800 t per year between 2011 and 2015. The average monthly landings of beach seines peaked at >120 t in April and July to September but declined to ~ 50 t per month between October and February (Fig. 2d). Chicocota landings had a similar seasonal pattern peaking at 90 t in April and 75 t in September, with less pronounced monthly variability than beach seines.

Nominal CPUE of beach seines declined from 111 kg/net.day^{-1} in 2007 to ~ 40 kg/net.day^{-1} between 2009 and 2015, with smaller peaks at ~ 60 kg/net.day^{-1} in 2010 and 2014 (Fig. 2e). Chicocota CPUE remained stable at 37 – 47 kg/net.day^{-1} between 2011 and 2015.

Table 2. Percentage by family and species of sampled catches in the Bons Sinais Estuary between 2008 and 2016 (n = 9563).

Family	Species	Percentage	
Penaeidae		29	
	Penaeus indicus		21
	Penaeus monodon		6
	Metapenaeus monoceros		1
	Mierspenaeopsis sculptilis		1
Engraulidae		29	
	Thryssa vitrirostris		25
	Thryssa setrirostris		4
Pristigasteridae		16	
	Pellona ditchela		16
Clupeidae		11	
	Hilsa kelee		6
	Sardinella albella		5
Haemulidae		7	
	Pomadasys kaakan		5
	Pomadasys maculatus		1
Sillaginidae		5	
	Sillago sihama		5
Sciaenidae		2	
	Otolithes ruber		2

The average monthly CPUE of both gear types was highest in April, and again between July and September (Fig. 2f).

Overall, the Quelimane district data showed a seasonal trend of lower fishing effort, landings and CPUE during the wet season which was more pronounced for beach seine than chicocota nets. Trends in fishing effort and landings suggested a partial conversion of the fishery, from using beach seines only to using both gears, after 2011. There was no significant difference between the CPUE (mean ± SD) of beach seine (51 ± 28 kg/net.day^{-1}) and chicocota nets (41 ± 4 kg/net.day^{-1}) (Student's t-test; $p = 0.45$).

Biological characteristics and species composition of landings

Sampling effort (numbers of fish and prawns sampled) was distributed evenly across four landing sites (19 to 29 % of total effort per site) but by gear, the bulk of sampling effort was expended on beach seine (79 %) and chicocota nets (12 %) (Table 1). Table 2 shows the landings composition (all gear combined) comprised of seven families and 13 species. By family, samples were dominated by Penaeidae (29 %), Engraulidae (29 %), Pristigasteridae (16 %) and Clupeidae (11 %), and by species *Thryssa vitrirostris* (25 %), *Penaeus indicus* (21 %) and *Pellona ditchela* (16 %) were most frequently sampled. *Penaeus monodon* (6 %), *Hilsa kelee* (6 %), *Sillago sihama* (5 %) and *Sardinella albella* (5 %) contributed similar quantities to samples, and species with larger body sizes, such as *Otolithes ruber* and *Pomadasys* spp. combined made up approximately 8 % of landings.

Beach seine, chicocota and gill nets were unselective and caught similar species groups, but relative proportions differed (Fig. 3). Penaeid prawns made up 22 % of beach seine and chicocota landings respectively, but only 8 % of gill net samples. Handlines were more selective, with samples comprising of *Pomadasys* spp., *O. ruber* and *S. sihama*. Data from handlines, seine nets and longlines were not analysed further because

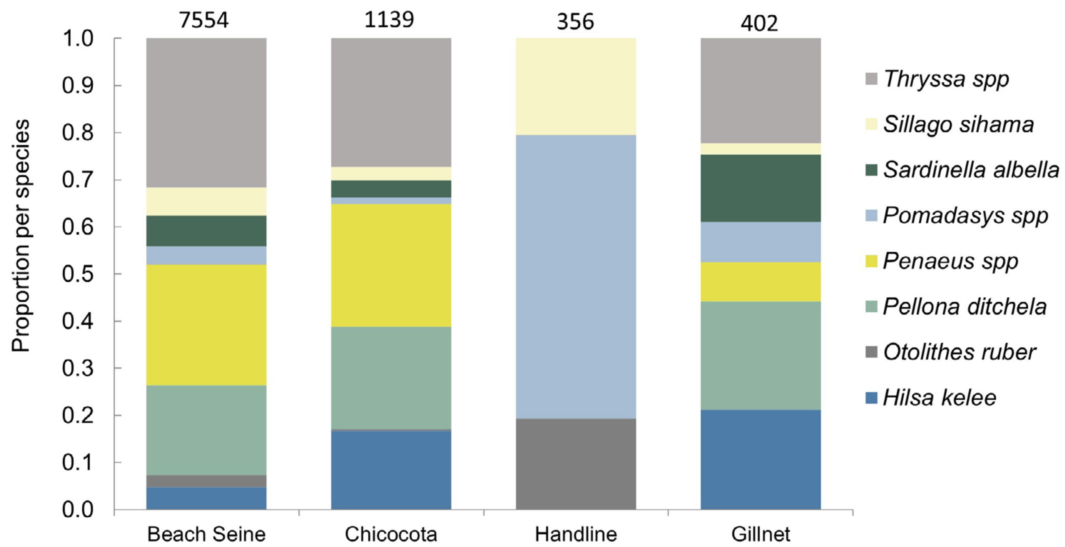

Figure 3. Proportion per species in samples collected with four gear types at all landing sites combined in the Bons Sinais Estuary (2008 - 2016). Sample size per gear type shown on top of bars. Data from longlines and seine nets not shown because of small sample sizes.

of small sample sizes. The seasonal composition of landings (beach seine and chicocota combined) was similar with a moderate increase in the importance of penaeid prawns (+5 %) and concomitant decrease of *P. ditchela* (-4 %) during the wet season in November to March (Fig. 4).

Penaeid prawns and *Thryssa* spp. dominated samples at all four landing sites, irrespective of gear sampled (beach seine or chicocota nets) (Fig. 5). No chicocota samples were available for Marrubune at the estuary mouth, where the channel widens making operation of the net impractical. Beach seine landings at the four sites were proportionally similar, except for *Hilsa kelee* which was absent at Marrubune but increased in importance at upstream sites, to 6 % at Icidua and 8 % at Chuabo Dembe. Like beach seines, the importance of *H. kelee* in chicocota nets increased at Icidua (19 %) and Chuabo Dembe (14 %). Chicocota samples at Gazelas were dominated by penaeids (67 %) based on a small sample (n = 75).

The size composition of *H. kelee*, *T. vitrirostris*, *P. ditchela* and penaeid prawns indicated that chicocota nets retained smaller individuals than beach seine nets (Fig. 6) except for prawns with a TL > 15 cm. The 15 cm plus-group comprised of large prawn samples for both beach seine (n = 124) and chicocota nets (n = 60) and the trend is therefore not considered to be artefactual of small sample sizes.

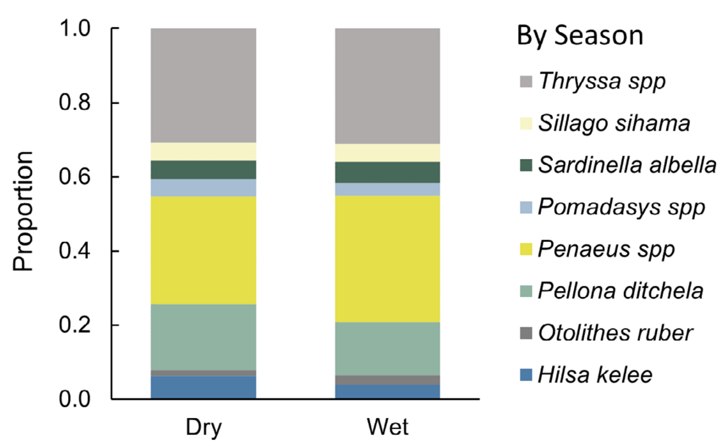

Figure 4. Catch composition during dry (April to October) and wet (November to March) seasons for beach seine and chicocota nets combined.

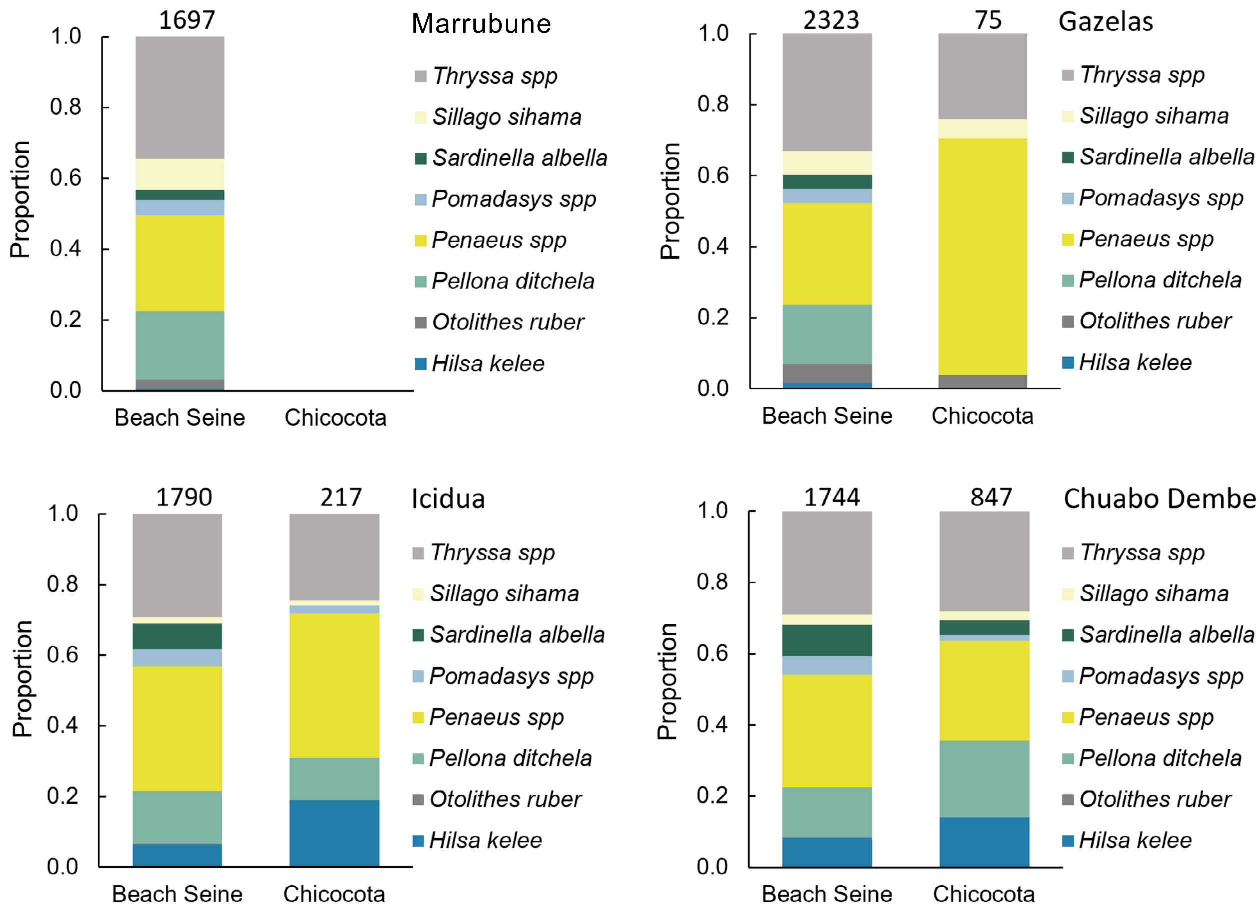

Figure 5. Proportional catch composition of beach seine and chicocota nets at four landing sites in the Bons Sinais Estuary. Chicocota nets were not sampled in Marrubune. The number of fish sampled per gear and site is indicated on the bars.

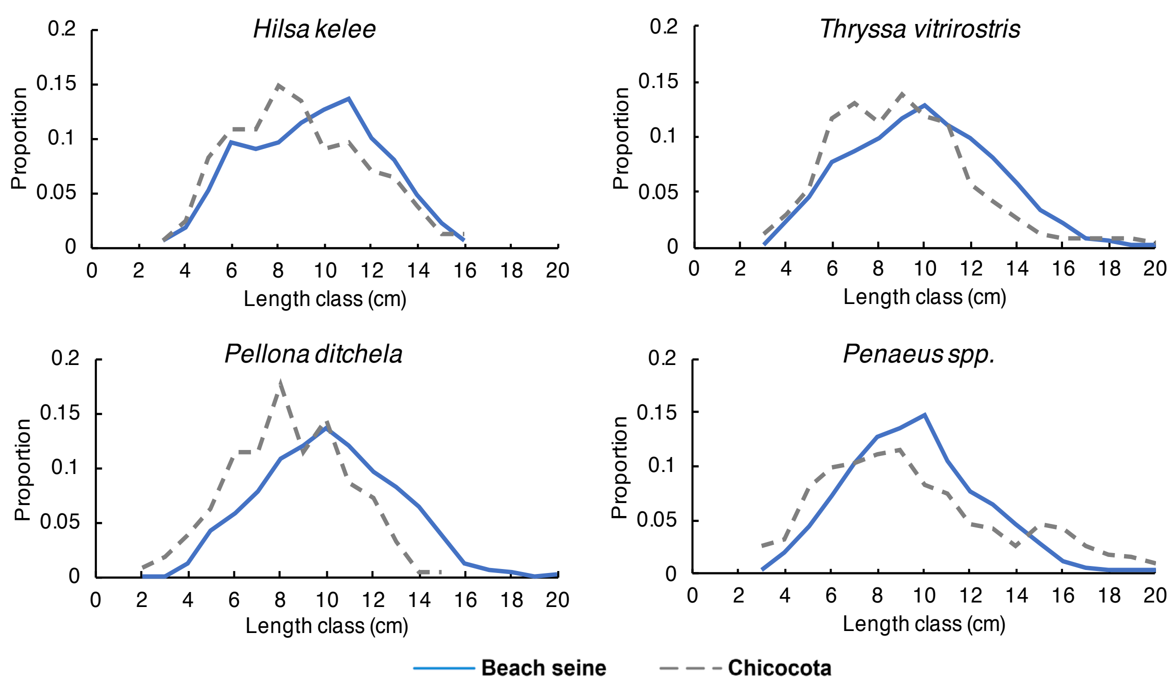

Figure 6. Length composition (TL, cm) of *Hilsa kelee*, *Thryssa vitrirostris*, *Pellona ditchela* and *Penaeus* spp. caught with beach seine and chicocota nets respectively.

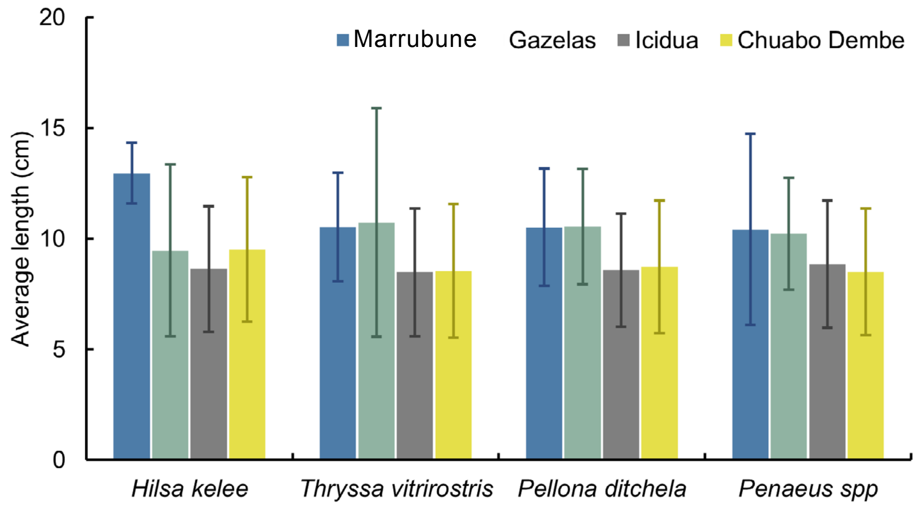

Figure 7. Average total length (TL, cm) by landing site across landing sites for *Hilsa kelee, Thryssa vitrirostris, Pellona ditchela* and *Penaeus* spp. for beach seine and chicocota nets combined.

Single-factor ANOVA indicated that the mean TL of individual species differed among landing sites (Fig. 7; $p < 0.05$ for each of the four species individually). *H. kelee* caught at Marrubune reached a mean TL of 13 cm, significantly larger than at any of the other sites, where means were < 10 cm (Tukey HSD test; $p < 0.05$ in all cases). The mean size of *Thryssa vitrirostris* caught at Marrubune and Gazelas (both sites near the estuary mouth) did not differ from each other significantly but was significantly larger than those caught at the upstream sites at Icidua and Chuabo Dembe (Tukey HSD test; $p < 0.05$ for pairwise comparisons of Marrubune with Icidua and Chuabo Dembe, and of Gazelas with Icidua and Chuabo Dembe). The mean TL of *P. ditchela* and *Penaeus* spp., respectively, differed significantly among sites (ANOVA, $p < 0.05$ in both cases) but pairwise differences between sites were not significant. Even so, declines in mean size between the estuary mouth and upper stations were apparent from Fig. 7.

The overall size profiles of landings by beach seine and chicocota nets (including all catches of the four main species at all four landing sites) overlapped. Length frequencies of chicocota landings peaked in the 7-9 cm TL class, probably reflecting availability in the estuary, whereas beach seine landings peaked in the 9-11 cm TL class, suggesting a more selective retention pattern. The retention curve was calculated for the 2-15 cm size range, resulting in an overall L_{50} of 9 cm for the four species combined for beach-seine nets, and a selection range ($L_{25} - L_{75}$) of about 6-12 cm (Fig. 8). Beach seine and chicocota nets exploited the

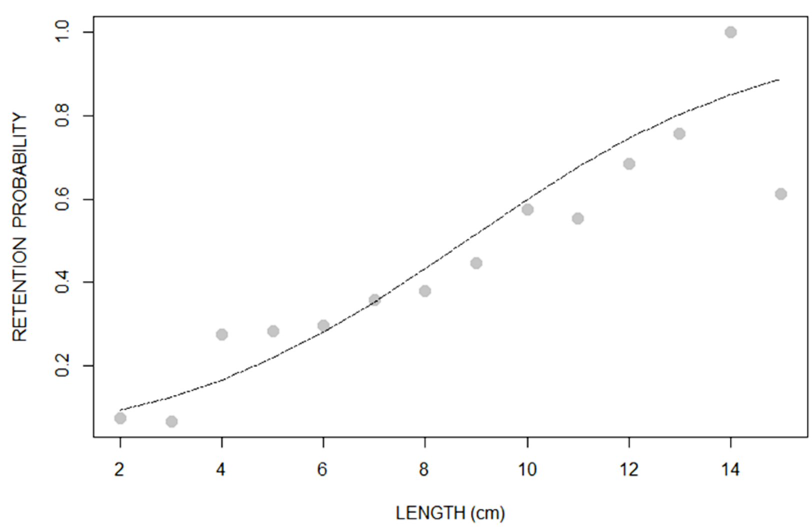

Figure 8. Selectivity curve of the beach seines for the four species combined, with length measured as total length.

estuarine ecosystem at marginally different trophic levels, near the base of the food web. The trophic level of catches made by beach seines (TL*c*) was estimated at 3.0 (TLg=4.0) and that of chicocota nets at 2.8 (TLg=3.8). Chicocota nets caught proportionally more detritivores and planktivores, like *H. kelee* and *Penaeus* spp., and beach seines caught more zooplanktivorous and piscivorous fish like *P. ditchela* and *T. vitrirostris.*

Discussion

Small-scale fisheries are critically important as a source of food security, nutrition, livelihoods and employment in coastal Mozambique, yet quantitative information on fishing effort and catch composition remains sparse (Jacquet *et al.*, 2010; Benkenstein, 2013). This is especially so for estuarine fisheries, which are widespread, informal and difficult to monitor. Therefore, this study on the small-scale fisheries of the Bons Sinais Estuary is considered representative of similar data-poor estuarine fisheries along the central Mozambique coast, and potentially the wider WIO region.

The data obtained from the IIP onshore data collection programme in Quelimane focuses on selected (mainly marine) species perceived to have commercial importance (IIP, 2018). Several key estuarine (e.g., sea catfish *Arius africanus*) and freshwater species (e.g., Mozambique tilapia *Oreochromis mossambicus;* sharptooth catfish *Clarias gariepinus*) were absent from the data, because they were not sampled by monitors at landing sites, even when present in landings (pers. com. IIP; Costa *et al.*, 2020). No data were available for landings by traditional gear types (spears, homemade traps) or hand-collected species, such as clams (pers. obs.) and not all landing sites along the length of the estuary were sampled. Quantitative data on fishing effort and landings by species were therefore incomplete (see Jacquet *et al.*, 2010) and the assumptions of random sampling could not always be met. The limitations of the data affected the scope of the study, and the findings must be seen within the context of data-poor systems.

Fine-mesh mosquito netting is commonly used in the centre panels or cod-ends of beach seine and chicocota nets in the Bons Sinais fisheries and explained the predominantly small size of organisms caught (Wilson, 2012; Short *et al.*, 2018; Costa *et al.*, 2020). Both gears were unselective, with chicocota nets catching a broader size range, assumed to reflect both the availability of fish and retention properties of the gear (Millar and Freyer, 1999). Beach seines were relatively more selective, with a selection range of 6 – 12 cm (L_{50} = 9 cm TL). Beach seines are active gears dragged horizontally through the water whereas chicocota nets are stationary and spanned across channels. The mode of operation and different habitats targeted by the two gear types plausibly explained the difference in selectivity, even when both were fitted with mosquito net cod-ends (Karama *et al.*, 2017). Beach seines are commonly used in different littoral environments in the WIO (Wilson, 2012) making their properties a convenient benchmark for evaluating the selectivity of alternative gears, by using a relative selectivity measure as demonstrated here.

Landings comprised mainly of small pelagic fishes and penaeid prawns, confirming the findings of previous studies on small-scale fisheries in coastal Mozambique (Gjosaeter and Sousa, 1983; Mualeque and Santos, 2011; Wilson, 2012; Cardinale *et al.*, 2014; Hoguane and Armando, 2015). Similar taxa were caught by beach seine and chicocota nets at the estuary mouth and upper estuary (~ 30 km upstream) consistent with a well-mixed marine dominated system (Hoguane *et al.*, 2020; 2021). The marine dominance stems from reduced river runoff following the construction of the Kariba- (1955) and Cahora Bassa dams (1974) in the upper Zambezi River (Beilfuss and dos Santos, 2001). The absence of clear seasonality in the species composition of landings (Fig. 4) presumably reflects reduced seasonal freshwater flooding – hence the estuary remains predominantly marine throughout the year, with salinity levels too high for some freshwater species to tolerate (Whitfield, 2015). Alternatively, the absence of freshwater species in the data was an artefact of the selective sampling strategy, which focussed on marine species.

The average size of small pelagic fishes and penaeid prawns declined between the estuary mouth and upper estuary, supporting the hypothesis that the upper estuary is a nursery area. Surveys by the research vessel (RV) Dr Fridtjof Nansen have shown large aggregations of clupeid and engraulid fishes offshore over the Sofala Bank from where they approach the coast seasonally and enter estuaries to spawn (Gislason and Sousa, 1985; Mualeque and Santos, 2011; Krakstad *et al.*, 2017); for example *T. vitrirostris* (Blaber, 1979) and *H. kelee* (Gjøsaeter and Sousa, 1983). Penaeid prawns spawn on the Sofala Bank near river mouths (Malauene *et al.*, 2021) and larvae drift into bays or estuaries as nursery areas before migrating back to the offshore banks as larger juveniles (Brito and Pena, 2007).

The observed size increase of small pelagic fishes and penaeid prawns between the upper estuary and mouth therefore fits well with a seaward migration of larger juveniles from upstream nursery areas to adult habitats in nearshore waters (Blaber, 2013).

Species captured by beach seine and chicocota nets were predominantly detritivores (prawns) or planktivorous (small pelagics). Low trophic values (TLc) of 2.8 for chicocota nets and 3.0 for beach seines confirmed that they exploited low trophic level species near the base of the food web. Chicocota nets caught proportionally more detritivores and planktivores (*Penaeus* spp and *H. kelee*) whereas beach seines caught more zooplanktivores and piscivores (*P. ditchela* and *T. vitrirostris*), explaining the difference in trophic values. Larger species were also caught and utilized, but in general, beach seine and chicocota nets exploited the most productive components of the ecosystem, often with generation times < 1.5 years, high resilience, and low vulnerability (www.fishbase.org). Handlines and longlines caught larger species (*Pomadasys* spp. and *Otolithes ruber*) at higher trophic levels, often at the mouth of the estuary where larger marine fish enter.

Based on the size and species distribution of landings, the estuarine fishery followed a 'balanced harvest' approach in which removals were proportional to natural productivity and relative abundance (Garcia *et al.*, 2012; Kolding *et al*., 2016). Beach seine and chicocota nets harvested mainly low trophic level species with high productivity and variable recruitment affected by environmental conditions (Somarakis *et al*., 2019), whereas hand lines harvested smaller numbers of larger species (see Fig. 3). The mosquito net cod-ends of beach seine and chicocota nets also caught juveniles of many species in the estuary, confirming a similar finding by Costa *et al*. (2020). Modelling studies and limited empirical evidence from small-scale fisheries in Africa (Kolding and van Zwieten, 2011) have suggested that balanced harvest strategies can reduce the impact of fishing on ecosystem structure and increase aggregate yield under certain conditions (reviewed by Zhou *et al*., 2019) although the concept has also been criticised (Froese *et al*., 2016). Under the present conditions, fishing effort in the Bons Sinais Estuary is adaptive, largely regulated by natural production, and serves as a 'social security system' (Kolding and van Zwieten, 2011). Enforcing a selective fishing strategy is presently impractical and will undermine the livelihood opportunities and socio-economic role of small-scale fishers. Overall, present analyses suggest the presence of a *de facto* balanced harvest pattern in the Bons Sinais Estuary, based on landings of unselective gear.

Small fish caught by beach seine and chicocota nets are sun-dried (pers. obs.) and either consumed by fisher households or sold locally, as a staple food for nearby communities. Penaeid prawns and larger fish species have a higher market value and are used to generate a cash income. Blythe *et al*. (2014) showed that local fishing communities used different strategies to adapt to livelihood stressors arising from socioeconomic (e.g., disease, theft, food insecurity) and ecological sources (e.g., severe storms or drought). Specialized fishers were organized in fishers' groups with access to fishing assets, and intensified fishing effort when catch rates declined. Poorer fishers diversified into non-fishing work, such as small business, mangrove harvesting, and casual labour. Adaptation to livelihood stressors was heterogenous and influenced by multiple factors. Hamerlynck *et al*. (2020) described fish-based farming systems as a flexible livelihood portfolio along the edges of Africa's water bodies, able to maintain the drivers of ecosystem productivity, and Mwamlavya *et al*. (2021) demonstrated that coastal and upstream communities in the Tana Estuary in Kenya relied on different livelihood strategies (fishing, part-time fishing and farming) and that the strategies were site-specific and seasonal. In the Bons Sinais Estuary, lower fishing effort (and landings) during the wet season potentially reflected more difficult access to fishing areas and a switch to other occupations than fishing. Small-scale fisheries in the Bons Sinais Estuary should therefore be seen as key components of a complex socio-ecological system that supports traditional and more contemporary livelihood strategies, rather than in isolation as 'fisheries to be managed'.

Fisheries in the Bons Sinais Estuary are monitored and managed by a regional fisheries authority located in Quelimane (Zambézia branch of IIP, National Institute of Fisheries Research) reporting to a fisheries ministry at national level (REPMAR, 2003). A minimum mesh size of 38 mm set at national level applies to all beach seine nets in Mozambique. At local level some beach seine fisheries have applied local management measures such as voluntary closed seasons. In a co-management mechanism, Community Fisheries Councils (CCPs) composed of fishers and community leaders mediate compliance with both national fisheries legislation and local measures. Compliance with management measures, including mesh size and closed seasons, is 'extremely low' (Wilson, 2012) and not consistently enforced by CCPs – to a large extent because CCP members do not all agree with the measures. Chicocota nets are illegal gear in Mozambique, but the ban is not enforced. The chicocota fishery is now as important as the beach seine fishery in the estuary, and its landings have been officially monitored by the IIP since 2011.

In conclusion, the role of official fisheries management structures appears to have been marginalized by small-scale fishers in favour of subsisting on a broad range of harvestable resources – including all available sizes and species of fish and invertebrates. The prevalence of beach seine and chicocota nets therefore also reflect a social, rather than an ecological challenge alone, requiring policies that favour diversification of livelihoods in combination with enforcement of regulations (Kolding and van Zwieten, 2011). The *de facto* balanced harvest strategy observed in the small-scale fisheries of the Bons Sinais Estuary relies mainly on low trophic level species and forms an integral part of local socio-ecological systems.

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Appendix

Calculation of trophic levels of the two gears

LENGTH	HK BS	TV BS	PD BS	PEN BS	LENGTH	HK CC	TV CC	PD CC	PEN CC
2	0	0	2	0	2	0	0	2	0
3	2	3	2	9	3	1	3	4	10
4	6	49	17	45	4	4	8	8	12
5	16	93	52	103	5	13	14	13	30
6	30	157	73	166	6	17	30	24	37
7	28	179	98	236	7	17	34	24	39
8	30	202	134	295	8	23	29	37	42
9	35	239	148	315	9	21	36	24	43
10	39	262	169	340	10	14	31	30	31
11	42	228	148	245	11	15	29	18	28
12	31	201	119	176	12	11	15	15	17
13	25	167	103	148	13	10	11	7	16
14	15	117	79	108	14	6	7	1	10
15	7	68	49	63	15	2	3	1	17
16	2	45	15	26	16	2	2	0	16
17	0	16	9	12	17	0	2	0	10
18	0	12	6	9	18	0	2	0	7
19	0	3	2	8	19	0	2	0	6
20	0	5	3	6	20	0	1	0	4
Length-weight relationship a and b					*Length-weight relationship a and b*				
a	-4,821	-5,285	-4,921	0,00000112	a	-4,821	-5,285	-4,921	0,00000112
b	3,014	3,067	2,977	3,32	b	3,014	3,067	2,977	3,32
				biomass B=w x n, (g)					biomass B=w x n, (g)

LENGTH	HK BS	TV BS	PD BS	PEN BS	LENGTH	HK CC	TV CC	PD CC	PEN CC
2	0	0	0	0	2	0	0	0	0
3	0	0	0	1	3	0	0	1	1
4	3	17	8	11	4	2	3	4	3
5	16	66	46	50	5	13	10	11	15
6	54	194	110	149	6	30	37	36	33
7	80	354	234	353	7	48	67	57	58
8	127	602	477	688	8	98	86	132	98
9	212	1023	748	1085	9	127	154	121	148
10	325	1549	1169	1662	10	117	183	207	152
11	466	1806	1359	1644	11	166	230	165	188
12	447	2079	1416	1576	12	159	155	179	152
13	459	2208	1556	1729	13	184	145	106	187
14	344	1941	1488	1614	14	138	116	19	149
15	198	1394	1133	1184	15	56	62	23	319
16	69	1125	420	605	16	69	50	0	372
17	0	482	302	342	17	0	60	0	285
18	0	430	239	310	18	0	72	0	241
19	0	127	93	329	19	0	85	0	247
20	0	248	163	293	20	0	50	0	195
SUM (g)	2799	15645	10962	13624	SUM (g)	1207	1565	1062	2844
f	0,07	0,36	0,25	0,32	f	0,18	0,23	0,16	0,43
	HK BS	TV BS	PD BS	PEN BS		HK CC	TV CC	PD CC	PEN CC
Trophic level	2,5	3,5	3,0	2,5	Trophic level	2,5	3,5	3,0	2,5

Socio-ecological change in the Ruvu Estuary in Tanzania, inferred from land-use and land-cover (LULC) analysis and estuarine fisheries

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Abstract

Ecosystem goods and services derived from estuaries have sustained coastal livelihoods in the Western Indian Ocean (WIO) region throughout recorded history. Estuaries provide fertile and seasonally irrigated space for planting crops, mangrove products for construction and fuel, and fish as a protein source. Human population growth and an escalating demand for natural resources threaten estuarine critical habitats and their functioning, exacerbated by the effects of climate change. Decadal and seasonal land-use and land-cover (LULC) changes in the Ruvu Estuary in Tanzania were investigated through analysis of Landsat 5/8 and Sentinel-2 satellite images. The estuary is river-dominated and truncated near the coast during high river flow, with tidal influence extending approximately 12 km upstream during low river flow. LULC change detection targeting nine classes (water, developed, barren, forest, grasslands, cultivated, mangroves, wetlands and mudflats) showed that estuary-associated wetlands and mangroves had declined significantly over the past two decades (1995-2016) making way for developed land (growth of Bagamoyo Town), cultivated land (agricultural expansion with increasing population) and grasslands (coastal habitat changes). Seasonal LULC changes were conversion of wetlands to cultivated land after the wet season, and transformation of fallow wetlands to grasslands. The estuarine fishery relied on a small number of mainly freshwater and marine migrant species, compared to a highly diverse mix of mainly marine species in the nearby coastal fishery. The sparsity of quantitative fisheries data, spectral confusion when modelling land-cover change, and absence of household survey data to assess livelihood activities remain major information gaps. Generalized recommendations for improving socio-ecological change studies in WIO estuarine systems are provided.

Keywords: Estuarize-WIO, Ruvu Estuary, land-use/ land-cover analysis, small-scale fisheries

Introduction

Estuaries are amongst the most productive ecosystems in the world (Costanza *et al*., 1997) and have supported a range of rural to urban coastal communities throughout recorded history (Gari *et al*., 2015). In the Western Indian Ocean (WIO), over-exploitation by fast-growing human populations now threatens the ecological functioning of estuaries and the essential benefits derived from them (Hamerlynck *et al*., 2010; Barbier *et al*., 2011; papers in Diop *et al*., 2016). For example, reduced freshwater inflow because of damming or freshwater extraction in upstream catchment areas threaten critical estuarine habitats (e.g., mangroves; Friess *et al*., 2019) which in turn affects estuarine nursery function (Gillanders and Kingsford, 2002) and therefore recruitment of juvenile fish and prawns to fished populations. Local over-exploitation of goods and services in estuaries, such as harvesting of mangroves, fishing and encroachment worsen the effects of freshwater scarcity, hastening the degradation of critical habitats (Diop *et al*., 2016).

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Socio-ecological systems (SES) assessments of estuaries can be complex with a high data demand – yet the interactions between the human and natural systems cannot be ignored if estuaries are to continue to provide natural resources for livelihoods (Milner-Gulland, 2012). As a case study in a data-poor environment, a SES assessment of the Ruvu Estuary in Tanzania was undertaken. The area has been settled for millennia by a succession of civilizations (Mosha and Plevoets, 2020) and is a highly productive part of the coast that supplies local and distant markets with fish and agricultural products (Mkama *et al.*, 2010). SES at the Ruvu Estuary, as elsewhere in the WIO, are dominated by fish-based farming (FBF) systems (Hamerlynck *et al.*, 2020; Francisco *et al.*, 2021; Furaca *et al.*, 2021; Mwamlavya *et al.*, 2021), in which households derive some 30 to 50 % of their income from fisheries and engage in a wide livelihood portfolio, including farming, use of mangrove products, livestock herding, bee keeping and operating small business enterprises (Hamerlynck *et al.*, 2020).

Seasonal and decadal changes in land-use and land-cover (LULC) are good indicators of socio-ecological interactions, because they provide information on hydrological and ecological conditions that govern natural capital use (e.g., Ngondo *et al.*, 2021; Taylor and Suthers, 2021). The aims of this study were to: assess seasonal and decadal change in LULC based on an analysis of satellite images downloaded from NASA's Landsat 5/8 and ESA's Sentinel-2 programmes; and infer the importance of estuarine fisheries in FBF systems at the Ruvu Estuary based on observational and published information. A preliminary socio-ecological change assessment of the Ruvu Estuary over the past two decades and seasonally is provided, with recommendations for future research in data-poor estuarine systems of the tropical WIO.

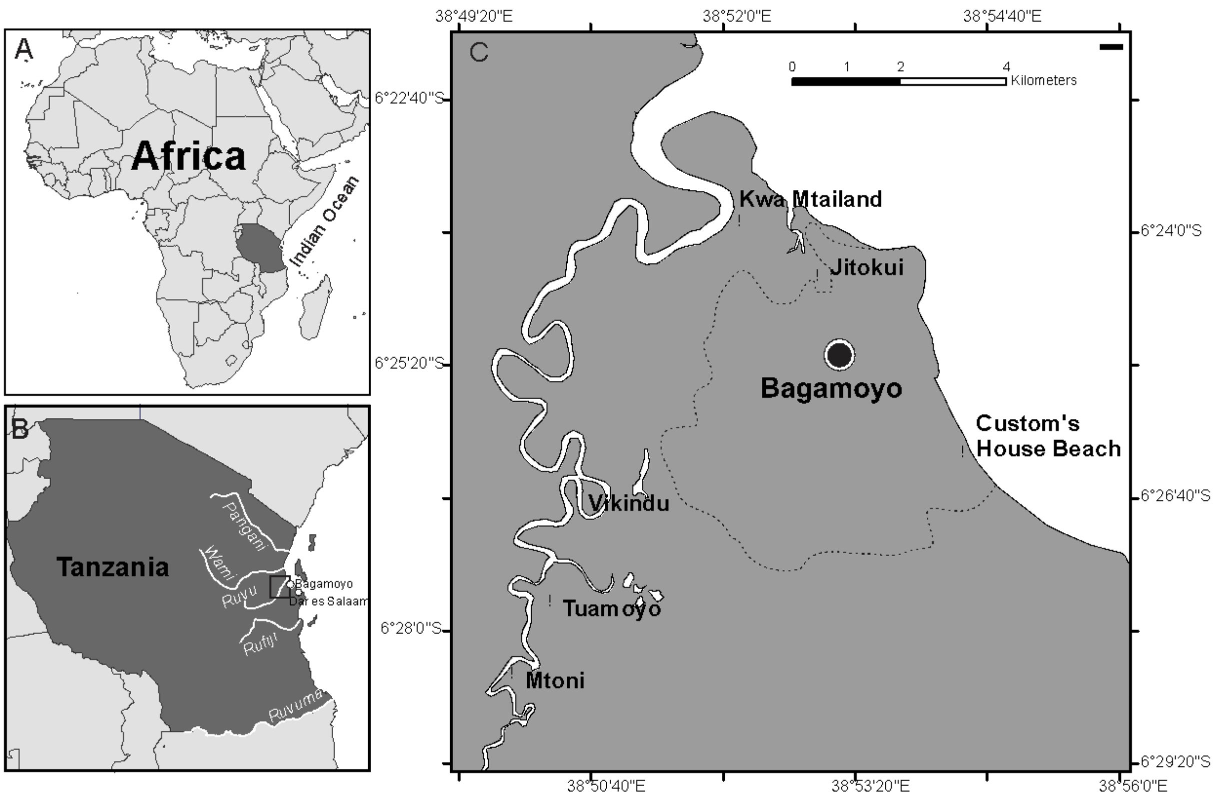

Figure 1. Location of the Ruvu Estuary study area in (A) the Western Indian Ocean and (B) relative to other major river systems and estuaries in Tanzania. In (C), fish landing sites mentioned in the text are shown.

Materials and methods

Study area

The Ruvu Estuary receives freshwater inflow from the Wami Ruvu Basin (WRB) and discharges into the WIO on the mainland side of the Zanzibar Channel, some 5 km north of the coastal town of Bagamoyo (Fig. 1). Rainfall (900 to 1300 mm p/a; GLOWS-FIU, 2014a) occurs in March-May and October-December, and direct freshwater flow into the estuary reaches a monthly maximum of 150 m^3/s at Morogoro Bridge, some 45 km upstream of the estuary mouth (GLOWS-FIU, 2014b; 2014c). Upstream of the estuary, the Ruvu River flows through major agricultural, industrial, and urban areas where freshwater is diverted for irrigation, industrial, aquaculture and domestic use (Ngondo *et al.*, 2021). With rapid coastal expansion, particularly at Dar es Salaam where there is a critical water supply/demand deficit, the WRB is of high strategic importance and has been the subject of numerous impact assessments, predictive models, policy documents and published research (e.g., GLOWS-FIU, 2014a-d; van Eeden *et al.*, 2016; Mdee, 2017; Alphayo and Sharma, 2018; Miraji *et al.*, 2019; Ngondo *et al.*, 2021). The WRB is managed by the Wami Ruvu Basin Water Office (WRBWO) of the Ministry of Water and Irrigation in Tanzania.

The area of interest (AOI) for this study was taken as the final 10 to 12 km of the Ruvu Estuary, to include the lower river, the river-estuary transition, estuary (based on upstream salinity penetration; GLOWS-FIU, 2014d), and an area of the offshore bay highly influenced by river/estuarine water during tidal exchange and floods. Eight zones within the AOI were identified according to proximity to the estuary: estuary-supporting habitats (zones 1-2); river adjacent and river influencing landscape (zone 3); urbanized land including Bagamoyo Town (zones 4 and 5); and land influenced by this urbanization to the south. Bagamoyo Town lies outside the estuarine functional zone but was included in the LULC assessment because its urban growth (built-up area and population size) was considered a major driver of socio-ecological change and anthropogenic impact on estuarine resources (summarized in Groeneveld *et al.*, 2021). Zones 6-7 are less urban-influenced and span some of the land between the Ruvu and the Wami estuaries to the north, and zone 8 includes the offshore plume area off the Ruvu mouth. The study area comprised 458 km^2, of which 358 km^2 was land.

Catchment basin

Information on rainfall, river discharge, water level, geology, hydrogeology, administration, infrastructure and population demographics in the catchment area of the Ruvu River were obtained from an online 'Digital Atlas of Water Resources' (http://glows/fiu.edu). Geographically, the information originates from outside the estuarine study area, but is crucial for quantifying the variability of long term and seasonal freshwater discharge into the estuary. Spatial patterns of water supply, demand and use at the WRB hydrological station at Morogoro Road Bridge showed peak discharge in April to May with a secondary peak in November to January (GLOWS-FIU, 2014b; http://glows/fiu.edu). Multiple studies have shown a longer term decrease in flows to the coast (GLOWS-FIU, 2013; 2014a-d) and the possible impacts across ecosystems and people (Semesi *et al.*, 1998; Kiwango *et al.*, 2015; Shaghude, 2016; Duvail *et al.*, 2017; Miraji *et al.*, 2019; Macharia *et al.*, 2020). The lack of environmental flow management and enforcement in the WRB influences freshwater flow into the Ruvu Estuary, as a vital component of estuarine ecology (e.g., nutrient processing, sediment trapping, maintenance of critical habitats; Kiwango *et al.*, 2015) all of which are necessary to sustain livelihoods of coastal communities.

Estuary zones based on salinity profiles

Salinity is a critical variable in estuaries, which governs the distribution of biota through mixing of freshwater inflow and tidal influence at various spatio-temporal scales. Salinity gradients influence the distribution of estuarine habitats, availability of freshwater, land-cover (LC), land-use (LU) and fished resources. Defining salinity zones that correlate with biological tolerance and distribution of species throughout the estuary (some being directly targeted for subsistence by nearby communities) was the initial step. A broad-category system was adopted with oligohaline (0.5-5.0 psu), mesohaline (5.0-18.0 psu), and polyhaline (18.0 to 30.0 psu) conditions (see Montagna *et al.*, 2013). Salinity measurements obtained from GLOWS-FIU (2014c) for June 2013 and TAFIRI (November 2017 and May 2018) datasets ranged between 0 psu (freshwater) and 32 psu (marine) in the estuary with well-mixed conditions throughout and across data collection times. Four salinity-based estuarine zones could be defined as: mouth/bay (20-30 psu), lower reaches (10-19 psu), middle reaches (5-9 psu) and upper reaches (0.5-4 psu).

Simple interpolation on a 2D GIS platform was used to estimate the range of salinity profiles in the upper and lower water column during low and high flow periods. The estuary was highly river-dominated during the high flow seasons, and relatively truncated with mixed salinity only at the coast (Fig. 2). The estuary extended offshore during high flow seasons (Fig. 2) creating an offshore mixing area with high fluvial settlement, unique marine habitats (mud banks), processes (e.g., Scharler *et al.*, 2016) and communities (e.g.,

Figure 2. Salinity zones based on average salinity conditions (surface and bottom) across the Ruvu Estuary during high flow (Apr-May) and low flow (Jul-Sep) seasons. Salinity measurements were obtained from GLOWS-FIU (2014c) for 2013 and from field measurements taken by TAFIRI in 2017/2018.

MacKay *et al.*, 2016). During low flow conditions, the salinity-based zones extended some 10 km upstream from the estuary mouth creating a significantly larger estuarine area. A larger land-based estuary will equate to greater ecological function during these times, as estuary function depends on the salinity gradient (Whitfield *et al.*, 2012). Water temperature in June 2013 (low flow) ranged between 25.1 and 26.7 °C (GLOWS-FIU, 2014b), and during November 2017 and May 2018 (high flows) it ranged between 26.5 and 34.5 °C, with slightly higher temperatures on the outgoing tide. The difference was attributed to marine and fluvial influences during low and high flow periods, respectively and confirmed a strongly seasonal estuary.

Remote sensing of land use and land cover (LULC)

Satellite images of the Ruvu Estuary, including from NASA's Landsat 5/8 missions and the ESA's Sentinel-2 programme, were sourced from the USGS

Table 1. Satellite imagery sources, acquisition dates and % cloud cover in the study area.

Decadal Study				Seasonal Study			
Date	**Satellite**	**Cloud Cover %**	**Season**	**Date**	**Satellite**	**Cloud Cover %**	**Season**
1995-06-25	Landsat 5	0.01	Wet	2016-12-27	Sentinel-2	5.16	Dry (L)
2006-06-07	Landsat 5	1.44	Wet	2017-07-15	Sentinel-2	1.38	Wet (H)
2011-07-07	Landsat 5	0.06	Wet	2018-01-01	Sentinel-2	4.82	Dry (L)
2016-07-04	Landsat 8	0.39	Wet	2018-06-10	Sentinel-2	1.12	Wet (H)

EarthExplorer platform (https://earthexplorer.usgs.gov/). Landsat imagery was assessed (30 m resolution) to compare decadal changes from four images (<20 % cloud cover), spanning a 21-year period (1995, 2006, 2011, 2016) during wet southeast (SE) monsoon conditions (June, July) (Table 1). For the seasonal comparison, higher resolution (10 m) Sentinel-2 satellite images representative of year/month combinations (<20 % cloud cover) for the wet SE monsoon (July 2017 and June 2018) and the drier northeast (NE) monsoon seasons (December 2016 and January 2018) were used. Radiometric calibration converted digital numbers (DN) to surface reflectance values to compare different images, the Apparent Reflectance function was used for further adjustments and red, green, blue and near-infrared spectral bands were input into modelling and assessment. A land-cover classification scheme was adapted from the USGS and NOAA Coastal Change Analysis Program (C-CAP) to fit this study. The scheme was collapsed into nine LULC classes: Water, Developed, Barren, Cultivated, Forests, Mangroves, Mudflats, Wetlands and Grasslands for the decadal and seasonal assessments (Table 2), with an expanded selection of 22 classes to detect change at a higher, seasonal resolution (see adjunct to Fig. 6). Supervised classification (decadal change) and object-based imagery analysis approaches (seasonal change) were adopted using a support vector machine classifier on a GIS (ArcMap™ GIS) and the RGB and NIR bands (Red, Green, Blue and Near-Infrared). Classification of land-cover categories used the maximum likelihood classification algorithm.

Table 2. Classes used for land use/land cover change detection.

LC	Type	Description
1	Water	Coastal open water, estuarine water and plumes, rivers
2	Developed	Medium to low density housing, industry, urban mixed use
3	Barren	Coastal bare sand, exposed soil
4	Forest	Coastal, disturbed, mixed woodlands, tree cover and thickets
5	Grasslands	Natural or disturbed grasslands, herbaceous cover
6	Cultivated	Subsistence or agricultural harvested and fallow croplands, mariculture and salt pans
7	Mangroves	Dense or spare mangrove crown cover, including freshwater swamp forests
8	Wetlands	Vegetated or non-vegetated water bodies, swamps and marshes
9	Mudflats	Estuarine intertidal mudflats

Model training and validation relied on a combination of ground truth methods. Of the 365 ground truth points used, 165 were geolocated photographs and 200 were points from Google Earth™ or ESRI base map imagery (source DigitalGlobe, 0.5 m resolution). Overall classification accuracy was determined as the percentage of correctly classified samples of an error matrix (Producer and User Accuracies), and the Kappa statistic provided a statistically valid assessment of the classification quality. A Kappa value > 50 % was considered satisfactory for modelling land use change (Pontius, 2000).

To illustrate the relationship between LULC categories and the percentage coverage in each AOI zone during the selected seasons, a distance-based redundancy analysis (dbRDA) was conducted. The ordination was constrained by the best-fit explanatory variables from a multivariate multiple regression analysis (DISTLM) with vector overlays for predictors explaining significant proportions of the variation.

Fish and shellfish resources

The species of fish and shellfish caught with bottom-set nets and landed at four sites in the channels of the Ruvu Estuary were identified during field sampling undertaken by TAFIRI between November 2017 and March 2018. A standard field guide (Anam and Mostarda, 2012) was used to aid species identification. The Kwa Mtailand and Jitokui sites were in the lower estuary (mostly poly- and mesohaline conditions) and the Vikundu and Mtoni sites were in the upper estuary and river-estuary transition (meso- and oligohaline) (Fig. 1; Fig 2). Fish species present at the Customs House fish market in Bagamoyo Town were photographed using a cell-phone camera and identified from the photographs. Because market samples were mixed, the origin of identified species (estuary channels, bay, offshore marine) could not be discerned. Additional information on species present in the estuary was obtained from reports by Yona (2017) and GLOWS-FIU (2014c).

The observed species were categorized into estuarine-use functional groups after Elliott *et al.* (2007). Five groups were defined: freshwater stragglers comprising of freshwater species found in low numbers in estuaries and whose distribution is limited to the low salinity upper reaches of estuaries; freshwater migrants found regularly and in moderate numbers in estuaries, extending beyond the oligohaline sections; estuarine species, including estuarine residents and migrants; marine migrants including species that spawn at sea and enter estuaries in large numbers, mainly as juveniles, and including marine-estuarine dependent and opportunist species; and marine stragglers that spawn at sea and only enter estuaries in low numbers in areas where salinities are high (Harrison and Whitfield, 2008). Adult habitats, feeding ecology and mean trophic level (± SE) based on food items were obtained from Fishbase (https://www.fishbase.se).

Results and Discussion

Decadal land cover change based on Landsat 5/8 imagery (1995 – 2016)

Landsat imagery showed a significant decline in estuary-associated wetlands from 42 % of the AOI in 1995 to 17 % in 2016 (Fig. 3). The similarity of water area coverage across all temporal comparisons (20 – 23 % of the

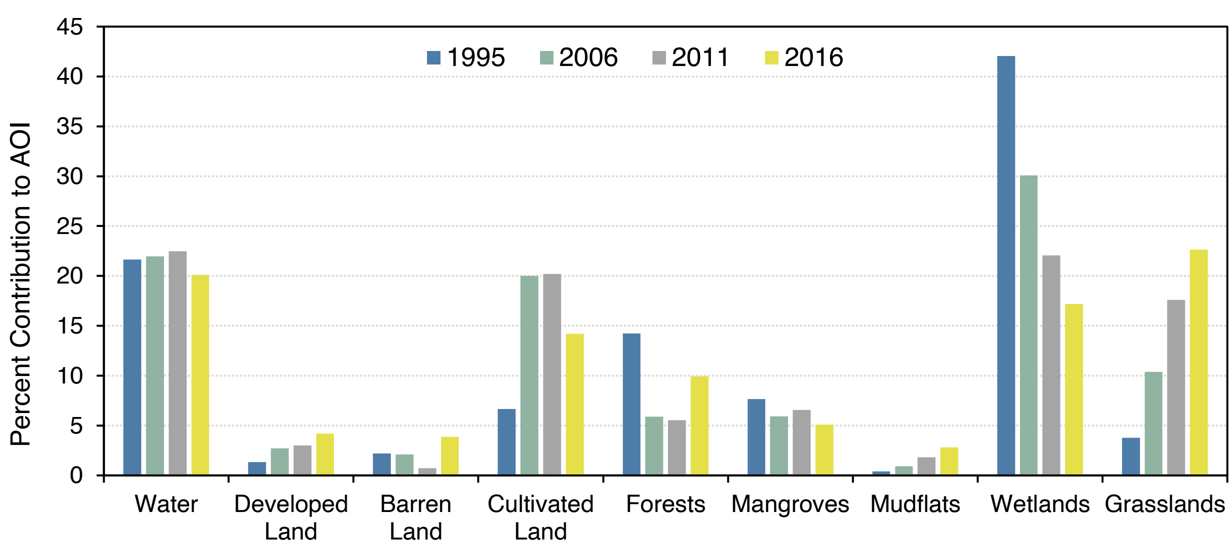

Figure 3. Historical changes (interdecadal) in LC around the Ruvu Estuary. Percent cover across nine categories related to estuary, estuary supporting habitats and developed land.

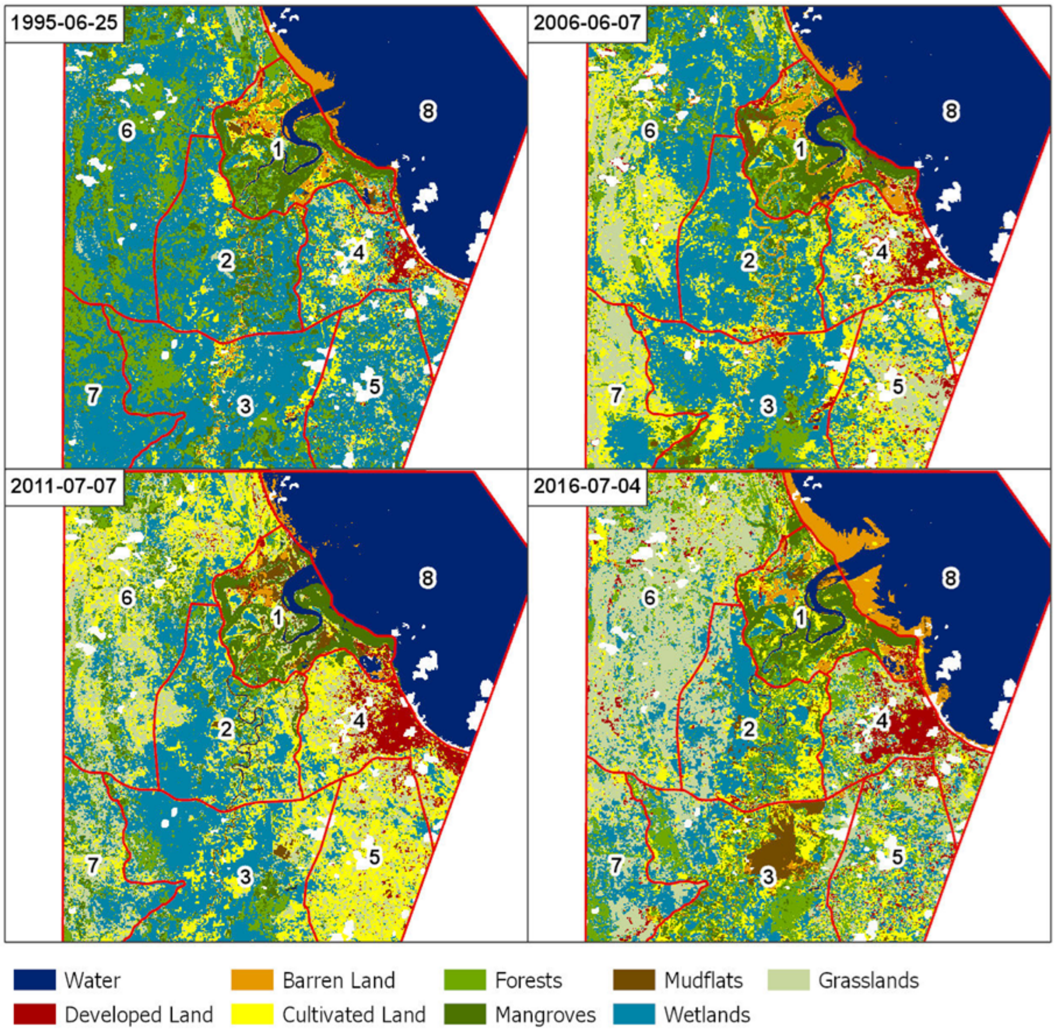

Figure 4. Historical changes in land use/land cover around the Ruvu Estuary based on an analysis of Landsat 5/8 satellite images for the period 1995-2016.

AOI) confirmed that studied periods had similar hydrological characteristics (Fig. 3). Mangrove-cover declined from 8 % to 5 % of the AOI in contrast to other LC classes. Linear increases were found in grasslands (4 % to 23 %), developed land (1 % to 4 %) and mudflats (<1 % to 3 %). Cultivated land (7 % to 14 %) and forested land (14 % to 10 %) showed variable levels of change between 1995 and 2016, but with overall expansion of these classes. Overall, the significant changes since 1995 have been the increase in developed land (reflecting the growth of Bagamoyo Town), cultivation (reflecting agricultural expansion with increasing population) and grasslands (coastal habitat changes with changing land use activities) at the expense of wetlands. Noting however, that 2016 was the driest rainfall year of the change assessment and possibly over-emphasized grassland expansion.

The model assessment performance was moderately high (0.74, Kappa of 0.70). Model performance (Producer's Accuracy) showed 97 % reliability of developed land prediction and good predictability of grasslands (84 %), forests (80 %) and cultivated land (70 %). Only 28 % of mudflat areas were modelled correctly and with similar spectral signatures to pans for salt production and mariculture. The User's Accuracy showed a good reliability of the classes selected, with water, barren land, grasslands, wetlands and forests classified correctly >80 % of the time. Least accurate were mudflats (45 % agreement), being confused with cultivated land.

The remotely sensed LULC trends reflected long term change around the Ruvu Estuary and were related directly or indirectly to the expansion of Bagamoyo Town over the past 21 years (Fig. 4). The spectral confusion amongst some classes (interchangeable cultivated- and wetland spectral signatures next to the estuary and mangroves and forests having similar

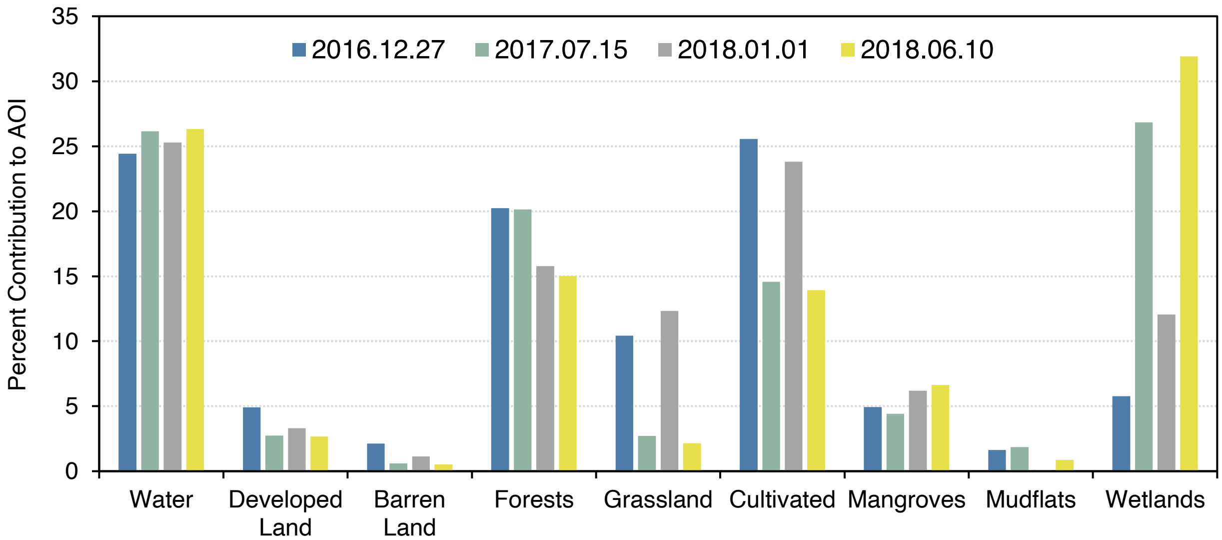

Figure 5. Seasonal LC change around the Ruvu Estuary from four alternating dry/wet timestamps (2016-2018). Percent cover across nine categories related to estuary, or estuary supporting, habitats.

spectral signatures) were mostly well resolved through rule-based selection procedures (such as proximity to the estuary). Cultivation is the main land use activity in this coastal area of the WRB, with main crops of maize, rice, cassava, cashew, sisal, vegetables, and citrus. Cultivation directly affects water quality flowing into the estuary with high turbidity throughout the year, and high nutrients (NO_3, NH_4, SRP and TP) emanating from fertilizer-contaminated return flows (Ngoye and Machiwa, 2004).

Seasonal land cover change based on Sentinel-2 imagery (2016-2018)

Seasonality was evident in LULC change detection analyses. Water (24 – 26 %), cultivated land (14 – 26 %), forests (15 – 20 %) and wetlands (6 – 32 %) dominated land cover in the AOI during the four time periods (Fig. 5). Seasonal changes in wetlands, cultivated land and grasslands were most pronounced. Wetlands decreased notably during the dry season, as cultivation increased, and grassland areas spread through drier terrains. Water area coverage increased marginally during the wet season, but forests, mangroves and mudflats showed no seasonal trends from these data. In 2016, developed land covered a similar proportion of the AOI (4.9 %) to the Landsat analysis (4.2 %), providing some confidence in the compatibility of decadal and seasonal models.

The analysis supported a broad seasonal pattern, with wetlands being converted to cultivated areas during the dry season, and uncultivated wetlands becoming grasslands (Fig. 6). However, the estimates of seasonal change in land cover were affected by mosaics of pixels that could alternatively be attributed to wetlands, grasslands or mudflats, caused by classification confusion from similar spectral signatures. Cultivated land next to the estuary differed substantially from cultivated land further away (e.g., between developed land parcels), attributed to differing agricultural activities. The model did not satisfactorily distinguish between mudflats, non-vegetated wetlands, grasslands and cultivated land during the dry season. Distinguishing between cultivated land, wetlands, forests and mangroves was also challenging during the wet season. Despite land-cover classification inconsistencies in the model, there was a moderately high assessment performance of 76 % (Kappa of 0.72). Producer's Accuracy showed good performance of classification of water (89 % accurate), forests (86 %), cultivated land (83 %) and developed land (82 %). Worst performing classifications were of grasslands (40 %) and mudflats (44 % modelled correctly). Class reliability (User's Accuracy) indicated excellent to moderately good results with water and barren land classes showing excellent results (>95 %) and wetlands and forests having >80 % accuracy. Remaining land classes had reliability of 60 – 70 %.

Linear modelling of spatio-temporal changes incorporating seasonality across all AOI zones showed that zone 1 (estuary) is a unique land-cover functional area dominated by mangroves (Fig. 7). Mangroves are an important resource (wood) and ecological support service (nursery area) (Semesi *et al.*, 1998) but their extent is threatened by freshwater deficits and concomitant saltwater intrusion. Of the seven mangrove species

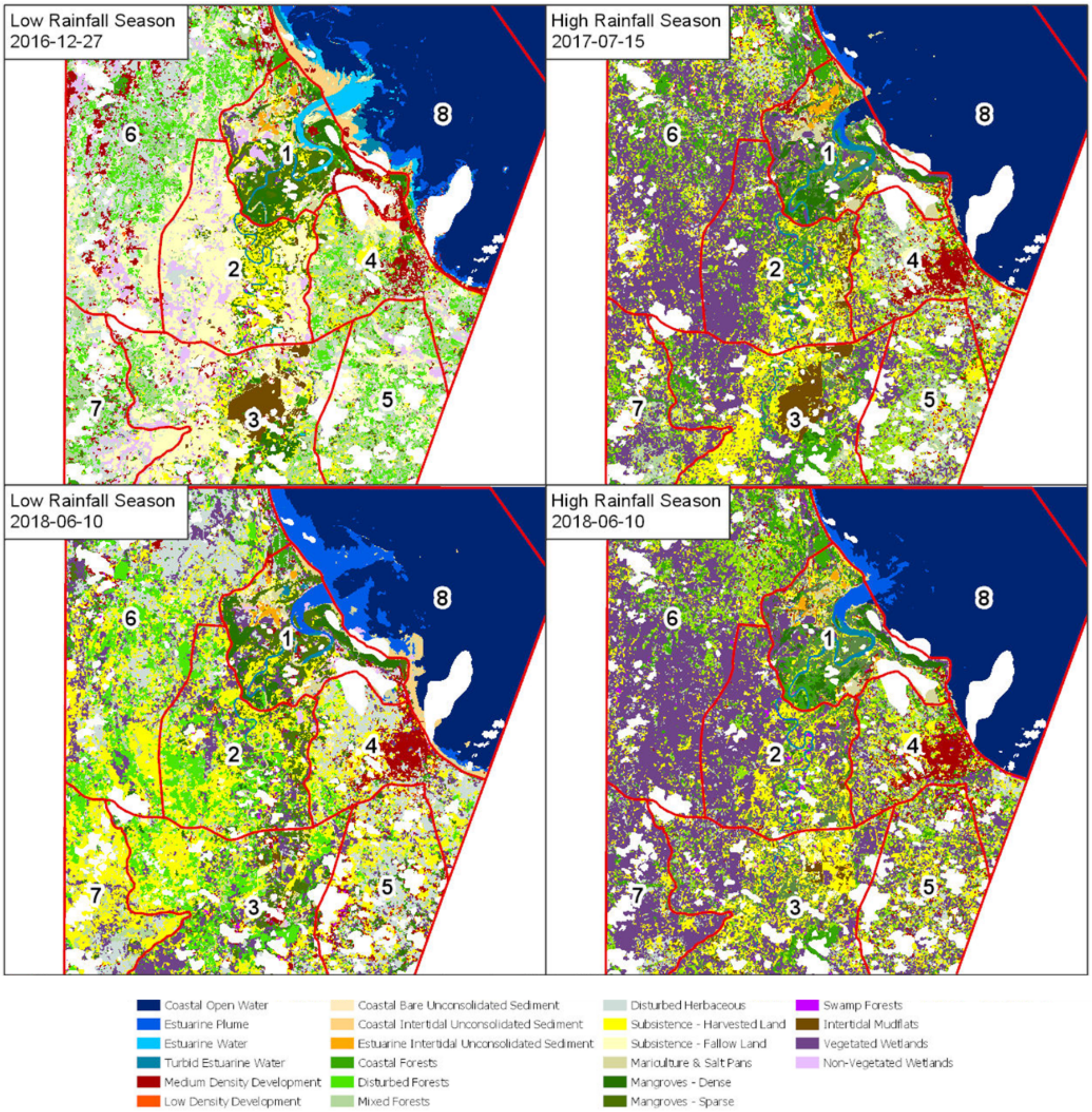

Figure 6. Seasonal land use/land cover assessment around the Ruvu Estuary, based on a comparison of Sentinel-2 satellite images of wet (SE monsoon) and dry (NE monsoon) seasons in 2016-2018. The expanded selection of 22 land cover classes to detect change at a higher, seasonal resolution is shown.

represented in the Ruvu, only two (*Sonneratia alba* and *Rhizophora mucronata*) have a high relative salinity tolerance, all other species being medium-to low tolerant (GLOWS-FIU, 2014c). The upper estuary and estuary-river transition (zones 2 and 3) are highly seasonal, with LULC changes alternating between wetlands and cultivated lands. The zones with expanding development (zones 4 and 5) show fewer seasonal signals, as development has a 'harder' permanent footprint precluding other land uses. In patchy mosaics between developed areas, cultivated (including salt and mariculture pans) and grassland areas are expanding at the expense of previous wetland areas.

Historical and seasonal trends for the main LULC classes in seven zones (excluding zone 8) are summarised in Table 3. There are critical declines in wetlands in all zones since the 1990s, with increasing cultivation in most zones (except zones 1 and 7). These overall findings agree with a larger LULC study of the WRB (Ngondo *et al.*, 2021) and are related to water resource implications. Since 1990, coastal populations have increased significantly with related demands for agricultural products and water, resulting in the conversion of wetlands to cultivated lands. Significant changes to freshwater flow was also recognized in response to potable and agri-sector demands.

Table 3. Summary of land use/land cover spatio-temporal change around the Ruvu Estuary. Changes depicted as increasing (↑) or decreasing (↓) trends. Trends in estuary or estuary-associated habitats shown in bold.

AOI ZONE	1	2	3	4	5	6	7
Area size (km^2)	36.10	47.59	68.07	34.81	45.31	97.93	27.93
Mean Elevation (m)	6.65	4.13	12.37	4.54	14.24	2.43	1.68
Mean Slope ()	2.71	1.89	2.32	2.76	3.08	2.72	2.64
Main Land Cover Classes	Mangroves Cultivation	Cultivation Wetlands	Cultivation Wetlands Forests	Forests Cultivation Developed Grasslands	Forests Cultivation Wetlands Grasslands	Wetlands Forests Grasslands Cultivation	Wetlands Forests Cultivation
Historical Trend	Forests↓ **Wetlands↓** Grasslands↑	**Wetlands↓** **Mangroves↓** Cultivation↑	Forests↓ **Wetlands↓** Cultivation↑	Developed↑ Grasslands↑ **Wetlands↓**	Cultivation↑ **Wetlands↓**	Cultivation↑ Grasslands↑ **Wetlands↓**	**Wetlands↓**
Ave. Seasonal Trend (wet to dry)	**Mangroves↑** Cultivation↑ Forests↓	Cultivation↑ **Wetlands↓**	Cultivation↑ **Wetlands↓**	Cultivation↑ **Wetlands↓**	Cultivation↑ **Wetlands↓**	Grasslands↑ Cultivation↑ **Wetlands↓**	Grasslands↑ Cultivation↑ **Wetlands↓**

Flows are set to further decline with changes in climate, especially at the coast where rainfall has decreased since 1990 (Ngondo *et al.*, 2021).

Fish and shellfish resources

A total of 77 fish and shellfish species were identified, of which 82 % were bony fishes and 10 % were crustaceans (Appendix 1). The remaining 8 % included three ray species, two cephalopods and a sea cucumber. The best represented fish families, by number of species observed, were carangids (Carangidae, 6 spp), snappers (Lutjanidae, 5), emperors (Lethrinidae, 4), and three species each of anchovies (Engraulidae), ponyfishes (Leiognathidae), parrot fishes (Scaridae) and mackerels and tunas (Scombridae). Wrasses, rabbitfish, catfish, mullet, croaker, goatfish, grouper and barracuda were also present. Crustaceans comprised of five penaeid prawn species (Penaeidae) common in WIO coastal areas (i.e., *Fenneropenaeus indicus*, *Metapenaeus monoceros*, *Penaeus monodon*, *P. japonicus* and *P. semisulcatus*), mangrove crab *Scylla serrata* (Portunidae), spiny lobster *Panulirus ornatus* (Palinuridae) and the invasive giant freshwater prawn *Macrobrachium rosenbergii* (Palaemonidae) (Kuguru *et al.*, 2019). The species list included freshwater, brackish and marine species of which several were anadromous (e.g., marine species that utilize estuaries as nursery areas). The final species list (Appendix 1) did not fully represent all the taxa present in the Ruvu Estuary and surrounding coastal areas because sampling routines were selective for species with higher commercial value and cryptic or uncommon species could not be identified. Shortcomings of the present species list are highlighted when compared with a more comprehensive list compiled by Yona (2017) for estuarine (Ruvu) and non-estuarine mangroves (Bagamoyo).

Monitoring fish zonation and guilds against a reference situation is a useful tool to measure the impact of human or other disturbance on the structure of fish communities, as an indicator of ecological integrity (Aarts and Nienhuis, 2003; Harrison and Whitfield,

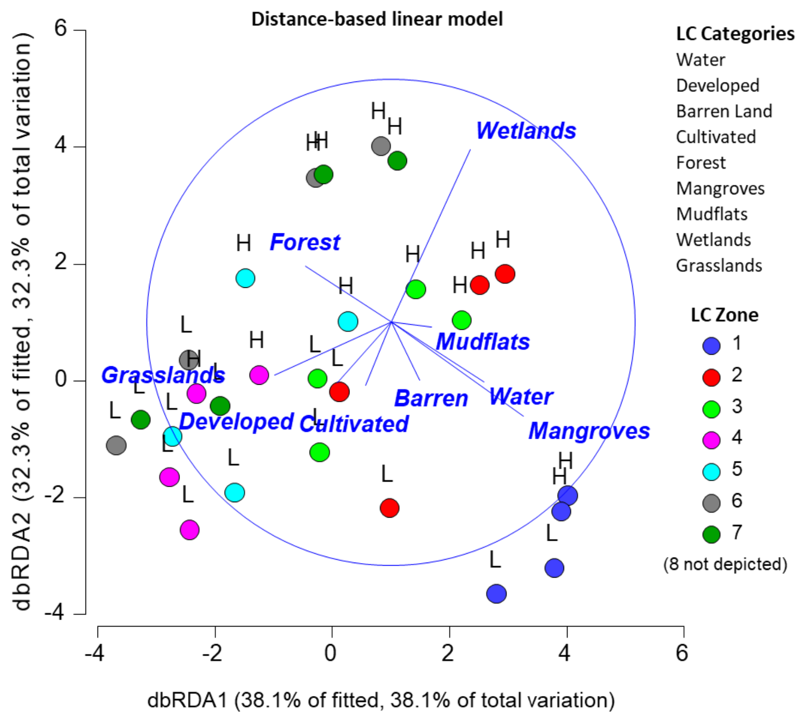

Figure 7. Distance based linear model of Ruvu Estuary land use/land cover assessments according to estuary zones (AOI zone 1-7), wet (high flow – H) and dry (low flow – L) seasons and across nine land cover classes. Axes dbRDA1 and 2 account for 70.4 % of variation.

2008). Nine species were recorded in dry-season samples obtained from fishers operating with bottom-set nets within the channels of the Ruvu Estuary. All were either benthopelagic or demersal species, consistent with the gear used. Three species were present in samples in both zone 1 (lower estuary with poly- and mesohaline conditions of 10-30 psu) and zone 2 (upper estuary with meso- and oligohaline conditions of 0.5-9 psu); African sea catfish *Arius africanus*, giant freshwater prawn *M. rosenbergii* and sharptooth croaker *Otolithes ruber* (Table 4). *Arius africanus* and *M. rosenbergii* are both freshwater migrants that are found regularly and in substantial numbers in estuaries, and in the case of *A. africanus*, also in marine waters along the coast. *M. rosenbergii* requires estuarine conditions to complete its life cycle and sustain viable populations. *O. ruber* is an amphidromous marine migrant, which regularly migrates between freshwater and the sea (in both directions) but not for the purpose of breeding.

Three species were present in zone 1 only, the marine migrants grey mullet (*Mugil cephalus*) and tiger prawn (*P. monodon*), and the honeycomb stingray (*Hymantura uarnak)*, a marine straggler. Two species present in zone 2 only were freshwater stragglers, sharptooth catfish (*Clarias gariepinus*) and tilapia (*Oreochromis esculentus*). A third species present only in zone 2 was darkfin eel catfish (*Plotosus limbatus*), categorized as an estuarine species that undertakes migrations to marine and freshwater areas. For all nine species, capture locations within the estuary corresponded well with their estuary-associated guilds obtained from the literature (Harrison and Whitfield, 2008; https://www.fishbase.se).

Based on food items (detritus, plankton, plant and algal material, small crustaceans and fish) all nine species occupied mid to lower levels in estuarine foodwebs, with trophic values ranging from 2.5 ± 0.2 (detritivores) to 3.9 ± 0.6 (omnivorous bottom feeders or smaller piscivores) (Table 4). Species observations were however constrained by sampling of a single gear type (bottom-set nets), and therefore conclusions could not be drawn on species selected by other gear types, such as gillnets or seine nets. In particular, small pelagic fishes were absent from samples taken in the Ruvu Estuary, in direct contrast with several other WIO estuaries where they made up the bulk of landings (Mugabe *et al.*, 2021; Manyenze *et al.*, 2021).

Based on the available data, the estuarine fishery in the Ruvu relies on few species and is not as important to local communities as the nearshore coastal fishery,

Table 4. Estuarine use functional groups (after Elliot *et al*., 2007 and Harrison and Whitfield, 2008) of species observed in catches made by bottom-set nets in the channel of the Ruvu Estuary. Zone 1 refers to the Kwa Mtailand and Jitokui landing sites (lower estuary) and Zone 2 to the Vikundu and Mtoni sites (upper estuary and river-estuary transition). Adult habitat, feeding ecology, mean trophic level (± SE) and vulnerability obtained from https://www.fishbase.se.

Estuarine functional group	Common name	Species	Family	Zone 1	Zone 2	Adult habitat	Feeding ecology	Trophic level
Freshwater straggler	African sharptooth catfish	*Clarias gariepinus*	Claridae		1	Benthopelagic	Omnivorous bottom-feeder	3.8 ± 0.4
Freshwater straggler	Sigida tilapia	*Oreochromis esculentus*	Cichlidae		1	Benthopelagic	Planktivorous	2.5 ± 0.2
Freshwater migrant	African sea catfish	*Arius africanus*	Ariidae	1	1	Benthopelagic	Omnivorous bottom-feeder	3.8 ± 0.6
Freshwater migrant	Giant freshwater prawn	*Macrobrachium rosenbergii*	Palaemonidae	1	1	Demersal	Omnivorous bottom feeder	3.4
Estuarine species	Darkfin eel catfish	*Plotosus limbatus*	Plotosidae		1	Demersal	Piscivorous	3.9 ± 0.6
Marine migrant	Flathead grey mullet	*Mugil cephalus*	Mugilidae	1		Benthopelagic	Detritivorous	2.5 ± 0.2
Marine migrant	Giant tiger prawn	*Penaeus monodon*	Penaeidae	1		Demersal	Detritivorous	3.4
Marine migrant	Tigertooth croaker	*Otolithes ruber*	Sciaenidae	1	1	Benthopelagic	Piscivorous	3.6 ± 0.6
Marine straggler	Honeycomb stingray	*Hymantura uarnak*	Dasyatidae	1		Demersal	Piscivorous	3.6 ± 0.6

which relies on multiple gear types and habitats to capture a rich mix of species landed at Bagamoyo. Freshwater dominance of the Ruvu Estuary during a large part of the year, and a resulting truncated estuary with fewer habitats than at larger marine-dominated estuaries in the WIO, can plausibly explain the reliance of estuarine fishers on a few species.

Conclusion and recommendations

The Ruvu Estuary is strongly seasonal and river-dominated during high river flow periods, when it becomes longitudinally truncated with mixed salinity only at the coast. Tidal influence extended some 10 km upstream during low river flow, creating a larger estuarine area. Modelling of land-cover change, although moderately affected by spectral confusion, showed significant declines in estuary-associated wetlands and mangroves between 1995 and 2016, with concomitant expansion of grasslands, cultivated and developed land. Wetlands are converted to cultivation during the dry season, and when uncultivated, wetlands become grasslands. The estuarine fishery relied mainly on freshwater and marine migrants, compared to a highly diverse species mix landed by a coastal fishery at Bagamoyo Town. Within the context of a socio-ecological study of the Ruvu Estuary, the absence of quantitative data on fisheries landings by species, gear type, season and georeferenced location remain major information gaps. Household surveys to determine livelihood activities and their reliance on estuarine resources are a key component of socio-ecological studies, but data were not available to address this aspect in the present study. For example, important aspects to clarify would be whether estuarine fish catches are marketed or used for home consumption; and how widespread opportunistic fishing for high-value invasive freshwater prawns is within the estuary.

Estuarine extent is a first step towards determining the freshwater needs of estuaries, which have been mostly overlooked in the WIO region (Kiwango *et al.*, 2015). To improve studies of estuaries and their associated socio-ecological systems, it is recommended that: (1) short periods of continuous monitoring of estuarine flow is undertaken, to obtain the full range of physico-chemical conditions across seasons; (2) a LULC classification system suited to complex tropical socio-ecological systems is developed, to reduce spectral confusion and increase modelling accuracy; (3) random sampling of fish landings in estuaries are undertaken to determine spatio-temporal variability; and (4) that household surveys of livelihood dependence on estuarine goods and services are required for constructing fully integrated socio-ecological change assessments.

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Appendix

Fish and shellfish species observed during field sampling at the Customs House beach landing site in Bagamoyo (Zone 8), lower estuary (Zone 1; Kwa Mtailand and Jitokui) and upper estuary and river-estuary transition (Zone 2; Vikindu and Mtoni). Bagamoyo samples represented presence/absence only.

			Location observed			
Family	**Species**	**Bagamoyo**	**Kwa Mtailand**	**Jitokui**	**Vikindu**	**Mtoni**
Acanthuridae	*Acanthurus xanthopterus*	1				
Apogonidae	*Apogon* sp	1				
Ariidae	Arius africanus	1	13	34	20	14
Atherionidae	*Atherion africanus*	1				
Belonidae	*Tylosurus crocodilus*	1				
Carangidae	*Atule mate*	1				
Carangidae	*Carangoides ferdau*	1				
Carangidae	*Caranx heberi*	1				
Carangidae	*Caranx ignobilis*	1				
Carangidae	*Coryphaena equiselis*	1				
Carangidae	*Decapterus sp*	1				
Cichlidae	*Oreochromis esculentus*				4	
Clariidae	*Clarias gariepinus*				23	27
Clupeidae	*Hilsa kelee*	1				
Congridae	*Conger cinereus*	1				
Dasyatidae	*Himantura gerrardi*	1				
Dasyatidae	*Himantura uarnak*	1		1		
Dasyatidae	*Taeniura lymna*	1				
Elopidae	*Elops machnata*	1				
Engraulidae	*Stolephorus indicus*	1				
Engraulidae	*Thryssa setirostris*	1				
Engraulidae	*Thryssa vitrirostris*	1				
Fistulariidae	*Fistularia commersonnii*	1				
Gerreidae	*Gerres filamentosus*	1				
Gerreidae	*Gerres oyena*	1				
Haemulidae	*Pomadasys kaakan*	1				
Haemulidae	*Pomadasys maculatus*	1				
Hemiramphidae	*Hemiramphus far*	1				
Holothuriidae	*Holothuria scabra*	1				
Leiognathidae	*Leiognathus equulus*	1				
Leiognathidae	*Leiognathus leuciscus*	1				
Leiognathidae	*Secutor incidiator*	1				
Lethrinidae	*Lethrinus harak*	1				
Lethrinidae	*Lethrinus lentjan*	1				
Lethrinidae	*Lethrinus microdon*	1				
Lethrinidae	*Lethrinus rubrioperculatus*	1				

		Location observed				
Family	**Species**	**Bagamoyo**	**Kwa Mtailand**	**Jitokui**	**Vikindu**	**Mtoni**
Lobotidae	*Lobotes surinamensis*	1				
Loliginidae	*Uroteuthis duvaucelli*	1				
Lutjanidae	*Aprion virescens*	1				
Lutjanidae	*Lutjanus argentimaculatus*	1				
Lutjanidae	*Lutjanus lutjanus*	1				
Lutjanidae	*Lutjanus sanguineus*	1				
Lutjanidae	*Lutjanus sebae*	1				
Mugilidae	*Mugil cephalus*			3		
Mullidae	*Upeneus taeniopterus*	1				
Mullidae	Upeneus tragula	1				
Octopodidae	*Octopus vulgaris*	1				
Ostraciidae	*Lactoria cornuta*	1				
Palaemonidae	*Macrobrachium rosenbergii*		46	1	227	
Palinuridae	*Panulirus ornatus*	1				
Penaeidae	*Fenneropenaeus indicus*	1				
Penaeidae	*Metapenaeus monoceros*	1				
Penaeidae	*Penaeus japonicus*	1				
Penaeidae	*Penaeus monodon*	1		78		
Penaeidae	*Penaeus semisulcatus*	1				
Plotosidae	*Plotosus limbatus*				18	9
Portunidae	*Scylla serrata*	1				
Psettodidae	*Psettodes erumei*	1				
Scaridae	*Leptoscarus vaigiensis*	1				
Scaridae	*Scarus ghobban*	1				
Scaridae	*Scarus rubroviolaceus*	1				
Sciaenidae	*Johnius dussumieri*	1				
Sciaenidae	*Otolithes ruber*	1	41	24	26	
Scombridae	*Auxis thazard*	1				
Scombridae	*Scomberoides commersonnianus*	1				
Scombridae	*Scomberomorus commerson*	1				
Serranidae	*Epinephelus lanceolatus*	1				
Serranidae	*Epinephelus malabaricus*	1				
Siganidae	*Siganus sutor*	1				
Silliganidae	*Sillago sihama*	1				
Sparidae	*Rhabdosargus thorpei*	1				
Sphyraenidae	*Sphyraena baracuda*	1				
Sphyraenidae	*Sphyraena jello*	1				
Synodontidae	*Saurida tumbil*	1				
Terapontidae	*Pelates quadrilineatus*	1				
Terapontidae	*Terapon jarbua*	1				
Trichiuridae	*Trichiurus lepturus*	1				

Small-scale fisheries of the Tana Estuary in Kenya

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Abstract

The role of small-scale fisheries in maintaining socio-ecological systems (SES) in the Western Indian Ocean is well-documented, yet few studies have addressed estuarine fisheries in the region. Small-scale fisheries in the Tana Estuary in Kenya are described in this paper, accounting for location along a salinity gradient, seasonality, gear types used, species composition and relative abundance of landings. Monthly shore-based sampling was undertaken at four locations in 2017 – Ungwana Bay near the estuary mouth, lower and mid-estuary, and upper estuary at Ozi village, ~10 km upstream. Fishing gear comprised of seine nets, gillnets, hook-and-line and traditional gear such as self-made traps, sticks and spears operated from the shore (foot fishers), dugout canoes, dhows and fibreglass boats with outboard engines. A total of 12,840 fish and crustacean specimens belonging to 89 species in 45 families were sampled. Landings were dominated by catfishes *Arius africanus* (31 %) and *Clarias gariepinus* (21 %), small pelagic fishes *Pellona ditchela* (10 %) and several sardine species (~5 %), croaker *Otolithes ruber* (10 %), eel catfish *Plotosus limbatus* (6 %), mullet *Mugil cephalus* (4 %) and Nile tilapia *Oreochromis niloticus* (4 %). Multivariate analyses (nMDS and ANOSIM) found that fishing gear ($p < 0.05$) and location ($p = 0.001$) significantly influenced catch composition, but season ($p = 0.146$) was not significant. Traps were used in the upper and mid estuary only and were selective for three catfish species. Seine nets (54 species) and gillnets (40 species) were least selective and used at all four locations. Rarefaction curves indicated that species diversity was higher at the bay and lower estuary than the mid and upper estuary, and that diversity was highest for canoe-gillnet and canoe-encircling net combinations. Catch rates (avg. of 2.3 to 8.4 $kg.fisher^{-1}.day^{-1}$) depended on gear type and was highest for monofilament gillnets. Catches comprised a broad size range of multiple species, but on average, seine nets selected smaller individuals than traps, gillnets and long lines. The high complexity and organization of the fishery at an estuary-scale makes it a good example of a relatively intact SES suitable for regional comparative analyses.

Keywords: artisanal fishery, species composition, fishing pressure, estuary, Western Indian Ocean

Introduction

Small-scale fisheries in coastal waters, estuaries and surrounding wetlands of the Western Indian Ocean region (WIO) are a vital source of food security and economic activity (van der Elst *et al.*, 2005; Groeneveld, 2015). These fisheries are highly diverse, exploiting multiple species using different types of traditional and modern fishing gear, either from the shore or from small craft, such as dugout canoes and seagoing dhows (Jiddawi and Ohman, 2002; Samoilys *et al.*, 2011; Munga *et al.*, 2014a; Fondo *et al.*, 2015; www.wiofish.org). The high socio-economic importance and diversity of WIO fisheries make them difficult to manage using conventional fishery management practices (McClanahan and Mangi, 2004; van der Elst *et al.*, 2005).

Several fisheries studies have focused on Ungwana Bay along the northern Kenya coast. The Tana and Athi-Sabaki estuaries discharge into the bay, thus enriching it with terrigenous sediments, nutrients and

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biological material (Kitheka *et al*., 2005; Kitheka and Mavuti, 2016). Recent studies of Ungwana Bay have focused on shallow water shrimp semi-industrial trawl fisheries (Munga *et al*., 2012, 2013, 2016); fish bycatch and resource use conflicts (Munga *et al*., 2014b; Tunje *et al*., 2016); socio-economics and fishery management systems (Fulanda *et al*., 2009, 2011; Munga, 2013; Munga *et al*., 2014a); larval dispersal and recruitment to fisheries (Mkare *et al*., 2014, 2017); and ecological vulnerability of coastal fishing communities to climate variability (Hamerlynck *et al*., 2010; Dzoga *et al*., 2018, 2019, 2020). The above studies focused mainly on the marine environment, with less attention given to fisheries in the enclosed parts of the Tana and Athi-Sabaki estuaries (Mireri, 2010).

Small-scale fishing in the Tana Estuary (defined as the northern-most channel of the Tana River Delta that discharges near Kipini town; Groeneveld *et al*., 2021) forms an important part of a socio-ecological entity that traditionally includes livestock keeping, flood-recession agriculture and tidal rice cultivation, hunting and gathering, utilization of woody and non-woody forest products and beekeeping (Hamerlynck *et al*., 2010, 2020; Mwamlavya *et al*., 2021). The productive delta ecosystems that support traditional livelihoods have remained relatively intact (van Beukering *et al*., 2015; Duvail *et al*., 2017). Activities are strongly seasonal, driven by the influence of semi-annual flood pulses in November to December (short rains associated with the northeast [NE] monsoon) and April to May (long rains associated with the southeast [SE] monsoon). Upstream damming and freshwater abstraction in catchments of the Tana River for economic development have disrupted the seasonal timing and volume of freshwater pulses, with impacts on estuarine functioning and dependent socio-ecological systems (SES) (Hamerlynck *et al*., 2010, 2020; Duvail *et al*., 2012, 2017; Leauthaud *et al*., 2013; Kitheka and Mavuti, 2016; Mwaguni *et al*., 2016; Odhiambo-Ochiewo *et al*., 2016).

Fishing in the Tana Estuary takes place in the main estuary channel, smaller tributaries, wetland lakes and in nearshore coastal waters (van Beukering *et al*., 2015). Full-time fishers at Kipini (including seasonal migrants; see Fulanda *et al*., 2009) fish mainly in Ungwana Bay and the lower Tana Estuary. Munga *et al*. (2014a, 2014b) reported 177 fish species from small-scale fisheries and 223 species from trawl samples in the bay. Ndoro *et al*. (2014) found 20 decapod crustacean species, including 9 portunid crab and 5 penaeid prawn species. The brackish water habitats and mangrove forests of the Tana Estuary provide vital habitats and nursery grounds for juvenile fish and crustaceans, including those with marine-dependent life history phases (de Freitas, 1998; Mkare *et al*., 2014). At Ozi village (~10 km upstream from the estuary mouth) part-time fishers set their gear in the oligohaline backwaters and wetlands to catch fish to consume or augment their income from farming (Mwamlavya *et al*., 2021). The fresh and brackish water of the lower Tana Delta is relatively ichthyo-diverse, with 9 fish families (Mochokidae, Protopteridae, Claroteidae, Schilbeidae, Cichlidae, Alestidae, Clariidae, Mormyridae and Cyprinidae) and at least 48 species (Odhengo *et al*., 2012).

Several studies have described the management of Kenyan fisheries (Fondo *et al*., 2015). Fishing has been an open-access activity for many centuries but increases in human population size and more effective fishing methods have increased fishing pressure leading to localized depletions over the past decades (Botsford *et al*., 1997; Mansfield, 2011). A top-down governance approach has failed to curb increases in fishing effort. Collaborative fisheries management in which stakeholders and resource users are involved in decision making processes (e.g., Beach Management Units or BMUs) have been active for >20 years but have been plagued by low transparency and accountability, and mismatched priorities between officials and members (Oluoch and Obura, 2008; Kanyange *et al*., 2014). A deeper understanding of small-scale fisheries in the Tana Estuary and of traditional decision-making is required, so that fisheries management objectives and livelihood priorities can be better aligned. It was hypothesized that local estuary-scale conditions would determine the fishing gear used, and the species composition and relative abundance of landings made by small-scale fishers operating between Ungwana Bay (near-marine) and Ozi village (oligohaline) in the Tana Estuary. Small-scale fisheries are described with emphasis on spatio-temporal trends in species composition and relative abundance of landings and gear selectivity. The new information is useful for detailed socio-ecological assessments of the role of small-scale fisheries in WIO estuaries (see Groeneveld *et al*., 2021; Santos *et al*., 2021).

Materials and methods

Study area

The Tana River Delta is roughly triangular in shape, with its apex at Lake Bilisa (north of Garsen town) and its base a 50 km stretch of beach along Ungwana Bay, stretching from Kipini town in the north-east to Mto Kilifi in the south-west (Mireri, 2010). The delta is a low-lying area bounded by higher land to the east and west and to the south by a dune ridge parallel to the shore, which separates it from the bay. The delta is characterized by fresh- and brackish water lakes and streams, fresh water and saline grasslands and wetlands, and successional stages of forest and woodland on the riverbanks and dune ridges (Mireri, 2010). The delta discharges into the bay through several estuaries that extend inland for up to 10 km, with a mean depth of about 5 m (Scheren *et al.*, 2016). Mangrove forests line the estuary banks and coastal depressions, providing a natural buffer to flooding, vital habitats for estuarine fish and crustaceans, and a diversity of forest products used by local coastal communities, including wood for building and fuel (Bosire *et al.*, 2016). Information on the geographical setting of the Tana Estuary, ecosystems, socio-ecological importance and drivers of change is summarized by Groeneveld *et al.* (2021).

Four sampling locations were defined (Fig. 1): upper estuary - riverine channels around Ozi with fresh or oligohaline water with <2 ppt salinity; mid estuary - tidal channels and mangroves on both banks, river-dominated with a moderate tidal influence and salinity fluctuating between 2 and 10 ppt; lower estuary - enclosed marine transition area with mixed tidal - and river currents, mesohaline water with salinity mostly >10 ppt; and the bay - exposed nearshore marine-dominated waters influenced by tidal currents, waves and floods with salinity fluctuating mainly >20 ppt. The salinity categories were adapted from the classification by Rhoadles *et al.* (1992). The four sampling locations were verified with in-situ salinity measurements using a YSI salinity meter, with readings falling within expected ranges: i.e., 1.2 ± 0.5 ppt (upper); 9.1 ± 0.4 ppt (mid): 12.5 ± 0.7 ppt (lower); and 24.7 ppt (bay).

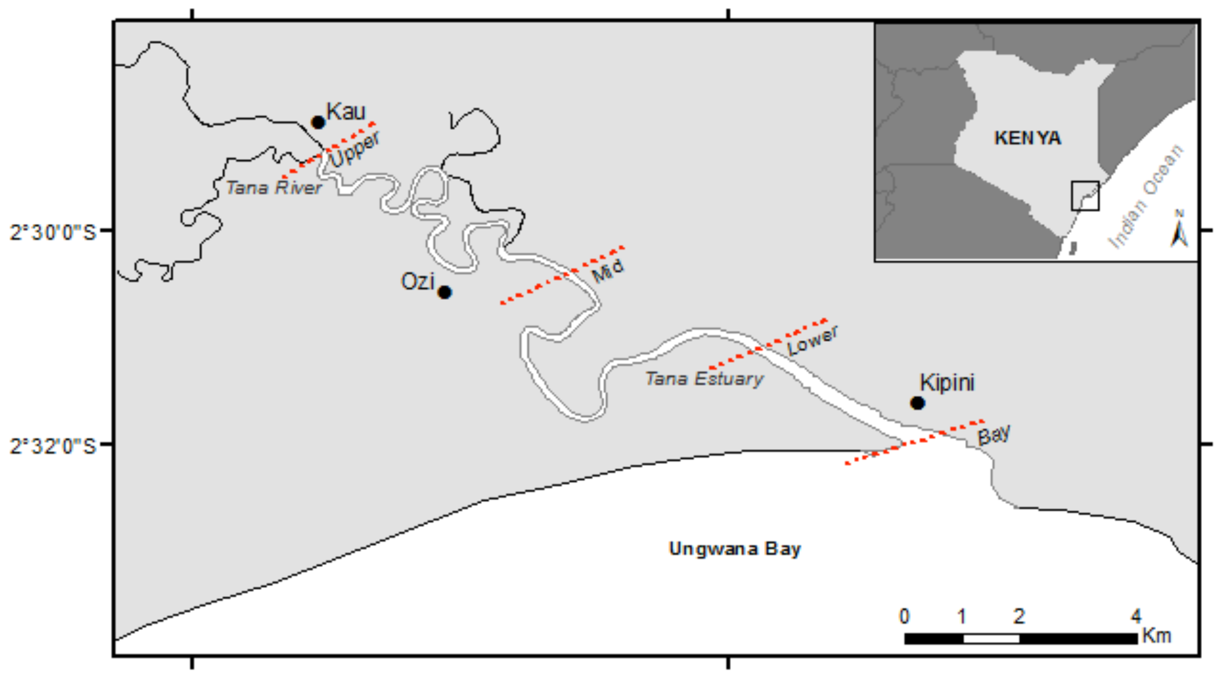

Figure 1. The Tana Estuary in Kenya (see inset) showing the four sampling locations in the bay, lower estuary, mid estuary and upper estuary, separated by dotted red lines. The town at Kipini and villages at Ozi and Kau are also indicated.

Data collection

Field sampling surveys to collect detailed fisheries data were conducted between March and December 2017 (incl. 5-day surveys in March and June). The types of fishing gear and craft used, number of fishermen and landings at sites between Kipini and Ozi were investigated. Total landings per fishing craft and gear were weighed to the nearest kilogram (kg) on a weighing balance. For large landings, the catch was first mixed before scooping up a random sub-sample; for small landings the entire catch was sampled. Samples were identified to the lowest possible taxonomic

Table 1. Gear types observed at four locations in the Tana Estuary in Kenya during shore-based sampling in 2017. Sampling locations were Ungwana Bay (bay), lower, mid and upper Tana Estuary between Kipini town and Ozi village. Gear descriptions relied on technical details in Samoilys *et al*., (2011). The most abundant families in landings by gear type are shown.

Gear type	Description of fishing gear	Most abundant families in landings by gear type
Encircling nets (includes cast nets and seine nets)	Cast nets: Circular nets with weighted edges, monofilament nylon, and 7-30 mm mesh. Deployed from canoe, boat or while wading. Cast over shoal of fish and hauled back. Used in the lower Tana Estuary.	Ariidae, Clupeidae Engraulidae, Sciaenidae
	Seine nets: Monofilament nylon, attached to mangrove poles or bars at each end. Small mesh. Deployed on foot by dragging it towards the shore by 1-3 fishers or from a canoe while drifting with one end attached. Sometime set across mangrove channels. 1.8 x 20 m long. Larger multifilament beach seine nets (illegal in Kenya) were not observed. Used at all 4 locations.	Ariidae, Belonidae, Cichlidae, Claridae, Clupeidae, Mugilidae, Sciaenidae, Penaeidae, Palaemonidae, Plotosidae, Pristigasteridae
Gillnets (includes mono- and multifilament gillnets)	Stationary gillnets with small floats at the top, weights at the bottom and varying mesh size (2.5 – 12 cm). Deployed from canoe or boat after anchoring 1 end, sometimes across channels, by 2-4 fishers. Set at bottom, mid or surface, depending on target species. Hauled after a few hours. Variable length: 2.5 x 20 m, or up to 50 m. Monofilament nets are lighter and require less maintenance but are illegal in Kenya. Used at all 4 locations.	Ariidae, Cichlidae, Claridae, Clupeidae, Mugilidae, Sciaenidae, Pristigasteridae
Handline	Single monofilament nylon line with baited steel hooks, deployed from canoe, boat or shore. Used in the upper and mid Tana Estuary and in Ungwana Bay.	Ariidae, Clupeidae, Monodactylidae, Sciaenidae
Longline	Single mainline of monofilament nylon buoyed horizontally, often anchored. Series of short vertical nylon snoods with baited hooks attached at intervals. Deployed from boat. Used at all 4 locations.	Ariidae, Claridae, Sciaenidae, Pristigasteridae
Shark net	Demersal gillnet with large mesh. Used in Ungwana Bay.	Ariidae, Carcharhinidae, Sphyraenidae
Traditional traps	Traditional traps made locally from poles tied together in a conical shape with entrance at one side. Set in deep areas along the estuary bank using canoes or by foot. Used in the upper and mid estuary.	Ariidae, Claridae, Plotosidae
Other gear (spear, harpoon, hooked sticks)	Spears or home-made spearguns; harpoons are wooden poles with or without metallic tip. Used mainly from the shore by foot fishers. Used at all 4 locations.	Claridae, Octopodidae

level (mostly species level) using available fish identification guides (Smith and Heemstra, 1998; Lieske and Myers, 2001; Anam and Mostarda, 2012). The total length (TL in cm) of selected species (based on abundance and importance to fishers) was measured on a calibrated fish measuring board, and individual weights determined to the nearest gram (g) using a digital weighing balance (Ashton Meyers® 7767).

Trophic levels (rankings of how many steps a species is above primary producers at the base of the food web) of captured fish were obtained from FishBase (Froese and Pauly, 2019), where a mean trophic level per family has been determined from fish diet composition. The diet composition of fish depends on food availability which varies between locations – hence the trophic levels obtained from FishBase were indicative only. Trophic level 1 comprises primary producers (plants and algae that make their own food, mainly through photosynthesis), level 2 are herbivores, level 3 are secondary consumers (carnivores that eat herbivores) and level 4 are tertiary consumers (carnivores that eat other carnivores). In this study, the mean trophic levels of landings were calculated based on numerically weighted contributions of all species caught per gear and location, respectively.

Data analysis

Data were stratified by season (SE monsoon between April and September; NE monsoon between October and March), sampling locality (bay, lower-, mid- and upper estuary), gear type and fishing craft used to catch sampled fish. Fishing gear were described based on field observations and grouped into categories for encircling nets, gillnets, hook-and-line, and traditional gears (Table 1). Additional information on gear types, including mesh size, construction material and method of deployment was obtained from Samoilys *et al.* (2011).

The number of individuals per species was used to calculate the relative abundance in landings (%) using the following formula:

$$\textit{Relative abundance}\ (\%) = \frac{\textit{Number of individuals of species 'A' in location 'S'}}{\textit{Total number of individuals of all species in location 'S'}}\ x\ 100$$

Catch composition by gear, location and season was investigated using a multivariate non-Metric Multidimensional Scaling (nMDS) technique and 1-way Analysis of Similarity (ANOSIM). Differences in catch composition were confirmed using 1-way SIMPER analysis to ascertain which species contributed most to the dissimilarity. Both ANOSIM and SIMPER analyses were based on Bray-Curtis similarity using PRIMER statistical software version 6 (Clarke *et al.*, 2014).

To standardize for non-uniform sampling and sample sizes, rarefaction curves (Sanders, 1968) were used to determine the expected number of species per sample across combinations of gear type and fishing location. Catch rates were calculated as $kg.fisher^{-1}.day^{-1}$ for each

Table 2. Proportional distribution of fish sampled per location and gear type in the Tana Estuary in Kenya during shore-based sampling in 2017. Locations were: bay (mudbanks in Ungwana Bay near the estuary mouth); lower-, mid-, and upper estuary.

Gear	Sampling location				
	Bay	Lower	Mid	Upper	Combined
Castnet		1.00			<0.01
Gillnet	0.90	0.10			0.10
Handline	0.98		0.01	0.01	0.01
Longline	0.76	0.05	0.17	0.02	0.10
Monofilament gillnet	0.77	0.04	0.05	0.14	0.28
Seine	0.32	0.02	0.28	0.38	0.31
Sharknet	1.00				<0.01
Spear/stick	0.07		0.18	0.75	0.01
Traditional trap			0.35	0.65	0.18
Proportion of gear sampled per location	0.49	0.03	0.18	0.29	1

gear, by dividing the total weight of catch landed by the number of associated fishers. Differences in catch rates were compared using 1-way ANOVA, followed by a post hoc pair-wise comparison using the Tukey Honest Significant Difference (HSD) test. Homogeneity of variance was tested with Levene's test (Levene, 1960).

Results

Descriptive analysis

Fishing craft were dugout canoes (constructed from a single log approx. 4 m long with flat bottom for stability, with or without outriggers); dhows (mean length of 5 m, constructed from timber planks and with a flat bottom, pointed bow and round or pointed stern, propelled by triangular sail); and fibreglass boats with outboard engines of varying size. Foot fishers accessed shallow fishing grounds by foot. Dugout canoes without outriggers were observed at all four locations, but those with an outrigger for stability were observed mainly in the lower estuary and bay. Dhows were also used in the lower estuary and bay. A single sample was obtained from a fibreglass boat fishing in the lower estuary. Foot fishers were present at all four locations. Some 85 % of 12,840 sampled fish were obtained from dugout canoes, 13 % from foot fishers, and 2 % from dhows and fibreglass boats combined.

By gear, samples originated from seine nets (31 % by number), monofilament gillnets (28 %), traditional traps (18 %), multifilament gillnets (10 %) and long lines (10 %) (Table 2). Samples from cast nets, shark nets, hand lines, spears and hooked sticks combined made up the remaining 3 %. Samples from traditional traps were available for the mid and upper estuary only, whereas samples from seine nets were relatively evenly spread between the bay, upper and mid estuary (28-38 % per location). Samples from multifilament gillnets originated from the bay and lower estuary only; samples from monofilament gillnets originated predominantly from the bay (77 %), with smaller proportions captured at the other three locations (4 – 14 %). The bulk of samples from long lines originated from the bay (76 %), with lower percentages from the three enclosed locations. Overall, sampling effort between locations was uneven, dominated by the bay (49 %) and upper estuary (29 %), and with lower representation from the mid (18 %) and lower estuary (3 %) (Table 2).

A total of 12,840 specimens belonging to 89 species in 45 families were sampled (see Appendix 1 for full list) of which 58 species comprised of <10 specimens each. The African sea catfish *Arius africanus* made up the bulk of all sampled fish (31 % of all samples combined; Fig. 2), followed by freshwater African catfish *Clarias gariepinus* (21 %). Both catfish species are benthopelagic and inhabit tropical and subtropical climates (www.fishbase.org). Tigertooth croaker *Otolithes ruber* (10 %)

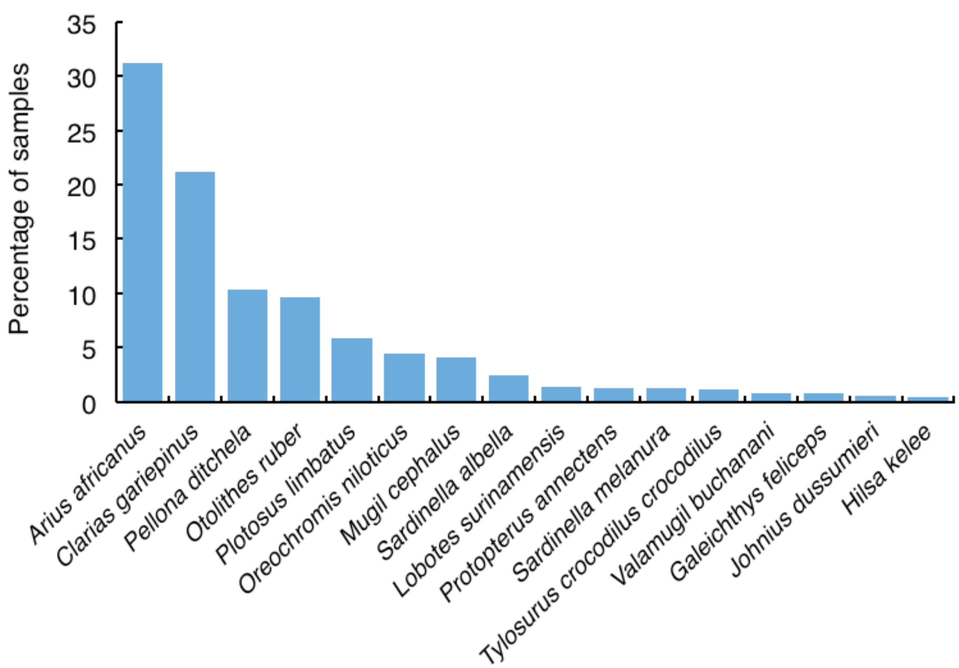

Figure 2. Observed relative abundance of fish in landings of small-scale fishers in the Tana Estuary in Kenya during shore-based sampling of landings in 2017.

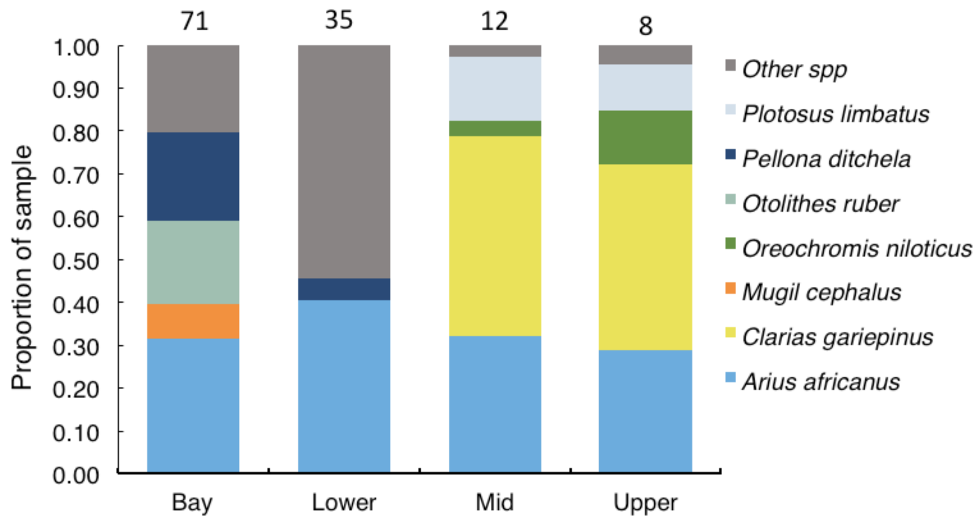

Figure 3. Proportional abundance of key species in landings of small-scale fishers at four sampled locations in the Tana Estuary in Kenya during shore-based sampling of landings in 2017. Species with < 5 % representation in landings were grouped as Other spp. The total number of species observed per location is shown above the bars.

was also a common benthopelagic species in landings. Small pelagic species were mostly Indian pellona *Pellona ditchela* (10 %) and several sardine species (~5 %). Other common species in samples were Darkfin eel catfish *Plotosus limbatus* (5 %), Nile tilapia *Oreochromis niloticus* (5 %) and Flathead grey mullet *Mugil cephalus* (4 %). Crustaceans were not well-represented in samples, although several species occurred in small numbers, i.e., shrimps *Penaeus indicus*, *P. monodon* and *Metapenaeus monoceros*, mud crab *Scylla serrata*, freshwater crayfish *Macrobrachium* spp. and spiny lobster *Panulirus ornatus*.

The euryhaline catfish species *A. africanus* was abundant in landings at all four sampling locations (29 - 41 % of fish landed per location; Fig. 3). The freshwater species *Clarias gariepinus* made up the bulk of sampled landings in the upper (43 %) and mid estuary (46 %) but was absent from the more brackish waters of the lower estuary and bay. Similarly, freshwater species *O. niloticus* and *P. limbatus* were common in landings in the mid (4 % and 15 %, respectively) and upper estuary (13 % and 11 %) but scarce in the lower estuary and bay. The anadromous small pelagic fish *P. ditchela* appeared in samples in the bay (21 %) and lower estuary (5 %) only,

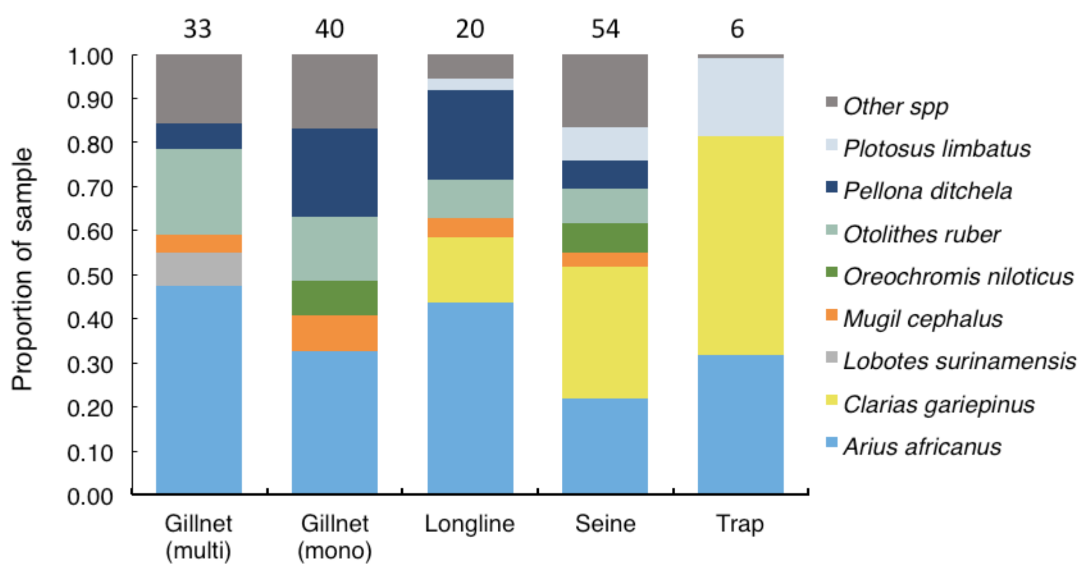

Figure 4. Proportional abundance of key species in landings of small-scale fishers using five gear types in the Tana Estuary in Kenya during shore-based sampling of landings in 2017. Species with < 5 % representation in landings were grouped as Other spp. The total number of species per gear type is shown above the bars.

and catadromous mullet *M. cephalus* made up 8 % of landings in the bay. *Otolithes ruber*, an amphidromous species, made up 19 % of landings at the bay location. The number of sampled species decreased sharply between the bay (71 species recorded) and upper estuary locations (8 species).

Traditional traps were highly selective gear and caught only three species in noteworthy quantities, *C. gariepinus* (50 % of all landings caught by traps), *A. africanus* (32 %) and *P. limbatus* (18 %) (Fig. 4). The high selectivity of traps can partly be explained by their use in the upper and mid estuary locations only, where species

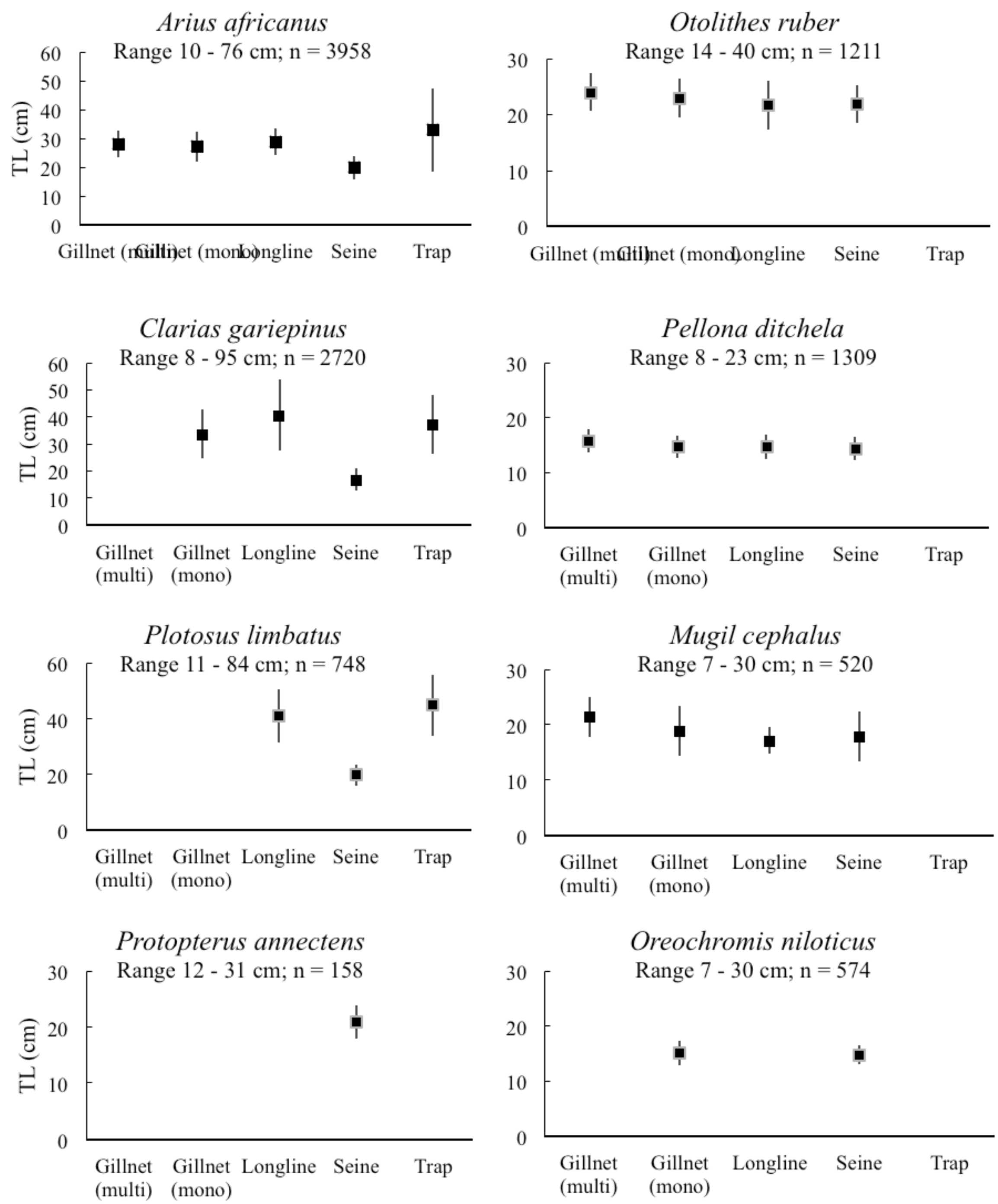

Figure 5. The mean size (Total Length ± SD cm) of selected fish species caught per gear type by small-scale fishers in the Tana Estuary in Kenya during shore-based sampling of landings in 2017. Observed size ranges and sample sizes (n) are shown. Data of fish caught by cast nets, shark nets, hand lines and spears / sticks were excluded because of small samples.

diversity was much lower than in the bay and lower estuary. Seine nets (54 species recorded from landings) and monofilament gillnets (40 species) were unselective gears used at all four locations. Seine nets caught a mixture of freshwater, estuarine and marine species, and they also caught a mixture of small pelagic, benthopelagic and demersal species. Monofilament gillnets were similarly unselective, although few *C. gariepinus* or *P. limbatus*, both abundant in samples from seine net and trap catches, were caught by gillnets. Multifilament gillnets were unselective for marine and brackish water species occurring in the bay and lower estuary locations, and they were not used in the mid and upper estuary. *Arius africanus* made up a large proportion of landings made by all five gear types, particularly multifilament gillnets (47 % of sampled landings) and long lines (44 %).

Gear types selected fish of different sizes, but size-selectivity also depended on gear-species interactions (Fig. 5). The largest *A. africanus* were caught in traps (mean TL of 33.1 ± 14.3 cm) and the smallest in seine nets (19.9 ± 4.3 cm), whereas multi- and monofilament gill nets and long lines caught intermediate sizes with TL of between 27.1 and 28.9 cm. Large *C. gariepinus* were caught by long lines (40.5 ± 13.2 cm) and traps (36.9 ± 10.9 cm) but seine nets caught only small ones (16.6 ± 4.1 cm). Size selectivity by gear was less obvious for *M. cephalus*, *O. ruber* and *P. ditchela*, where multi- and monofilament gillnets, long lines and seine nets caught similar-sized fish, and traps caught none. *Oreochromis niloticus* caught by monofilament gillnets were similar in size to those caught by seine nets (means of 15 ± 2 cm in both cases), but they were not caught by any other gear. Seine nets caught small *P. limbatus* (19.8 ± 3.8 cm) compared to long lines (40.9 ± 9.6 cm) and traps (45.0 ± 10.1 cm), but they were absent from gillnet catches. *P. annectens* were caught in seine nets only (21.0 ± 3.0 cm).

Catch rates by fishing location indicated higher fishing intensity in the bay, mid and upper estuary than in the lower estuary (Fig. 6). Monofilament nets, long lines and seine nets were recorded at all four fishing locations, traps only in the mid and upper estuary, and multifilament gillnets only in the bay. Overall catch rates kg.fisher^{-1}.day^{-1} differed significantly between gear types (1-way ANOVA: df = 4; f =23.737; p = 0.001). Post hoc pair-wise comparison using the Tukey HSD test confirmed catch rates of multifilament gillnets differed significantly from those of monofilament gillnets, traps and seine nets ($p < 0.01$ in all cases) while monofilament gillnets differed significantly from traps and seine nets ($p < 0.01$ in both cases). Catch rates of long lines differed significantly from those of traps and seine nets ($p < 0.01$ in both cases). Average catch rates were highest for monofilament gillnets (8.4 ± 0.6 kg) followed by long lines (6.6 ± 0.4 kg) and seine nets (4.1 ± 0.5 kg). Multifilament gillnets and traps recorded lower catch rates of 3.1 ± 0.4 and 2.3 ± 0.5 kg, respectively.

Trophic levels (weighted average) of catches made by multifilament gillnets were highest (4.08) followed by traps (3.79), spears and long lines (3.73). Monofilament

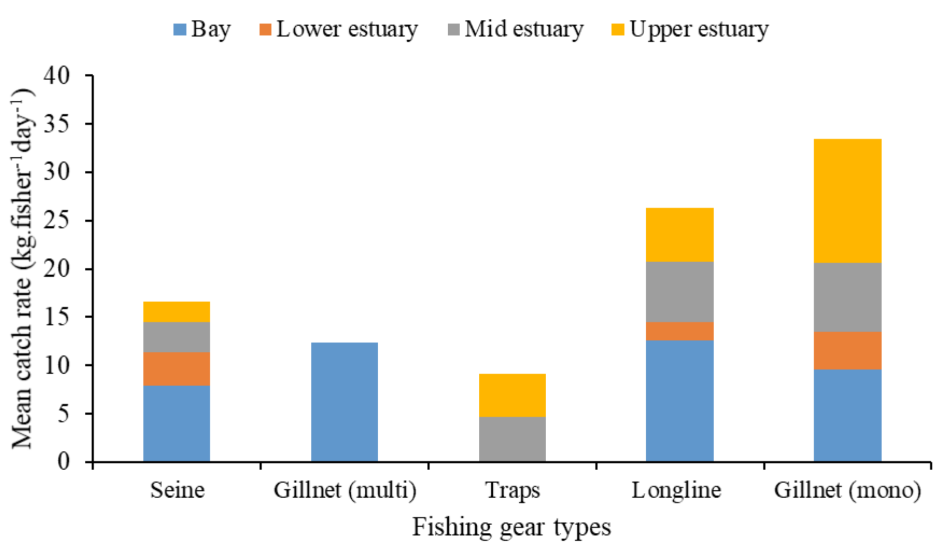

Figure 6. Mean catch rate (kg.fisher^{-1}day^{-1}) per gear type and fishing location during shore-based sampling of landings and fishing effort in the Tana Estuary in Kenya in 2017.

gillnets (3.49) and seine nets (3.55) caught fish at lower trophic levels. By fishing location, the trophic level of catches was marginally lower in the bay and lower estuary (3.58 and 3.44, respectively) than in the mid and upper estuary (3.72 and 3.57). In general, traps and long lines caught more carnivores whereas gill nets and seine nets caught a mixture of herbivorous, omnivorous and carnivorous fish species.

Multivariate analysis

Results of nMDS plots showed no distinct seasonal pattern in species composition of sampled landings (stress value of 0.11) (Fig. 7A). Results of 1-way ANOSIM confirmed no significant difference in catch composition between seasons ($p = 0.146$). The 20 most abundant species were observed in both NE and SE monsoon seasons, except for *Moolgarda seheli* (NE monsoon only), *Liza vaigiensis, P. annectens* and *Acanthopagrus berda* (SE monsoon only).

The nMDS plots could differentiate landings across sampling locations (Fig. 7B; ANOSIM; $R = 0.42$; $p = 0.001$), but no pairwise difference could be found between landings from the mid and upper estuary ($p > 0.05$; Appendix 2). Species that contributed most to dissimilarities between sampling locations in 1-way SIMPER analyses were more abundant *P. ditchela* and *O. ruber* in the bay compared to abundant *Thryssa vitrirostris, Macrobrachium* spp. and *O. niloticus* in the lower estuary, and more abundant *P. ditchela*, *O. ruber*, *L. surinamensis*, *S. melanura* and *S. albella* in the bay compared to *C. gariepinus*, *P. limbatus* and *O. niloticus* in the mid and upper estuary (Appendix 2). The dissimilarity between the lower and mid estuary was attributed to more *T. vitrirostris, Johnius dussumieri*, *Macrobrachium* spp., *L. surinamensis* and *P. ditchella* in the lower estuary compared to *C. gariepinus* and *P. limbatus* in mid estuary. The same species contributed most to the dissimilarity between lower and upper estuaries (Appendix 2).

The nMDS plots could differentiate landings among gear types, most clearly between traditional gears (traps, spears / sticks) and the rest of the gears (Fig. 7C). Pairwise differences in landing composition were found between encircling nets (combined seine and cast nets) and gillnets (combined multi- and monofilament gillnets), long lines and traditional gears, respectively ($p = 0.001$ in all cases) (Appendix

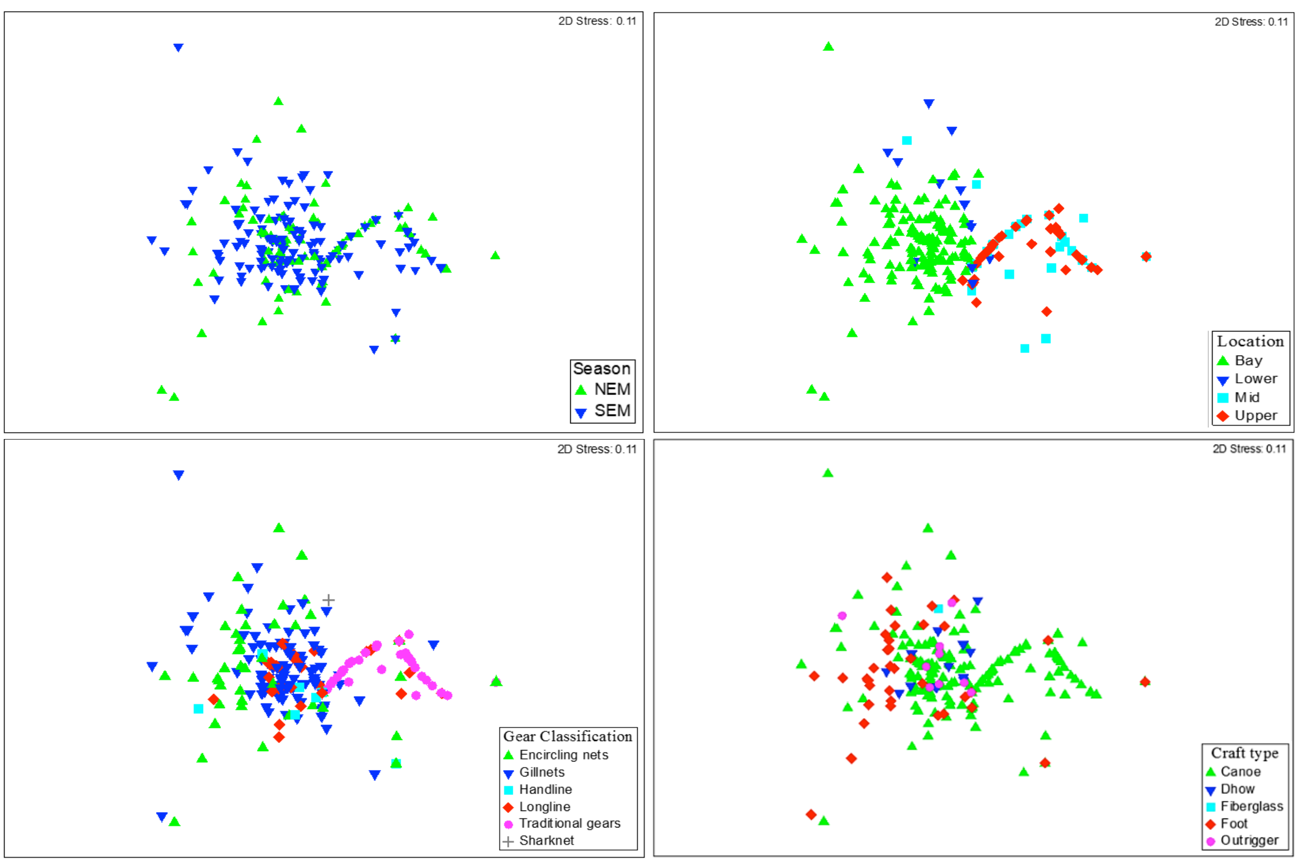

Figure 7. Non-metric MDS plots showing the composition of catches by (A) season; (B) location; (C) gear type; and (D) fishing craft type in the Tana Estuary in Kenya determined from shore-based sampling of landings and fishing effort in 2017. 24

2). The landings composition of gillnets differed from traditional gears and long lines, respectively, and hand lines differed from long lines (p = 0.001 in all cases). Species that contributed most to dissimilarities between gears in 1-way SIMPER analyses were abundant *C. gariepinus* and *P. limbatus* in encircling nets versus *A. africanus* and *Lobotes surinamensis* in gillnets; abundant *O. niloticus, T. crocodilus* and *S. albella* in encircling nets compared to *A. africanus* in long lines; abundant *P. ditchela, O. ruber, O. niloticus, T. crocodilus, S. albella* and *S. melanura* in encircling nets compared to *C. gariepinus* and *P. limbatus* in traditional gears; abundant *O. ruber, P. ditchela, L. surinamensis, M. cephalus, O. niloticus, G. feliceps* and *S. albella* in gillnets compared to *C. gariepinus* and *P. limbatus* in traditional gears; abundant *O. niloticus, S. albella,* and *M. seheli* in hand lines compared to *P. ditchela* and *C. gariepinus* in long lines; and abundant *A. africanus, P. ditchela, O. ruber* associated with long line catches compared to *C. gariepinus* and *P. limbatus* caught with traditional gears.

The nMDS plots could differentiate landings originating from various fishing craft types (Fig. 7D). Landings originating from dugout canoes (incl. those with outrigger) and foot fishers were dispersed, but those made from dhows were clustered closely. The ANOSIM indicated a significant difference in the landings composition between the fishing crafts (R = 0.133; p = 0.001).

Rarefaction curves based on craft-gear combinations across fishing locations indicated higher diversity in landings originating from canoe-gillnet and canoe-encircling net combinations in the bay and lower estuary (3.5 to 7 species expected) compared to canoe-traditional gear (also canoe-gillnet, and canoe-encircling net combinations) in the mid- and upper estuary (<3 species) (Figure 8). A medium-high diversity of landings made by the foot fisher-encircling net combination in the bay (>4 species) suggests that overall, location had a greater influence on landings diversity than craft-gear combinations. The canoe-long line combination was an exception, with low diversity in the bay (~2 species), suggesting that long lines were more selective than other gears used in the bay.

Discussion

The use of the multivariate non-metric multidimensional technique was appropriate in the analysis of a multigear and multispecies fishery. The results confirmed that the small-scale fishery in the Tana Estuary is typical of tropical coastal fisheries, in which multiple species are caught with diverse fishing gears (van der Elst *et al.*, 2005). The fishery operates along a salinity gradient between the upper Tana Estuary and Ungwana Bay, resulting in mixed landings of freshwater (dominated by *C. gariepinus, O. niloticus, P. limbatus*), brackish water (*A. africanus, M. cephalus*) and marine species (*P. ditchela, Sardinella albella*). The diversity of landings was further enhanced because multiple gear types (encircling nets, gillnets, hook-and-line and traditional traps) were used to access different habitats, and therefore exploit several distinct fish assemblages. As a result, landings comprised of a mixture of small pelagic, benthopelagic and demersal fish species, ranging from herbivores (several sardine species) to medium-sized and large predatory fishes, including sharks.

Key assumptions made during the study were that shore-based sampling of landings would reflect the species / size composition of catches made by fishers; that samples would include all landed species in proportion to their numerical abundance in the fishery; that seasonality in catch composition would be adequately represented by a monthly sampling protocol spanning a single year; and that the timing and water volume of the annual flooding regime in 2017, when sampling took place, followed a typical annual pattern. The assumptions were only partially met in most cases, with implications for the interpretation of results.

Small-scale fishers retain nearly all catches made, irrespective of species and size (Mangi and Roberts, 2006), and therefore shore-based sampling of landings was considered representative of the catch. Landings were processed in several different ways (sun-dried, smoked, fried and fresh; pers. obs. JCG) for local consumption and sale at fish markets (see also Wamukota, 2009). The scarcity of crustaceans (Penaeidae, Palaemonidae, Portunidae) in the data suggests that this taxon was undersampled, thus breaching the assumption of proportionality in samples. Ungwana Bay is well-known for penaeid prawn fisheries (Munga *et al.*, 2013, 2014b, 2016) and it is unlikely that so few prawns would have been present in landings. Undersampling of prawns and other crustaceans is plausibly explained by selective sampling of finfish during fieldwork, and by more rapid processing of prawn landings by fishers and buyers to maintain their quality for established markets, thus precluding representative sampling at landing sites.

The absence of a significant seasonal effect in our study contradicts the finding of Munga *et al.*, (2013), that species richness and diversity of landings in

Ungwana Bay increased during the NE monsoon season, when sea conditions are favorable for fishing. Undersampling of prawns, a seasonally abundant taxon, may have obscured the seasonal trend in the current study (see above). Alternatively, the absence of observed seasonality in this study potentially reflects year-round fishing in the enclosed (sheltered) part of the estuary, compared to strongly seasonal fishing in the bay observed by Munga *et al.* (2013), exacerbated by seasonal movements of migrant fishers that fish mainly in nearshore waters (Fulanda *et al.*, 2009).

The flooding regime during the sampling period in 2017 was anomalous, because the March-May long rains began late across most of Kenya, and Tana River County received only 25 to 50 % of normal rainfall (Government of Kenya, 2017). Lower flood levels in 2017 would have reduced land available for flood-recession agriculture, thus increasing the reliance of farmers on fishing (see Mwamlavya *et al.*, 2021). Flexibility in time spent on farming and fishing, as an adaptive livelihood strategy to cope with inter-annual flood variability, is well established in the highly dynamic deltaic systems of the WIO (Duvail *et al.*, 2017; Hamerlynck *et al.*, 2020). In this study, increased fishing effort in the mid and upper estuary by communities that predominantly farm may have obscured typical seasonal trends in the species diversity of fish landings.

Negi and Mamgain (2013) found that fish communities in riverine and estuarine systems follow a pattern of increasing species richness, diversity and abundance from upstream to downstream. The same pattern was observed by Odhengo *et al.*, (2012) in the Lower Tana River Delta, with higher species richness in the lower delta and estuary compared to further upstream in the river. The current study showed a clear gradient in the number of species recorded per location, increasing sharply from the upper (8 spp) and mid estuary (12 spp) to the lower estuary (35 spp) and

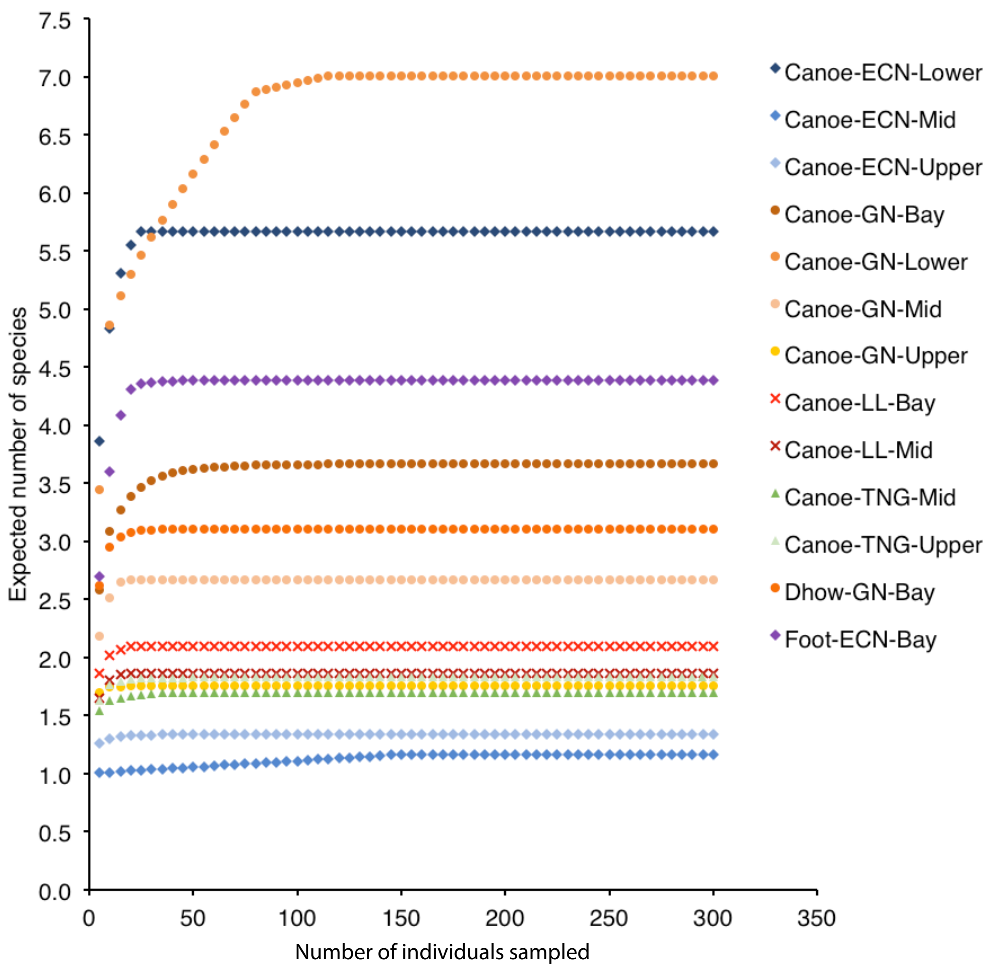

Figure 8. Rarefaction curves indicating the expected total number of species caught by craft-gear combination categories at four locations in the Tana Estuary in Kenya, determined from shore-based sampling of landings and fishing effort in 2017.

bay (71 spp) (Fig. 3). The gradient was not affected by combinations of fishing gear and craft used by fishers, as demonstrated by rarefaction curves in which the expected number of species were consistently greater in the bay and lower estuary compared to upstream locations, irrespective of the gear-craft combinations tested (Fig. 8). Higher biological productivity in brackish water and the presence of estuary-dependent marine species can explain the enhanced species richness in the bay and lower estuary. In contrast, the mid and upper estuary were dominated by a small number of freshwater species.

Factors that influenced the choice of gear were affordability, whether it can be constructed from local materials and easily repaired when damaged (e.g., traps used by part-time fishers in the upper estuary; Mwamlavya *et al.*, 2021), number of fishers required to operate the gear (e.g., 8-15 fishers for large seine nets; Samoilys *et al.*, 2011), gear propulsion by foot, dugout canoe or dhow (Munga *et al.*, 2014a), physical environment (open bay, intertidal or narrow backwater channels) and target assemblage (small pelagic fishes, benthopelagic or demersal fish or invertebrates). Monofilament gillnets are light and easy to transport with canoes and deploy in estuaries and they recorded the highest catch rates in the fishery. The gillnet-canoe combination was popular among fishers in this study, in agreement with Munga *et al.* (2014a). Traditional traps are made locally and cheaply and set in channels to target mainly catfishes (*A. africanus, C. gariepinus* and *P. limbatus*). These species are also targeted by spanning monofilament gillnets across narrow channels, or with seine nets along estuary banks.

Salinity is the dominant factor influencing the distribution of fish species in estuaries (Barletta *et al.*, 2005). The salinity profile of the Tana Estuary is influenced by tides and seasonal freshwater inflow (Kitheka and Mavuti, 2016). Droughts and floods are regular occurrences in Kenya (listed chronologically by Mwaguni *et al.*, 2016), implying that the salinity profile of the Tana Estuary is highly variable. Fishes that are stenohaline, for example *C. gariepinus* that tolerate only low salinity levels up to 2.2 ppt (Brummett, 2008) may undertake lateral migrations, upstream to escape increasing salinity during dry periods, or downstream when the river is in flood. The species composition of landings at any location in the estuary is therefore inherently inconsistant, depending on flood or drought mediated salinity profiles. The results of this study, particularly the species selection by location, should be seen in this light.

In conclusion, the small-scale fishery in the Tana Estuary has a multi-species character and relies on multiple gear types to access different habitats in the estuary. Species composition correlated well with the location of landing sites in the estuary, along a salinity gradient. Seine nets were used throughout the estuary, captured the highest number of species among gear types, and caught smaller individuals of some abundant species (*A. africanus*, *C. gariepinus* and *P. limbatus*) than other gears. Gillnets (mono- and multifilament) also captured a high number of species, mainly in the bay. Traditional traps were used in the upper and mid estuary and caught mainly catfish species. The high complexity and apparent organization of the fishery at estuary-scale makes it a good example of a relatively intact socio-ecological system (SES) in the WIO region, suitable for regional comparative analyses within a theoretical SES framework (Berkes *et al.*, 2014; Santos *et al.*, 2021).

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Appendices

Appendix 1. List of all fish species sampled, including their guild and trophic level (www.fishbase.org) per location (Bay, Upper, Mid and Lower estuary) in the Tana Estuary in Kenya in 2017. (Y=Present, N=Absent)

No.	Species name	Guild	Trophic level	Bay	Lower	Mid	Upper
1	*Arius africanus*	Estuarine	3.8	Y	Y	Y	Y
2	*Clarias gariepinus*	Freshwater	3.76	N	N	Y	Y
3	*Pellona ditchela*	Estuarine	3.95	Y	Y	N	N
4	*Otolithes ruber*	Estuarine	3.6	Y	N	N	N
5	*Plotosus limbatus*	Freshwater	3.91	N	N	Y	Y
6	*Oreochromis niloticus*	Freshwater	2	N	Y	Y	Y
7	*Mugil cephalus*	Estuarine	2.48	Y	Y	Y	N
8	*Sardinella albella*	Estuarine	2.62	Y	N	N	N
9	*Lobotes surinamensis*	Estuarine	4.04	Y	Y	N	N
10	*Protopterus annectens*	Estuarine	3.83	N	N	N	Y
11	*Sardinella melanura*	Estuarine	2.84	Y	N	N	N
12	*Tylosurus crocodilus crocodilus*	Estuarine	4.43	Y	N	N	N
13	*Valamugil buchanani*	Estuarine	2.22	Y	Y	N	N
14	*Galeichthys feliceps*	Estuarine	3.75	Y	N	N	N
15	*Johnius dussumieri*	Estuarine	4.09	Y	Y	N	N
16	*Hilsa kelee*	Estuarine	2.85	Y	Y	N	N
17	*Moolgarda seheli*	Estuarine	2.32	Y	N	N	N
18	*Liza vaigiensis*	Estuarine	2.18	Y	N	N	N
19	*Thryssa vitrirostris*	Estuarine	3.31	Y	Y	N	N
20	*Acanthopagrus berda*	Estuarine	3.5	Y	N	Y	N
21	*Lutjanus fulviflamma*	Estuarine	3.79	Y	N	N	N
22	*Sardinella gibbosa*	Estuarine	2.85	Y	N	N	N
23	*Macrobrachium sp.*	Estuarine		N	Y	N	N
24	*Pomadasys opercularis*	Estuarine	3.53	Y	N	N	N
25	*Nemipterus randalli*	Estuarine	3.5	N	Y	N	N
26	*Sphyrna lewini*	Estuarine	4.08	Y	N	N	N
27	*Trachinotus botla*	Estuarine	3.21	Y	Y	N	N
28	*Carcharhinus leucas*	Estuarine	4.31	Y	N	N	N

No.	Species name	Guild	Trophic level	Bay	Lower	Mid	Upper
29	*Carcharhinus amblyrhincos*	Estuarine	4.11	Y	Y	N	N
30	*Lutjanus rivulatus*	Estuarine	4.13	Y	N	Y	N
31	*Megalops cyprinoides*	Estuarine	3.48	N	N	Y	N
32	*Gerres filamentosus*	Estuarine	3.34	Y	N	N	N
33	*Lethrinus nebulosus*	Estuarine	3.76	Y	N	Y	N
34	*Amphilius jacksonii*	Riverine	2.96	N	N	Y	Y
35	*Euthynnus affinis*	Estuarine	4.13	Y	N	N	N
36	*Penaeus indicus*	Estuarine	3.32	Y	Y	N	N
37	*Plotosus japonicus*	Estuarine	3.66	N	Y	N	N
38	*Gazza minuta*	Estuarine	4.19	Y	Y	N	N
39	*Carcharhinus plumbeus*	Estuarine	4.49	Y	Y	N	N
40	*Epinephelus tauvina*	Estuarine	4.13	Y	N	N	N
41	*Terapon jarbua*	Estuarine	3.93	Y	N	N	N
42	*Lutjanus argentimaculatus*	Estuarine	3.58	N	Y	N	N
43	*Octopus vulgaris*	Estuarine	3.74	Y	N	N	N
44	*Oreochromis hunteri*	Estuarine	2	N	Y	N	N
45	*Penaeus monodon*	Estuarine	3.36	N	Y	N	N
46	*Scylla serrata*	Estuarine	3.17	Y	Y	N	N
47	*Pardiglanis tarabinii*	Riverine	3.47	N	N	N	Y
48	*Pomadasys maculatus*	Estuarine	4.04	Y	N	N	N
49	*Sardinella neglecta*	Estuarine	2	Y	N	N	N
50	*Ambassis natalensis*	Estuarine	3.42	Y	Y	N	N
51	*Caranx ignobilis*	Estuarine	4.22	N	Y	N	N
52	*Carcharhinus melanopterus*	Estuarine	3.94	Y	N	N	N
53	*Chirocentrus dorab*	Estuarine	4.2	Y	N	N	N
54	*Leiognathus equulus*	Estuarine	3.01	Y	Y	N	N
55	*Metapenaeus monoceros*	Estuarine	3.35	N	Y	N	N
56	*Nematopalaemon tenuipes*	Estuarine	3.15	N	Y	N	N
57	*Sillago sihama*	Estuarine	3.33	Y	N	N	N
58	*Epinephelus coioides*	Estuarine	4	Y	Y	N	N
59	*Epinephelus malabaricus*	Riverine	4.16	N	N	Y	N
60	*Leiognathus berbis*	Estuarine	3.31	N	Y	N	N

No.	Species name	Guild	Trophic level	Bay	Lower	Mid	Upper
61	*Panulirus ornatus*	Estuarine	3.74	Y	N	N	N
62	*Plectorhinchus flavomaculatus*	Estuarine	3.99	Y	N	N	N
63	*Scomberoides commersonnianus*	Estuarine	4.36	Y	N	N	N
64	*Sphyraena obtusata*	Estuarine	4.5	Y	N	N	N
65	*Aprion virescens*	Estuarine	4.28	Y	N	N	N
66	*Carangoides ferdau*	Estuarine	4.31	Y	N	N	N
67	*Caranx heberi*	Estuarine	3.7	N	Y	N	N
68	*Carcharhinus macloti*	Estuarine	4.22	Y	N	N	N
69	*Cociella crocodillus*	Estuarine	3.86	N	Y	N	N
70	*Drepane longimana*	Estuarine	3.5	Y	N	N	N
71	*Elops machnata*	Estuarine	3.97	Y	N	N	N
72	*Elops saurus*	Estuarine	3.49	Y	N	N	N
73	*Epinephelus areolatus*	Estuarine	3.74	Y	N	N	N
74	*Gerres oyena*	Estuarine	2.72	Y	N	N	N
75	*Himantura gerrardi*	Estuarine	3.73	Y	N	N	N
76	*Johnius amblycephalus*	Estuarine	3.81	Y	N	N	N
77	*Leiognathus dussumieri*	Estuarine	3.22	Y	N	N	N
78	*Liza melineptera*	Estuarine	2.32	Y	N	N	N
79	*Loxodon macrorhinus*	Estuarine	3.95	Y	N	N	N
80	*Marsupenaeus japonicus*	Estuarine	3.2	Y	N	N	N
81	*Plectorhinchus chubbi*	Estuarine	3.86	Y	N	N	N
82	*Sardinella longiceps*	Estuarine	2.41	N	Y	N	N
83	*Schilbe uranoscopus*	Riverine	3.53	N	N	N	Y
84	*Scomberoides lysan*	Estuarine	4.04	Y	N	N	N
85	*Scomberomorus commerson*	Estuarine	4.36	Y	N	N	N
86	*Secutor insidiator*	Estuarine	2.84	Y	N	N	N
87	*Squalus megalops*	Estuarine	4.34	Y	N	N	N
88	*Stolephorus indicus*	Estuarine	3.33	N	Y	N	N
89	*Trachinotus baillonii*	Estuarine	3.21	Y	Y	N	N

Appendix 2a. Pair-wise comparison tests showing significant differences in species composition of landings by location ($p < 0.05$, bold and italic) in the Tana Estuary in Kenya during shore-based sampling in 2017.

Fishing location comparisons	R-Statistic	P-Value	Possible Permutations	Actual permutations
Bay, Lower	0.226	***0.003***	Very large	999
Bay, Mid	0.57	***0.001***	Very large	999
Bay, Upper	0.469	***0.001***	Very large	999
Lower, Mid	0.409	***0.001***	Very large	999
Lower, Upper	0.426	***0.001***	Very large	999
Mid, Upper	0.014	0.221	Very large	999

Appendix 2b. One-way SIMPER Analysis: Species contributing to the dissimilarity in terms of abundance (%) between locations (bay versus lower) with an average dissimilarity of 86.6 %; bold numbers being species that were most abundant in one season compared to the other season.

	Bay	Lower		
Species	Average Abundance (%)	Average Abundance (%)	Average Dissimilarity (%)	Contribution (%)
Arius africanus	41.38	45.98	19.91	27.15
Pellona ditchela	16.23	**3.25**	8.30	11.31
Otolithes ruber	**14.72**	**0.15**	7.36	10.04
Thryssa vitrirostris	**0.49**	**6.68**	3.41	4.65
Lobotes surinamensis	4.05	3.73	3.39	4.63
Mugil cephalus	4.38	2.50	3.09	4.21
Johnius dussumieri	1.18	5.14	2.95	4.03
Macrobrachium sp.	**0.08**	**4.46**	2.26	3.08
Oreochromis niloticus	**0.00**	**4.31**	2.15	2.94
Sardinella melanura	3.43	0.00	1.71	2.34

Appendix 2c. One-way SIMPER Analysis: Species contributing to the dissimilarity in terms of abundance (%) between locations (bay versus mid) with an average dissimilarity of 88.68 %; bold numbers being species that were most abundant in one season compared to the other season.

	Bay	Mid		
Species	**Average Abundance (%)**	**Average Abundance (%)**	**Average Dissimilarity (%)**	**Contribution (%)**
Clarias gariepinus	0.00	**51.08**	25.54	28.80
Arius africanus	41.38	21.26	20.10	22.67
Pellona ditchela	**16.23**	0.00	8.11	9.15
Otolithes ruber	**14.72**	0.00	7.36	8.30
Plotosus limbatus	0.00	**10.86**	5.43	6.12
Oreochromis niloticus	0.00	**9.51**	4.76	5.36
Mugil cephalus	4.38	2.33	3.25	3.67
Lobotes surinamensis	**4.05**	0.00	2.02	2.28
Sardinella melanura	**3.43**	0.00	1.71	1.93
Sardinella albella	**3.16**	0.00	1.58	1.78

Appendix 2d. One-way SIMPER Analysis: Species contributing to the dissimilarity in terms of abundance (%) between locations (bay versus upper) with an average dissimilarity of 84.40 %; bold numbers being species that were most abundant in one season compared to the other season.

	Bay	Upper		
Species	**Average Abundance (%)**	**Average Abundance (%)**	**Average Dissimilarity (%)**	**Contribution (%)**
Clarias gariepinus	0.00	**50.79**	25.40	30.09
Arius africanus	41.38	29.49	19.84	23.50
Pellona ditchela	**16.23**	0.00	8.11	9.61
Otolithes ruber	**14.72**	0.00	7.36	8.72
Plotosus limbatus	0.00	**11.70**	5.85	6.93
Oreochromis niloticus	0.00	**6.34**	3.17	3.76
Mugil cephalus	**4.38**	0.00	2.19	2.59
Lobotes surinamensis	**4.05**	0.00	2.02	2.40
Sardinella melanura	**3.43**	0.00	1.71	2.03
Sardinella albella	**3.16**	0.00	1.58	1.87

Appendix 2e. One-way SIMPER Analysis: Species contributing to the dissimilarity in terms of abundance (%) between locations (lower versus mid) with an average dissimilarity of 86.82 %; bold numbers being species that were most abundant in one season compared to the other season.

	Lower	Mid		
Species	**Average Abundance (%)**	**Average Abundance (%)**	**Average Dissimilarity (%)**	**Contribution (%)**
Clarias gariepinus	1.40	**51.08**	25.23	29.06
Arius africanus	45.98	21.26	22.16	25.52
Oreochromis niloticus	4.31	9.51	6.26	7.22
Plotosus limbatus	0.00	**10.86**	5.43	6.25
Thryssa vitrirostris	**6.68**	0.00	3.34	3.85
Johnius dussumieri	**5.14**	0.00	2.57	2.96
Mugil cephalus	2.50	2.33	2.35	2.71
Macrobrachium sp.	**4.46**	0.00	2.23	2.57
Lobotes surinamensis	**3.73**	0.00	1.86	2.15
Pellona ditchela	**3.25**	0.00	1.63	1.87

Appendix 2f. One-way SIMPER Analysis: Species contributing to the dissimilarity in terms of abundance (%) between locations (lower versus upper) with an average dissimilarity of 82.58 %; bold numbers being species that were most abundant in one season compared to the other season.

	Lower	Upper		
Species	**Average Abundance (%)**	**Average Abundance (%)**	**Average Dissimilarity (%)**	**Contribution (%)**
Clarias gariepinus	1.40	**50.79**	25.05	30.33
Arius africanus	45.98	29.49	21.86	26.48
Plotosus limbatus	0.00	**11.70**	5.85	7.08
Oreochromis niloticus	4.31	6.34	4.83	5.84
Thryssa vitrirostris	**6.68**	0.00	3.34	4.05
Johnius dussumieri	**5.14**	0.00	2.57	3.11
Macrobrachium sp.	**4.46**	0.00	2.23	2.70
Lobotes surinamensis	**3.73**	0.00	1.86	2.26
Pellona ditchela	**3.25**	0.00	1.63	1.97
Mugil cephalus	**2.50**	0.00	1.25	1.51

Natural resource-use in the Lower Tana River Delta based on household surveys and remote sensing of land cover and land use patterns

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Abstract
Household survey data and spatially explicit Sentinel-2 satellite images of land cover and land use during the dry and wet seasons were used to investigate livelihood strategies in the Lower Tana River Delta in Kenya, where food security and economic activity rely almost exclusively on ecosystem goods and services. Land cover classification of satellite imagery successfully showed seasonal changes to estuary-related vegetation and habitats from which land use cycles could be inferred. Flood-recession agriculture and part-time fishing were the most common activities at Ozi village, some 10 km upstream from the estuary mouth, whereas full-time fishing dominated activities at Kipini town, where the Tana Estuary discharges into Ungwana Bay. Seasonality of fishing at Kipini depended on favourable sea conditions, arrival of migrant fishers and peaks in shrimp abundance. Seasonality of agriculture at Ozi depended on the freshwater flooding regime, visible in satellite images as an inverse relationship of areas covered by wetlands and cultivated lands. The predominance of fishing assets at Kipini indicated specialization, which underlies a socio-economic network of fish processing, marketing, distribution and logistical support services. In contrast, mixed farming assets and traditional fishing gear at Ozi reflected more diversified farmer-fisher livelihoods, as a risk avoidance strategy. Key outcomes of this study were that land cover and land use were strongly seasonal, that coastal and upstream communities in the Tana Estuary relied on different combinations of ecosystem goods and services, and that livelihood strategies at the two locations differed fundamentally. Combining social, spatial and ecological data to describe socio-ecological systems typical of the Tana Estuary provided a broad platform for shared resource management strategies.

Keywords: Tana Estuary, resource-use, livelihoods, artisanal fishing, flood-recession farming

Introduction
Deltas and estuaries of the Western Indian Ocean (WIO) form unique and highly productive wetland ecosystems, including mosaics of mangrove and riverine forests, floodplain grasslands, vegetated sand dunes, brackish water habitats and seasonal freshwater lakes (Kitheka *et al.*, 1998; Hamerlynck *et al.*, 2010; Scheren *et al.*, 2016). They are rich in natural resources and have high socio-economic importance as a source of food, freshwater, fuelwood and building materials to local communities. Rural livelihood strategies associated with these deltas are adapted to seasonal flooding patterns, and are diversified and often complementary (Duvail *et al.*, 2017).

The Tana River Delta in Kenya discharges into Ungwana Bay through four main estuaries – the main channel that discharges into the bay at Kipini town

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(hereafter called Tana Estuary), Mto Kilifi, Mto Tana and Mto Moni (Scheren *et al.*, 2016). The Tana Estuary is typical of the WIO region, where seasonal flooding replenishes freshwater resources, nutrients and sediments (Leauthaud *et al.*, 2013; Duvail *et al.*, 2017). Livelihood activities around the estuary are highly diverse, including typical 'fish-based farming systems' made up of mixed fishing/farming households (Hamerlynck *et al.*, 2020). Livelihood activities are organized according to the availability of arable land, adequate fresh water supply, access rights, cultural institutions, and social and demographic dynamics (Smalley and Corbera, 2012). Key activities are flood-recession farming of rice, horticulture of mangoes, coconuts, bananas, beans and vegetables on sandy levees, and maize in mixed soils, fishing in freshwater wetlands, the estuary and nearshore Ungwana Bay, livestock herding on communal rangeland, and small-scale businesses to supply basic needs (Hamerlynck *et al.*, 2010, 2020).

Small-scale fisheries are a key socio-economic component of estuary-dependent livelihoods in the WIO (Dzoga *et al.*, 2020; Manyenze *et al.*, 2021; Mugabe *et al.*, 2021). In the Ungwana Bay region, Ochiewo *et al.*, (2006) identified fisher age, size of fishing vessel and fishing duration as factors that influenced yields from fishing, and Dzoga *et al.*, (2018) found fishing communities to be vulnerable to ecological change. Conflicts between fishing sectors reflected competition for fish resources (Munga *et al.*, 2014a), exacerbated by a seasonal influx of coastal migrant fishers (Fulanda *et al.*, 2009). Dzoga *et al.*, (2020) and Manyenze *et al.*, (2021) described the fishing gear and crafts used in the Tana Estuary, selectivity of gear, and the key species in landings. Apart from the latter studies, research on fisheries resources and fishers have focused mainly on coastal and offshore resources in Ungwana Bay (Fulanda, 2003; Fulanda *et al.*, 2011; Munga *et al.*, 2012, 2013, 2014a, 2014b, 2016), but the importance of fishing in livelihood strategies around the Tana Estuary has received scant attention.

Agriculture is of great importance to the Kenyan economy, and even more so in rural areas such as Tana River County, where some 86 % of the inhabitants have livelihoods based on farming (Muraguri and Gioto, 2013; van Beukering *et al.*, 2015). Not surprisingly, most socio-economic studies in the region have focused on the broader Tana River Basin, to address impacts of damming, water abstraction (Maingi and Marsh, 2002; van Beukering *et al.*, 2015) and agricultural intrusions into adjacent habitats on livelihoods (Terer *et al.*, 2004; Mireri *et al.*, 2008; Lebrun *et al.*, 2010; Duvail *et al.*, 2012, 2017; Leauthaud *et al.*, 2013; Krijtenburg and Evers, 2014). Ecosystem assessments of the Tana River Basin found substantial degradation in the upper catchment, moderate degradation in the middle catchment, and low degradation levels in the lower basin, which includes the present study area (Kamau and Wasonga, 2015; van Beukering *et al.*, 2015). Despite low ecological degradation levels in the Tana Estuary, upstream water abstraction and land cover change for agriculture and economic development disrupt the volumes and seasonal pulses of freshwater flooding, thus affecting traditional livelihood strategies based on crop farming, fishing and livestock herding (Hamerlynck *et al.*, 2010; Kamau and Wasonga, 2015; Kitheka and Mavuti, 2016; Mwaguni *et al.*, 2016; Odhiambo-Ochiewo *et al.*, 2016).

A key environmental management objective in developing countries is to devise appropriate strategies for natural resource use, without disrupting livelihood and food security imperatives (Sulu *et al.*, 2015). In the WIO, formal (top-down) resource management strategies cannot be successfully implemented without accounting for pre-existing traditional resource management systems, which arose from a historical trial and error process (McClanahan *et al.*, 2009; Benkenstein, 2013). Socio-ecological systems (2-way feedback relationships that link human to natural systems in a dynamic equilibrium) are complex and adaptive, and facilitate resilience and sustainability (Berkes *et al.*, 2003; Gallopín, 2006; Ostrom, 2009). A multi-user and multifunctional socio-ecological entity, adapted to local conditions in the Lower Tana, has for centuries supported local communities while also maintaining exceptional biodiversity value (Terer *et al.*, 2004; Hamerlynck *et al.*, 2010), demonstrating high resilience and flexibility. Nevertheless, livelihoods are now under threat from the combined effects of climate change, altered river flow and flooding regimes caused by building of dams and land use change in catchment areas, and increasing exploitation of local resources to support a growing population (Hamerlynck *et al.*, 2010; Duvail *et al.*, 2017).

The use of household survey data to obtain information on household budgets (income and expenditure), assets and livelihood activities is explored by Deaton (1997), with Blythe *et al.* (2014) and Blythe (2014) providing good examples of studies on WIO small-scale fisheries. Remote sensing is a useful tool for mapping coastal and marine habitats (van Sydow, 2002) and critical ecosystems (e.g. mangroves) particularly in inaccessible regions (Kirui *et al.*, 2013; Furaca *et al.*, 2021). Depending on the spatial and spectral resolution and the image analysis used, satellite images can provide a cost-effective means of mapping physiognomic vegetation features (e.g. Marzialeti *et al.*, 2019), coastal wetlands (Mahdavi *et al.*, 2017) and coastline morphology (Kumar *et al.*, 2010), including shoreline changes resulting from sediment deposition or floods (Shaghude *et al.*, 2003). Remote sensing also lends itself to estimating socio-economic and social anthropological effects and changes in coastal communities, i.e. the spatial and structural changes of agriculture over time (Pricope *et al.*, 2019; Furaca *et al.*, 2021). The aims of this study were to assess the livelihood strategies of communities residing around the Tana Estuary, and their reliance on seasonally variable ecosystem goods and services, based on data from household surveys and a spatial analysis of land cover images. A spatially explicit baseline map of land cover and key livelihood activities is provided for two rural communities; Kipini town at the mouth of the Tana Estuary, and Ozi village, some 10 km upstream.

Figure 1. Sentinel-2 satellite imagery used for land cover changes over the seasonal cycle of high (25th June 2017; 10th July 2018) and low (25th February 2018; 2nd March 2019) rainfall in the Tana Estuary and lower delta Area of Interest (AOI).

Materials and methods

Existing information on the geographical setting, ecosystems and socio-ecological importance, and key drivers of socio-ecological change around the Tana Estuary have been summarized in the introductory paper of this Special Issue (Groeneveld *et al.*, 2021). Briefly, the Tana Estuary (Fig. 1) receives runoff from a medium-sized basin comprising the Central Kenya Highlands, particularly the southern slopes of Mount Kenya and eastern slopes of the Aberdare mountain ranges (Maingi and Marsh, 2002). The basin is seasonally flushed during the transitions between the Northeast (NE) and Southeast (SE) monsoons, although downstream flow is partially regulated by dams and changes in land-use (Scheren *et al.*, 2016). The communities surrounding the Tana Estuary and lower delta comprise Pokomo, Orma, Bajuni and other smaller ethnic groups (Government of Kenya, 2009). Traditionally, Pokomo are farmers and riverine fishers while Orma are pastoralists (Leauthaud *et al.*, 2013). The Ozi and Kipini study sites are inhabited by distinct communities. Ozi is almost entirely inhabited by Pokomo, whereas Kipini is multi-ethnic with several groups represented, also from other parts of Kenya. Both Kipini and Ozi were categorized as low-density developments; these two areas are quite remote in a county with population density of 8 persons/km^2 (Government of Kenya, 2019).

Study area

An area of interest (143.41 km^2) was selected around the Tana Estuary incorporating the estuarine-related and supporting habitats across several zones. The zones were based on a combination of *in situ* estuarine attributes (e.g. salinity), information from satellite images of land cover and land use and ascertained knowledge of livelihood activities of inhabitants. On the ground data collection was concentrated in only two of six zones; around Kipini town and Ozi village. Zone 1 around Kipini (45.49 km^2) comprised mainly densely and sparsely distributed mangroves, barren land, grasslands, coastal and mixed forests, estuarine open water and cultivated land. Zone 2 around Ozi (9.28 km^2) comprised cultivated land, mainly rice paddies mixed with banana and mango farming, some fallow land, vegetated wetlands and mixed forests. The zones were used to define resource use activities as they related to land cover and land use.

Spatial data collection

Remotely sensed images of the Tana Estuary were used to establish seasonal land cover changes. Sentinel-2 images from the European Space Agency Copernicus Program, available since 2016, were used with two criteria: that images had at least 5-6 month intervals to represent rainfall seasonality, and that cloud cover was <20 % of the area of interest. A land cover classification scheme was adapted from the United States Geological Survey (USGS) and the National Oceanic and Atmospheric Administration (NOAA) Coastal Change Analysis Program (C-CAP). The classification scheme comprised of 7 high-level categories and 23 sub-categories relevant to estuarine systems (Table 1). An object-based imagery analysis approach was adopted using a support vector machine classifier on a GIS (ArcMap™ GIS) using the RGB and NIR bands (Red, Green, Blue and Near-Infrared). Classification of land cover categories was carried out using the maximum likelihood classification algorithm. Model training and validation was conducted using a combination of ground truth methods. Limited study area access and human capacity mostly obligated the use of high-resolution imagery for this analysis step. Of 314 ground truth points used, 15 were geolocated ground photos, 81 were obtained from Google Earth™ imagery and 218 from ESRI base map imagery (source DigitalGlobe, 0.5 m resolution). Accuracy assessments were conducted using the overall classification accuracy, being the percentage of correctly classified samples of an error matrix and the Kappa statistic providing a statistically valid assessment of the classification quality. A Kappa value > 0.5 was considered as satisfactory for modelling land use change (Pontius, 2000).

Household surveys and collection of other socio-economic data

The study proposal was approved by the Ethics Review Committee of Pwani University (No. ERC/MSc/016/2018) accredited by the National Commission for Science, Technology and Innovation (NACOSTI) of Kenya. A systematic sampling design was used for household surveys, in which each ith house was selected after dividing the total number of households in each village by the required sample size to get approximately 12.3 % coverage. Sample size for each village adopted calculations by Dzoga *et al.*, (2018) which were determined by the infinite Cochran (1977) formula. The survey targeted household heads, where a household was defined as all individuals housed and dependent on one head (Kronen *et al.*, 2007, 2012). In cases where the selected house could not be sampled, the next house was chosen, with the assistance of the local Beach Management Unit (BMU) chairman. Semi-structured interviews using questionnaires were conducted in Swahili, and the expression of new ideas was encouraged. Information was captured on household location, gender and age of household head, household size, livelihood activities, education level, and monthly income with variables on assets used for fishing and farming. Categories for livelihood activities were derived from the number of activities in which a household was engaged. Following Béné (2009), fisher households were grouped into two categories according to the importance of fish as a source of income: full-time fishers not engaged in any other activity for income generation; and part-time fishers that derive their income from fishing but are also engaged in other activities (e.g. fishing, farming

Table 1. Land Cover/ Land Use classification system and definitions used for Tana Estuary study (adapted from Michigan Resource Information System, MIRIS National Oceanic and Atmospheric Administration, NOAA, 1976).

	ID	Land cover category	Definition
Water	1	Coastal open water	All areas of open coastal water.
	2	Estuarine plume	Formation of water resulting from the discharge of low-salinity water into marine waters of the ocean, forming a distinct layer of water on top of the seawater due to its lower density.
	3	Estuarine water	Partially enclosed water body where saltwater is measurably diluted with fresh water.
	4	Turbid estuarine water	Suspended sediment, muddy water within the estuary. Influenced by the catchment, runoff and/or recent rains/floods.
Developed Land	5	Medium density - formal development	Contains a mixture of residential, commercial and industrial development, including infrastructure.
	6	Low density - informal development	Sparsely distributed informal rural settlements.
Barren Land	7	Coastal bare unconsolidated sediment	Includes material such as sand that lacks vegetation and falls outside the intertidal zone along the coast.
	8	Coastal intertidal unconsolidated sediment	Includes material such as sand that is subject to inundation and redistribution due to the action of water. Substrates lack vegetation and falls within the intertidal zone.
	9	Estuarine intertidal unconsolidated sediment	Includes material such as sand within the estuary that is subject to inundation and redistribution due to the action of water. Substrates lack vegetation and falls within the intertidal zone.
Forest Land	10	Coastal forests	Woody vegetation closely located to the seashore.
	11	Disturbed forests	Areas dominated by woody vegetation in between agricultural land and developed areas.
	12	Mixed forests	Consists of forested areas where there is a mixture of woody vegetation and shrubland.
Grassland	13	Disturbed herbaceous	Areas dominated by grammanoid or herbaceous vegetation often occuring in between agricultural land and developed areas. Could include previous agricultural/transformed land now occupied by vegetation.
Cultivated Land	14	Subsistence - harvested land	Contains subsistence agricultural areas that are managed for the production of harvested row or field crops. Often fairly mixed in between fallow land.
	15	Subsistence - fallow land	Contains agricultural areas that have no physical indication of present agricultural use. These areas include both abandoned cropland and fields left fallow or in a process of a crop rotation cycle. An indication of inactive cropland is the presence of any woody stems in the field.
	16	Mariculture	Structures related to mariculture

	ID	Land cover category	Definition
Wetlands	17	Mangroves - densely distributed	Woody vegetated wetland areas and floodplain forests dominated by densely distributed mangroves. This could either be different mangrove species or well-established mangroves which appears to be densely packed.
	18	Mangroves - sparsely distributed	Forested wetland areas and floodplain forests dominated by sparsely distributed mangroves. This could either be different mangrove species or younger mangroves which appear to be more scattered.
	19	Swamp forests	Areas dominated by woody vegetation (other than mangroves) where the soil or substrate is periodically saturated with or covered with water.
	20	Intertidal mudflats	Areas of non-vegetated, natural cover that are subject to seasonal and tidal ponding, soil saturation, or flooding.
	21	Vegetated wetlands	Wetland areas dominated by lowland brush, shrubs and herbaceous vegetation.
	22	Non-vegetated wetlands	Wetland areas lacking vegetation.
	23	Vegetated wetlands burnt	Wetland areas that have burnt

and others). Four categories were selected for education level; *viz* no education, primary education, secondary education and higher education. Focus group discussions were undertaken at the two study sites to define resource use activities in each estuary zone, based on the perceptions of locals.

Data on the numbers of fishing craft and gear types used by communities at Kipini and Ozi were obtained from Manyenze *et al.*, (2021). Information on population demographics was obtained from reviewing existing data from the Kenya National Bureau of Statistics (Government of Kenya, 2009), and information on migrant fishers, vessel owners and crew as summarized by Fulanda *et al.*, (2009).

Results

Land cover and estuary-related habitats

The first monsoon period (June, July) was considered to be 'high rainfall' and the hot, dry period after the second rains (February, March) to be the 'low rainfall' period for land cover comparisons. In this context, the lower delta is a highly dynamic system with changes dictated by annual flooding events. Satellite imagery showed a vastly different estuary during the high- (25.06.2017, 10.07.2018) compared to the low rainfall period (25.02.2018, 02.03.2019) (Fig. 1). Land cover classification using seasonal timestamps was successful in showing changes to estuary-related vegetation and habitats (Fig. 2). The sediment-laden water plume into Ungwana Bay with a dominant oligohaline salinity signature was associated with the high rainfall period. In contrast, the plume disappeared during dry periods, suggesting a stratified salinity gradient between upper and lower water masses.

For the accuracy assessment (i.e., how good the images and classifications were at depicting land cover), the 25.02.2018 image was used as it had the least amount and spread of clouds. Of 314 ground truth points, 12 were cloud-covered and had to be removed. An overall accuracy of 71 % was achieved (kappa value of 0.64) translating to a moderate to substantial strength of agreement. Classification classes contributing to lower accuracy scores were cultivated land (32 % modelled correctly), forests (28 % of modelled forests were actual forests after validation) and mudflats (50 % accurately classified after validation).

Across successive wet and dry cycles, the most prominent seasonal changes were observed in wetland, mangrove, cultivated land and grassland categories.

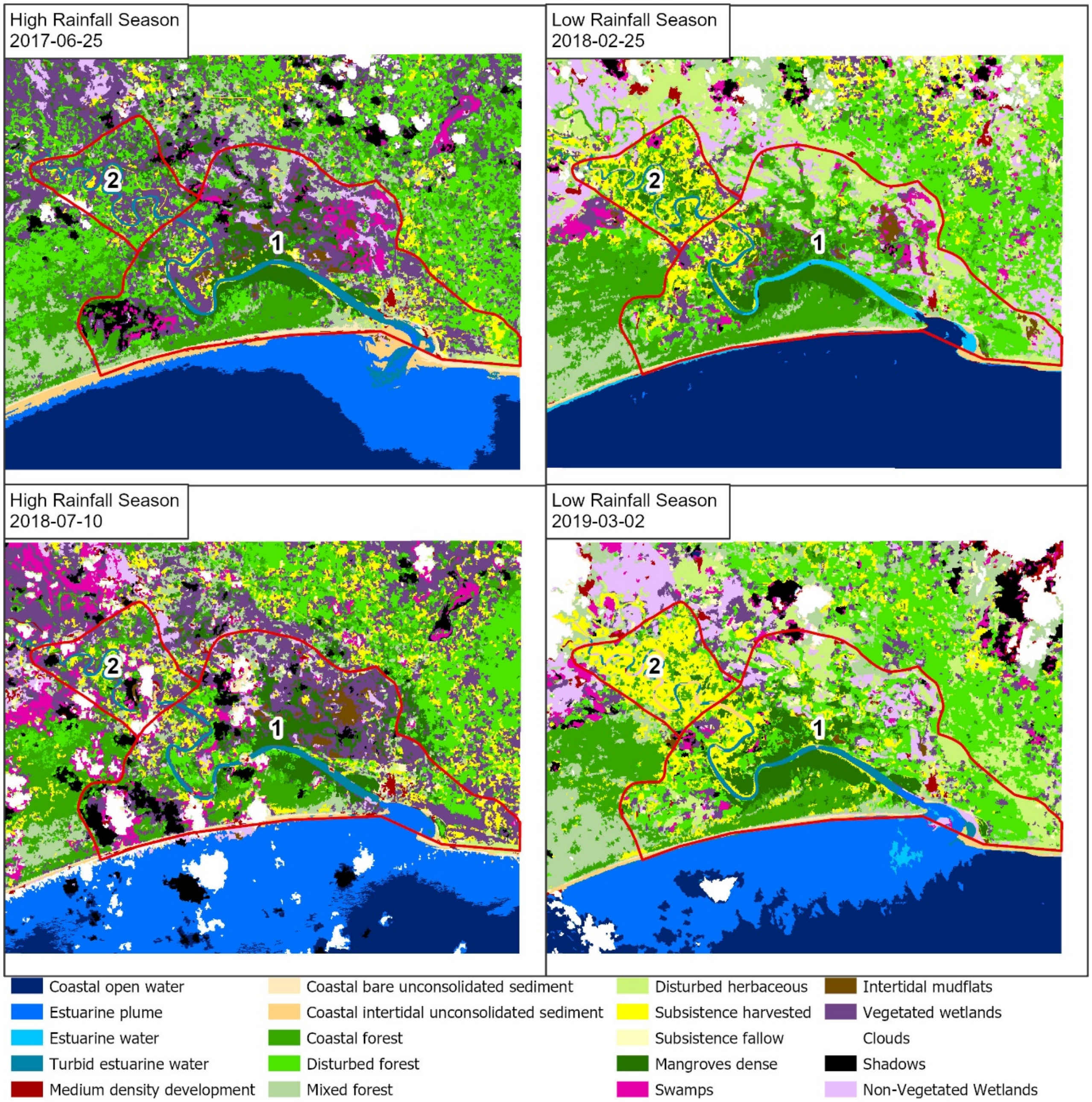

Figure 2. Land cover classification zones at Kipini (Zone 1) and Ozi (Zone 2) over the seasonal cycle of high and low rainfall in the Tana Estuary and lower delta.

Wetlands dominated during the wet seasons and were related to an increase in mangroves and a decrease in cultivated lands and grasslands, which increased during the dry season (Fig. 3). These changes had a marked influence on the temporal use of livelihood resources by inhabitants. In Zone 1 (influenced by Kipini), wetlands and grasslands decreased during the dry months, with cultivation increasing marginally across seasons after the high rainfall season (Fig. 4). Kipini residents were more reliant on fishing during the dry season, when prawns were seasonally abundant (Munga *et al.*, 2013), and depressions along the main channel in Zone 1 were flooded by marine waters during high tides, making flood plains unsuitable for crops such as rice. Grasslands in slightly elevated areas in Zone 1 increased when freshwater wetlands, further from the main channel, dried during the dry season, making Zone 1 suitable for cattle herding. Wetlands showed a strong seasonal rhythm, approximately doubling in size during the wet months. In Zone 2 (Ozi) the size of the wetlands and cultivated lands were inversely related, reflecting the expansion of rice paddies during

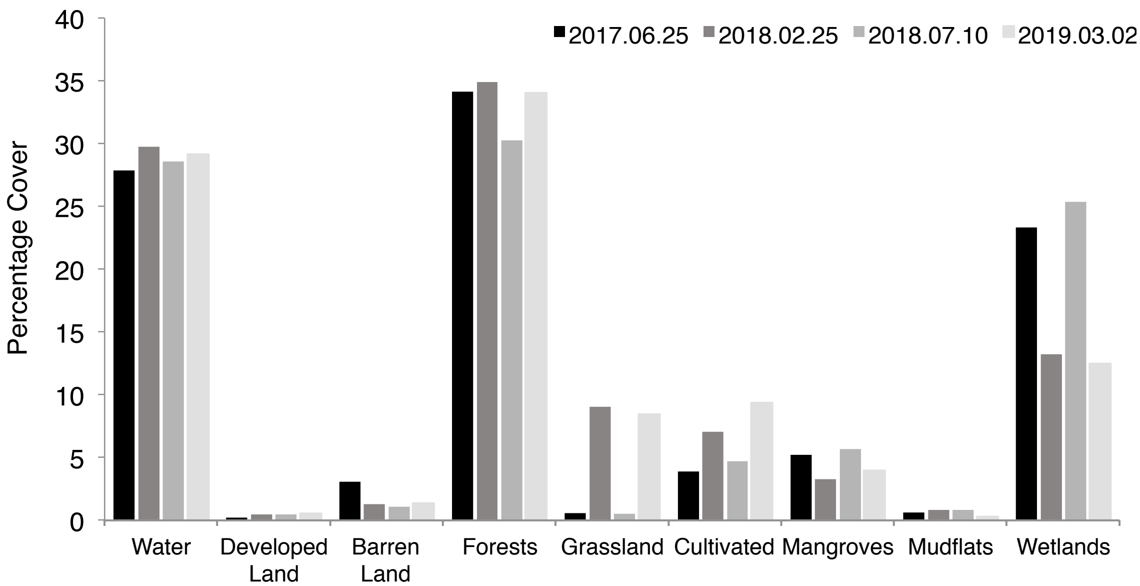

Figure 3. Tana Estuary and lower delta AOI seasonal land cover (%) change across estuarine function and habitat categories. Rainfall seasons are high (25th June 2017; 10th July 2018) and low (25th February 2018; 2nd March 2019).

the flood recession after the rainy season, as arable land becomes available for planting after floods (Fig. 4).

Socio-economic analysis (demography, income and assets)

The population census (Government of Kenya, 2009) indicated a total of 801 and 389 households at Kipini town and Ozi village, respectively. Data from 146 households were analyzed comprising 71 from Kipini (8.9 % of households) and 75 from Ozi (19.3 % of households). Crop farming, fishing, livestock keeping, and other small businesses were key parts of local economies at the two sites. Farming was the main livelihood activity at Ozi compared to full-time fishing at Kipini (Fig. 5). By gender, farming was the preferred activity of men and women respondents (Fig. 5), but only men were full-time fishers. Some women fished part-time from the shore. Some 60 % of farmers had a secondary

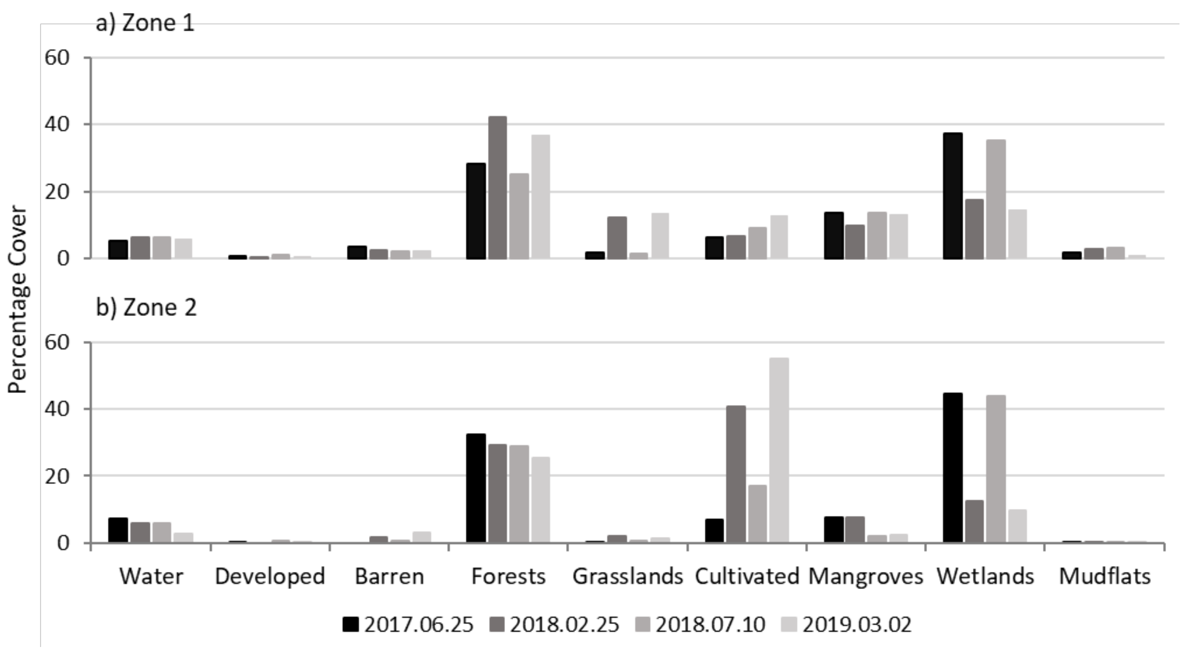

Figure 4. Tana Estuary and lower delta seasonal land-cover (%) change across categories associated with estuarine function and habitat in a) AOI Zone 1 (Kipini) and in b) Zone 2 (Ozi). Rainfall seasons are high (25th June 2017; 10th July 2018) and low (25th February 2018; 2nd March 2019).

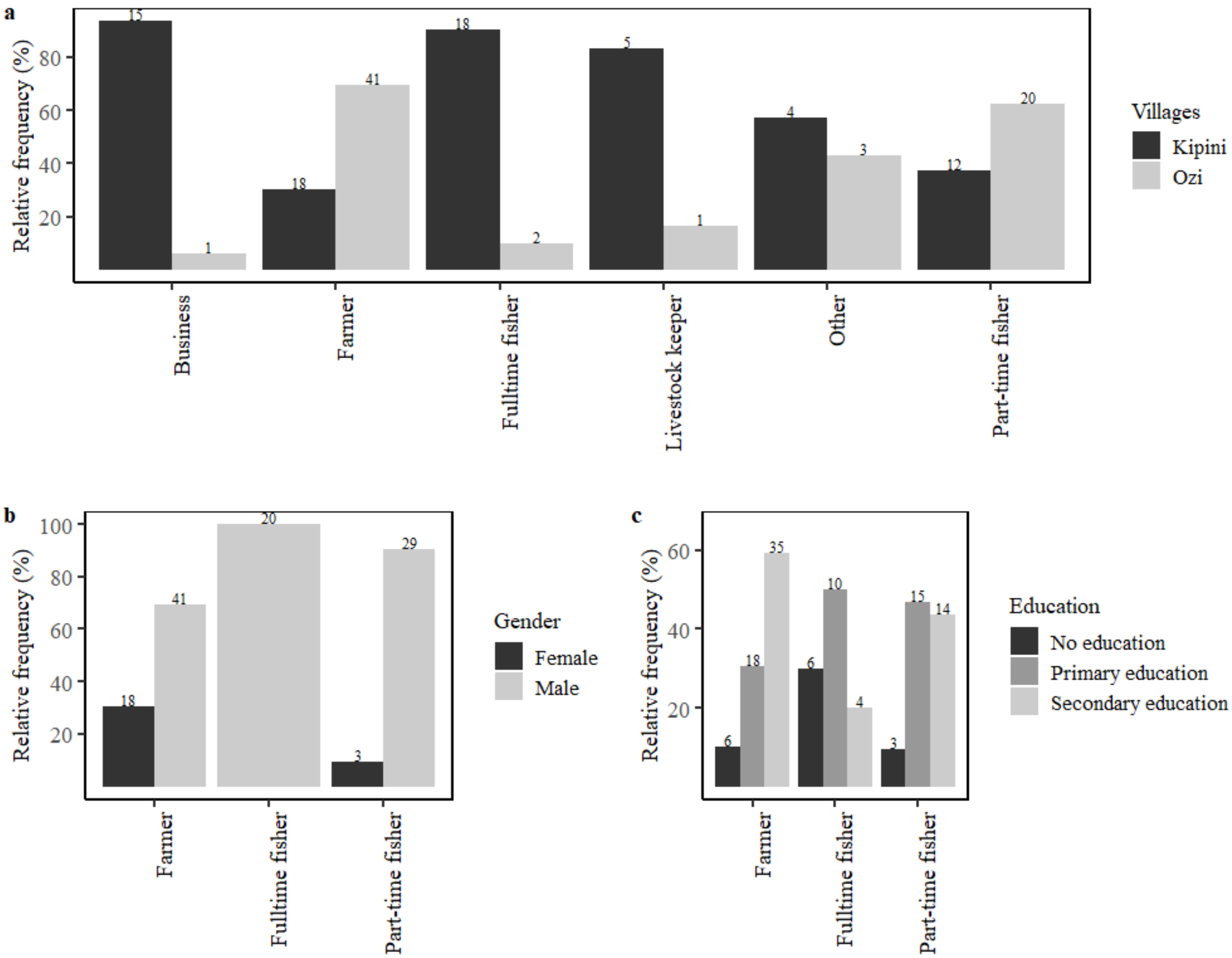

Figure 5. Relative frequency of livelihood activities in the Tana Estuary and lower delta, obtained from household survey data. The frequency of activities was compared: (a) by location; (b) by gender; and (c) by level of education.

Table 2. Relative importance of fishing crafts and fishing gear types at Kipini and Ozi, respectively, obtained from a shore-based survey of small-scale fisheries (see Manyenze *et al.* 2021; dash means not recorded).

	Kipini		**Ozi**	
Fishing craft	(n)	(prop)	(n)	(prop)
Canoes	289	0.92	226	1.00
Dhows	22	0.07		
Fibreglass boat with outboard engine	2	0.01		
Fishing gear	(n)	(prop)	(n)	(prop)
Gillnets	242	0.62	32	0.14
Seine nets	73	0.19	40	0.17
Hook-and-line	73	0.19	16	0.07
Traditional traps	-	-	132	0.57
Other	5	0.01	13	0.06

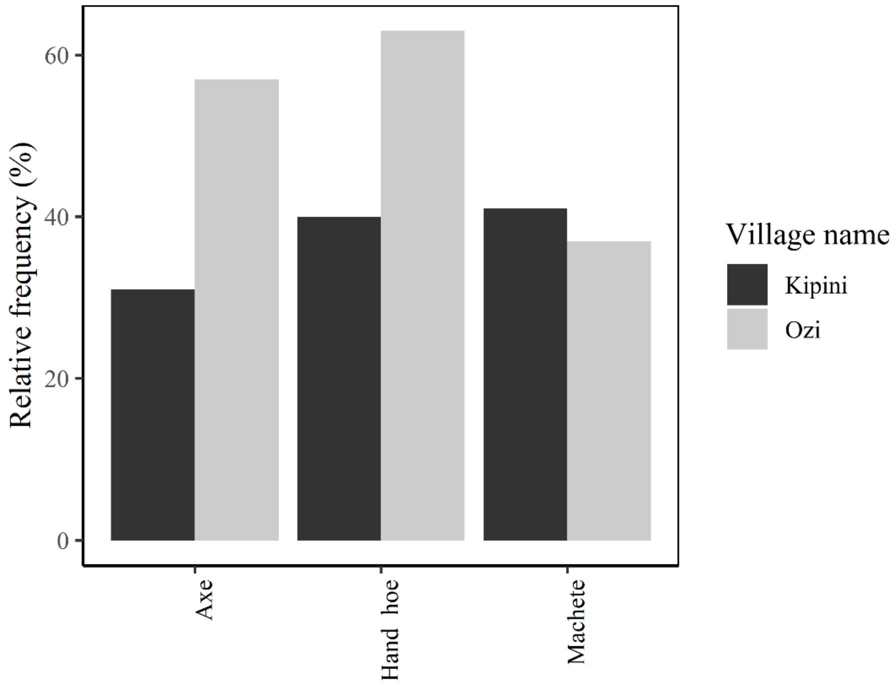

Figure 6. Relative number of farming assets and their distribution among communities at Kipini and Ozi.

school education, followed by 45 % of part-time fishers. Most full-time fishers had either a primary school education (~50 %) or had not been to school (~30 %). Household size of full-time fishers was 7 ± 3 people, and slightly fewer at 6 ± 3 for part-time fishers and farmers, respectively. Farmer household heads were 44 ± 14 yrs old, compared to part-time fisher household heads (42 ± 10 yrs) and full-time fishers (40 ± 8 yrs). A Kruskal-Wallis test indicated no significant difference in household size (K = 1.4377; p = 0.4873) and household head age (K = 1.3493; p = 0.5093) between the different livelihood activities.

Farmers earned an income of US$ 110 ± 70 per month, compared to US$ 140 ± 90 for full-time fishers. Combining the two activities as part-time fishers increased earnings to US$ 170 ± 100 per month. Men earned some 50 % more than women (US$ 150 ± 110 versus US$ 100 ± 80 per month). A Kruskal-Wallis test confirmed that the mean income of household heads differed significantly between livelihood activities (K = 9.3147; p = 0.009), and a pair-wise post-hoc comparison confirmed that farmer and part-time fisher incomes differed significantly (p = 0.007).

Dug-out canoes were the most common craft type at Kipini and Ozi, used for fishing and transporting people and goods (Table 2). Dhows and fiberglass boats with outboard engines were present at Kipini for use in Ungwana Bay, but they were absent from Ozi. Traditional traps made from locally available wood and fibre made up 57 % of gear used around Ozi, but they were absent from the Kipini landing site. The bulk of fishing gear at Kipini comprised of gillnets (62 %), seine nets (19 %) and hook-and-line (19 %, including longlines and handlines). Overall, assets used for fishing activities were more abundant at Kipini (62 % of all gears) than at Ozi. A greater proportion of respondents at Ozi owned farming tools than at Kipini, including axes (61 % of respondents at Ozi *versus* 39 % at Kipini) and hand hoes (65 % *versus* 35 %), but machetes were evenly distributed (47 % *versus* 53 %) (Fig. 6).

Discussion

Household survey information confirmed that livelihood strategies at Kipini and Ozi differed according to the available natural resources, inferred from the land cover assessment. Farming (mainly flood recession agriculture) and fishing were the two most important economic elements, with their intensity varying spatially and seasonally. Full-time fishing as a livelihood source dominated at Kipini, where fishing in Ungwana Bay and the lower Tana Estuary provided employment opportunities to fishers, processors, distributors and in the maintenance of gear and craft. In contrast, flood recession agriculture dominated at Ozi, complemented by part-time fishing in the upper Tana Estuary.

Wetlands at Ozi approximately doubled during wet months, and cultivated land and wetlands were inversely related in this area (see Fig. 4). Rice is planted biannually at the start of each rainy season in paddies on the upper floodplains near Ozi. Paddies are located so that they are irrigated when daily incoming tides elevate fresh surface waters onto the floodplains (Terer *et al.*, 2004). Hedges between rice paddies (elevated by ~1 m) were often stabilized by banana plantations. Other crops such as maize, beans, squash, sweet potatoes and cassava are cultivated shortly after the floods on slightly higher and sandier zones. Leathaud *et al.* (2013) noted that crops were selected according to water requirements and planted along the hydrological upper floodplain-lower floodplain gradient, gradually following the recession after floods. Cultivated mango plantations were located further from the floodplain, on higher ground, although some large trees grew close to the riverbank near Ozi.

Part-time fishing at Ozi complemented the income from agriculture and increased seasonally during periods when fields are inundated by flood waters. Locally made traditional fish traps (mgono) are set as stationary gear in flooded areas and deeper water along the riverbank (Dzoga *et al.*, 2020; Manyenze *et al.*, 2021). Trapping is a passive fishing method, and hence a farmer can leave the trap to fish while his effort is directed elsewhere. For example, traps and longlines (also a passive gear) can be set while in transit between crop fields, by foot or canoe, and retrieved on return. Apart from traps and longlines, sharpened sticks, seine nets and sometimes gillnets are also used for fishing in the mid and upper Tana Estuary (Dzoga *et al.*, 2020; Manyenze *et al.*, 2021). Farming combined with part-time fishing contributed more to household incomes at Ozi than farming alone.

Full-time fishing at Kipini utilized both the bay and lower estuary, with access to extensive fishing grounds that include several productive habitat types and many different fish and invertebrate species. Household data indicated that fishing in Kipini is seasonal, with rough seas during the windy SE monsoon season restricting fishers to shallow waters and sheltered river channels. The SE monsoon coincides with a period of high rainfall and high shrimp abundance in the estuary and on mudbanks in Ungwana Bay (Munga *et al.*, 2013). During this period, monofilament nets attached to two mangrove poles are dragged over the substrate in shallow waters to catch shrimps. Shrimps fetch good prices in urban centers such as Mombasa and Malindi (Munga *et al.*, 2013) and are therefore popular target species. Migrant fishers arrive after the SE monsoon during calmer sea conditions to target finfish in productive areas in nearshore waters where the Tana Estuary discharges into Ungwana Bay (Fulanda *et al.*, 2011). The satellite images could not provide any additional information on the full-time fishery at Kipini.

Based on household information, livestock keeping was a household amenity rather than a livelihood source at the two study sites. Livestock roamed freely and were observed to drink from the estuary at Kipini, most likely during an ebb tide when freshwater at the surface replaced denser saline water. Terer *et al.* (2004) noted that livestock keeping was an important livelihood activity for pastoralists living further upstream from the present study sites, because of access to freshwater and grasslands on floodplains. The satellite images confirmed the seasonal expansion and contraction of grasslands. Pastoralists move livestock herds closer to the delta for grazing during the dry season, when riparian grasslands expand following the flood recession (Duvail *et al.*, 2017; Hamerlynck *et al.*, 2020).

The ownership of fishing and farming assets in the Ozi and Kipini communities reflected the dominant livelihood activities. At Ozi, dugout canoes were used for transport and fishing, but at Kipini the use of dugout canoes was augmented by larger seagoing vessels such as dhows. A broad range of gear types was used for fishing at both sites, but home-made traditional traps were the gear of choice at Ozi, compared to gillnets, seine nets and hook-and-line at Kipini (also see Munga *et al.*, 2014b; Dzoga *et al.*, 2020; Manyenze *et al.*, 2021). A higher investment in fishing gear at Kipini reflected specialization in fishing as an economic activity to supply local markets. Kipini fishers spent more days per week fishing compared to Ozi, where flexible farmer-fisher livelihoods prevailed as a risk-avoidance strategy (Terer *et al.*, 2004; Duvail *et al.*, 2017; Hamerlynck *et al.*, 2010, 2020). Blythe *et al.* (2014) showed that specialized fishers in Mozambique adapted to declining catches by intensifying their fishing effort, in contrast to other groups without access to fishing gear, who adapted through diversification. They concluded that adaptation is a heterogeneous process that is influenced by multiple factors. Likewise, the results of the present study suggest that specialized fishers and farmer-fisher communities at the Tana Estuary would rely on different strategies to adapt to increased livelihood stressors, such as declining catch rates, droughts and floods.

Household surveys at Kipini and Ozi could not detect a difference in household size, or the age of household head, irrespective of livelihood strategies followed. Primary and secondary school education levels were most common, with fewer full-time fishers having a secondary education, presumably because migrant fishers without formal education were included in sampling. Mwangudza *et al.* (2016) similarly reported low education levels in resource dependent communities, which prevented them from acquiring the necessary skills to secure formal employment. Kipini recorded a higher number of respondents engaged in 'other businesses' (i.e. not fishing or farming) showing diversification, but Ozi remains a remote community, reliant on the exploitation of natural resources within an established socio-ecological entity. The low levels of formal education at both localities are expected to hinder adaptation to a modernizing economy (Benkenstein *et al.*, 2013; Blythe *et al.*, 2014).

The present study found important linkages between local livelihood strategies and natural resource distribution around the Tana Estuary. Critical questions that now need to be asked are how the two communities will adapt to the effects of climate change, population growth and the livelihood stressors brought by a modernizing economy and infrastructure development in catchment areas? Further semi-quantitative modelling of the socio-ecological entities described in the present study, to predict the effects of changes brought by governance initiatives, societal flux or natural perturbations, is provided by Santos *et al.*, (2021).

In conclusion, complementary use of household survey data and satellite images to assess the relationship between livelihood strategies and seasonal flux in land cover and land use practices at the Tana Estuary provided several important insights. Full-time fishing dominated activities at Kipini, compared to farming (mainly flood-recession agriculture) and part-time fishing at Ozi. Activities at both locations were strongly seasonal, but not in synchrony. At Kipini, seasonality of fishing was determined by sea conditions in Ungwana Bay (unfavourable during the SE monsoon), arrival of migrant fishers and seasonal shrimp abundance in nearshore waters. At Ozi, the flooding regime determined seasonal agricultural and fishing activities, confirmed by the inverse relationship between wetlands and cultivated lands, and wetlands and grasslands, shown on satellite images. As a larger town with an established economy, Kipini offers diverse employment opportunities. In contrast, livelihood strategies at Ozi depended almost entirely on natural resource use, with flexibility to cope with variable resource availability. Key outcomes of this study were that land cover and land use were strongly seasonal, that coastal and upstream communities in the Tana Estuary relied on different combinations of ecosystem goods and services, and that fundamentally different livelihood strategies included both specialization and diversification. Environmental change will therefore affect the communities at Kipini and Ozi in different ways.

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A regional assessment of seasonal-to-decadal changes in estuarine socio-ecological systems in the Western Indian Ocean

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Abstract
Estuarine socio-ecological systems (SES) in the Western Indian Ocean (WIO) region face mounting pressures from overexploitation, habitat degradation, impacts of climate change and governance inadequacies. A regional assessment of seasonal-to-decadal change in SES of three estuaries (Bons Sinais in Mozambique, Ruvu in Tanzania and Tana in Kenya) was undertaken along 2000 km of tropical coastline (3°-18°S), using a systems-oriented approach and information collected during the Estuarize-WIO project (2016-2019). All three estuaries were open and tidal, but differed along gradients of geomorphology, annual precipitation, exposure to tropical storms, drought, sea level rise, and rural to urban development. Despite physical differences, similar marine species, mangrove assemblages, seasonality in fish-based farming systems and cultivated crops, and fishing methods were apparent across the region. Key differences were related to the scale of anthropogenic disturbance, discerned from land use / land cover (LULC) change analysis, which showed decadal increases in developed-, cultivated- and grasslands, at the expense of wetlands and forests, and seasonal transformation of wetlands to agriculture and grasslands. The three estuaries represented a gradient along urban-production-conservation dimensions, brought about by rural to urban transformation, and by freshwater and sediment diversion for economic development in upstream catchment areas. Household surveys indicated strongly seasonal livelihood strategies, with highest diversity in peri-urban settings, and reliance on different combinations of ecosystem goods and services in coastal and upstream rural settings. Estuarine fisheries ranged from unselective, low trophic-level fisheries using fine-mesh nets at the urbanized and most-disturbed Bons Sinais Estuary, to a more complex organized fishery at the least-disturbed Tana. At Ruvu, fisheries and agriculture production exit the system to distant markets. The systems-oriented approach demonstrated that human-induced processes affected WIO estuaries and dependent livelihoods more deeply than inherent physical differences. A key conclusion is that research, management and governance will benefit from regional cooperation, given the similarities of the systems and the different levels of disturbance.

Keywords: estuaries, socio-ecological change, WIO region, fisheries, regional comparative analysis, systems-level causal loop analysis, East Africa

Introduction
The Estuarize-WIO project (2016-2019) was funded by the Western Indian Ocean Marine Science Association (WIOMSA; www.wiomsa.org) to compile datasets on biophysical, ecological, socio-economic and fisheries aspects of selected estuaries in the Western Indian Ocean (WIO), and to integrate the information using a socio-ecological systems (SES) framework (Groeneveld *et al*., 2021a). Analysis of the datasets resulted in a series of peer-reviewed studies published in the present Special Issue (SI). Individual studies of the Bons Sinais Estuary in Mozambique (located at 18°S) focused on the

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circulation profile of the estuary (Hoguane *et al.*, 2021), household dependence on fish-based farming (FBF) systems (Francisco *et al.*, 2021), and urbanization and critical habitat loss through land cover change (Furaca *et al.*, 2021). Estuarine fisheries using unselective gear from trends in land use and land cover (LULC) and estuarine fisheries (Groeneveld *et al.*, 2021b), including an opportunistic fishery for invasive freshwater prawns (Kuguru *et al.*, 2019). At the Tana Estuary in Kenya (3°S), LULC was strongly seasonal, with coastal and upstream

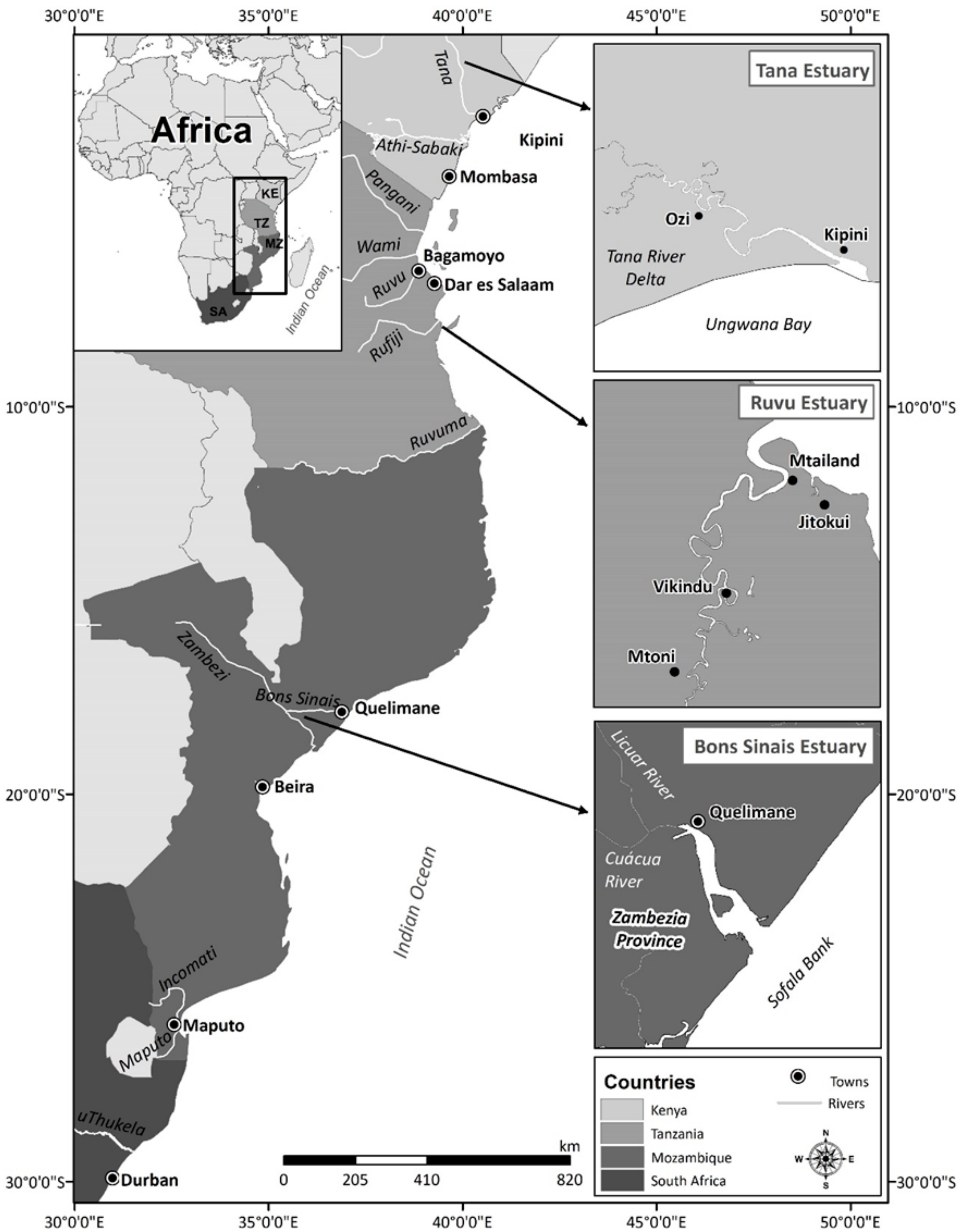

Figure 1. Study area showing the locations of the Bons Sinais-, Ruvu- and Tana Estuaries in the Western Indian Ocean. Insets show place names at each estuary (Source: Groeneveld *et al.*, 2021a).

relied on low trophic level species, mainly small pelagic fishes and penaeid prawns, and formed an integral part of local SES (Mugabe *et al.*, 2021). At the Ruvu Estuary in Tanzania (6°S) socio-ecological change was inferred communities relying on different combinations of ecosystem goods and services (Mwamlavya *et al.*, 2021). Estuarine fisheries at Tana were complex and highly organized at an estuary scale (Manyenze *et al.*, 2021).

The Estuarize-WIO studies have now generated a substantial volume of information on the individual estuaries, but a comparative study across WIO estuaries is still lacking. The Bons Sinais, Ruvu and Tana Estuaries represent a coastline of some 2 000 km along a tropical latitudinal gradient (3°S-18°S) (Fig. 1). They are located in some of the least developed countries of the global south, where traditional livelihoods still dominate in rural areas, contrasted with a transition to urban livelihoods and an increasingly modern lifestyle in growing towns and cities (UNEP-Nairobi Convention and WIOMSA, 2015). Traditional livelihoods along water bodies in the WIO (typically FBF systems; Hamerlynck *et al.*, 2020) have faced several pressures in recent history: increasing demand and overexploitation of natural resources by rapidly growing human populations; degradation of habitats caused by human activities; and the effects of climate change on the distribution of resources (UNEP-Nairobi Convention and WIOMSA, 2015). Governance systems in the WIO region are ill-equipped to deal with the mounting challenges, with funding, logistical and skilled manpower shortages, and an incomplete understanding of the coastal systems to be managed (UNEP-Nairobi Convention and WIOMSA, 2015).

The objectives of this final paper of the Estuarize-WIO SI were to: a) summarize the information available to Estuarize-WIO; b) undertake a regional comparison between the three estuaries; and c) explore SES and interactions (linkages and feed-back loops) between human use patterns and natural resources (goods and services). For the latter, a systems- and causal loop analysis was used (Haraldsson, 2004; Ortiz *et al.*, 2021) and it was assumed that the three estuaries share various traits because of their geographical location in the WIO, but that they are uniquely influenced by subtle differences in climate, estuarine morphology and hydrodynamics (influencing each ecosystem), and anthropogenic impacts. It is shown that the methodological approach developed for Estuarize-WIO (see Groeneveld *et al.*, 2021a) is well-suited to socio-ecological research in data poor systems with limited field accessibility and research infrastructure.

Materials and methods

Regional comparison

The study area (Fig. 1) is described in detail in Groeneveld *et al.* (2021a). Spatial scales considered were individual estuaries and specific zones within estuaries, defined by salinity gradients (Hoguane *et al.*, 2021; Groeneveld *et al.*, 2021b; Manyenze *et al.*, 2021), LULC patterns (Furaca *et al.*, 2021; Mwamlavya *et al.*, 2021) and the influence of urbanization (Francisco *et al.*, 2021). Temporal scales were seasons within a year (wet and dry; high and low river flow; southeast [SE] monsoon and northeast [NE] monsoon conditions) and decades, extending back to the mid-1980s and early 1990s (Furaca *et al.*, 2021; Groeneveld *et al.*, 2021b; Mwamlavya *et al.*, 2021).

All information used in the regional assessment (including from original research and a comprehensive literature survey) are summarized by discipline for: physical and hydrological characteristics (Supplementary Table S1); demography, urbanization, socio-economy, livelihoods and governance (Table S2); trends in LULC (Table S3); and estuarine fisheries (Table S4). The metadata of datasets collected during field sampling for Estuarize-WIO are provided in Table S5, and individual datasets are available on request.

Integration across disciplines made use of schematic representations to illustrate trends and gradients by estuary and across the region. Two sources of anthropogenic impacts on estuaries were considered throughout this study: local resource use patterns within the estuary (direct); and activities in catchments (indirect) that affect the volume, water quality and seasonality of freshwater discharged into estuaries (e.g., papers in Diop *et al.*, 2016; Duvail *et al.*, 2017).

Exploration of interactions (links, feedback loops) in SES

The social-hydrological-technological-ecological systems observed in the three river-estuary-coast continuums form typical complex systems, with positive and negative feedbacks at different scales (Wesselink, 2020). To highlight the causes and disentangle them from the effects in such a complex setting, wider-scale systems-thinking was adopted. Frameworks that are strongly structural with pre-defined procedures, such as DPSIR (Binder *et al.*, 2013), were therefore rejected, and inter-disciplinary frameworks with common protocols were rather relied upon to develop a systems-oriented approach to show how sub-sets of this general framework can be used to intervene in local SES. The multi-scale and multi-disciplinary approach required a varied data acquisition strategy, from literature searches to satellite imagery, field observation, expert interviews, semi-structured interviews of households, fish sample collection and analysis of official catch and effort statistics (see Supplementary Tables S1-S5).

Table 1. Working hypotheses and justification for causal loop analysis and exploration of interactions (links, feedback) in socio-ecological systems (SES) of the Western Indian Ocean (WIO).

Working hypothesis	Theoretical justification	Key questions
A close connection exists between social and natural systems, with feedback loops	Interactions have co-evolved since historical times to form complex relationships in SES theory (Berkes *et al.*, 2014)	Are interactions similar across estuaries of the WIO?
Seasonal rhythms of human activity are adapted to a range of alternative livelihoods	Seasonally variable environments have given rise to generalist knowledge and skills (Elliott and Quintino, 2007; Blythe, 2014)	Do differences in SES fit a seasonal pattern of alternative livelihood activities?
Latitudinal gradients exist in WIO estuarine ecology, socio-economic organization and cultural influences	Subtle differences in climate, topography, biota and culture are expected to exist along a 2000 km long coastline	Do differences in SES fit a latitudinal pattern, or are they externally determined?
Natural resource use is opportunistic and broad-based, with limited regard for prescribed governance measures	Livelihood strategies follow tradition, suited to culture and environment, as opposed to official regulations (Benkenstein, 2013)	Should environmental management primarily reflect traditional, or modern theoretical approaches?
Demand for natural resources outstrips supply, resulting in overexploitation, habitat degradation and loss of function	Global climate change, population growth, dwindling resources and lack of leadership threaten estuarine SES (UNEP-Nairobi Convention and WIOMSA, 2015)	How can the effects of climate change on SES in WIO estuaries be mitigated?

A causal loop analysis was selected which relies on diagrammes that connect nodes through flows (Haraldsson, 2004; Ortiz *et al.*, 2021). Causal loop analysis is appropriate for the diagnosis of recurrent dilemmas, and the search for potential solutions by comparing similar situations and remedies across estuaries in the WIO. In causal loop diagrammes, arrows connect variables, and a change in one variable may cause an increase (+ arrow) or decrease (- arrow) in another variable in the system. Double arrows (+ and -) were also used to indicate new mechanisms introduced to mitigate obvious problems, for example dredging to deepen channels for shipping.

The framework of Brondizio *et al.* (2016) was adapted to characterize functional interdependencies as coupled socio-ecological systems. At an estuary scale, the livelihood strategies of households, seasonality of farming practices, fish catches made in different estuary zones and gear selectivity, ecological footprints of fishing inferred from trophic analysis, areas covered by mangroves, and the growth of developed (urbanized) areas were analysed. At a regional scale, explorative models considered different types of tele-coupling (Liu, 2013), including socio-demographic (e.g., population growth, ethnic groups, migrations, core-periphery relationships), economic (market chains, livelihood strategies, exports), ecological (fishing technology, trophic levels, invasive species, land-cover), material (abstraction of freshwater, sediments and nutrients, land-use), and climate-hydrological (seasonal trends, precipitation and weather regimes, estuarine circulation). The working hypotheses for constructing models reflected the comparative nature of the study (Table 1).

Results and discussion

Regional comparative analysis

Climate and seasonality (Fig. 2)

Two distinct seasons occur along the East African Coast, dictated by the position of the Inter-Tropical Convergence Zone. The SE monsoon (March to October) is characterized by strong southerly winds, high cloud cover, rainfall, river discharge and terrestrial runoff (McClanahan, 1988). These parameters are reversed during the NE monsoon (November to

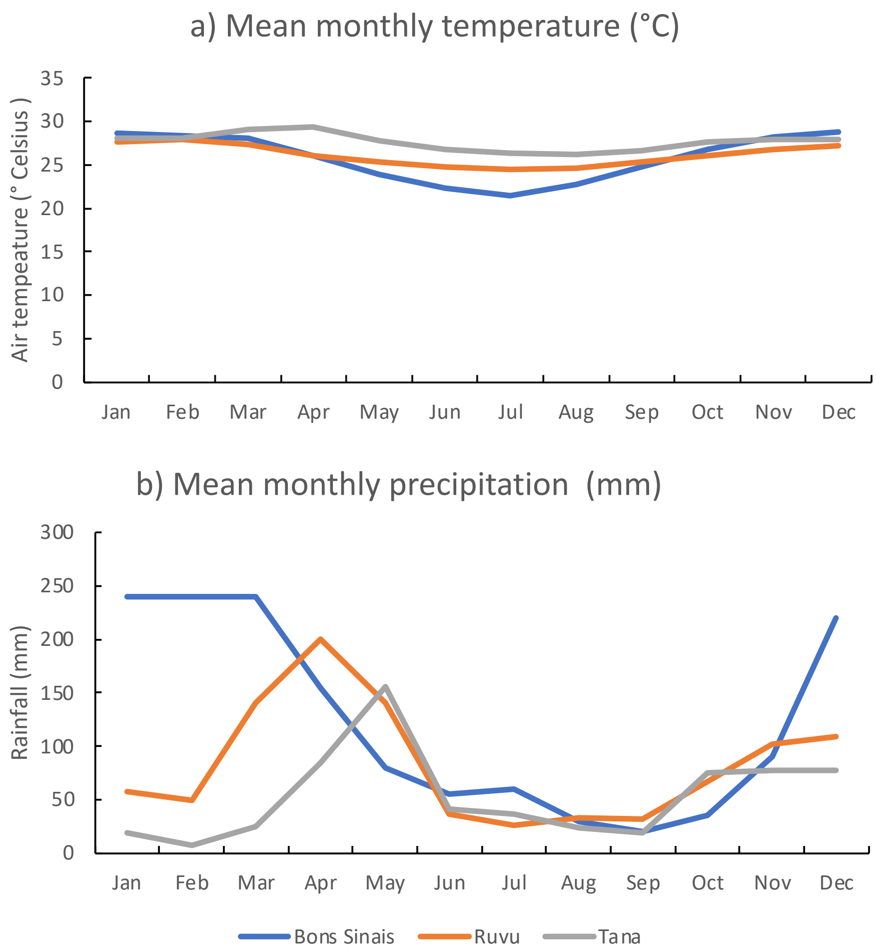

Figure 2. Mean monthly temperature (a) and precipitation (b) at the Bons Sinais- Ruvu- and Tana-Estuaries (https://world-climates.com and https://www.weather-atlas.com/en/kenya/kipini)

February). The Bons Sinais Estuary lies at the southern extreme of the monsoon system, where its effects are less evident than at Ruvu and Tana. Atmospheric circulation and rainfall at Bons Sinais are associated with the South Indian Convergence Zone, which brings summer rains and dry winters to SE Africa.

Monthly mean temperatures across the WIO region fluctuate only moderately (Fig. 2a), with highest variability at Bons Sinais (>28 °C in summer months declining to 21 – 23 °C in winter, minimum values of 16 – 17 °C). Temperature differences are less marked at Ruvu (24 – 28 °C, remaining > 21 °C in winter) and at Tana, the most equatorial estuary (26 – 29 °C, remaining > 23 °C in winter).

Mean annual precipitation (mm) declines from south to north (~ 1500 mm/y at Bons Sinais; 1000 mm/y at Ruvu; 900 mm/y at Tana). Mean monthly precipitation at Bons Sinais is > 200 mm/month in December to March declining to < 60 mm/month in June to October (Fig. 2b). Precipitation at Ruvu is bimodal, peaking in March-May (~200 mm/month) and November to December (~100 mm/month). Precipitation at Tana peaks during the inter-monsoon (March-May; 45 % of annual rainfall) called the long rains, and again in November to December (25 %) called the short rains. Regionally, precipitation is lower between July and October (dry season) and the wet season shifts from summer at Bons Sinais (December to March) to a bimodal pattern of long and short rains at Ruvu and Tana.

Physical characteristics and freshwater flow (Table S1; Fig. 3)

Morphology: The Bons Sinais Estuary is a remnant of the large deltaic floodplain of the Zambezi-system, reduced to a single relatively shallow channel (~10 m deep) with a gentle slope. It discharges onto the northern part of the Sofala Bank, a coastal area exposed to adverse sea and weather conditions. The Ruvu Estuary was originally part of a medium-sized fluvially

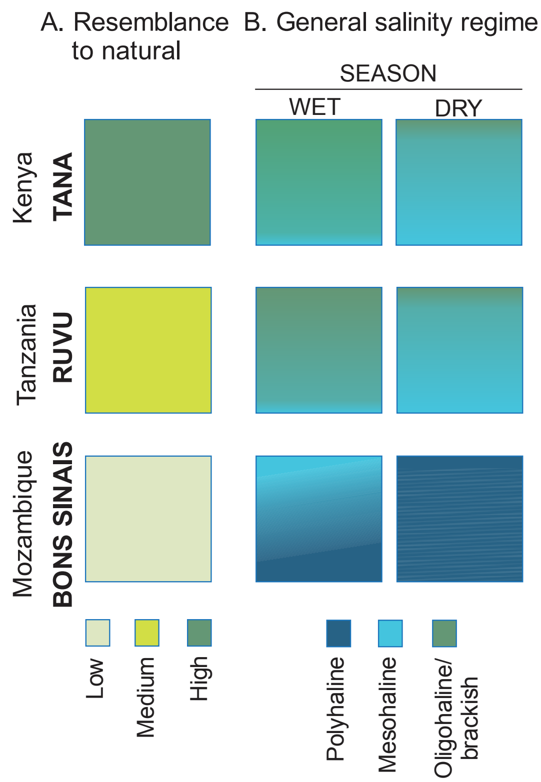

Figure 3. Overall estuary characteristics for the Bons Sinais, Ruvu and Tana estuaries as: (A) resemblance to natural function in terms of freshwater flow and estuarine-related habitats; and (B) present salinity regime that drives estuary functions (e.g. nursery function) during wet and dry seasons.

dominated deltaic system, of which the remnant is a single shallow and meandering estuary channel (~ 3 m deep) with deltaic characteristics at its mouth and offshore. The slope is steeper than at Bons Sinais, and the estuary discharges into the shallow Zanzibar Channel. The present Tana Estuary was originally a smaller outflow of the lower Tana Delta, with the main estuary (called Mto Tana) located 30 km to the SW. Human intervention changed the configuration of deltaic estuaries in the late 19th Century. Mto Tana became a silted tidal creek and other channels were closed to avoid salinization of wetlands. The present estuary is a single shallow channel (~ 5-8 m deep) with a funnel shaped mouth. The slope is steeper than the Bons Sinais, and discharges into Ungwana Bay.

Tidal reach: A large tidal amplitude (>4 m at spring tides) in the WIO and regulated freshwater runoff have given rise to tidally dominated estuaries during dry seasons. The tidal influence is most prominent at Bons Sinais, reaching ~30 km upstream, resulting from a flat landscape and severely reduced freshwater supply (Fig. 3). Tidal sandbars indicate transport of marine sediments into the estuary by strong currents. A high incidence of tropical storms in a low-lying coastal area creates a high risk of exposure to sea-level rise. The steeper landscapes at Ruvu and Tana reduces tidal reach to <15 km upstream of the mouth. Both estuaries have funnel-shaped mouth areas and channel geometry that reflect a strong tidal influence. Tidal reach in the Tana increases during droughts, and now extends further than before dam construction upstream in the 1980s, which resulted in sediment deficits and erosion in the estuary.

Freshwater supply: Upstream water extraction and damming for hydro-electric power, domestic use, agriculture and industry combined with changing land use practices in catchments have substantially reduced freshwater input to the three estuaries. The Bons Sinais is the most severely impacted. Damming of the upper Zambezi River for hydro-electric power during the 1950s to 1970s, and of the Shire River greatly reduced the extent of floods and floodplains, disconnecting the Cuacua River (a tributary feeding into the upper Bons Sinais River) from the main Zambezi Channel. Runoff into the Bons Sinais Estuary now relies on direct rainfall and flow through feeder rivers. The Ruvu River supplies critical freshwater resources for domestic use, industrial and agricultural development in and around Dar es Salaam and the coast. Wastewater from the cosmopolitan area has moderately impacted downstream water quality (Alphayo and Sharma, 2018). Freshwater derived from the Wami-Ruvu catchment is an important strategic resource, managed by the Wami-Ruvu Basin Water Office. Groundwater extraction along the coast between Dar es Salaam and Bagamoyo contributes to salinization of the water table (GLOWS-FIU, 2014a). The freshwater flow into the Tana Estuary is similarly depressed and delayed through discharge regulation at upstream dams with extraction for agriculture and domestic use. Freshwater flooding is highly seasonal with frequent droughts.

Salinity regime: Seasonal salinity profiles differ substantially among the three estuaries (Fig. 3). The Bons Sinais has a small sub-catchment area and a truncated river inflow. Freshwater inflow is mainly rainfed, resulting in a partially to well-mixed polyhaline estuary over its entire length during the dry season, becoming mesohaline in its upper reaches during the wet season. The Ruvu is fluvially dominated and rainfed during the wet season and estuarine conditions are then truncated near the mouth and offshore, with mainly oligohaline / brackish and freshwater conditions extending upstream from the mouth. Mesohaline conditions extend further upstream during the dry season, when fluvial influence decreases. The Tana is oligohaline along its full length during the 3-month wet season, becoming mesohaline in its lower and mid-reaches during the remainder of the year.

Land / sea connectivity (exchange of water, sediments, nutrients, biological material; access for ships): Connectivity and the typical estuarine regime at Bons Sinais has been severely impacted, as inferred from a predominantly marine salinity regime and tidal dominance. Satellite images show increased prevalence of sandbanks in the lower estuary which will require continuous dredging to prevent future mouth closure. Dredging maintains access for shipping to the port in Quelimane. Land / sea connectivity at Ruvu is highly dynamic – the estuary moves offshore during the high flow season and satellite images show that fluvial sediments contribute to a delta forming north of the mouth (Shagude *et al.*, 2003). The mostly intact land / sea connectivity makes Ruvu a major contributor of important sediments, nutrients and biological material to the Zanzibar Channel. The Tana discharges significant amounts of nutrients and sediments into Ungwana Bay, reaching ~24,000 tons per day during the March-April rainy season (Mutia *et al.*, 2021). The coastal enrichment is a major driver of phytoplankton biomass in Ungwana Bay, but remains locally within the bay rather than influencing the broader open waters of the North Kenya Banks. Sand banks at the estuary mouth and coastal erosion north of the mouth indicate reduced connectivity during the dry season.

Mangroves: Extensive mangrove forests at all three estuaries provide critical nursery habitats for fish and crustaceans that inhabit the estuarine and coastal areas of the WIO, as well as a diversity of coastal services, such as land stabilization and storm protection. *Avicennia* (a pioneer species adapted to disturbance and changes in temperature and salinity) dominate at Bons Sinais, which additionally indicate the variable climate there, intensive mangrove harvesting and habitat degradation associated with urbanization. At Ruvu, mangroves are dominated by *Rhizophora* along the exposed marine edge and in tidal creeks, with *Avicennia* more prevalent in the upper reaches and bordering on freshwater creeks. The mangrove forest at Tana is dominated by *Rhizophora*, *Ceriops* and *Avicennia* along an ocean-upstream gradient of stable seawater tidal inundation to more inhospitable, less inundated inland forest margins. The gradient is more prevalent at Tana and Ruvu than at the more disturbed peri-urban forests at Bons Sinais.

Historical settlements, urbanization, demographics, socio-economics and livelihoods (Table S2; Fig. 4)

Historical settlement and recent trends in urbanization: The Bons Sinais is located along a challenging coast for maritime navigation, with few alternative natural harbours nearby. The estuary provides a navigable passage for ships (max. length 86 m; draught 3.2 m; GRT 3135t; www.marinetraffic.com) surrounded by mangrove forests and protected from easterly storms. Access to the hinterland (initially along waterways) made it a good outpost for trading, originally as a Swahili trade center in the pre-colonial era, and as a Portuguese colonial town (Quelimane) after 1761. Rapid population growth in 1977-1992 occurred during civil war displacements from the inland to the coast. Urban growth over the past 30 years (2.6 % population growth; expansion of built area) increased the population of Quelimane to 400 000 in 2020 (https://populationstat.com/mozambique/quelimane), with a high demand for space, water, food, fuelwood, transport,

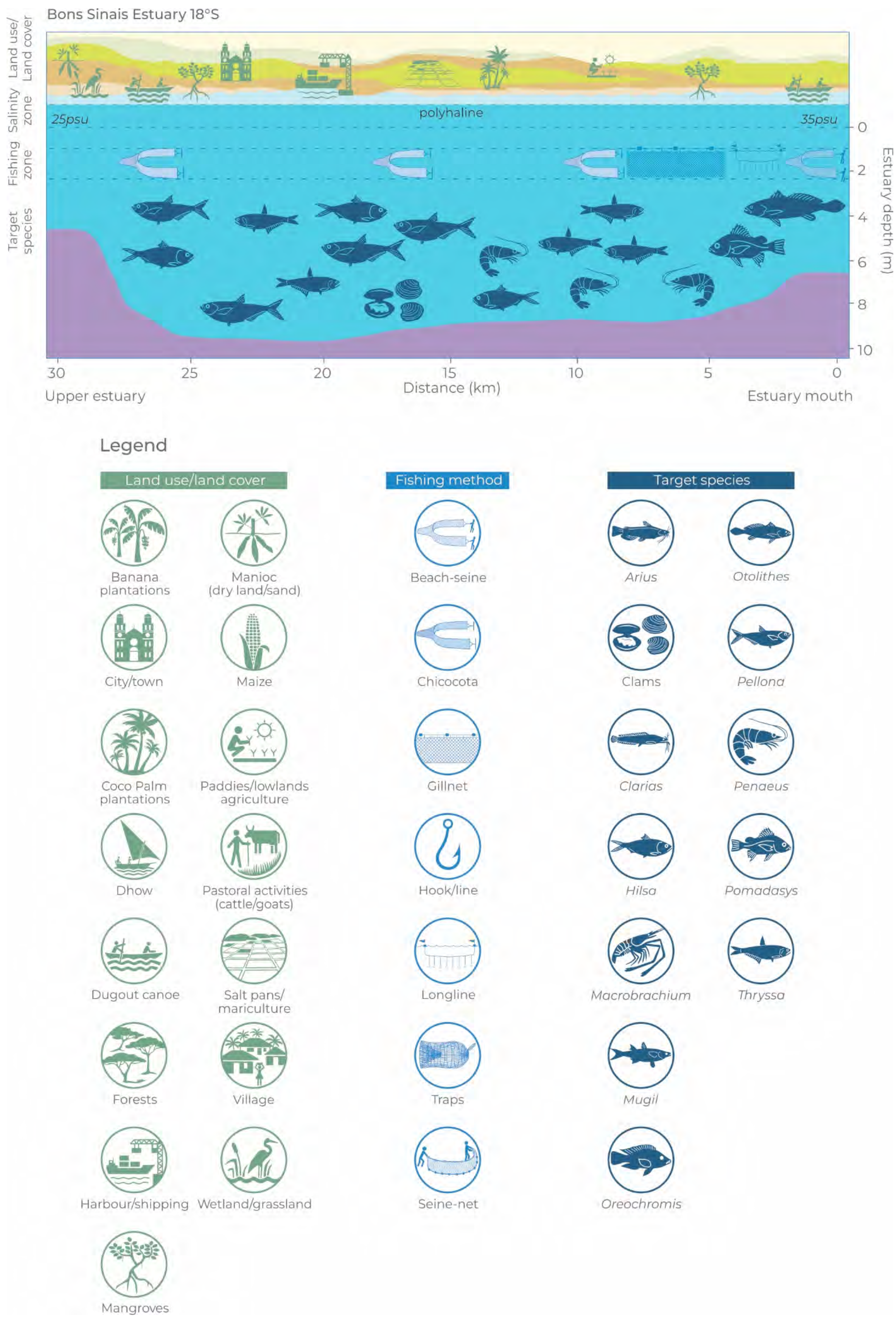

Figure 4a. Schematic diagramme of the Bons Sinais Estuary in Mozambique, depicting its physical characteristics (length, depth, salinity zones), land use and land cover, fishing zones, gears and commonly fished species per zone (not to scale).

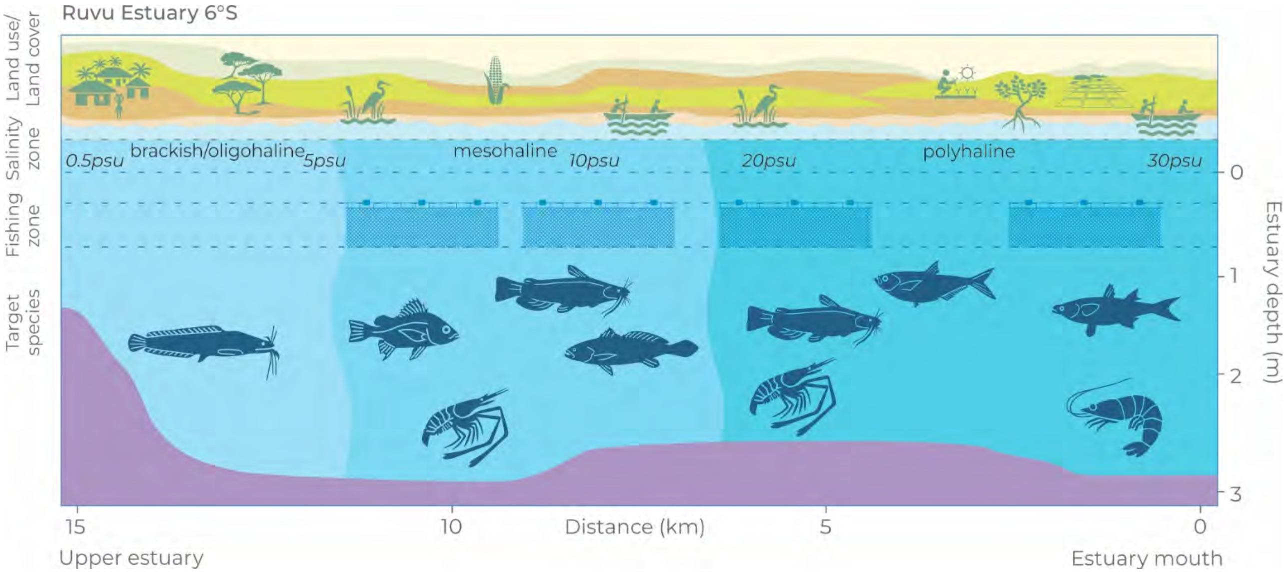

Figure 4b. Schematic diagram of the Ruvu Estuary in Tanzania, depicting its physical characteristics (length, depth, salinity zones), land use and land cover, fishing zones, gears and commonly fished species per zone (not to scale). Icons shown in 4a.

and economic activity. Quelimane is the most developed urban and industrial centre among the three estuaries, with large expanses of the district dedicated to administration and services, a harbour including industrial fishing vessels, salt pans, industrial aquaculture and farming enterprises.

At the Ruvu Estuary, historical settlements at Kaole and Bagamoyo expanded along the shore of the wider estuarine bay, as opposed to the estuary channel, it being too shallow for shipping. The bay provided convenient access for ships, was close to natural resources (fish; forest products) and close to Zanzibar, a historical trading hub. Against this background, the estuary became a rural, agriculture-dominated area, and Bagamoyo Town developed into a fishing, trade and administrative center with geo-political importance, until it was overshadowed by the growth of nearby Dar es Salaam. Over the past 20 years, Bagamoyo has been marketed as a cultural, beach, and conference destination, alongside fisheries (which supply local and Dar es Salaam markets), small-scale and commercial agriculture. Economic development initiatives have been partially successful, hindered by complex economic and social challenges. Importantly, urban development at Bagamoyo Town is less

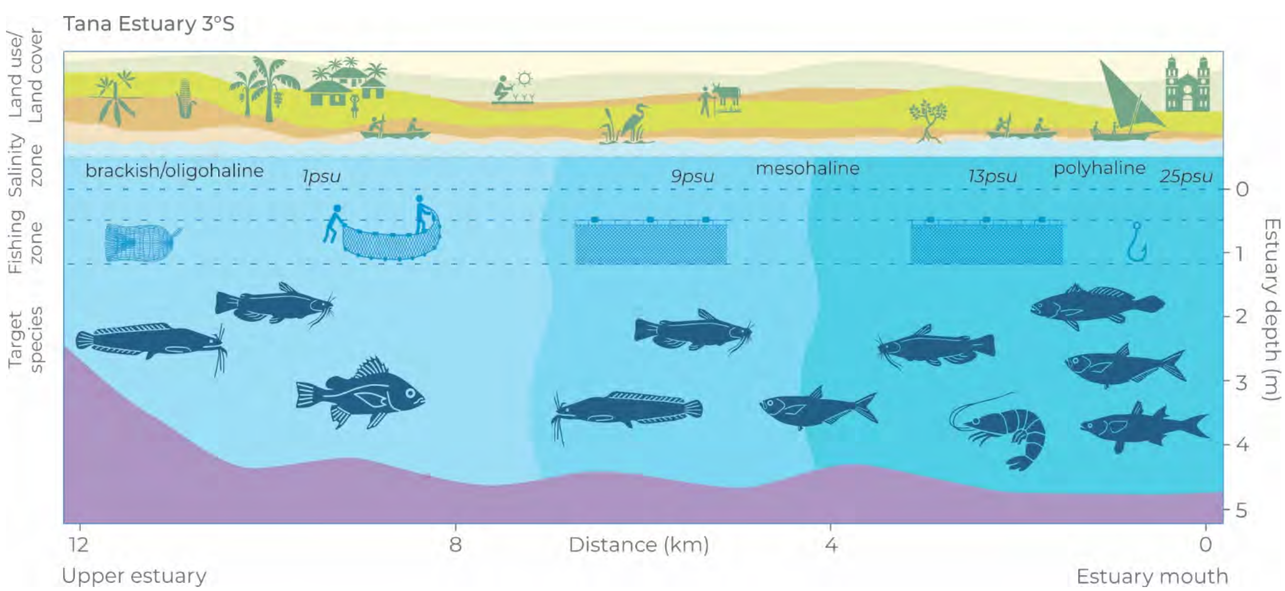

Figure 4c. Schematic diagram of the Tana Estuary in Kenya, depicting its physical characteristics (length, depth, salinity zones), land use and land cover, fishing zones, gears and commonly fished species per zone (not to scale). Icons shown in 4a.

concentrated and further from the Ruvu Estuary, than Quelimane is from the Bons Sinais.

Of the three estuaries, Tana is the least urbanized. Historical impediments to development were the prominence of other coastal cities and natural harbours nearby (e.g., Lamu, Malindi) which were more accessible. Recent barriers to expansion are security issues stemming from external militia and internal political instability. Kipini is a rural town and Ozi a small village, both with some administrative functions and basic goods and services, but no harbour infrastructure. The present estuary forms the lower reaches of a sparsely populated Tana Delta region – a productive region for agriculture, herding and fishing.

Demographics and ethnic mix: Population growth rates in recent years have been high at all three estuaries: 2.6 % pa at Quelimane; 3.1 % at Bagamoyo; 2.8 % in the Tana River County. People younger than 19 years (>50 %) and aged 20-29 years (>16 %), dominate the population demographics. Inhabitants of Quelimane and Bagamoyo comprised a broader ethnic mix resulting from long histories as trade centers and recent urbanization. Ethnicity is a more prominent issue at Tana, where the Pokomo are farmers and subsistence river fishers and the Orma are pastoralists using rangelands in nomadic or semi-nomadic ways. The inhabitants of Kipini are mixed, but mostly Pokomo live at Ozi. Conflict over access to resources have generally been along ethnic lines, often related to resource utilization (water, pasture). Demographic composition at all three estuaries is influenced by seasonal movements of migrant fishers along the coast. The major religions at Bons Sinais are Christianity (>60 %) and Islamic (>20 %), and at Ruvu and Tana it is >80 % Islamic, but the effects of religion on livelihood strategies was unclear.

Rural livelihoods, seasonality and spatial effects: Fish-based farming (FBF) systems (mixed fishing / farming households) that may also include livestock, hunting, gathering forest products and wage-earning are the most common rural livelihood systems at all three estuaries. Deltaic FBF systems of the WIO are adapted to seasonal floods and dry periods. In general, fishing takes place during floods, planting of rice and other crops during flood recession and grazing by livestock afterwards. Rice, maize and cassava are cultivated on floodplains, adapted to flooding frequency, height, and duration. Banana plantations are common and tree crops include coconut, mangoes, various other fruits, nuts and palms. The basic economic unit of FBF systems is the household (or extended family) with some individuals focusing on fisheries while others predominantly farm. It includes both genders, with women contributing to farming, fishing in shallow waters along the estuary shore, and to small-scale fish processing. FBF systems are flexible and increase resilience and adaptive capacity of households during periods of change (Hamerlynck *et al*., 2020).

At Bons Sinais, recession agriculture takes place as water levels recede on floodplains, although some wetlands in the lower estuary become mudflats and fallow grassland vegetation is burnt at the end of the dry season in preparation of crop tilling. Periods of high fishing effort and farming overlap seasonally, suggesting a division of labour within households during peak periods. Households are well-adapted to seasonal change, with a generalist strategy providing substantial redundancy within the social system.

Data insufficiencies precluded the description of seasonal livelihood activities at Ruvu, where wetlands and mangroves have been converted to salt production (large salt pans) and few farmers live within the estuary functional zone – most reside in Bagamoyo Town. There, communities include subsistence farmers that sometimes fish. Fishing in the bay area, highly influenced by the estuary, is generally performed by full-time fishers, with catches comprising multiple species and yields varying with season – for example, yields of penaeid prawns are associated with the rainy season, increasing between January and June. The central and southern part of the bay are seagrass and coral dominated, and offer an alternative blue-water fishery, not observed at the other two estuaries.

The seasonal pattern at Tana fits the generalized deltaic FBF system of the WIO. As floodwaters recede, rice is cultivated in low-lying paddies on the floodplains near Ozi, and at the margins of floodplains a mosaic of crops are planted, ranging from banana to maize, beans, squash and sweet potatoes, with cassava and mangoes planted in the highest, often sandy, grounds. The timing of the flood recession at the onset of the SE monsoon, when sea conditions in Ungwana Bay are unfavorable for fishing, facilitates seasonality of farming and fishing at Kipini. Seawater ingress makes the lower estuary less suitable for crops such as rice during the dry season, at which time the remaining wetlands dry out and attract cattle herders for grazing. Fishing by farmers with traditional gear (traps, spears) within the estuary channels takes place throughout the year.

In the Bons Sinais and Tana estuaries, clear spatial trends in FBF livelihoods were observed, with fishing being prevalent over farming at the coast or near the estuary mouth, and vice versa in the upper estuary. A gradient of livelihood dependence was observed, with specialist fishers and supporting trades more frequent at the coast, fisher-farmers in the lower estuaries and farmer-fishers in the upper estuary. Livelihood strategies in the upper- and lower estuaries were adapted to different combinations of ecosystems goods and services.

Peri-urban livelihoods, markets and the roles of gender and education: Peri-urban livelihoods increase opportunities through markets, small business sectors (retail outlets, transport, telecommunications, construction) and formal employment in administrative, education and health sectors. Core-periphery relationships (services provided in town, relying on produce from FBF systems in peripheral areas) differed amongst the three estuaries. At Bons Sinais, sites distant from Quelimane relied on primary activities (fishing and farming) diversifying towards the city where the role of women became more important in the cash economy, as small business owners and traders of charcoal, mangrove products and fish processing. Goods reached markets in Quelimane along a poor secondary road infrastructure (sometimes transported by foot or bicycle), or by canoes along waterways. Smaller local markets operated at distant landing points. Higher education levels in the city and the prevalence of services over manufacturing denoted a clear core-periphery relationship at economic, social and political levels.

Peri-urban livelihoods at Ruvu offered diverse livelihood opportunities in Bagamoyo Town, primarily related to commercial fishing (including fish processing, marketing and distribution), farming, transport, tourism in a cultural heritage environment, administration, health and education at schools and a local university campus. The proximity of Bagamoyo to Dar es Salaam along a modern tarred road, along which fish and farmed produce are transported to larger city markets, changes the core-periphery relationship – with Ruvu and Bagamoyo becoming peripheral to external market forces in Dar es Salaam, as the core. The growth of Bagamoyo Town and peri-urban livelihoods are therefore conditioned by interactions with Dar es Salaam – as in historical times.

Peri-urban livelihoods around Kipini and Ozi at Tana remain modest, providing essential services through small businesses in the village centre. Road access connecting Kipini to Malindi and Lamu is relatively good, but Ozi is more isolated, relying on waterways for transport. Livelihoods reflect a multi-dimensional system of cultures, ethnicities, religions and primary sources of livelihood, including age and gender roles within households.

Leadership and governance: Leadership is mainly pluralistic, with multiple leaders exerting influence through formal and informal means. The land policy in Mozambique recognizes customary rights over land (including inheritance systems) and the role of local community leaders in conflict prevention and resolution, but it remains difficult for individuals or communities to obtain land deeds, and thereby rights. The *de facto* power of traditional community leaders is fairly limited. Traditional leadership plays a modest role under the current administrative setup at Ruvu but customary systems are relied upon to resolve water-related conflicts. Traditional leadership is not formally recognized in Kenya despite its role in customary law. At all three estuaries, the power of fishers and small landowners to participate in decisions regarding water management upstream is inconsequential, as demonstrated at Tana (Elfversson, 2019; Zenebe *et al*., 2021). Local fisheries, particularly within the estuaries, remain open access with limited intervention from traditional or central institutions.

Land Use/Land Cover (LULC) change at seasonal and historical scales (Table S3; Fig. 5)

Historical trends: Analysis of Landsat images from the past three decades showed growth of developed (built up) and cultivated (farmed) land at Bons Sinais and Ruvu, where wetlands, forests and mangroves shrank (Fig. 5). At Bons Sinais (1991-2018), land covered by cultivated crops increased by 90 %, developed land (including Quelimane and rural settlements) increased by 80 % and intertidal mudflats grew by 27 %, with concomitant declines in critical wetland (-9 %) and mangrove (-12 %) cover. At Ruvu (1995-2016), developed land (Bagamoyo Town and rural settlements) increased by 216 %, cultivated land by 113 % and grassland by 500 %. Over the same period wetlands shrank by -59 % and mangrove cover by -34 %. Historical trends at Tana (1987 to 2018) showed increasing cultivation (+189 %) and grasslands (+60 %) with decreasing wetlands (-55 %) and mangroves (-30 %).

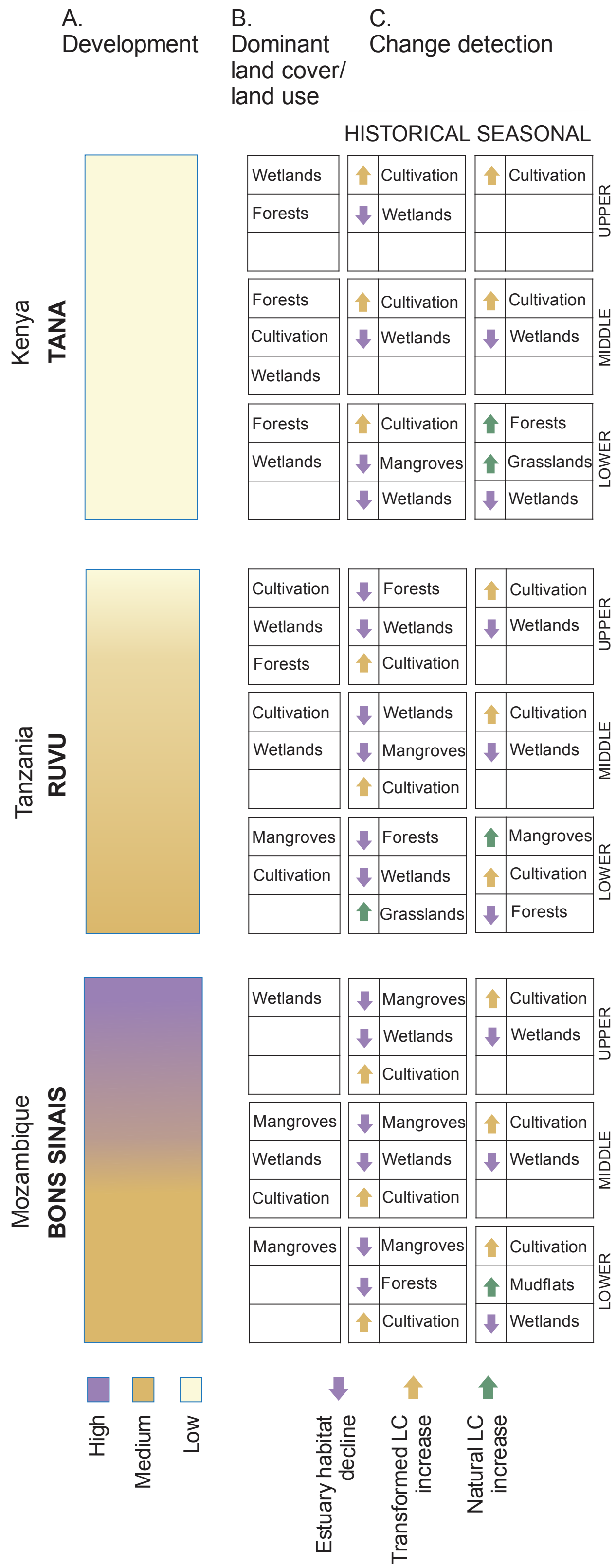

Figure 5. Land cover and land use characteristics influencing ecosystem services and provision of natural goods to the Bons Sinais, Ruvu and Tana estuaries. (A) Development or level of urbanization; (B) Dominant land cover/land use; and (C) Historic and seasonal change detection. Seasonal change shown from a wet to a dry period.

The instream sediment balance has changed over a longer term in at least two of the estuaries. Siltation or ingression of marine sediments at Bons Sinais Estuary is particularly visible on satellite images as sand banks at the estuary mouth. This is common in closing estuaries, for example on the eastern coast of South Africa, where sediments are no longer flushed by seasonal runoff or tides. At Tana, coastal erosion at the mouth reflects reduced fluvial sediment supply because of upstream damming. It is unclear how the sediment balance has changed at Ruvu, where northwards growth of an offshore delta was visible in satellite images.

The location of built-up areas and informal settlements at Quelimane encroaches on the estuarine functional zone (i.e., contributing habitats to estuarine natural processes). At Ruvu the built-up area of Bagamoyo is on higher land some 5 km to the south of the estuary mouth. Developed or built-up land at Kipini, adjacent to the mouth of the Tana, made up a negligible percentage of the study area (<1 %), but is riskily located in an area subject to coastal erosion.

LULC gradients and seasonality: The lower reaches of all three estuaries were dominated by mangroves and mud flats (coastal bare or intertidal) which have been converted to salt pans (subsistence or larger scale) in some areas at Bons Sinais and Ruvu. At Tana, coastal forests extended into the lower estuary. The mid estuary at Bons Sinais comprised mixed mangroves, wetlands, cultivated land and salt pans, and the upper estuary comprised mainly wetlands. The estuarine salinity zones at Ruvu were highly dynamic, moving offshore or becoming truncated near the mouth during the wet season – hence gradients were difficult to define relative to estuarine zones. Even so, a mosaic of wetlands and cultivated land characterized the mid and upper estuary. The mid and upper Tana was dominated by a patchwork of wetlands, forests, cultivated lands and grasslands.

Satellite images showed distinct seasonality in LULC in all three estuaries. Vegetated wetlands and forests increased during the wet season, replaced by cultivated lands and grasslands during the dry season. Burning of dried wetlands was commonly observed at Bons Sinais Estuary.

Estuarine fisheries and trophic effects (Table S4; Fig. 4a-c)

Fishing gear, selectivity and species captured: Fishing vessels comprised of dugout canoes (sometimes with outriggers), some planked canoes, small boats with outboard engines and various classes of dhows, the latter used mainly in coastal waters at Sofala Bank, the Zanzibar Channel and Ungwana Bay. Foot fishers set gear from the estuary banks. Fishing gears were similar among estuaries (e.g., beach seines, other seine nets, chicocota nets, gillnets, hook and line, traditional traps), often improvised to save on costs or availability of materials, or to target specific habitats or groups of species.

At Bons Sinais, beach seine and chicocota nets with insets of fine-mesh mosquito netting were common, used to target small pelagic fishes (Engraulidae 31 %, Pristigasteridae 16 %, Clupeidae 11 %) and prawns (Penaeidae 31 %). Catch rates of chicocota and beach-seines were 41-51 kg/net per day. Larger marine predators were caught near the estuary mouth with hook-and-line gear. Freshwater species were scarce in samples, reflecting the marine-dominated state of the estuary. Reliance on small pelagic fishes and prawns (i.e., the populations with highest turnover rates, abundance and natural productivity) is an opportunistic strategy with elements of a 'balanced harvest' approach (Zhou *et al.*, 2019), which coincides with an open access fishery without strictly enforced gear or size limitations.

The fishery at Ruvu had two distinct components: within the estuary channels; and in the offshore estuarine-influenced bay, with landings made at Bagamoyo Town. Fisheries in the estuary channels relied on a small number of mainly freshwater and marine migrant species, including several catfish species, penaeid prawns, tilapia, and invasive giant freshwater prawn *Macrobrachium rosenbergii*. Available samples were, however, restricted to those collected from bottom-set nets only, with no information on catches of pelagic fishes in the channel. Species captured at different locations corresponded well with known estuary-associated guilds based on salinity zones. In contrast, fishing in the offshore estuary and coastal waters yielded a diverse mix of mainly marine species from a variety of habitats (sandy to muddy substrates, coral reefs, seagrasses, pelagic habitats). The geographical origin of landings at Bagamoyo remained inconclusive because fishing grounds were not disclosed.

Estuarine fisheries at Tana were more complex and organized, with clear differences in gear use and species targeted at Ungwana Bay (near the estuary mouth), the lower, mid and upper estuary channels. Multiple gears (seine, gillnet, hook-and-line) were used at the mouth, lower and mid estuary to catch small pelagic, benthic and benthopelagic species (including *Arius africanus*, *Clarias gariepinus*, *Pellona ditchela*, *Sardinella* spp., *Mugil* spp. and *Otolithes ruber*) – mainly marine and freshwater migrants. In the upper estuary near Ozi, fishing was more opportunistic, using passive gear and traditional methods (home-made traps, spears) to catch freshwater species or migrants such as catfishes *C. gariepinus*, *A. africanus* and *Plotosus limbatus*, and tilapia *Oreochromis* spp. The catch composition was more diverse at the mouth and lower Tana Estuary than in the upper estuary. The complexity and organization of the fishery, combined with seasonal farming, suggests that a relatively intact SES remains active at Tana.

Seasonality in fishing effort and catches: Monsoon winds that influence sea conditions are key determinants of fishing effort in the coastal WIO. Strong SE monsoon winds impede the movements of migrant fishers along the coast, fishing activity of resident fishers and part-time fishers (e.g. generalist fisher-farmers). Fishing in enclosed estuary channels is more sheltered and occurs year-round, for example, setting of traps or stationary nets.

At Bons Sinais, fishing effort, landings and catch rates increased in March-October, after the summer rains; at Ruvu, declines in estuarine fishing effort occurred during the wet / high flow seasons in March to May and November to January, although data were scant. Season was not a significant influence on fishing effort in the Tana Estuary, but it was significant in the adjacent Ungwana Bay. Most fishing effort shifted from the estuary to the bay during the NE monsoon, with favorable sea conditions for fishing and the arrival of migrant fishers.

Numbers of fishers, landings and markets: The numbers of fishers active in estuaries were difficult to establish. Part-time fishers (or fisher-farmers) were often not registered and landed their catches at numerous points along estuary banks, unreported to fisheries observers. A census in 2012 found some 800 fishers with boats and 500 foot fishers at Bons Sinais. Declared landings of small-scale fisheries in Quelimane district is on average 10 000 t/y, of which 2 000 t/y originate from the estuary, mostly caught by beach-seine and chicocota nets. At Ruvu, the fishery in the estuary channels is virtually unstudied – but apparently pursued by fisher-farmers that catch small numbers of mainly freshwater and marine migrants and *M. rosenbergii* when they are available. At Tana, 180 registered fishers were recorded at Ozi and 300 at Kipini, many of them internal migrants. Estuarine catches were under-reported, if at all, and a record of 36 t in 2017 was almost certainly an underestimate.

At Bons Sinais, small pelagic fishes were sundried and smoked, and then used either for household consumption, sold at local markets or transported to larger markets in Quelimane or the hinterland. Penaeid prawns and more valuable fish were sold for cash. Prawns from industrial aquaculture (100 t) and Sofala Bank trawling (500 t) landed in Quelimane are exported. At Ruvu, fishing in the estuary was mainly for household consumption or marketed at Bagamoyo or Mtoni (upstream) markets. *Macrobrachium rosenbergii* fetches a higher price. Landings from the offshore fishery at Bagamoyo were either processed (fried, smoked) by women dealers at the landing site, and/or distributed by road to markets in Dar es Salaam and its outskirts. At Tana, fishing at Kipini supplied local needs and inland markets after processing (fresh, dried, fried, smoked). Fishing at Ozi was for household consumption or sale, with dried catfish distributed to inland markets.

Ecological and trophic effects of estuarine fisheries: Subtle differences in ecological status and trophic effects could be discerned from fish landings. Small pelagic fish and penaeid prawns dominated throughout the Bons Sinais Estuary - they are marine migrants, some with estuarine dependence. Most of them were juveniles or sub-adults with larger size-classes observed near the estuary mouth. Larger predators caught near the estuary mouth were marine stragglers or migrants.

Freshwater migrants and stragglers inhabited the Ruvu Estuary, with the freshwater migrant *A. africanus* extending into the offshore estuary. A wide size range of the invasive freshwater *M. rosenbergii*, a prawn species with estuarine dependence, was caught in the estuary including reproductively active females. Few small pelagic fishes were observed, potentially an artefact of the data, which excluded seine net catches.

A clear spatial effect was observed along the length of the Tana. Freshwater migrants occurred in the upper estuary and marine migrants in the lower estuary. Species diversity was higher in the bay and lower estuary, than upstream. Size composition of catches depended on gear type and gear-species interactions (e.g., seine nets caught smaller individuals of different species than long lines and traps).

Fisheries at all three estuaries targeted low to mid trophic levels. The bulk of landings at Bons Sinais were of detritivores to smaller piscivores (TL = 2.8-3.0), mainly species with high resilience and short generation times (<15 months). At Ruvu, detritivores to piscivores at low to mid trophic levels (TL = 2.5-4.0) dominated catches made by bottom nets. At Tana, trophic levels were marginally lower in the bay and lower estuary (3.5) than the mid and upper estuary (3.6), potentially because larger species were caught in traditional traps set in the upper estuary.

Estuarine systems diagnostics (by means of causal loop analysis)

Despite the large distance between the three estuaries, remarkable similarities in their ecology and social texture were observed. Similar marine fish species dominated the lower estuaries, mangrove assemblages were similar, and the types of crops, fishing methods, seasonality and livelihood strategies bore a strong resemblance. The scale of anthropogenic disturbance, brought about by proximity to city centers and the extent of upstream water and sediment diversion, differed markedly between estuaries. Drivers of disturbances were rapid population growth and associated welfare aspirations (Verkaart *et al.*, 2018) at local and regional levels. Superimposed on these were more subtle forces, some linear (e.g., climate change; sea level rise) and others occasional or acute. Acute events included tropical storms (Bons Sinais), drought (Tana), epizootics (loss of palm plantations through coconut lethal yellowing disease at Bons Sinais), and pandemics such as the SARS-CoV-2 which affected fish trade everywhere. Some disturbances and feedbacks were more site-specific, but all could to some extent be detected regionally.

Typical traits and feedback cycles in SES per estuary are demonstrated below, using a causal flow approach.

Bons Sinais Estuary (Fig. 6)

Low freshwater flow resulting from dams built for energy production in the Zambezi and Shire Rivers has led to salinization of the Bons Sinais, making it marine-dominated. Weakened seasonal runoff has reduced flushing, with sand banks forming in the estuary as a result of marine sediment influx. Sedimentation has not noticeably disturbed estuarine nursery function, but in combination with unselective fisheries, it may have led to a scarcity of fish predators, which tend to avoid shallow waters (Blaber, 2008, 2012). Fisheries have become increasingly dependent

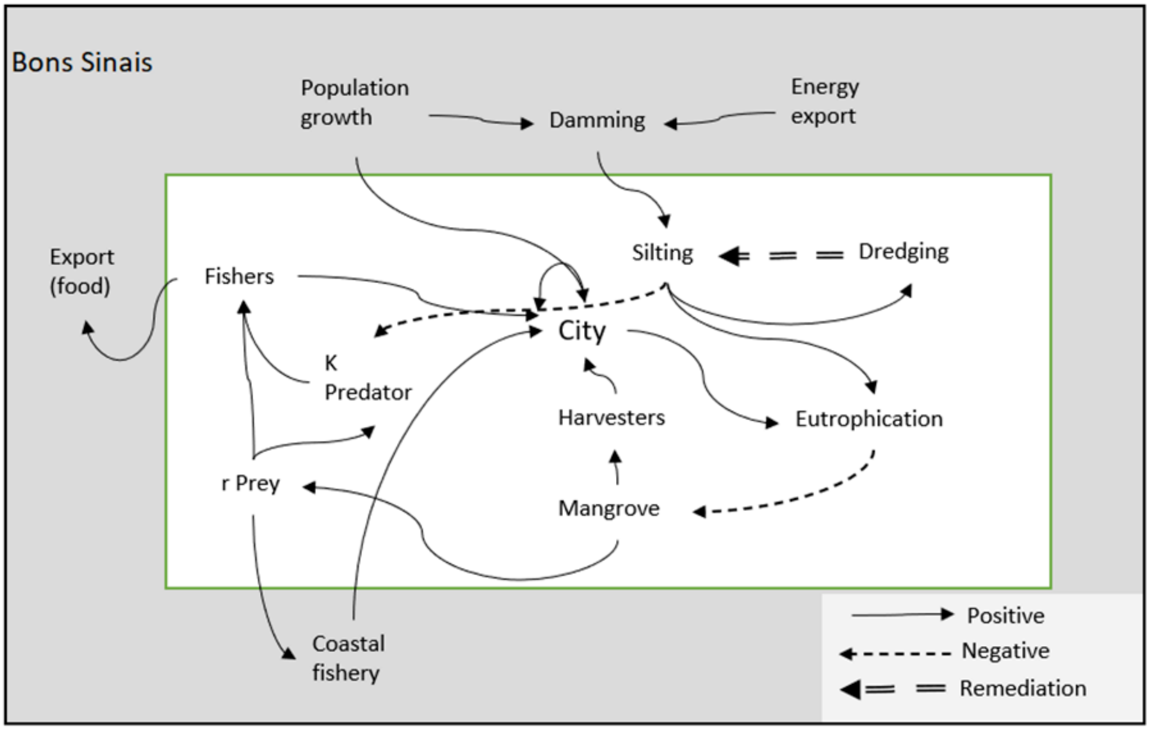

Figure 6. The Bons Sinais Estuary (central box) and its external environment as a socio-ecological-technological network with the most important connections in the present estuary state. Dredging is a technological mitigation remedy to maintain open channels for shipping. The estuary is strongly marine-influenced because of upstream damming, but remains functional.

on unselective gear and practices, and appear to be locked into a low trophic level, high productivity, low profitability state. Labour and economic imperatives of fishery operations have led to a migration from beach-seine to chicocota nets, further reducing the size and trophic level of captured fish. The present fishing regime meets the large demand for small fish and prawns in Quelimane and the hinterland. At the same time, the city and the aquaculture industry have encroached on the estuary, creating conditions for eutrophication, a high biological oxygen demand, and an increased demand for mangrove wood for fuel and construction. Systematic dredging of estuary channels when they become too shallow for navigation has an indirect positive effect on the functionality of estuarine ecosystems, by maintaining the estuary mouth open for seawater exchange and oxygenation. Dredging is therefore a technological solution to a technological problem created by damming elsewhere, albeit a costly solution that can only occasionally be afforded.

Ruvu Estuary (Fig. 7)

Over three decades, the population of the Wami-Ruvu basin in Tanzania grew three-fold, to ~10 million people, precipitation declined and temperature increased by ~1 °C, leading to greater evaporative water loss in the coastal zone (Ngondo *et al.*, 2021). The average water discharge of the Ruvu and Wami Rivers declined by 33 % between 1990 and 2018 (-36 % during rainy-, and -18 % during dry seasons), caused by agricultural expansion in the upper catchment basin and population growth in coastal areas, exacerbated by inadequate water management (Ngondo *et al.*, 2021). Sediments become trapped in hydropower reservoirs (GLOWS-FIU, 2014a; Amasi *et al.*, 2021) with a reduced volume transported through the Ruvu system. Remote sensing observations of delta-building at the mouth of the Ruvu Estuary is likely caused by erosion following deforestation and agriculture in the lower catchment and estuary. Erosion in the estuary may also have a secondary negative impact on the mangrove forest, a first line of defense against tropical storms (Törnqvist *et al.*, 2008), which occasionally devastate the Bagamoyo region (e.g., Brown, 1971). The projected water demand of agricultural projects, demographic and industrial growth up to 2035 adds ~142 % to the present freshwater use (Ngondo *et al.*, 2021). Freshwater scarcity will exacerbate saltwater intrusion into the Ruvu Estuary and salinization of the water table, but the extent may be limited by coastal topography. Loss of drinking water from wells and farmland are important consequences for farmers in Bagamoyo district, who also rely on occasional fishing. Reduced runoff from the Wami-Ruvu catchment

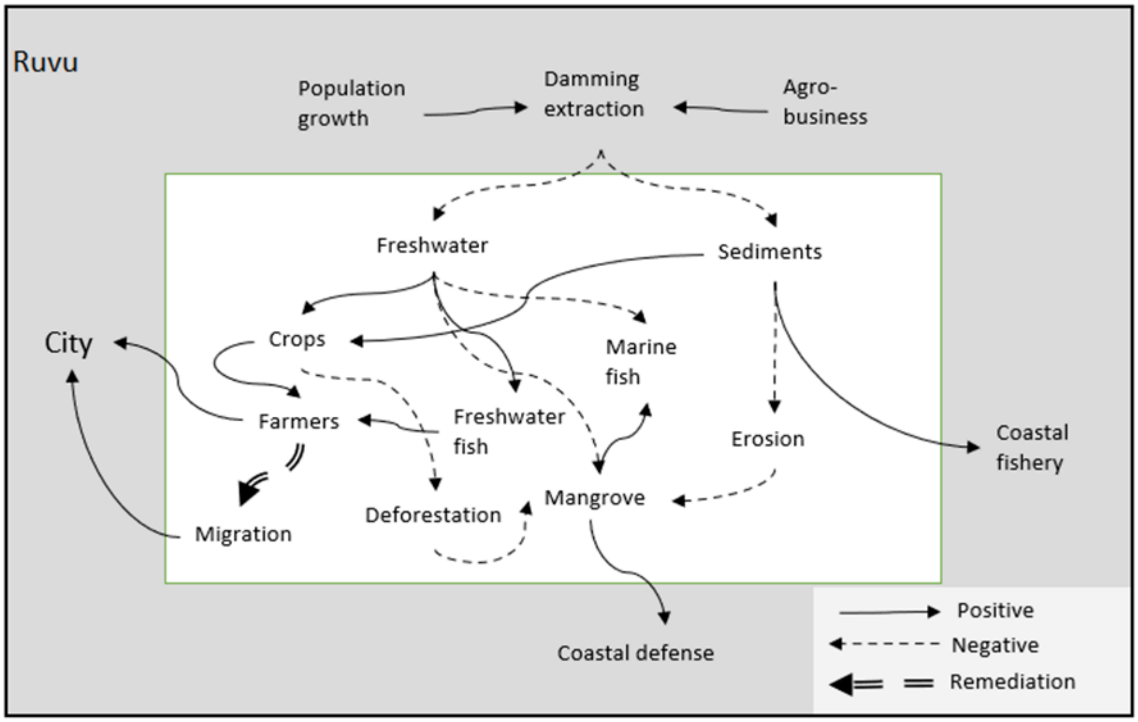

Figure 7. The Ruvu Estuary (central box) and its external environment as a socio-ecological-technological network with some important connections. The salinization of the water body after extensive water extraction upstream has had internal and external consequences, including crop failure in the lower estuary and deforestation. Migration to urban areas followed and the estuary is sparsely inhabited, though functional.

has likely affected coastal prawn fisheries which have become less productive than before, leading to moratoria on industrial prawn trawling. Some fisheries in the bay and offshore target blue-water environments (coral reefs, seagrass beds), which may be less affected by reduced freshwater runoff.

Bagamoyo Town has unfulfilled tourism potential, with hotels (some derelict) encroaching on the littoral zone. A lack of local livelihood alternatives is expected to increase unemployment. The social solution to this complex problem has been migration from the rural estuary to Bagamoyo Town, and ultimately to Dar es Salaam (Kerega, 2019). Migration is therefore a livelihood strategy (Singh, 2019) and social remedy for disturbance of a SES through external technological development (e.g., freshwater scarcity resulting from upstream abstraction and economic development). Migration from the system periphery to the core may offer temporary relief, but creates cultural, social and ecological challenges of its own, including fast-growing urban populations (Kerega, 2019; Peter and Yang, 2019).

Tana Estuary (Fig. 8)

Upstream water extraction has exacerbated seawater intrusion into the Tana Estuary and has increased erosion. Past remedies were closure of channels connecting the delta to the sea by farmers (a technological solution) with unreported impacts on estuarine fisheries. However, salinization and a sediment deficit continued along the present main channel of the Tana. Reduced suitable water for cattle and land for farmers have led to land appropriation elsewhere, through conversion of natural forests (deforestation). Conflict for resources between farmers and herders is exacerbated by land-grabbing for the agro-industry and droughts that reduced distant pastures and farmlands (Hamerlynck *et al.*, 2010). Government and NGO resources have been used to pacify conflict and improve relations between ethnic groups (a social remedy). New rice varieties that tolerate brackish water were introduced (a biotechnological remedy), but they are more expensive and difficult to grow than native variants (Bornstein, 2015). None of these solutions are self-sustaining, and will require long-term support from external sources. As in other areas with a tight ecological connectivity between estuarine and coastal environments, conflict between small-scale and industrial fishers exist over shared fisheries resources (Munga *et al.*, 2013, 2014). A social remedy – prohibition of industrial trawling <3 nautical mile from the shore – has been implemented to reduce the conflict.

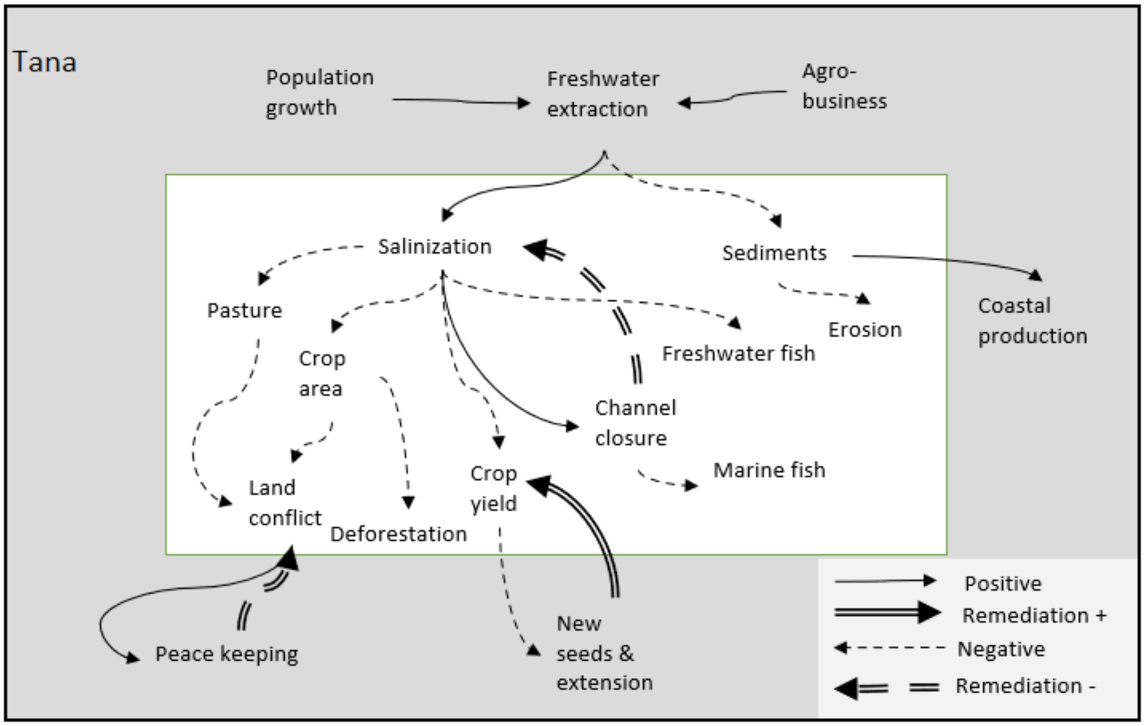

Figure 8. The Tana Estuary (central box) and its external environment as a socio-ecological-technological network with some important connections and features in the present state. Salinization was first remedied by artificial closure of some channels to the sea. Conflicts for space and water occur between farmers and herders, and for fish between small-scale and industrial trawl fishers. Social and biotechnological mitigation includes a peace-keeping presence, and introduction of rice plants tolerant to brackish water, supported by government and foreign donors.

Transformation of WIO estuaries: Seasonally changing monsoons and freshwater flow define the types of resources available and livelihoods opportunities around WIO estuaries. Natural and human induced phenomena that condition local livelihoods are large tidal prisms, a gradient of aridity northwards from Mozambique, and a tropical storm belt in mid-Mozambique. Central Mozambique has extensive coastal lowlands with high exposure to sea-level rise, and a high density of poverty-stricken coastal inhabitants (Muscova *et al.*, 2021), making it particularly vulnerable to the effects of climate change.

Fluvial inputs and recruitment of biota from estuaries are key components of coastal ecosystems, but their relevance is modulated by local conditions. Coastal currents disperse the fluvial sediments further offshore (e.g., Tana), or retain them closer to the coast (e.g., Bons Sinais, Ruvu). In this SI, the major changes occurring at the landscape level of three estuaries were described, showing clear increases in cultivated- and developed land, and concomitant declines in natural wetland habitats over three decades (Furaca *et al.*, 2021; Groeneveld *et al.*, 2021b; Mwamlavya *et al.*, 2021). We corroborated findings in the literature (see papers in Diop *et al.*, 2016) of estuarine sedimentation in some cases and erosion in others, resulting from upstream water diversion. In the most extreme case, the Bons Sinais Estuary may be approaching closure and loss of functionality. At Ruvu, offshore delta-building appears to take place during floods (Shagude *et al.*, 2003), and at Tana coastal erosion is severe.

Of the three estuaries, Bons Sinais has been the most transformed through urbanization, industrial development (extensive coconut plantations, saltworks, aquaculture) and primary activities (fishing, agriculture, forest exploitation). The Ruvu is an intermediate estuary along the urban-production gradient, less transformed than at Bons Sinais, and with goods extracted from it distributed externally (e.g., fish sold at Bagamoyo Town or in Dar es Salaam). The Tana, where the human population density is low, has been least transformed through urbanization and the estuary retains many of its natural resources. Significant qualitative differences in the natural capital of the three estuaries situated 2000 km apart were not found. The typical composition of estuarine fish and mangrove species were similar, and in the mesohaline estuaries (Tana, Ruvu) the freshwater fish composition was also similar. Similar crops were planted in flood recession zones. Differences in the resource base of the three estuaries could be traced to changes in historical and more recent freshwater discharge and water management regimes in catchment areas. A measure of ecological resilience remains, but the most disturbed landscape (e.g., Bons Sinais) is clearly dominated by early colonizing, opportunists with high productivity (small pelagic fishes, prawns, *Avicennia*).

The human factor: To explain differences in the urban-production dimension, it was hypothesized that estuarine location and geomorphology influenced the historical emergence and development of cities and towns, and that in return, the existence of cities near estuaries greatly influenced their utilization and ecological functioning, through re-enforcement loops. Core-periphery relationships along the rural-urban cline were apparent in the nature and diversity of livelihood activities, education levels and participation of women in the visible economy. On the rural periphery, specialized full-time fishers lived near the coast, and generalist FBF communities lived in the mid- to upper estuary (Blythe, 2014; Francisco *et al.*, 2021; Mwamlavya *et al.*, 2021). The vertical and horizontal value chains of fish products were well developed throughout the WIO region.

Ethnical and cultural diversity around all three estuaries stemmed from their historical origin as centers of trade, and more recently as refuges for people displaced from inland areas (e.g., Bons Sinais; Francisco *et al.*, 2021). Seasonal migrant fishers are common and cross international boundaries in search of fish (Wanyoni *et al.*, 2016). Ethnical conflict follows competition for natural resources (pasture, freshwater, fish) particularly during droughts (WIOMSA, 2011; Elfversson, 2019). Conflict resolution models motivated for political and religious reasons occur throughout the WIO, but were not addressed in this SI.

In line with the "naturally stressed environment" theory of Elliott and Quintino (2007) for the ecological estuary, estuarine livelihoods were adapted to a strongly variable resource base on seasonal timescales. Household members that rely on FBF systems had multiple skills, which they applied to agriculture, fishing, gathering forest products and trade, even without formal education. Local knowledge, individual skills and diversity of local livelihood options were well-developed but were countered by low risk-perception and preparedness, and a lack of access to financial assets, education and technology (Kwazu and Chang-Richards, 2020). Hence, livelihood strategies were resilient (able to adapt or recover to changing circumstances) below a threshold level (Blythe, 2014) but vulnerable to more extreme events such as droughts, floods, tropical storms or political instability. Migrations to cities or larger towns formed a part of livelihood strategies, with remaining household members supported through remittances (Jena, 2018). Best described for coastal Tanzania (incl. Ruvu), this process is widespread in the WIO, partly driven by a declining resource base per capita, including at estuaries.

Fish and fisheries in estuarine SES: Fisheries had strong seasonal characteristics, affected by weather systems, catchability of fish, and effort required for seasonal agricultural activities. The relationships between fish diversity and fisher specialization was demonstrated, with both traits increasing towards the lower estuaries and the sea (Mugabe *et al.*, 2021; Groeneveld *et al.*, 2021b; Manyenze *et al.*, 2021). In the upper estuaries, FBF systems relied on simple passive gears such as chicocota nets or traps, with catches ranging from marine migrant, to estuarine and freshwater species. Fish diversity increased lower in the estuary with the appearance of marine-dependent species, providing opportunities for diversification of gear and fished target groups. The diversity of fished species, gear types, vessels and people was highest at the estuary mouth and coast, including the number of migrant fishers. Coastal fisheries targeted commercially more-valuable species, including larger penaeid prawns which have estuary-dependent juvenile phases. The importance of local estuarine habitats for prawn recruitment to the Ungwana Bay fishing grounds was demonstrated by Mkare *et al.* (2014) through genetic analysis of prawn populations.

In the most exploited of the three estuaries (Bons Sinais), the fishery was locked into an unselective, low trophic-level productive cycle based on beach-seine and chicocota nets (Mugabe *et al.*, 2021). Larger predators that avoid shallow areas were subject to selective exploitation near the estuary mouth. Removal of natural predators plausibly explained the abundance of small pelagic fishes available to the estuarine fishery. Increased salinization in the mid and upper Ruvu and Tana was also expected to displace freshwater fish and customary crops further inland, but it was not as noticeable as at Bons Sinais.

The big picture: The future of deltas around the world is bleak and many are bound to irreversible change (Wesselink *et al.*, 2020) owing to processes (mainly water use) related to human population growth, intensive agricultural production systems, economic development, and urbanization. Studies in this SI demonstrated that human-induced processes affected WIO estuaries (mostly part of deltaic systems) and dependent livelihoods more deeply than any physical differences between them. Little difference in the aquatic and terrestrial assemblages investigated, or in the embedded human livelihoods was found. Along the continuum of human intervention, Bons Sinais was the most industrialized, urbanized and exploited estuary, but retained a productive environment, now dominated by low trophic level or colonizing organisms. The Ruvu was most affected by contemporary water diversion and transformation in catchments. The growth of nearby Dar es Salaam accelerated impacts through an increased demand for freshwater, but may also be part of a solution, through a process of internal migration to urban centers. This is one of the most serious social and ecological issues in African countries today. The Tana was the least impacted owing to its distance from urban and industrial centers, but upstream freshwater diversion has aggravated conflict among resident farmers and nomadic herders for estuarine resources.

To conclude, water and landscape management have not kept pace with formidable population growth in Eastern Africa, and it is unlikely that it will do so in the coming decades. The degradation of estuarine ecosystems and natural resources that they support, loss of associated livelihood opportunities, increased conflict over declining resources and migrations to cities are some of the negative externalities faced by developing countries in the WIO region. In this dynamic scenario, traditional governance forms are lost, the power of central governments is limited, and resilience becomes difficult to define. The Estuarize-WIO project provided a systemic view of the components and critical links, with possible solutions at local, national and WIO regional scales.

Recommendations

The Estuarize-WIO project relied on research across international boundaries and partnerships with a range of public and private institutes with different mandates. It took place in the developing world, in estuarine environments with limited accessibility, and for which prior data were sparse and collected for different purposes. Data deficiencies placed limitations on the analyses that could be done. Based on the Estuarize-WIO experience, and to improve the knowledge-base and facilitate better management of complex estuarine systems that include a human dimension, the following is recommended:

- Regional cooperation so that successful interventions can be built on shared experiences across the WIO region
- Multi- or transdisciplinary approaches, without an upfront expectation that all aspects will be resolved – rather that key information gaps will emerge
- Use of freely accessible and online datasets, such as Landsat and Sentinel-2 satellite imagery used for LULC analyses – a powerful tool that provided key insights into change and pressures that moderate WIO estuarine health and function
- Development of a WIO-centric approach to estuary delineation, function and health determination to account for the unique biophysical and sociological setting of these ecosystems
- Relying on a methodology that is robust to unbalanced sampling regimes and variable data quality – even if this needs to be developed specifically for local conditions

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Appendix

Supplementary Table S1: Comparison of physical- and hydrological characteristics of the Bons Sinais- (Mozambique, 18°S), Ruvu- (Tanzania, 6°S) and Tana Estuary (Kenya, 3°S) based on contemporary literature and studies undertaken during the Estuarize-WIO project. The three estuaries are located along a latitudinal gradient in the tropical Western Indian Ocean, along a 2000 km stretch of coastline. Study areas per estuary (<5m amsl) were 2121 km2 (1630 km2 = land) at Bons Sinais, 458 km2 (358 km2 = land) at Ruvu, and 194 km2 (143 km2 = land) at Tana.

Characteristic	Bons Sinais Estuary (18°S)	Ruvu Estuary (6°S)	Tana Estuary (3°S)
Original state	Large fluvially dominated deltaic estuary	Medium fluvially dominated deltaic estuary	Medium fluvially dominated deltaic estuary
Present state	Mostly single-channel. Silted, marine dominated	Single channel. Retains deltaic characteristic at mouth and offshore	Single channel. Retains deltaic characteristic at mouth and in Ungwana Bay
Estuary length and mean depth	30 km long, mean depth 10 m	10-12 km long, mean depth 3 m	10-12 km long, mean depth 5-8 m
Slope and max elevation amsl	Shallow slope, max elevation 28 m	Steeper slope, max elevation 45 m	Steeper slope, max elevation 35 m
Tidal range	Meso-tidal, 3-4.5 m	Meso-tidal, 3-4.5 m	Meso-tidal, 3-4.5 m
Estuary character	Well-mixed, mostly marine/ estuarine	Estuarine/fresh in main channel. Lower estuary displaced offshore during high flow	Marine/estuarine/fresh depending on season
Estuary mouth	Northern Sofala Bank	Zanzibar Channel, Bagamoyo bay	Ungwana Bay
Feshwater supply	Small catchment area with unregulated feeder rivers. Runoff depends on coastal rainfall	Larger catchment, freshwater supply reduced by upstream use	Larger catchment, freshwater supply reduced by upstream use and dams
Freshwater utilization	Connection to Zambezi River lost after dam construction in 1960s and 70s, changing character of estuary	Freshwater diversion for irrigation, industrial, aquaculture and domestic use in Dar es Salaam	Changes to hydrology following land use changes. Flow regulated by dams, depressed and delayed
Seasonality	Tidal dominance and rain-fed. Peak discharge in Nov-Mar, dry in Apr-Oct (residual flow)	River and rain-fed. Peak discharge in Mar-May, smaller peak in Nov-Jan	River and rain-fed. High inter-annual variability. Peak discharge in May-Nov
Seasonal salinity profiles	Polyhaline along its length (29-23 psu) in dry season; mesohaline (22-12 psu) in wet season	Estuary truncated offshore of mouth at high freshwater flow, extends 10-12 km upstream at low flow. Polyhaline at mouth and bay; meso-, oligohaline seasonally variable in lower-, mid- and upper estuary	Polyhaline (~30 psu) to mid reaches at high tide. Mesohaline (~15 psu) to mid reaches at low tide
Critical estuarine habitat	Extensive mangroves. Nursery for fish / crustacean recruits to Sofala Bank	Extensive mangroves. Nursery for fish / crustacean recruits to Bagamoyo bay	Extensive mangroves. Nursery for fish / crustacean recruits to Ungwana Bay

References: Alphayo and Sharma, 2018; Beilfuss and dos Santos, 2001; Bouilon *et al.*, 2007; Coastal.climatecentral.org; Dalrymple and Choi, 2007; Furaca *et al.*, 2021; Groeneveld *et al.*, 2021a, 2021b; Hoguane *et al.*, 2021; Kaaya, 2019; Kitheka and Mavuti, 2016; Moore *et al.*, 2007; Msangameno *et al.*, 2017; Mwaguni *et al.*, 2016; Mwamlavya *et al.*, 2021; Shagude *et al.*, 2003; Tobey *et al.*, 2013 ; Ullgren and André, 2016; Ward *et al.*, 2016; Zavala-Garay *et al.*, 2015

Supplementary Table S2: Comparison of demographic profiles, urbanization, socio-economic circumstances, livelihood activities and governance at the Bons Sinais- (Mozambique, 18°S), Ruvu- (Tanzania, 6°S) and Tana Estuary (Kenya, 3°S) based on contemporary literature and studies undertaken during the Estuarize-WIO project.

Characteristic	Bons Sinais Estuary (18°S)	Ruvu Estuary (6°S)	Tana Estuary (3°S)
Population growth	Rapid population growth in 1977-1992 during civil war displacement from inland to coast and rural to urban areas. Avg population growth 2.6% pa in 2007-2017. Urban population in Quelimane is 400 000 (2020)	Population size in Bagamoyo district is 310 000, of which 30 000 in Bagamoyo town. Avg population growth 3.1% pa in 2002-2012	Population size of Tana River County 300 000, of which 3000 in Kipini town (2019). Avg population growth 2.8% pa
Urbanization	Urban growth in population and built area over 30 y with increasing space, water, food, fuelwood, transport, construction, economic needs	Bagamoyo a historical town on outskirts of Dar es Salaam. Growth affected by economic cycles and urbanization of nearby Dar es Salaam	Low urbanization at Kipini, connected to electrical grid and road access. Ozi is a rural village accessed by waterways
Demography	Young age distribution. 0-19 y = 55%; 20-29 y = 19%	Young age distribution. 0-19 y = 50%; 20-29 y = 17%	Young age distribution: 0-19 y = 59%; 20-29 y = 16%; rural = 76%; urban = 24%
Religion	Major religions Christianity and Islam, with variable proportions at different locations	90% Islamic	81% Islamic; 18% Christian; 1% Other
Ethnic mix	Historical trade center, pre-colonial and colonial periods, hub for trading, transport. Mixed rural-urban form of living. Chuabo the most common local language. Variety of backgrounds, incl. Muslims and Indians. Colleges and universities	Historical trade center, pre-colonial and colonial periods, hub for trading, transport. Bagamoyo population very mixed because of migration, settlement of different ethnic groups, proximity to Dar es Salaam, education centre	Pokomo are sedentary farmers and subsistence river fishers. Orma are pastoralists using rangelands in nomadic or semi-nomadic ways. Arabic influence from Zanzibar. Kipini population mixed, Ozi mostly Pokomo. Some ethnic conflict
Migrant fishers	Many coastal fishers originate from northern Zambezia, speak Muniga.	Local migrant fishers from nearby villages and districts, as far as Mafia Island	Seasonal local and foreign migrant fishers. Migrant fishers arrive during NE monsoon and operate offshore
Leadership (statutory and customary)	Pluralistic. Land policy recognizes customary rights over land and role of local community leaders in conflict prevention, resolution	Pluralistic. Traditional leadership plays minor role under the current administrative setup. Customary systems used to resolve water-related conflicts	Pluralistic. Traditional leadership not formally recognized but play role in customary law
Livelihood activities (rural)	Fish-based farming (FBF) systems = "mixed fishing / farming households. Can include livestock, hunting, gathering forest products, wage-earning. Both genders. Relative importance of activities depend on site-specific resources. High seasonality	FBF systems common around estuary. Fishing, farming provides food and cash income. Data limited but seasonality implied.	FBF systems common. Flood-recession agriculture, part-time fishing in mid- to upper estuary. Full-time fishing more common in lower estuary. Highly seasonal pattern.
Livelihood activities (peri-urban)	Diverse. Markets, transport, govt offices, schools, university, banks, hotels, businesses, admin. Clear core-periphery relationships.	Bagamoyo town. Diverse livelihood activities – fishing, fish market, farming, tourism, transport, university, schools, historical monuments, small business	Nascent peri-urban area. Mostly rural with small industries in town centre, mainly telecom and transport

Characteristic	Bons Sinais Estuary (18°S)	Ruvu Estuary (6°S)	Tana Estuary (3°S)
Involvement of women	Very active in households. Agriculture (20 - 26%) small businesses (6%), mangrove products (6%), other (4%) fishing / collecting at water edge (8-16%)	Many women observed at Customs House landing site operating fish processing (frying of fresh fish for immediate sale)	Some part-time fishing from shore, farming. Women in Kipini run small retail businesses, guest house
Access to markets (distance, transport)	Large markets in Quelimane. Poor road infrastructure along estuary. Transport of products by foot, bicycle or boats. Smaller local markets at distant landing points	Most fish landed at Bagamoyo sold fresh to traders who sell in Dar es Salaam urban areas. Good road access to Dar es Salaam	Few good roads – main access road connects Kipini to larger markets such as Malindi
Level of education	Literacy low, avg. 55% have primary school education, declining to 30% at rural sites. Similar education level in men, women	Literacy low, despite primary schools in Bagamoyo. Schools lack teaching facilities, have high drop-out rates	Full-time fishers (50 % primary school completed) had lower education than farmers (60% secondary education)

References: Agergaard and Ortenbjerg, 2017; Agergaard *et al.*, 2019; Bouillon *et al.*, 2007; Blythe, 2014; Blythe *et al.*, 2014; Brown, 1971; Duvail *et al.*, 2017; Francisco *et al.*, 2021; Furaca *et al.*, 2021; Groeneveld *et al.*, 2021a, 2021b; Hannerz, 2015; Hamerlynck *et al.*, 2010, 2020; INE, 2007, 2017; Maganga *et al.*, 2004; Mbwambo *et al.*, 2012; Mkama *et al.*, 2010; Mwamlavya *et al.*, 2021; Teikwa and Mgaya, 2003; Wanyoni *et al.*, 2016, 2017; www.populationstat.com; Zavala-Garay *et al.*, 2015

Supplementary Table S3: Comparative trends in land use and land cover (LULC) at the Bons Sinais- (Mozambique, 18°S), Ruvu- (Tanzania, 6°S) and Tana Estuary (Kenya, 3°S) based on contemporary literature and studies undertaken during the Estuarize-WIO project.

Characteristic	Bons Sinais Estuary (18°S)	Ruvu Estuary (6°S)	Tana Estuary (3°S)
Decadal LULC trends	Increasing cultivated and developed land (Quelimane city). Loss of wetlands, mangroves, forests	Increasing cultivated, grass and developed land (Bagamoyo and coastal resorts). Loss of wetlands and mangrove	Increased cultivation; loss of wetlands and mangroves. Region becoming dryer; upstream water regulation
Sediment balance	Siltation of estuary particularly visible at the mouth. Frequent dredging to maintain channel open. Mainly marine sediments	Strong northwards expansion of the delta outside the estuary mouth in some years, potentially terrigenous sediments following extreme rainfall events	Coastal erosion at the mouth attributed to reduced fluvial sediment supply following damming in catchment and sea level rise
Ecotones	Mangrove stands in lower estuary. Mixed mangrove, wetland, cultivation in mid-estuary; wetlands in upper estuary	Mangroves, artificial salt pans in lower estuary. Cultivation, wetlands and forest in upper estuary	Mangroves, forests in lower estuary. Wetlands and cultivation in mid- and upper estuary
Seasonality	Wet season increase in vegetated wetlands, forests. Dry season increase in cultivated land and burnt wetlands	Wet season increase in wetlands and forests. Dry season increase in grasslands, cultivated land and mangroves	Wet season increase in wetlands, mangroves. Rice planted after floods. Dry season increase in cultivated and grasslands
Location of built-up areas and urban areas	Quelimane. Fast-growing provincial capital partially within estuarine functional zone, ≈25 km from the mouth	Bagamoyo. Medium-size coastal town 5 km south of the estuary mouth. Dar es Salaam city suburbs close-by	Kipini. Small town near estuary mouth, within functional zone, affected by coastal erosion. Ozi. Rural village 10 km upstream

References: Furaca *et al.*, 2021; Groeneveld *et al.*, 2021b; Hamerlynck *et al.*, 2010; Kaaya, 2019; Kitheka and Mavuti, 2016; Mwaguni *et al.*, 2016; Mwamlavya *et al.*, 2021; Shagude *et al.*, 2003

Supplementary Table S4: Comparison of estuarine fisheries at the Bons Sinais- (Mozambique, 18°S), Ruvu- (Tanzania, 6°S) and Tana Estuary (Kenya, 3°S) based on contemporary literature and studies undertaken during the Estuarize-WIO project.

Characteristic	Bons Sinais Estuary (18°S)	Ruvu Estuary (6°S)	Tana Estuary (3°S)
Fishing Technology	Dugout and planked canoes, foot fishers. Beach-seine and chicocota nets most common. Some gillnets and longlines. Larger vessels used on Sofala Bank	Dugout canoes and foot fishers in fishery with bottom-set nets in estuary channels. Fishery in offshore estuary (Bagamoyo Bay) more diverse	Dugout canoes, foot fishers, dhows, few motorized boats. Larger booats used in Ungwana bay. Seines, gillnets, hook-and-line, traditional traps, sticks and spears
Gear selectivity	Beach-seine and chicocota nets unselective with fine-mesh (mosquito net) inserts	Bottom set gears adapted to catch giant freshwater prawn in upper estuary	Traps selective for catfish in mid- and upper estuary. Seine nets (54 spp) and gillnets (40 spp) least selective, used throughout estuary
Typical species caught	Marine small pelagics *Thryssa, Hilsa, Pellona* and penaeids dominate. Larger marine predators caught near mouth. Freshwater species scarce in samples	Low species diversity in estuary. Freshwater stragglers *Clarias* and *Oreochromis* and invasive freshwater prawn *M. rosenbergii* in mid/upper-estuary. *Arius* common throughout. *Otolithes, Mugil, Penaeus* in lower estuary	*Arius, Clarias, Oreochromis* in mid/upper estuary. Small pelagics, *Otolithes, Mugil* in lower estuary.
Fishing strategy	Unselective fishing gear used to exploit a mix of species - mainly small pelagics and prawns. Focus on short-lived species with high productivity and abundance	Opportunistic – especially fishery targeted at invasive *M. rosenbergii*. Farmers that fish part-time	High complexity and organization of fishery at estuary-scale. Strategy at Ozi is opportunistic, using passive gear and traditional methods. Greater diversity at Kipini, including active gears
Seasonality (fishery and other activities)	Fishing effort, landings and catch rates increase in dry season (Mar-Oct)	No data	Season not significant within the estuary. Effort diverts to Ungwana Bay during the dry season (NEM) when sea conditions improve. Two separate migrant groups focus on the bay (dry season) and upper estuary, respectively
Number of fishers (estuarine)	Full-time fishers, fisher-farmers, migrant fishers on Sofala Bank. A census in 2012 estimated 800 fishers with boats and another 500 without boats in the estuary	Few full-time fishers in estuary channels. Farmers that fish part-time. Large diverse fishery in the estuary-influenced bay incl. full-time, part-time and migrant fishers	Full-time fishers and fisher-farmers depending on location in estuary. Migrant fishers in Ungwana Bay. Kipini has 300 registered fishers and Ozi has 180
Catches (estuary / adjacent coast)	Average catch of small-scale fishery in Quelimane district is 10 000 t/y, of which 2 000 t/y are caught in the estuary. Catch rates for chicocota and beach-seine are 41-51 kg/net per day	Estuarine catch small (weight and species diversity) compared to offshore catch in bay landed at Bagamoyo	Year-round fishery in estuary. Seasonal fishery in Ungwana Bay, incl. migrants, semi-industrial fishery in dry season. Estuarine catch not reported. Record of 36 t in 2017 an underestimate

Characteristic	Bons Sinais Estuary (18°S)	Ruvu Estuary (6°S)	Tana Estuary (3°S)
Processing and markets	Fish and vegetables for subsistence and sale on local markets and Quelimane. Small pelagics dried, smoked, sold in hinterland, Malawi. Penaeids, valuable fish sold for cash. Prawns from industrial aquaculture (100 t) and Sofala Bank trawling (500 t) exported	Fishing for household consumption and sale. *Macrobrachium* sold at Bagamoyo or Mtoni markets. Fishery in bay supplies Dar es Salaam markets	Fishing at Kipini for local and inland markets after processing (fresh, dried, fried, smoked). Fishing at Ozi for household consumption or sale. Dried catfish for inland markets
Guilds and spatial effects	Marine small pelagic fish and penaeids caught throughout the estuary - they are marine migrants, some with estuarine dependence. Larger predators near mouth are marine stragglers or migrants	Freshwater migrants and stragglers in upper estuary. Marine migrants in lower estuary but also one freshwater straggler. Invasive *M. rosenbergii* a freshwater species with estuarine dependence	Clear spatial effect in landings at sites in bay, lower, mid and upper estuary. Freshwater migrants in upper estuary, marine migrants in lower estuary. Species diversity higher in bay and lower estuary
Average size of fish or prawns	Late juveniles of small pelagics and prawns (8-11 cm). Larger sizes at estuary mouth. Mainly juveniles in upper estuary	Variable. Few small pelagic fish in estuary landings, perhaps constrained by sampling gear. Mix of juvenile and adult *M. rosenbergii*	Highly variable, depending on gear type and gear-species interactions. Seine nets caught smaller individuals of different species than long lines and traps
Trophic level, resilience of main species	Detritivores to smaller piscivores, low trophic level (TL = 2.8-3.0), high resilience, short generation time (<15 mo). Chicocota operates at slightly lower TL than beach-seine	Detritivores to piscivores, mid-low trophic levels (TL = 2.5-4.0) in bottom net samples. Generally species with short generation times, high resilience	TL marginally lower in bay and lower estuary (3.5) than mid and upper estuary (3.6). By gear it varied from 3.6 (seines) to 4.1 (some gillnets). Mostly species with short generation times, high resilience

References: Benkenstein, 2013; Cardinale *et al*., 2014; Costa *et al*., 2020; Dzoga *et al*., 2020; Francisco *et al*., 2021; Groeneveld *et al*., 2021a, 2021b; Kuguru *et al*., 2019; Manyenze *et al*., 2021; McClanahan, 1988; Mugabe *et al*., 2021; Munga *et al*., 2013; Mwamlavya *et al*., 2021

Tabela S5 A: The central data files of the Estuarize project.

FileID	Article (DOI)	FileName	Type	Analyst (1)	Owner (1)	Taxonomy
2.1.1	http://dx.doi.org/10.4314/wiojms.si2021.1.2	BonsSinais_RCM_20170428.csv	Data	AH	UEM	Physical data water
2.1.2	http://dx.doi.org/10.4314/wiojms.si2021.1.2	BonsSinais_RCM_variables_20170428.csv	Data	AH	UEM	Physical data water
2.2.3	http://dx.doi.org/10.4314/wiojms.si2021.1.2	BonsSinais_ModelData_Hidrography.csv	Data	AH	UEM	Input parameters water
3.1.1.	http://dx.doi.org/10.4314/wiojms.si2021.1.3	20211123_BonsSinais_Social_Tables.xls	Tables	RF	UEM	Household aggregated
3.2.1	http://dx.doi.org/10.4314/wiojms.si2021.1.3	20211123_BonsSinais_GovernanceRules_Tables.xls	Tables	RF	UEM	Household aggregated
3.3.1	http://dx.doi.org/10.4314/wiojms.si2021.1.3	20211123_BonsSinais_EconomicValuation_Tables.xlsx	Tables	RF	UEM	Household aggregated
3.4.1	http://dx.doi.org/10.4314/wiojms.si2021.1.3	20211220_BS_Socioeconomic_Survey_data_Anon.txt	Data	RF	UEM	Household data
4.1.1	http://dx.doi.org/10.4314/wiojms.si2021.1.4	20211123_BonsSinais_Groudtruething_information.xls	Data	NF	UEM	Land cover types
4.1.2	http://dx.doi.org/10.4314/wiojms.si2021.1.4	20211123_BonsSinais_Image Data_Information.xlsx	Data	NF	ORI	Satellite image metadata
5.1.1	http://dx.doi.org/10.4314/wiojms.si2021.1.5	20211218_BS_Catch_Effort_Length_FishData.xlsx	Data	EV	IIP	Fish, crustaceans
5.2.1	http://dx.doi.org/10.4314/wiojms.si2021.1.5	20210402_TrophicLevelGearsBonsSinais.xlsx	Worksheet	JS	IIP	Fish, crustaceans
5.3.1	http://dx.doi.org/10.4314/wiojms.si2021.1.5	20210409_BonsSinaisSppGearSize.txt	Data	JS	IIP	Fish, crustaceans
5.3.2	http://dx.doi.org/10.4314/wiojms.si2021.1.5	20210409_BonsSinaisSppGearSize_variables.txt	Data	JS	BFE	Fish, crustaceans
5.3.3	http://dx.doi.org/10.4314/wiojms.si2021.1.5	20210409_Selectivity Beach seine.R	R-script	JS	BFE	Statistical script
6.1.1	http://dx.doi.org/10.4314/wiojms.si2021.1.6	Ruvu_Estuary_ Image Data_Information.xls	Data	FM	ORI	Satellite image metadata
6.1.2	http://dx.doi.org/10.4314/wiojms.si2021.1.6	Ruvu_ Estuary LCLU_validation.xls	Data	FM	ORI	Land cover types
6.2.1	http://dx.doi.org/10.4314/wiojms.si2021.1.6	Ruvu_CTD data_May2018.xls	Data	BK	TAFIRI	Conductivity Temperature Density
6.3.1	http://dx.doi.org/10.4314/wiojms.si2021.1.6	Ruvu_Fisheries_1_Species lists.xls	Table	BK	TAFIRI	Fish, crustaceans
6.3.2	http://dx.doi.org/10.4314/wiojms.si2021.1.6	Ruvu_fisheries_2-Estuarize samples 2017-2018.xls	Data	BK	TAFIRI	Fish, crustaceans
6.3.3	http://dx.doi.org/10.4314/wiojms.si2021.1.6	Ruvu_Fisheries_3- Prawn samples 2017-2019.xls	Data	BK	TAFIRI	Crustaceans
6.3.4	http://dx.doi.org/10.4314/wiojms.si2021.1.6	Ruvu_Fisheries_4_Macrobrachium 2017-2018.xls	Data	BK	TAFIRI	Crustaceans
7.1.1	http://dx.doi.org/10.4314/wiojms.si2021.1.7	na	na	FaM	KMFRI	Fish, crustacean
8.1.1	http://dx.doi.org/10.4314/wiojms.si2021.1.8	Tana_Estuary_ Image Data_Information.xls	Data	FM	ORI	Satellite image metadata
8.1.2	http://dx.doi.org/10.4314/wiojms.si2021.1.8	Tana_ Estuary LCLU validation.xls	Data	FM	ORI	Land cover types
8.1.3	http://dx.doi.org/10.4314/wiojms.si2021.1.8	Tana_Estuary_Remote_Sensing_Results.xls	Data	FM	ORI	Land cover types
8.2.1	http://dx.doi.org/10.4314/wiojms.si2021.1.8	na	na	HM	KMFRI	Household data
9.1.1	http://dx.doi.org/10.4314/wiojms.si2021.1.9	Climate and precipitation data.xls	Data	JG	ORI	Temperature Precipitation

(1) Acronyms: AH - Antonio Hoguane, BFE - Faculty of biosciences, fisheries and economics, BK -Baraka Kuguru, EV -Eulália Vetter, FaM - Fatma Manyenze, FM - Fiona MacKay, HM - Hamadi Mwamlavya, IIP - Fisheries Research Institute of Mozambique, JG - Johan Groeneveld, JS - Jorge Santos, KMFRI - Kenya Marine and Fisheries Research Institute, NF - Noca Furaca, ORI - Oceanographic Research Institute, RF - Rodrigues Francisco, TAFIRI -Tanzania Fisheries Research Institute, UEM - University Eduardo Mondlane.

Tabela S5 B: The central data files of the Estuarize project.

FileID	Abstract	Spatial (estuary)	Coordinate	Time
2.1.1	Depth profile hydrographic data in 11 stations along estuary, 601 observations			2011-2012
2.1.2	Variable (14) names and units of 2.1.1	Bons Sinais	18°01' S; 36°58' E	2011-2013
2.2.3	Input data estuarine circulation model			2018
3.1.1.	Household information and occupation by age and gender in landing sites (5)			2018
3.2.1	Governance system and traditional rules of nature exploitation by landing site (5)	Bons Sinais	18°01' S; 36°58' E	2018
3.3.1	Valuation of ecosystem goods and services by landing site (5)			2018
3.4.1	Household interview primary data anonymized			2018
4.1.1	Names, coordinates and vegetation class of validation points; three files	Bons Sinais	18°01' S; 36°58' E	2018
4.1.2	Images (6) and season, sensor, resolution and cloud cover information			1991-2018
5.1.1	Catch, effort, length by gear (6), species (13), landing site (4) and season (2), n= 9565			2008-2015
5.2.1	Calculation of weighted trophic level of catch and gear with aggregated data			2008-2015
5.3.1	Aggregated length composition of main species (4) in beach seines and chicocotas	Bons Sinais	18°01' S; 36°58' E	2008-2015
5.3.2	Variable (9) names and units in 5.3.1			2008-2015
5.3.3	Calculate relative selectivity of beach seines from data as in 5.3.1			2021
6.1.1	Images, date, season, sensor, resolution and cloud cover information			1995-2018
6.1.2	Land Cover validation (see file 6.1.4); classes set for Landsat and Sentinel imagery			1995-2019
6.2.1	CTD readings at Mtailand and Vikundu stations in Ruvu Estuary			2018
6.3.1	Species observed at Ruvu Estuary	Ruvu	6°38' S; 38°87' E	2014-2019
6.3.2	Non-random catch data in Ruvu estuary by species, landing site incl. weight and size			2017-2018
6.3.3	Non-random prawn catch data from Bagamoyo by species, landing site incl. weight and size			2017-2019
6.3.4	Macrobrachium catch data in Ruvu estuary by landing site, incl length and weight			2017-2018
7.1.1	Boat, gear, effort, crew, fishing grounds, fish species			2018
8.1.1	Images, date, season, sensor, resolution and cloud cover information			1987-2019
8.1.2	Land Cover validation from ground photographs; classes set for Landsat/Sentinel imagery	Tana	2°32'S; 40°32'E	1987-2020
8.1.3	Remote sensing (No. pixels & d % cover) for historical (Landsat) and seasonal (Sentinel)			1987-2021
8.2.1	Household info, fishing, catch, products and market			2018
9.1.1	Average ambient air temperature (Celsius) and precipitation (mm) (12 months)	ALL	18° S to 3° S	na

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  Example: Kirk TJO (1983) Light and photosynthesis in aquatic ecosystems. Cambridge University Press, Cambridge. 401 pp

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  Example: Sathyendranath S, Platt T (1993a) Remote sensing of water-column primary production. In: Li WKW, Maestrini SY (eds) Measurement of primary production from the molecular to the global Scale. ICES Marine Science Symposia, Vol. 97, Copenhagen. pp 236-243

- *Articles with a Digital Object Identifier (DOI).*

  Example: Gooseff MN, McKnight DM, Lyons HJ, Blum RJ (2002) Weathering reactions and hyporheic exchange controls on stream water chemistry in a glacial meltwater stream in the McMurdo Dry Valleys. Water Resources Bulletin 38 [doi: 10.1029/2001WR000834]

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