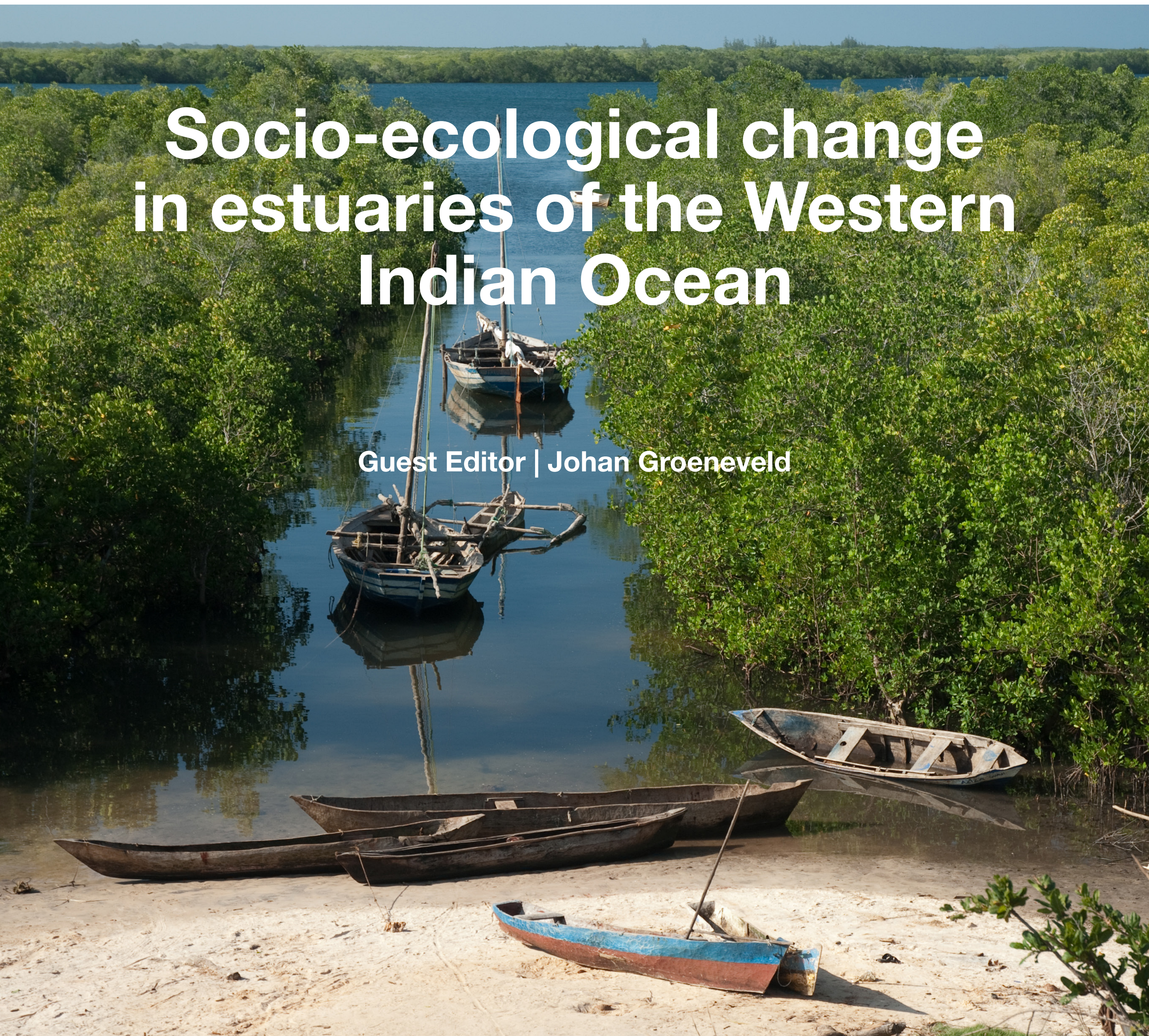
Western Indian Ocean JOURNAL OF Marine Science

Special Issue 1/2021 | ISSN: 0856-860X

Socio-ecological change in estuaries of the Western Indian Ocean

Guest Editor | Johan Groeneveld



Western Indian Ocean JOURNAL OF Marine Science

Chief Editor **José Paula** | Faculty of Sciences of University of Lisbon, Portugal

Copy Editor **Timothy Andrew**

Published biannually

Aims and scope: The *Western Indian Ocean Journal of Marine Science* provides an avenue for the wide dissemination of high quality research generated in the Western Indian Ocean (WIO) region, in particular on the sustainable use of coastal and marine resources. This is central to the goal of supporting and promoting sustainable coastal development in the region, as well as contributing to the global base of marine science. The journal publishes original research articles dealing with all aspects of marine science and coastal management. Topics include, but are not limited to: theoretical studies, oceanography, marine biology and ecology, fisheries, recovery and restoration processes, legal and institutional frameworks, and interactions/relationships between humans and the coastal and marine environment. In addition, *Western Indian Ocean Journal of Marine Science* features state-of-the-art review articles and short communications. The journal will, from time to time, consist of special issues on major events or important thematic issues. Submitted articles are subjected to standard peer-review prior to publication.
Manuscript submissions should be preferably made via the African Journals Online (AJOL) submission platform (http://www.ajol.info/index.php/wiojms/about/submissions). Any queries and further editorial correspondence should be sent by e-mail to the Chief Editor, wiojms@fc.ul.pt. Details concerning the preparation and submission of articles can be found in each issue and at http://www.wiomsa.org/wio-journal-of-marine-science/ and AJOL site.
Disclaimer: Statements in the Journal reflect the views of the authors, and not necessarily those of WIOMSA, the editors or publisher.

ISSN 0856-860X

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

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

Jorge Santos[1], Johan C. Groeneveld[2,3]*, Fiona MacKay[2,3], Cosmas N. Munga[4,5]

[1] Norwegian College of Fisheries Science, UiT – The Arctic University of Norway

[2] Oceanographic Research Institute, Durban, South Africa

[3] School of Life Sciences, University of KwaZulu-Natal, Durban, South Africa

[4] Department of Environment and Health Sciences, Marine and Fisheries Programme, Technical University of Mombasa, Kenya

[5] Department of Geography and Environmental Studies, School of Geography, University of the Witwatersrand, Johannesburg, South Africa

* Corresponding author: jgroeneveld@ori.org.za

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

http://dx.doi.org/10.4314/wiojms.si2021.1.9

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

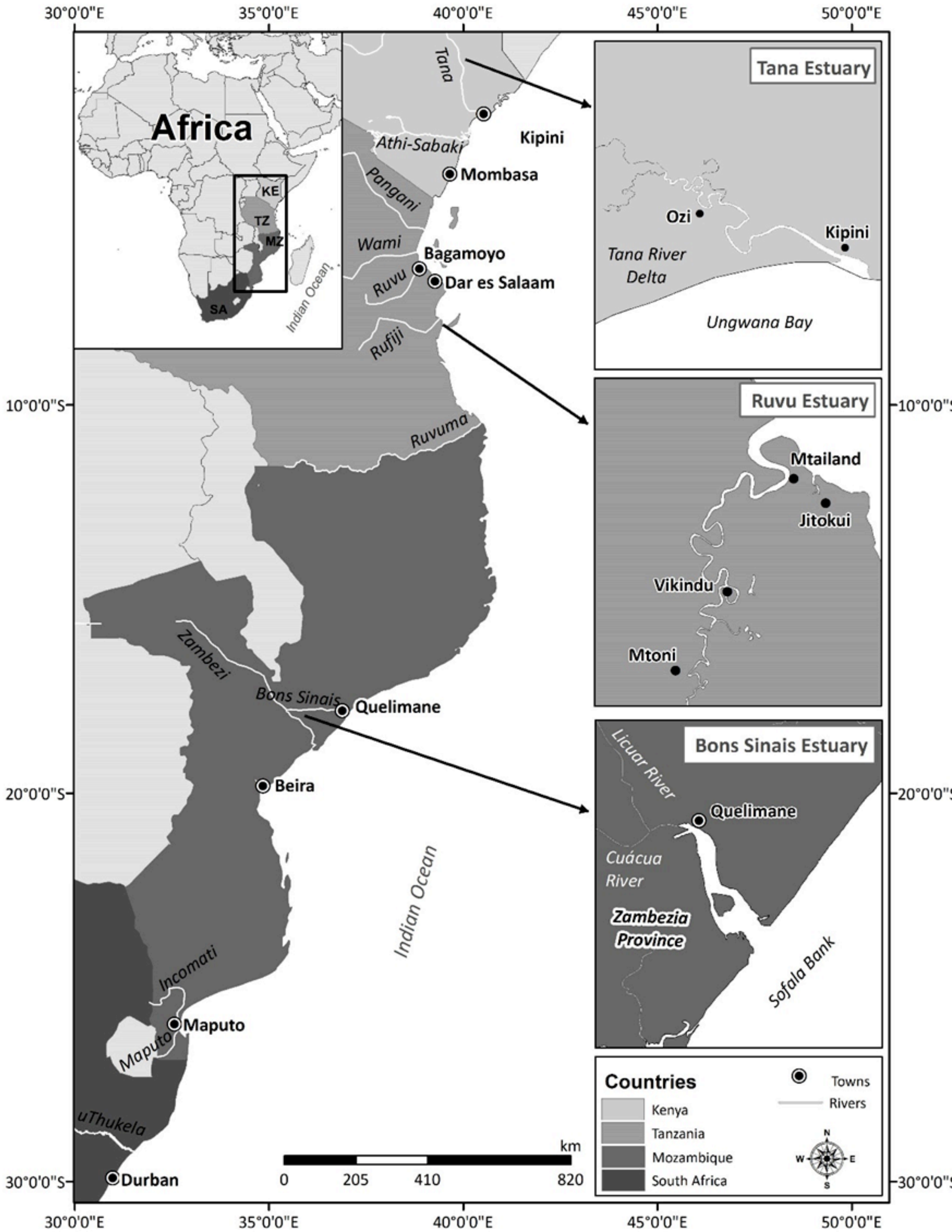


Figure 1. Study area showing the locations of the Bons Sinais-, Ruvu- and Tana Estuaries in the Western Indian Ocean. Insets show place names at each estuary (Source: Groeneveld *et al*., 2021a).

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

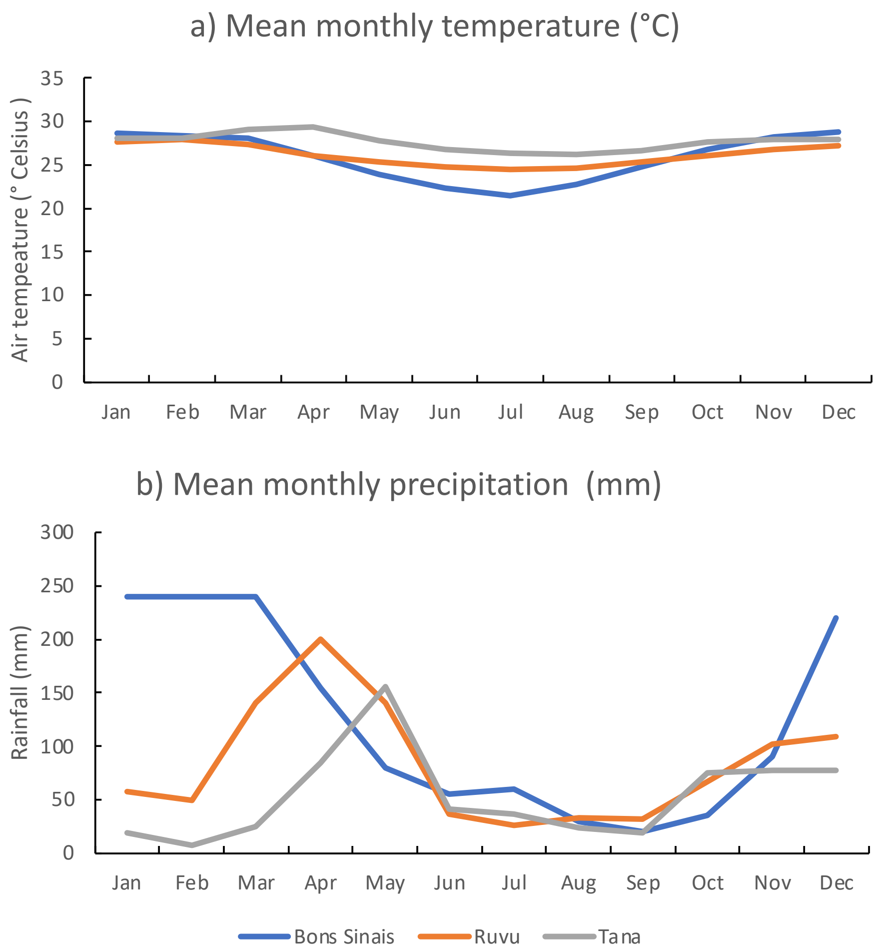


Figure 2. Mean monthly temperature (a) and precipitation (b) at the Bons Sinais- Ruvu- and Tana-Estuaries (https://world-climates.com and https://www.weather-atlas.com/en/kenya/kipini)

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

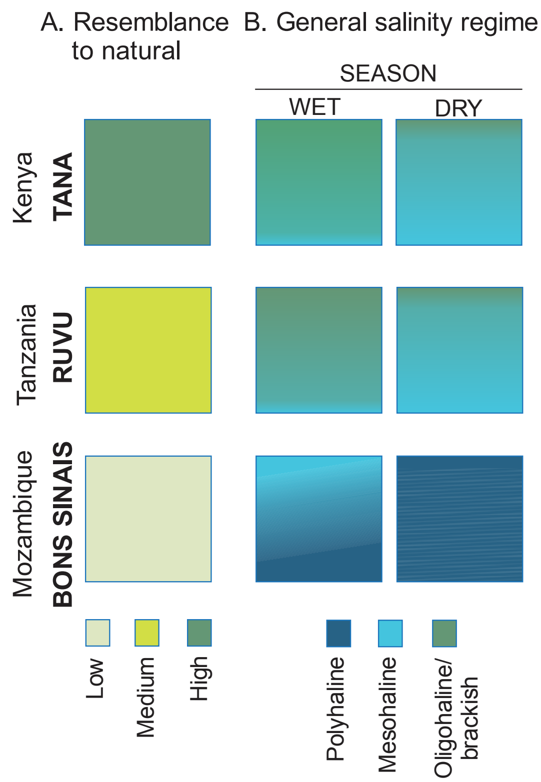


Figure 3. Overall estuary characteristics for the Bons Sinais, Ruvu and Tana estuaries as: (A) resemblance to natural function in terms of freshwater flow and estuarine-related habitats; and (B) present salinity regime that drives estuary functions (e.g. nursery function) during wet and dry seasons.

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,

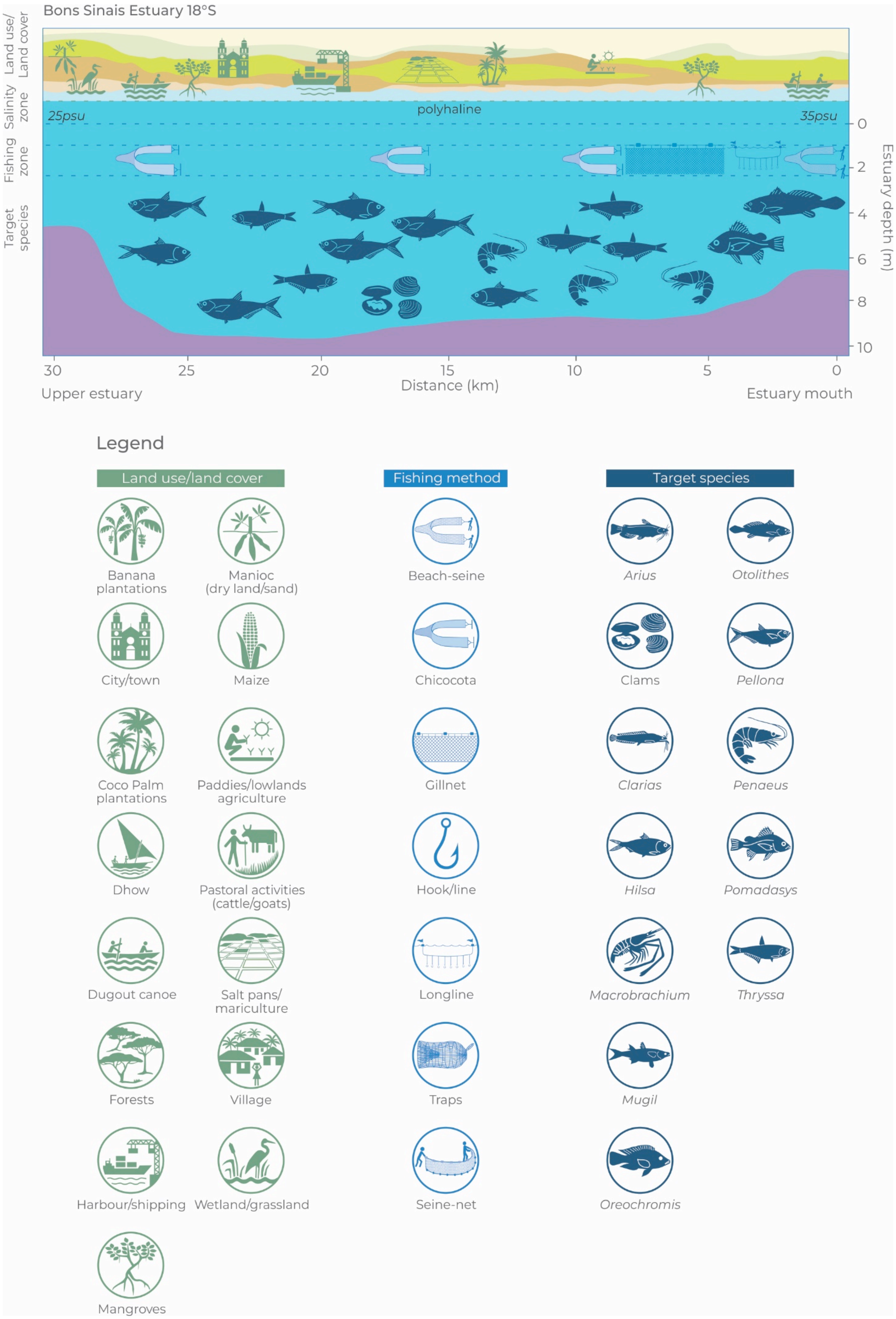


Figure 4a. Schematic diagramme of the Bons Sinais Estuary in Mozambique, depicting its physical characteristics (length, depth, salinity zones), land use and land cover, fishing zones, gears and commonly fished species per zone (not to scale).

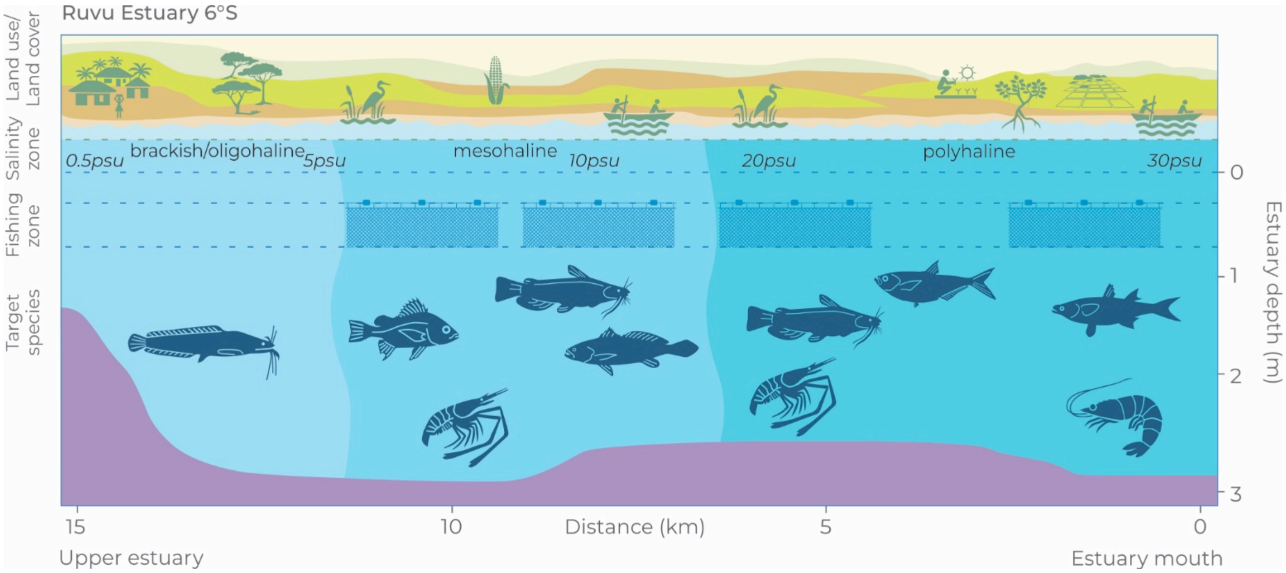


Figure 4b. Schematic diagram of the Ruvu Estuary in Tanzania, depicting its physical characteristics (length, depth, salinity zones), land use and land cover, fishing zones, gears and commonly fished species per zone (not to scale). Icons shown in 4a.

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

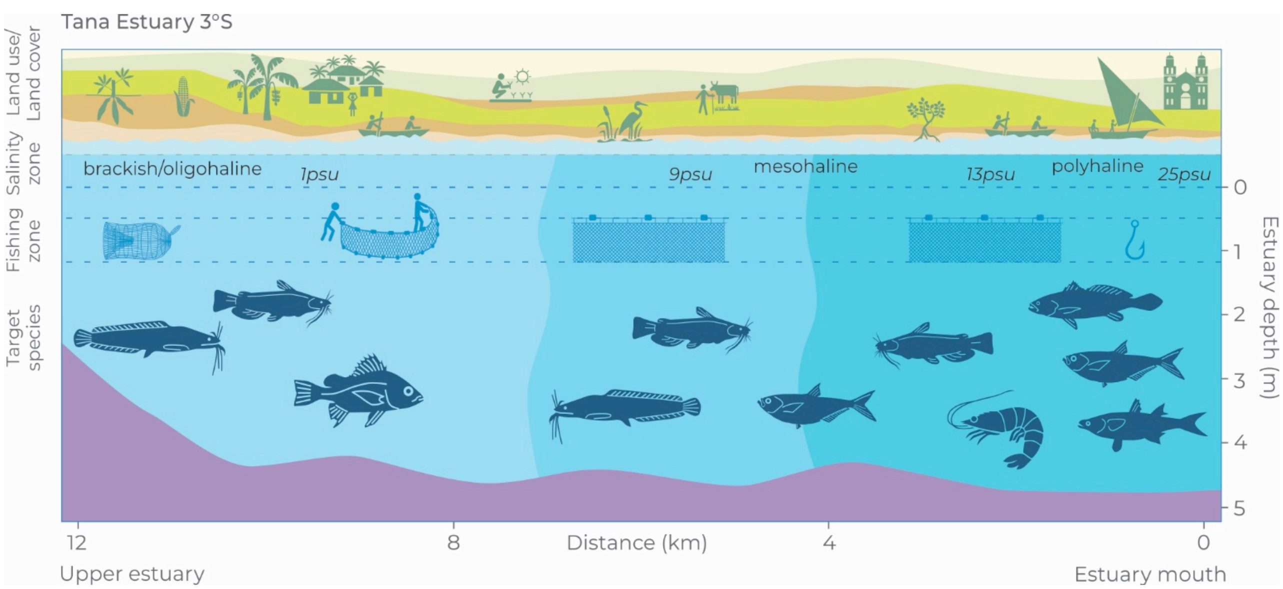


Figure 4c. Schematic diagram of the Tana Estuary in Kenya, depicting its physical characteristics (length, depth, salinity zones), land use and land cover, fishing zones, gears and commonly fished species per zone (not to scale). Icons shown in 4a.

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 %).

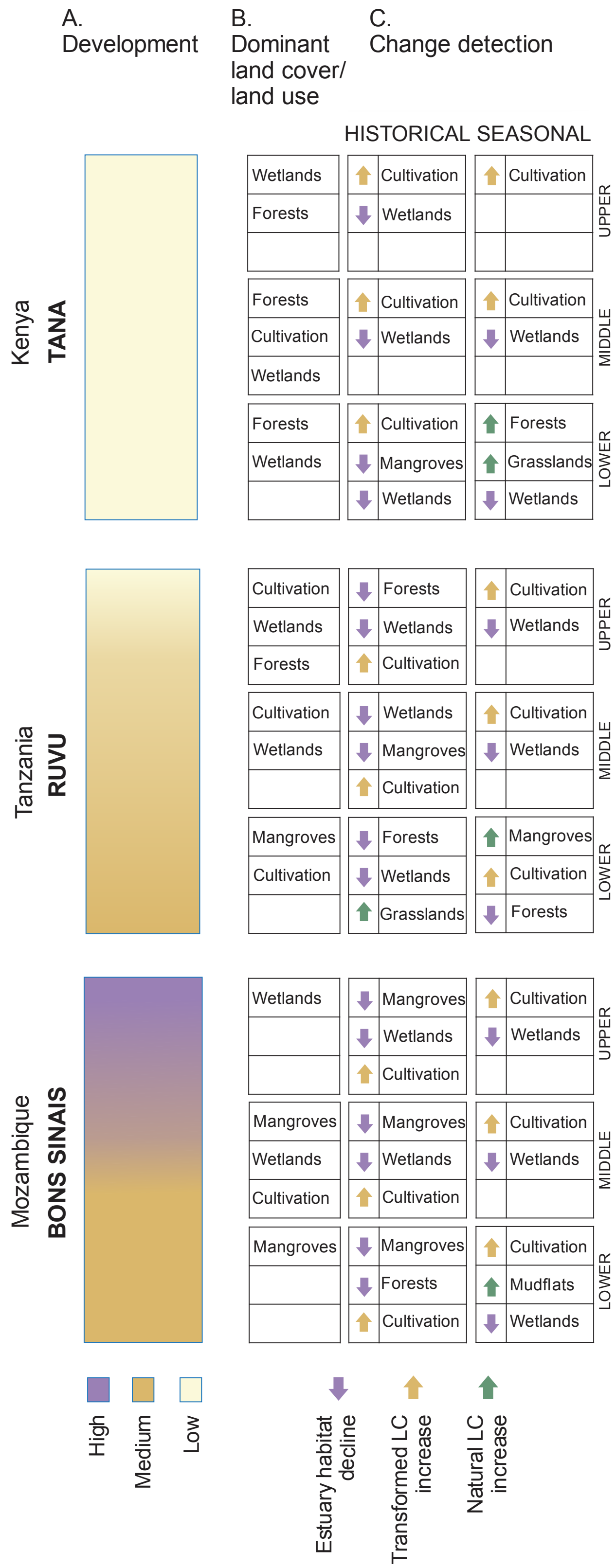


Figure 5. Land cover and land use characteristics influencing ecosystem services and provision of natural goods to the Bons Sinais, Ruvu and Tana estuaries. (A) Development or level of urbanization; (B) Dominant land cover/land use; and (C) Historic and seasonal change detection. Seasonal change shown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

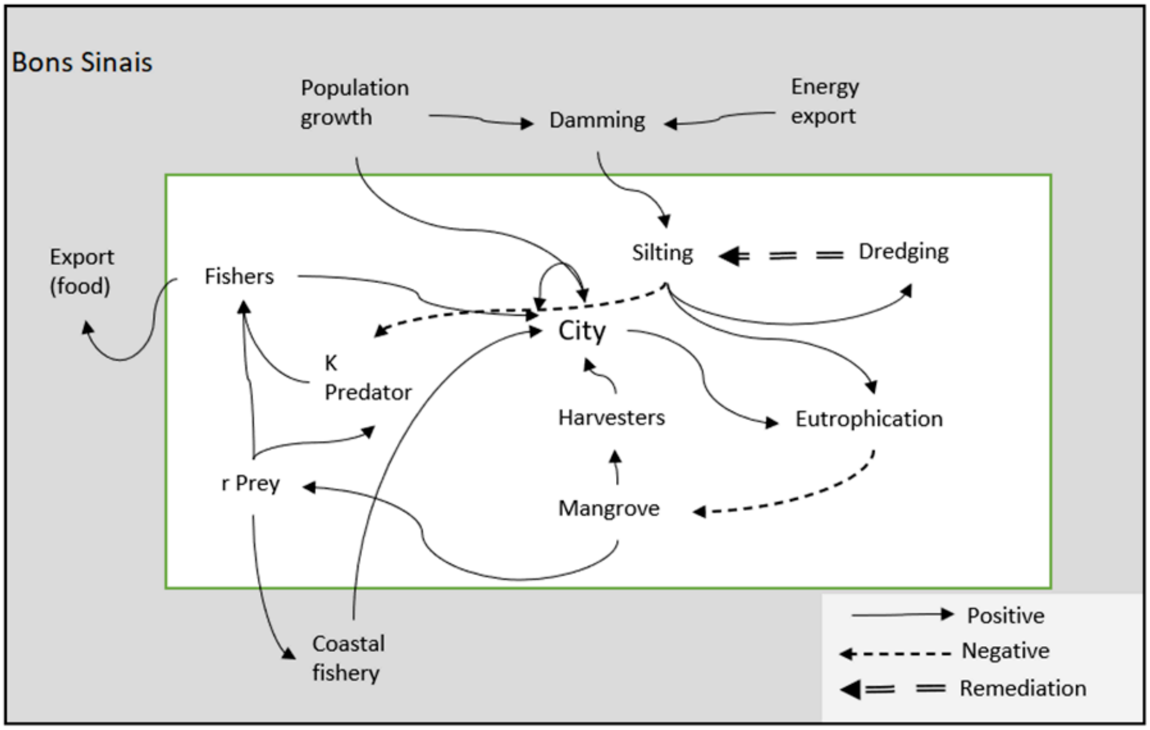


Figure 6. The Bons Sinais Estuary (central box) and its external environment as a socio-ecological-technological network with the most important connections in the present estuary state. Dredging is a technological mitigation remedy to maintain open channels for shipping. The estuary is strongly marine-influenced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

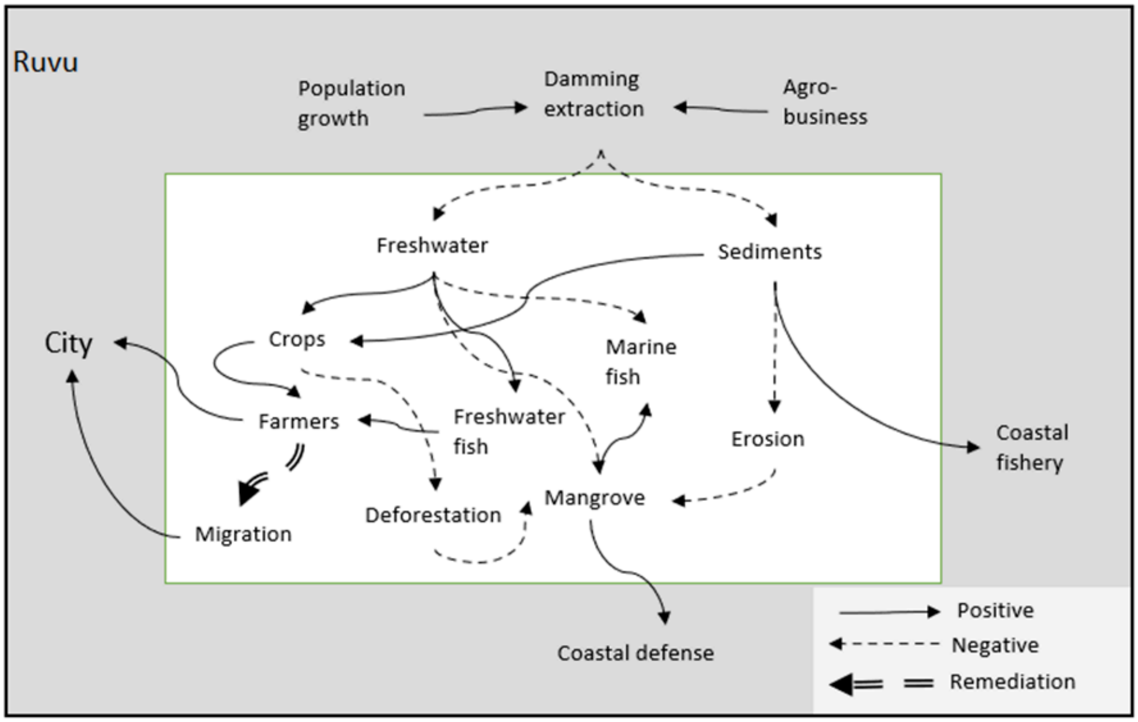


Figure 7. The Ruvu Estuary (central box) and its external environment as a socio-ecological-technological network with some important connections. The salinization of the water body after extensive water extraction upstream has had internal and external consequences, including crop failure in the lower 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.

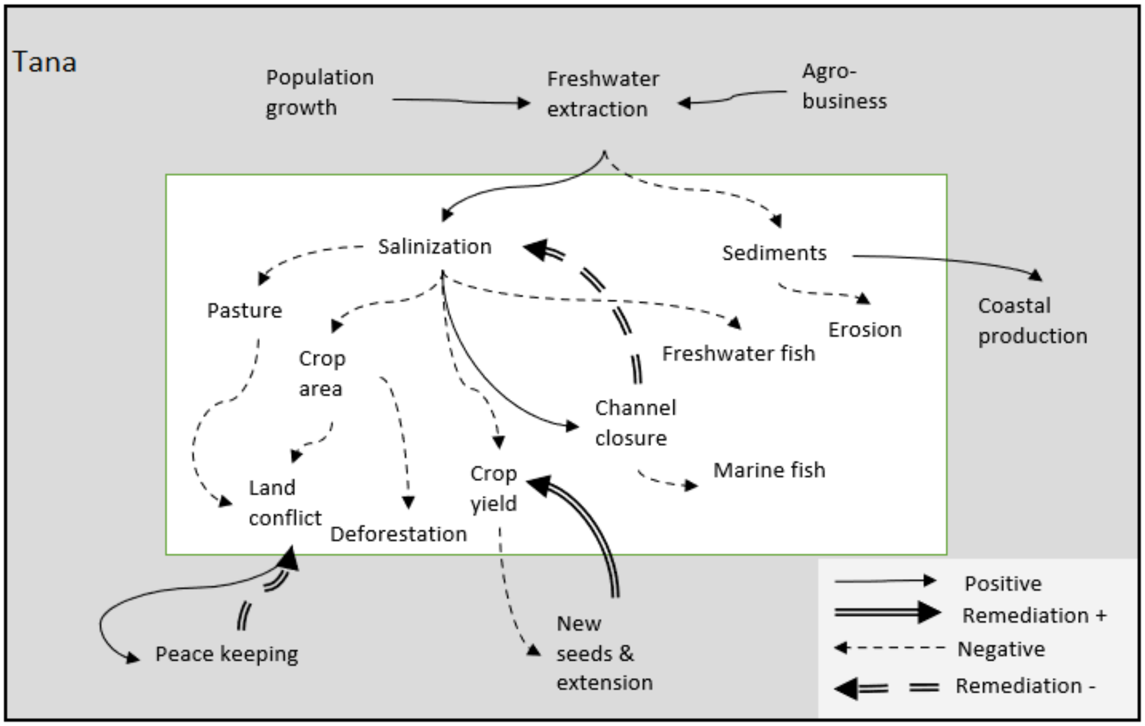


Figure 8. The Tana Estuary (central box) and its external environment as a socio-ecological-technological network with some important connections and features in the present state. Salinization was first remedied by artificial closure of some channels to the sea. Conflicts for space and water occur between 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

Acknowledgements

We thank the MASMA Programme of the Western Indian Ocean Marine Science Association (WIOMSA) for funding Estuarize-WIO (Grant no: MASMA/OP/2016/01). Partner organizations, the Oceanographic Research Institute (ORI, South Africa), Eduardo Mondlane University (Mozambique), Tanzania Institute for Fisheries Research (TAFIRI, Tanzania), University of Dar es Salaam (Tanzania), Kenya Marine and Fisheries Research Institute (KMFRI, Kenya), Technical University of Mombasa (Kenya) and UiT Arctic University of Norway (Norway) are thanked for their support, which included logistics, funding, equipment, data and scientific and technical staff. Among many unnamed individuals that contributed to Estuarize-WIO but are not co-authors of any of the papers in this Special Issue, special thanks go to Julius Francis and Lilian Omolo at WIOMSA.

References

Agergaard J, Ortenbjerg SB (2017) Urban transformations and rural-city connections in Africa. Geografisk Tidsskrift - Danish Journal of Geography 117 (2): 63-67

Agergaard J, Tacoli C, Steel G, Ørtenblad SB (2019) Revisiting rural–urban transformations and small town development in sub-Saharan Africa. European Journal of Development Research 31: 2-11

Alphayo SM, Sharma MP (2018) Water quality assessment of Ruvu River in Tanzania using NSFWQI. International Journal of Scientific Reports 20 (3): 1-9

Amasi AI, Wynants M, Kawalla RA, Sawe S, Munishi L, Blake WH, Mtei, KM (2021) Reconstructing the changes in sedimentation and source provenance in East African hydropower reservoirs: A case study of Nyumba ya Mungu in Tanzania. Earth 2 (3): 485-514

Beilfuss R, dos Santos D (2001) Patterns of hydrological change in the Zambezi Delta, Mozambique. Program for the Sustainable Management of Cahora Bassa Dam and the Lower Zambezi Valley. Working Paper no. 2. Direcção Nacional das Aguas, Maputo, Mozambique. 160 pp

Benkenstein A (2013) Small-Scale fisheries in a modernising economy: Opportunities and challenges in Mozambique. Research Report 13. Governance of Africa's Resources Programme. 55 pp

Berkes F, Armitage D, Ibarra MA, Charles A, Loucks L, Graham J, Seixas C, Makino M, Satria A, Abraham J (2014) Guidelines for analysis of social-ecological systems. CCRN Working Group on Social-Ecological Systems and Community Resilience [http://www.communityconservation.net/ wp-content/uploads/2016/01/FINAL_CCRN-Guidelines-for-Analysis-of-Social-Ecological-Systems-September-2014.pdf]

Binder CR, Hinkel J, Bots PW, Pahl-Wostl C (2013) Comparison of frameworks for analyzing social-ecological systems. Ecology and Society 18(4): 26 [http://dx.doi.org/10.5751/ES-05551-180426]

Blaber SJ (2008) Tropical estuarine fishes: ecology, exploitation and conservation. John Wiley & Sons. 384 pp

Blaber SJ (2012) Fishes and fisheries in tropical estuaries: the last 10 years. Estuarine, Coastal and Shelf Science 135: 57-65

Blythe JL (2014) Resilience and social thresholds in small scale fishing communities. Sustainability Science 10 (1): 157-165

Blythe JL, Murray G, Flaherty M (2014) Strengthening threatened communities through adaptation: insights from coastal Mozambique. Ecology and Society 19(2) [doi: 10.5751/ES-06408-190206]

Bornstein D (2015) The social realities of technology transfer: smallholder farmers' encounter with a new rice variety. African Geographical Review 34 (1): 8-1 2 [doi: 10.1080/19376812.2014.912139]

Bouillon S, Dehairs F, Schiettecatte LS, Borges AV (2007) Biogeochemistry of the Tana estuary and delta (northern Kenya). Limnology and Oceanography 52 (1): 46-59

Brondizio ES, O'Brien K, Bai X, Biermann F, Steffen W, Berkhout F, Cudennec C, Lemos MC, Wolfe A, Palma-Oliveira J, Chen CT (2016) Re-conceptualizing the Anthropocene: A call for collaboration. Global Environmental Change 39: 318-327

Brown WT (1971) The Politics of business: relations between Zanzibar and Bagamoyo in the late nineteenth century. African Historical Studies 4 (3): 631-643

Cardinale M, Chacate O, Casini M, Chaúca I, Helge Vølstad J (2014) CPUE trends of *Hilsa kelee* and *Thryssa vitrirostris* exploited by the artisanal finfish fisheries in Mozambique derived from an on-shore sampling of catches by trip. Scientia Marina 78 (1): 55-64

Costa EF, Mocuba J, Oliveira D, Teodósio MA, Leitão F (2020) Biological aspects of fish species from subsistence fisheries in "Bons Sinais" estuary, Mozambique. Regional Studies in Marine Science 39: 101438

Dalrymple RW, Choi K (2007) Morphologic and facies trends through the fluvial–marine transition in tide-dominated depositional systems: a schematic framework for environmental and sequence-stratigraphic interpretation. Earth-Science Reviews 81 (3-4): 135-174

Diop S, Scheren P, Machiwa JF (eds) (2016) Estuaries: A lifeline of ecosystem services in the Western Indian Ocean. Springer, Cham. 322 pp

Duvail S, Hamerlynck O, Paron P, Hervé D, Nyingi WD, Leone M (2017) The changing hydro-ecological dynamics of rivers and deltas of the Western Indian Ocean: Anthropogenic and environmental drivers, local adaptation and policy response. Comptes Rendus Geoscience 349 (6-7): 269-279

Dzoga M, Simatele D, Munga C (2020) Characterisation of artisanal catches in selected fishing areas of the Lower Tana Delta and Malindi-Ungwana Bay, Kenya. Western Indian Ocean Journal of Marine Science 19 (1): 45-53

Elfversson E (2019) The political conditions for local peacemaking: A comparative study of communal conflict resolution in Kenya. Comparative Political Studies 52 (13-14): 2061-2096

Elliott M, Quintino V (2007) The estuarine quality paradox, environmental homeostasis and the difficulty of detecting anthropogenic stress in naturally stressed areas. Marine Pollution Bulletin 54 (6): 640-645

Francisco RP, Hoguane AM, Simbine RL, Mabota HS (2021) Household dependence on fish-based farming systems in the Bons Sinais Estuary in Mozambique. Western Indian Ocean Journal of Marine Science, Special Issue 1/2021: 29-41

Furaca NB, Hoguane AM, MacKay CF, Willemse M, Langa AA (2021) Exploring urbanization and critical habitat loss through land cover change around the Bons Sinais Estuary, Mozambique. Western Indian Ocean Journal of Marine Science, Special Issue 1/2021: 43-58

GLOWS-FIU (2014a) Climate, forest cover and water resources vulnerability, Wami/Ruvu Basin, Tanzania. 87 pp [ISBN: 978-1-941993-03]

GLOWS-FIU (2014b) A Rapid ecohydrological assessment of the Ruvu River Estuary, Tanzania. Global Water for Sustainability Program, Florida International University. 76 pp

Groeneveld J, Hoguane A, Kuguru B, MacKay CF, Munga C, Santos J (2021a) Estuarize-WIO: A socio-ecological assessment of small-scale fisheries in estuaries of the Western Indian Ocean. Western Indian Ocean Journal of Marine Science, Special Issue 1/2021: 1-15

Groeneveld JC, MacKay CF, Mchomvu B, Kuguru B (2021b) Socio-ecological change in the Ruvu Estuary (Tanzania) inferred from land-use and land-cover (LULC) analysis and estuarine fisheries. Western Indian Ocean Journal of Marine Science, Special Issue 1/2021: 75-91

Hamerlynck O, Nyunja J, Luke Q, Nyingi D, Lebrun D, Duvail S (2010) The communal forest, wetland, rangeland and agricultural landscape mosaics of the Lower Tana, Kenya: A socio-ecological entity in peril. In: Bélair C, Ichikawa K, Wong BL, Mulongoy KJ (eds) Sustainable use of biological diversity in socio-ecological production landscapes. Secretariat of the Convention on Biological Diversity, Montreal. Technical Series 52: 54-62

Hamerlynck O, Nyingi DW, Paul J-L, Duvail S (2020) Fish-based farming systems: maintaining ecosystem health and flexible livelihood portfolios (Chapter 11). In: Dixon J, Garrity DP, Boffa J-M, Williams TO, Amede T, Auricht C, Lott R, Mburathi G (eds) Farming systems and food security in Africa: Priorities for science and policy under global change. Routledge. pp 354-392

Hannerz U (2001) Center–periphery relationships. In: Smelser NJ, Baltes PB (eds) International encyclopedia of social behavioral sciences. Censuses: History and methods. pp 1610-1613

Haraldsson HV (2004) Introduction to system thinking and causal loop diagrams. Reports in Ecology and Environmental Engineering. Department of Chemical Engineering, Lund University. 49 pp

Hoguane AM, Gammelsrød T, Furaca NB, Cafermane AC, António MHP (2021) The residual circulation profile of the Bons Sinais Estuary in central Mozambique – potential implications for larval dispersal and fisheries. Western Indian Ocean Journal of Marine Science, Special Issue 1/2021: 17-27

Jena F (2018) Migrant remittances and physical investment purchases: Evidence from Kenyan households. The Journal of Development Studies 54 (2): 312-326

Kaaya LT (2019) Ecological classification of estuaries along the Tanzanian mainland: a tool for conservation and management. Western Indian Ocean Journal of Marine Science 18 (1): 57-65

Kerega PA (2019) Exploration of the means of getting to the city and getting employed among young female domestic workers in Dar es Salaam, Tanzania. Open Journal of Social Sciences 7 (04). 95 pp

Kitheka JU, Mavuti KM (2016) Tana Delta and Sabaki Estuaries of Kenya: freshwater and sediment input, upstream threats and management challenges. In: Diop S, Scheren P, Machiwa J (eds) Estuaries: a lifeline of ecosystem services in the Western Indian Ocean. Springer, Cham. pp 89-109

Kuguru B, Groeneveld J, Singh S, Mchomvu B (2019) First record of giant freshwater prawn *Macrobrachium rosenbergii* (de Man, 1879) from small-scale fisheries in East Africa, confirmed with DNA barcoding. BioInvasions Records 8(2): 379-391 [doi.org/10.3391/bir.2019.8.2.19]

Kwazu G, Chang-Richards AY (2020) A metric of indicators and factors for assessing livelihood preparedness: A systematic review. International Journal of Disaster Risk Reduction. p.101966

Liu J, Hull V, Batistella M, DeFries R, Dietz T, Fu F, Hertel TW, Izaurralde RC, Lambin EF, Li S, Martinelli LA, McConnell WJ, Moran EF, Naylor R, Ouyang Z, Polenske KR, Reenberg A, de Miranda Rocha G, Simmons CS, Verburg PH, Vitousek PM, Zhang F, Zhu C (2013) Framing sustainability in a telecoupled world. Ecology and Society 18(2): 26 [http://dx.doi.org/10.5751/ ES-05873-180226]

Maganga FP, Kiwasila HL, Juma IH, Butterworth JA (2004) Implications of customary norms and laws for implementing IWRM: findings from Pangani and Rufiji basins, Tanzania. Physics and chemistry of the Earth, Parts A/B/C 29 (15-18): 1335-1342

Manyenze F, Munga C, Mwatete C, Mwamlavya H, Groeneveld J (2021) Small-scale fisheries of the Tana Estuary in Kenya. Western Indian Ocean Journal of Marine Science, Special Issue 1/2021: 93-114

Mbwambo SJ, Ndelolia D, Madalla N, Mnembuka B, Lamtane HA, Mwandya AW, Zahabu F (2012) Climate change impacts and adaptation among coastal and mangrove dependent communities: A case of Bagamoyo district. Proceedings of the first Climate

Change Impacts, Mitigation and Adaptation Programme Scientific Conference (CCIAM). Sokoine University of Agriculture, Tanzania. pp 131-141

McClanahan TR (1988) Seasonality in East Africa's coastal waters. Marine Ecology Progress Series 44: 191-199

Mkama W, Mposo A, Mselemu M, Tobey J, Kajubili P, Robadue D, Daffa J (2010) Fisheries value chain analysis Bagamoyo District, Tanzania. Coastal Resources Center, University of Rhode Island, Narragansett, Rhode Island. 28 pp

Mkare TK, von der Heyden S, Groeneveld JC, Matthee CA (2014) Genetic population structure and recruitment patterns of three sympatric shallow-water penaeid prawns in Ungwana Bay, Kenya, with implication for fisheries management. Marine and Freshwater Research 65: 255-266

Moore AE, Cotterill FP, Main MP, Williams HB (2007) The Zambezi River. Large rivers: geomorphology and management 13: 311-332

Msangameno DJ, Jiddawi NS, Yahya SA (2017) An update on the status of mangrove forests in the western coast of Unguja Island, Tanzania: a rural vs peri-urban comparison. Tropical Ecology 58 (1): 57-69

Mucova SA, Azeiteiro UM, Lopes CL, Dias JM, Pereira MJ (2021) Approaching Sea-Level Rise (SLR) change: Strengthening local responses to sea-level rise and coping with climate change in Northern Mozambique. Journal of Marine Science and Engineering 9 (2): 205 [https://doi.org/ 10.3390/jmse9020205]

Mugabe ED, Madeira AN, Mabota HS, Nataniel AN, Santos J, Groeneveld J (2021) Small-scale fisheries of the Bons Sinais Estuary in Mozambique with emphasis on utilization of unselective gear. Western Indian Ocean Journal of Marine Science, Special Issue 1/2021: 59-74

Munga CN, Mwangi S, Ong'anda H, Ruwa R, Manyala J, Groeneveld JC, Kimani E, Vanreusel A (2013) Species composition, distribution patterns and population structure of penaeid shrimps in Malindi-Ungwana Bay, Kenya, based on experimental bottom trawl surveys. Fisheries Research 147: 93-102

Munga CN, Mwangi S, Ong'anda H, Ruwa R, Manyala J, Groeneveld JC, Kimani E, Vanreusel A (2014) Fish catch composition of artisanal and bottom trawl fisheries in Malindi-Ungwana Bay, Kenya: a cause for conflict? Western Indian Ocean Journal of Marine Science 13: 31-46

Mutia D, Carpenter S, Jacobs Z, Jebri F, Kamau J, Kelly SJ, Kimeli A, Langat PK, Makori A, Nencioli F, Painter SC (2021) Productivity driven by Tana river discharge is spatially limited in Kenyan coastal waters. Ocean and Coastal Management 211: 105713

Mwaguni S, Ruwa RK, Odhiambo-Ochiewo J, Osore M (2016) Integrated water resources management in a changing climate: the implication of anthropogenic activities on the Tana and Athi/Sabaki Rivers water system for sustainable development. In: Diop S, Scheren P, Machiwa J (eds) Estuaries: A lifeline of ecosystem services in the Western Indian Ocean. Springer, Cham. pp 111-129

Mwamlavya H, Munga C, Fulanda B, Omukoto J, Thoya P, MacKay CF, Manyenze F, Groeneveld J (2021) Natural resource-use in the Lower Tana River Delta based on household surveys and remote sensing of land cover and land use patterns. Western Indian Ocean Journal of Marine Science, Special Issue 1/2021: 115-129

Ngondo J, Mango J, Liu R, Nobert J, Dubi A, Cheng H (2021) Land-Use and Land-Cover (LULC) change detection and the implications for coastal water resource management in the Wami–Ruvu Basin, Tanzania. Sustainability 13 (8): 4092

Ortiz AM, Outhwaite CL, Dalin C, Newbold T (2021) A review of the interactions between biodiversity, agriculture, climate change, and international trade: Research and policy priorities. One Earth 4 (1): 88-101

Peter LL, Yang Y (2019) Urban planning historical review of master plans and the way towards a sustainable city: Dar es Salaam, Tanzania. Frontiers of Architectural Research 8 (3): 359-377

Shaghude YW, Wannäs KO, Lundén B (2003) Assessment of shoreline changes in the western side of Zanzibar channel using satellite remote sensing. International Journal of Remote Sensing 24 (23): 4953-4967

Teikwa ED, Mgaya YD (2003) Abundance and reproductive biology of the penaeid prawns of Bagamoyo coastal waters, Tanzania. Western Indian Ocean Journal of Marine Science 2 (2): 117-125

Tobey J, Robadue D, Shaghude YW, Muhando C, Kalangahe B, Mahenge J, Daffa J (2013) State of Mbegani Bay: The ecosystem, livelihoods, and future status. Tanzania. Coastal Resources Center, Graduate School of Oceanography, University of Rhode Island, Narragansett, RI. 49 pp

Törnqvist TE, Wallace DJ, Storms JE, Wallinga J, Van Dam RL, Blaauw M, Derksen MS, Klerks CJ, Meijneken C, Snijders EM (2008) Mississippi Delta subsidence primarily caused by compaction of Holocene strata. Nature Geoscience 1 (3): 173-176

Ullgren JE, André E, Gammelsrød T, Hoguane AM (2016) Observations of strong ocean current events offshore Pemba, Northern Mozambique. Journal of Operational Oceanography 9 (1): 55-66

UNEP-Nairobi Convention and WIOMSA (2015) The regional state of the coast report: Western Indian Ocean. UNEP and WIOMSA, Nairobi, Kenya. 546 pp

Verkaart S, Mausch K, Harris D (2018) Who are those people we call farmers? Rural Kenyan aspirations and realities. Development in Practice 28 (4): 468-479

Wanyonyi IN, Wamukota A, Mesaki S, Guissamulo AT, Ochiewo J (2016) Artisanal fisher migration patterns in coastal East Africa. Ocean and Coastal Management 119: 93-108

Wanyonyi IN, Karisa JF, Gamoyo M, Mbugua J (2017) Factors influencing migrant fisher access to fishing grounds. Western Indian Ocean Journal of Marine Science 16 (2): 27-39

Ward RD, Friess DA, Day RH, MacKenzie RA (2016) Impacts of climate change on mangrove ecosystems: a region by region overview. Ecosystem Health and Sustainability 2 (4): e01211

Wesselink A, Fritsch O, Paavola J (2020) Earth system governance for transformation towards sustainable deltas: What does research into socio-eco-technological systems tell us? Earth System Governance: 100062

WIOMSA (2011) Migrant fishers and fishing in the Western Indian Ocean: Socio-economic dynamics and implications for management. Final Report of Commissioned Research Project MASMA/CR/2008/02. 159 pp

Zavala-Garay J, Theiss J, Moulton M, Walsh C, Van Woesik R, Mayorga-Adame CG, García-Reyes M, Mukaka DS, Whilden K, Shaghude YW (2015) On the dynamics of the Zanzibar Channel. Journal of Geophysical Research: Oceans120 (9): 6091-6113

Zenebe MG, Fleskens L, Ritsema C, Steenbergen FV (2021) Enhancing traditional floodwater governance for inclusive and resilient flood-based livelihood systems in Tana river floodplains, Kenya. Journal of Environmental Planning and Management: 1-17

Zhou S, Kolding J, Garcia SM, Plank MJ, Bundy A, Charles A, Hansen C, Heino M, Howell D, Jacobsen NS, Reid DG (2019) Balanced harvest: concept, policies, evidence, and management implications. Reviews in Fish Biology and Fisheries 29 (3): 711-733

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