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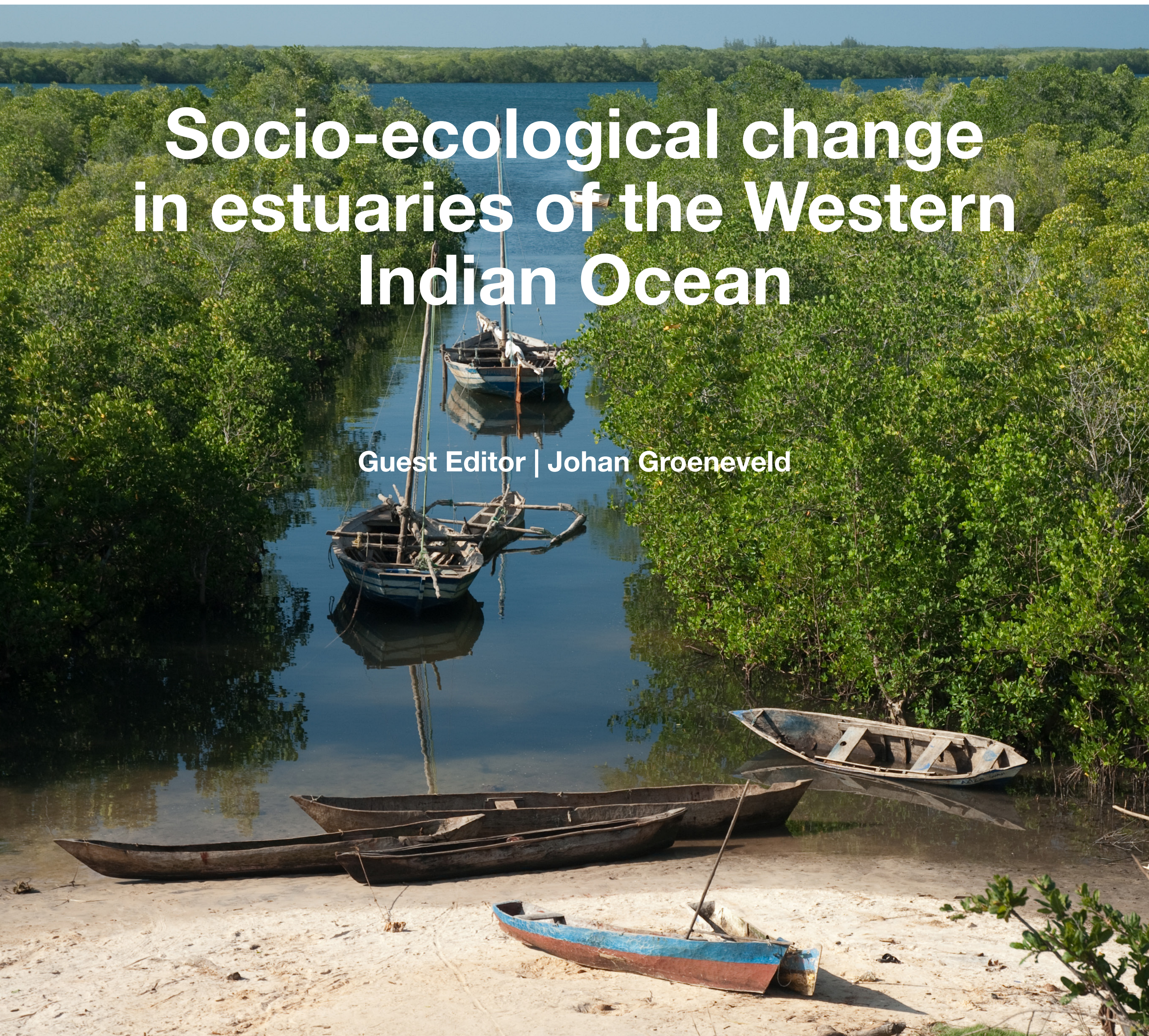

Socio-ecological change in estuaries of the Western Indian Ocean

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

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

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Abstract

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

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

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Background

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

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

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

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

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

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

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

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

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

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

The objectives of Estuarize-WIO were to:

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

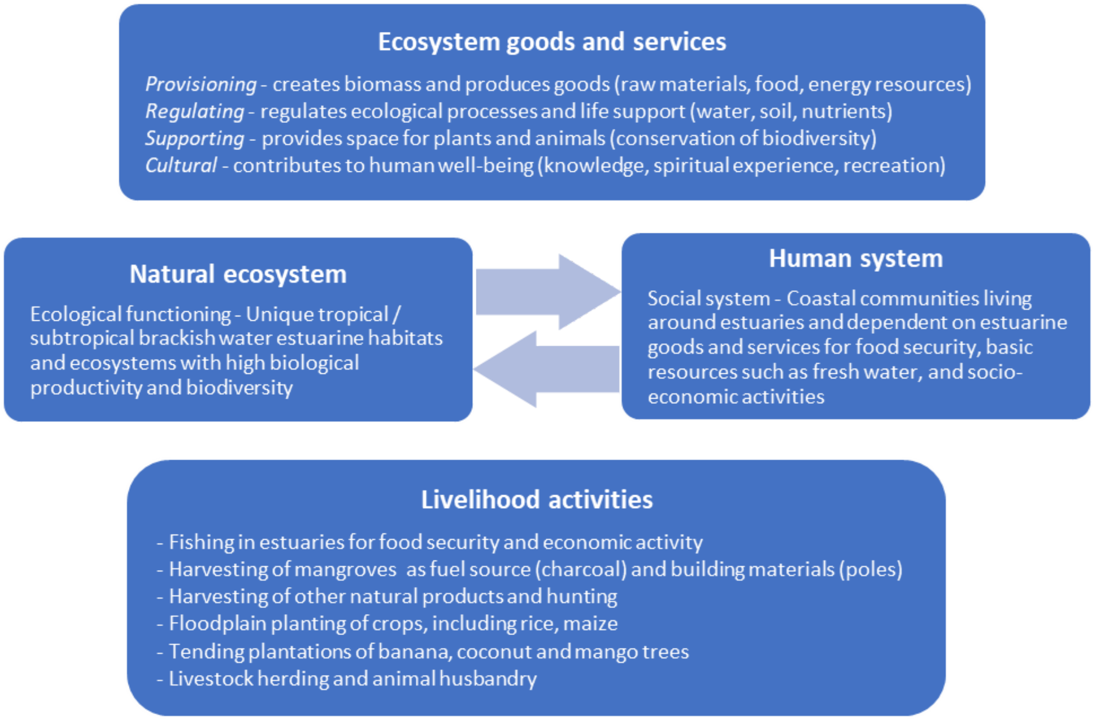

Figure 1. Simplified Socio Ecological Systems (SES) concept (Ostrom, 2009) showing key interactions between social and ecological systems in Western Indian Ocean estuaries (McNally *et al*., 2016).

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

Description of 'WIO estuaries'

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

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

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

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

Selection of estuaries for study by Estuarize-WIO

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

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

Bons Sinais Estuary in Mozambique

Geographical setting

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

Ecosystems and socio-ecological importance

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

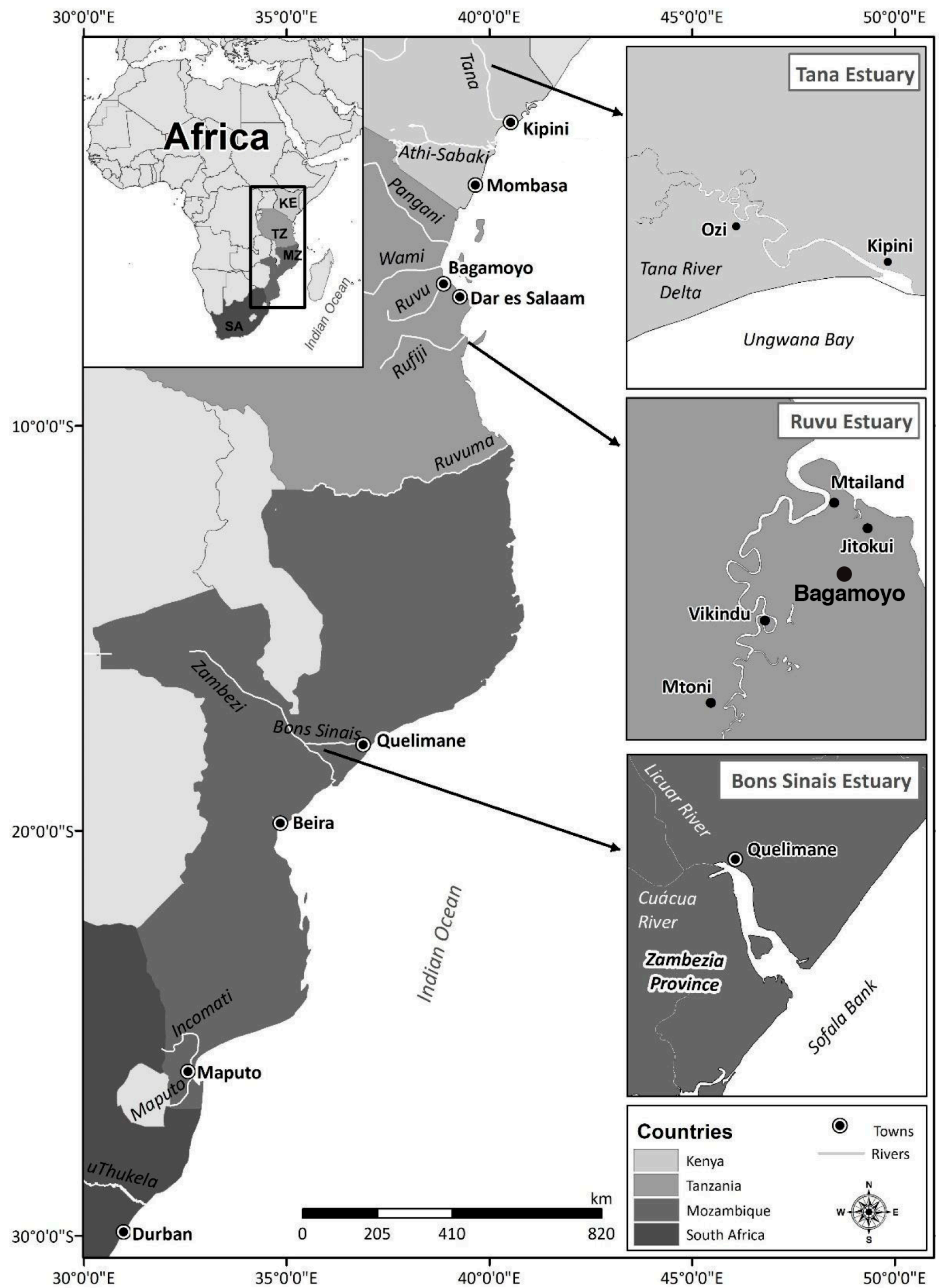

Figure 2. Estuarize-WIO study area in the Western Indian Ocean region, showing towns and estuaries mentioned in the text: Tana Estuary in Kenya (top right panel); Ruvu Estuary in Tanzania (middle) and Bons Sinais Estuary in central Mozambique (bottom).

Key drivers of socio-ecological change

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

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

Ruvu Estuary in Tanzania

Geographical setting

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

Ecosystems and socio-ecological importance

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

Key drivers of socio-ecological change

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

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

Tana Estuary in Kenya

Geographical setting

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

Ecosystems and socio-ecological importance

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

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

Key drivers of socio-ecological change

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

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

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

Project framework, research strategy and data sources

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

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

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

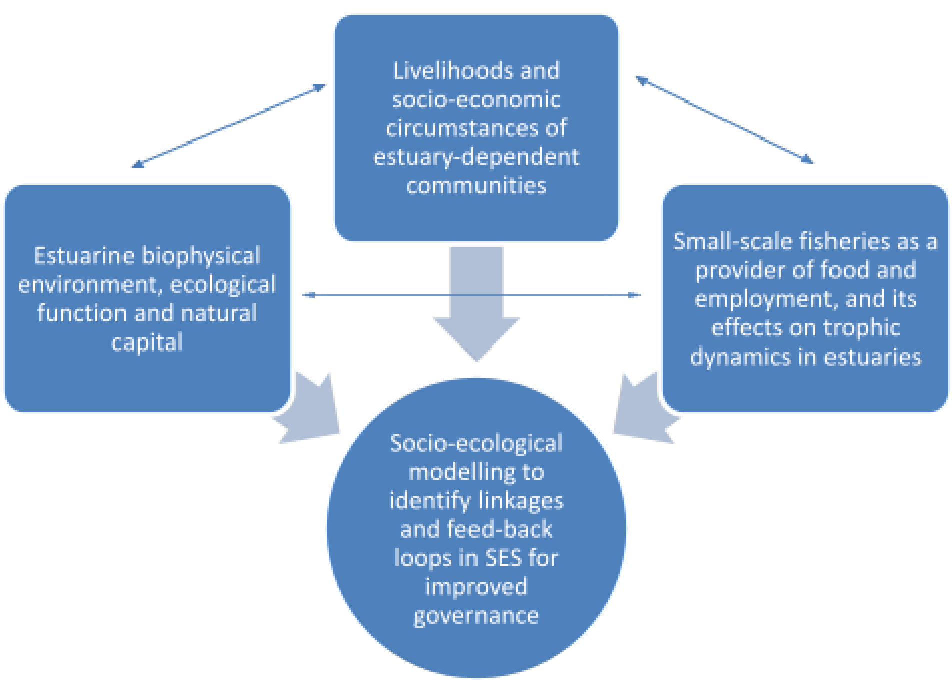

Figure 3. Relationships between Estuarize-WIO Work Packages (WP) for different disciplines, feeding into a socio-ecological system (SES) modelling framework.

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

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

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

Integration of Estuarize-WIO research papers into a Special Issue

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

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

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

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

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

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

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