CHO Chapter 13_Estuaries

Johan Groeneveld

Background

Commented [A1]: Do we need an Abstract/Summary?

Estuaries are partially enclosed coastal water bodies where rivers reach the sea. They are dynamic brackish water ecosystems that form the transition between freshwater and marine environments. The mixing of sea and fresh water in estuaries provides high levels of nutrients in the water column and sediments and their shallow depth ensures that biological processes take place near the surface, making them among the most productive natural habitats in the world (Elliott and McLusky, 2002). Estuaries are home to unique plant and animal communities that have adapted to brackish water, and they export sediments, nutrients and organic matter to nearshore habitats on the continental shelf, enriching marine ecosystems. Estuaries have been focal points of human settlement and resource use throughout history (Lotze et al., 2006). Over time, complex socio-ecological systems have evolved around estuaries, in which the 'human system' (eg, communities, society, economy) interacts with the 'natural system' (eg, coastal and marine ecosystems and renewable resources) in an adaptive and resilient manner.

Estuaries are not usually considered to be critical habitats; rather, they are ecosystems where complexes of organisms and their associated physical environments interact within a specified area (Tansley, 1935). Estuaries enclose, connect and support the functioning of many different habitats, often unique and critical for the maintenance of surrounding coastal and marine ecosystems. Critical habitats associated with Western Indian Ocean (WIO) estuaries are mangroves (Chapter 9), sea grasses (Chapter 10), salt marshes (Chapter 11), coral and biogenic reefs (Chapter 12) and nearshore environments that receive terrigenous sediments, nutrients and biological propagules from estuaries (Chapter 8). Mesohaline pelagic- or benthic habitats that support brackish water species, coastal lagoons, freshwater wetlands and coastal forests within the estuarine functional zone are common in the WIO region and are critical from ecological and socio-economic perspectives.

Estuaries are one of the coastal areas most at risk from human activities (Diop et al., 2016). Estuarine processes rely on riverine (fluvial) runoff from catchment basins and are vulnerable to changes in the frequency and volume of flooding. Disruption in fluvial regimes may originate far inland, when land-use patterns and vegetation cover are changed to increase agricultural production, water is abstracted for irrigation, or dams are built for hydro-electrical power (HP) generation (Duvail et al., 2017). All these activities have a high priority for food production and economic growth in developing countries, and take place far away from estuaries – nevertheless, their downstream impacts on estuarine processes and functioning can be severe from ecological and socio-economic perspectives. Estuaries are also influenced by sea-level rise and storm surges, which are set to increase under the present climate change predictions. Coastal erosion and salt-intrusion, driven by increasing tidal reach, can alter the physical state and hydro-biology of estuaries, affecting key processes and productivity.

Rapid population growth over the past decades, especially in the developing world, has increased the anthropogenic pressure on natural resources. Human population growth in the coastal areas of the WIO has likewise been rapid, and several cities have developed along the banks of estuaries (eg, Maputo, Beira, Dar es Salaam and Mombasa), where they are strategically placed as ports for ocean-going vessels and transport of goods, and to benefit from ecosystem goods, such as fish, fuelwood and mangrove wood for construction materials.

Within the context of a critical habitats outlook, 'WIO estuaries' was defined as the unit of assessment. A first attempt to use the IUCN Red List of Ecosystems (RLE) protocol (IUCN, 2015) as a risk assessment framework to determine the state of individual estuaries failed because of the incompatibility of existing information between individual estuaries (ie data deficient) or the complete absence of published information on smaller systems (ie not evaluated). A lack of historical data (pre-1970s), beyond anecdotal information, prevented direct trending of the ecological status of the WIO estuaries over the past 50 years. A simpler qualitative index was therefore used to assess estuaries according to the structure of the IUCN Red List of Ecosystems categories. Only 12 estuaries, for which reports and published information could be found, were assessed for this report but reference is made to several other estuaries where it could assist in understanding. The scale of the assessment was regional (ie sub-global), dealing with estuaries located in tropical / subtropical climates with strongly seasonal rainfall patterns. Ecologically meaningful similarities among the biota, abiotic environments and their interactions were therefore assumed to occur in estuaries across the WIO region.

Commented [A2]: This text is almost verbatim again on page 7. Need to decide where to include once only.

Description of 'WIO estuaries'

Steep headwater gradients and deltaic systems: Most of the rivers that drain into the WIO have steep headwater gradients along the high-elevation ridge stretching southwards from the Red Sea coast, through the Ethiopian relief and along the eastern edge of the Great Rift Valley down to southern Lake Malawi (Duvail et al., 2017) (Figure 1). South of that, several rivers that discharge in southern Mozambique and eastern South Africa originate in the highlands of Swaziland and Lesotho. In Madagascar, rivers that drain into the Mozambique Channel originate on the central plateau. Steep headwater gradients combined with erodible volcanic rock in source areas often result in high sediment loads (Vanmaercke et al., 2014). Deltaic estuarine systems, common in the WIO, then form when sediments are deposited on coastal floodplains, and are reshaped over time by sediment compaction, dewatering and renewed sedimentation by successive flood deposits (Duvail et al., 2017). Major fan-shaped deltas in the region have formed where the Zambezi, Rufiji and Tana rivers meet the ocean, and many other smaller estuaries also form deltas that discharge into Maputo Bay (eg, Incomati, Maputo), and further to the north (eg, Ruvuma, Ruvu, Athi-Sabaki).

Seasonal rainfall: Rainfall and flow characteristics of WIO estuaries are highly seasonal. Heavy extended rainfall occurs in March to May in northern Mozambique, Tanzania, Kenya and southern Somalia, before the SE monsoon, and short rains occur in the same region in October to December during the NE monsoon (Kitheka et al., 2004). The alternating dry and wet months result in high seasonal variability in runoff and sediment transport, with profound effects on estuarine functioning and exports of sediments and nutrients to nearby marine ecosystems. Peak rainfall in southern Mozambique and eastern South Africa occurs during summer, between November and February. The greater frequency and severity of floods and droughts resulting from climate change and their influences on river discharge and sediment transport further affects estuarine conditions (Mwaguni et al., 2016), adding to natural variability brought by the seasonal wet / dry cycle. 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).

Latitudinal rainfall trend: By latitude, annual rainfall decreases northwards from Mozambique (530-1140 mm per year) to Somalia (250-375 mm), and as a result larger estuaries are more prevalent in the southern part of the WIO, particularly in Mozambique (Taylor et al., 2003). The estimated total annual discharge in the northern part of the WIO (Kenya and Somalia) is in the range of 1.8-4.95 km^3/y, but it is substantially greater at 2.9-106 km^3/y in the central and southern WIO region (Tanzania, Mozambique and South Africa) (Hatziolos et al., 1996; Hirji et al., 1996; UNEP, 2001).

Tidal influence: The WIO deltas are mostly 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 tidal currents can be strong (> 2 m/s) in estuaries, and influence headwaters far upstream, especially where dams and upstream water abstraction reduces runoff, or during droughts. For example, salt water intrusion occurs up to 80 km from the mouth of the Zambezi delta and 55 km in the Thukela River (Scheren et al., 2016). Seasonal freshwater wetlands are common in low-lying areas of WIO deltas. Stratification of the estuary water-column, when dense seawater enters estuaries as a wedge below the fresh water layer at incoming tides (Hoguane and Antonio, 2016) facilitate irrigation of rice and other crops are cultivated in wetlands, often in areas cleared of mangroves.

Key habitats of WIO estuaries: Mangrove forests (see Chapter 9) are the most ubiquitous habitat in WIO estuaries, covering an estimated 1 million ha, mostly in Mozambique, Tanzania, Kenya and Madagascar (Bosire et al., 2016). Nine mangrove species occur in the region, with zonation from seaward to landward edges of estuaries depending on factors such as tolerance to salinity, varied tidal regimes and substrate types (Bosire et al., 2016). The most expansive mangrove forests occur in deltas, but small estuaries and non-estuarine habitats harbouring mangroves are also important ecosystems (Kimirei et al., 2016). Mangroves extend upstream along the banks of estuaries up to the furthest extent of seawater intrusion, where after pioneering species such as *Avicennia marina* make way for vegetation that are salt-intolerant.

Seagrasses are distributed throughout the WIO region, from the intertidal zone to about 40 m deep, and often occur in close connection with mangroves and coral reefs (Lugendo, 2015). Extensive seagrass beds occur in WIO deltas (eg, Rufiji, Tana, Ruvu and Wami), and they are sometimes limited to the sheltered waters of estuaries. Seagrasses are one of the most productive aquatic ecosystems in the world, and they serve as critical habitats (as nurseries and foraging grounds) for numerous fish and invertebrate species (see Chapter 10).

Mesohaline pelagic- or benthic habitats that support brackish water species are other key habitats of WIO estuaries. Mesohaline conditions are important as nursery or breeding areas for marine fish and crustaceans with estuary-dependent life-history phases, and loss of this habitat might have implications for nearshore fisheries. A stark example was the collapse of a prawn trawl fishery on the Thukela Bank in eastern South Africa, when the mouth of the St Lucia Estuary closed as a result of sedimentation. In that case, juvenile prawns in the St Lucia Estuary could not recruit to the nearshore marine mudbanks, leading to recruitment failure and the collapse of the fishery (Ayers et al., 2013).

Urbanization around estuaries: 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 much higher around deltas in southern Mozambique and Madagascar, ranging from 250 to 999 inhabitants/km^2. Urbanization along the banks of estuaries takes advantage of the plentiful resources that estuaries provide, including products from mangrove forests, fish resources, and their proximity to navigable waters and ports, to transport goods. Cities and large towns on the banks of estuaries in the WIO continue to expand rapidly (eg, Maputo, Beira, Quelimane, Dar es Salaam, Mombasa).

Selection of representative estuaries: For this report, ~~we selected~~ 12 representative estuaries were selected between the equator (northern Kenya) and 30°S (eastern South Africa), including one in northwest Madagascar (Figure 1). These estuaries represent the major rivers that discharge into the WIO (eg, Zambezi, Rufiji), as well as rivers with medium-sized (eg, Tana, Athi-Sabaki, Ruvuma, Incomati, Maputo and Thukela) and small basins (Umgeni). Basin sizes ranged from 4~~-~~500 km^2 for the Umgeni River to 1.3 million km^2 for the Zambezi, and estuaries likewise ranged from small and shallow (Umgeni, Thukela, Athi-Sabaki) to the extensive Zambezi delta which stretches > 100 km along the coast. The estuaries and their catchments covered a range of average flow rates, lengths, source altitudes and average slopes, and have transboundary catchment basins in at least 12 sub-Saharan countries, with estuaries in five of them (Table 1). Anthropogenic impacts such as urbanization, increasing agricultural cultivation, deforestation, water abstraction and infrastructure building differed in scale and relative importance between the chosen estuaries.

Aims of Chapter: ~~We used i~~Information was obtained from unpublished reports and the peer-reviewed literature to review the threats (drivers and pressures), present state, anthropogenic and climate-related impacts at ecosystem and socio-economic levels, and resulting policy and management responses regarding WIO estuaries. The importance of WIO estuaries as providers of ecosystems goods and services is highlighted, including their role in maintaining crucial supporting and regulating ecological processes. A key question is what the impacts of reduced (or absent) provisioning, supporting and regulating services provided by WIO estuaries would be on social wellbeing and economic growth. Policy and management options are recommended.

Commented [A3]: Perhaps this cold be the Abstract?

Ecological and socio-economic importance of WIO estuaries

Estuaries provide unique goods and services on which the social and economic prosperity of coastal communities rely. Estuarine goods and services are important at spatially different scales – locally for food security, coastline stabilization and economic activity; regionally for providing nutrients to marine habitats and nurseries for dispersive marine species; and globally as a carbon sink in dense mangrove forests (Bosire et al., 2016) and seagrass beds.

Ecosystem goods and services are typically grouped into four broad categories (Millennium Ecosystem Assessment, 2005; Agbenyega et al., 2009), also applicable to WIO estuaries:

- *provisioning*, defined as the capacity to create biomass and thereby produce goods such as food, raw materials, and energy resources;
- *regulating*, or the capacity to regulate essential ecological processes and life support systems, such as climatic, water, soil, nutrient, ecological and genetic conditions;
- *supporting*, or the provision of a place for plants and animals, and thus helping with the conservation of genetic, species and ecosystem diversity; and

- *cultural*, or the capacity to contribute to human well-being through knowledge and experience and sense of relationship with context eg spiritual experiences, aesthetic pleasure, cognition and recreation.

McNally et al. (2016) further subdivided the ecosystems goods and services provided by a typical WIO estuary (Wami, Tanzania) into roughly 30 specific ecosystem services, ranked according to stakeholder perceptions (Table 2). The relative scale and importance of goods and services are expected to differ between individual estuaries.

Ecological importance: Key ecological functions, common to all WIO estuaries, are the provision, maintenance and connectivity of critical habitats for unique brackish water plant and animal species. Estuaries function as spawning, nursery and feeding grounds for marine fish and crustaceans that later migrate to nearshore marine environments to complete their life cycles. Palearctic birds use WIO estuaries as migratory stopovers. Extensive mangrove forests and seagrass beds trap and recycle nutrients and sediments, contributing to high biological productivity that is common to estuarine ecosystems. Some estuaries support large floodplains and wetlands, including coastal forests, lakes, and surrounding habitats for many wildlife species, including legendary herds of large mammals, which have been severely depleted outside of protected areas (Beilfuss, 1999).

Nutrient-rich sediments support a productive soft sediment ecosystem dominated by benthic-feeding penaeid shrimps, both in the lower reaches of estuaries and on offshore mudbanks, maintained by exported terrigenous sediments and riverine organic matter (Forbes et al., 2002; de Lecea and Cooper, 2016). Nearshore marine mudbanks that are ecologically associated with WIO estuaries are the Thukela Bank (Thukela River in eastern South Africa), Maputo Bay (Maputo, Espirito Santo and Incomati estuaries in southern Mozambique), Sofala Bank (Zambezi delta in central Mozambique), shallow banks off the Rufiji delta (Tanzania) and off the Tana and Athi-Sabaki estuaries in Ungwana Bay (Kenya). The marine ecosystems of these nearshore shelf areas rely heavily on the catchment / coastal sea interactions, for sediments, organic matter, nutrients and recruitment of diadromous prawns and fishes. As an example, Hoguane and Armando (2015) emphasized the importance of Zambezi River runoff on fisheries production and artisanal catches on the Sofala Bank, a major fisheries zone in Mozambique.

Also of high ecological importance, is the natural buffer that estuaries form against biophysical stressors, predicted to intensify with climate change. Estuarine vegetation, especially mangroves, play a major role in erosion control and stabilization of sediments, thus protecting the coastline and low-lying areas from saltwater intrusion, storm surges and floods. The water retention capacity of estuarine wetlands mitigates the effects of droughts, by storing water for domestic use, livestock and agriculture. Stakeholders around the Wami estuary in Tanzania placed a high value on provision of domestic water, habitats for wild animals and plants and erosion control (McNally et al., 2016), but a lower value on saltwater intrusion, perhaps because the Wami estuary is located in a national park and is in an ecologically good condition. Upstream water abstraction appears to be comparatively moderate in the Wami catchment, but Kiwango et al. (2015) stressed the need to maintain minimum environmental flow requirements to preserve estuarine habitats and functioning.

Socio-economic importance: The capacity to create biomass and thereby produce goods such as food, raw materials, and energy resources make estuarine ecosystems valuable socio-economic assets, reflected in the growth of agriculture, towns and centres of commerce around them. In the WIO region, Maputo (pop. 1.2 million, 2018) is located on the shores of Maputo Bay – and surrounded by the Maputo, Incomati and Espirito Santo estuaries (Bandeira and Paula, 2014), Beira (pop. 0.53 million, 2017) is on the bank of the Pungwe, Quelimane (pop. 0.35 million, 2017) on the upper reaches of the Bons Sinais, Pangani (pop. 54 000, 2012) at the mouth of the Pangani estuary in Tanzania, and Kipini at the junction of the Tana delta with Ungwana Bay in Kenya. Both Dar es Salaam and Mombasa are located adjacent to estuaries and use them as ports for shipping. Increasing urbanization on the banks of WIO estuaries can be a mixed blessing, however, with the use of estuarine goods and services for socio-economic growth potentially bringing about their eventual depletion or degradation. For example, the use of peri-urban mangrove stands in Mombasa contributed to a 70 per cent% loss between 1985 and 2009 (Bosire et al., 2016).

Ecosystem goods and services typical of WIO estuaries (Table 2) include the provisioning of water for domestic use; fisheries for prawns by small-scale and industrial fishers, and for finfish, bivalves, gastropods and crabs for food security and local markets; cutting mangrove poles for construction; using wood (mainly mangrove cuttings) to make and sell charcoal for fuel; harvest of traditional medicinal plants; and mining of inorganic raw materials such as sand, or gravel for construction purposes. The WIO estuaries provide fertile land for flood recession agriculture and grazing, and for vegetable and fruit production. Commercial salt pans for making salt or ponds for mariculture are also common uses. Tourism is a growing activity, with several estuaries located within national parks, such as the transboundary Ruvuma estuary, shared by the Mnazi Bay-Ruvuma Estuary Marine Park in Tanzania and the Quirimbas National Park in northern Mozambique (Scheren et al., 2016). The Wami estuary in Tanzania is in the Saadani National Park, which was formally established in 2005 on land acquired over three decades (Anderson et al., 2007).

Threats to WIO estuarine ecosystems: multiple scales

Global scale: Climate change and human population growth, in terms of increasing demands for resources and living space, and the building of infrastructure for energy, transport and industry, are the most persistent pressures on the 21st century WIO environment (UNEP-Nairobi Convention and WIOMSA, 2015; Diop et al., 2016; McNally et al., 2016; Duvail et al., 2017) (Table 3). Estuaries are under increasing pressure from natural processes and human activity. On a global scale, climate change effects are clearly noticeable as changes in weather patterns, and as sea level rise. More severe floods and / or droughts are expected to influence freshwater runoff. Expected changes in the seasonality of rainfall – and hence seasonal flood-regimes – will further affect estuarine processes, and their ecological functioning. Rising sea-level and greater tidal ingress and salt-water intrusions are expected, thus altering the chemical properties of productive brackish-water habitats. Critical habitats of many plant and animal species adapted to brackish-water environments for food, shelter or reproduction, may be degraded, displaced or will disappear.

Regional scale: At a regional (catchment basin) scale, the pressure on natural resources emanate from rapid economic and infrastructure development, driven by the fundamental needs (food security, energy, clean water) of rapidly growing human populations (Table 3). Major threats to estuarine processes in catchment basins are the abstraction of water for irrigation and damming of rivers for hydro-electric power or drinking water for cities. Building of dams have often disregarded environmental flows required to support downstream habitats or ecosystems, including runoff volumes and seasonality of flooding (Duvail et al., 2017). Changes in land-use and vegetation cover in catchment basins, through conversion of natural habitats to cultivated croplands, also affect freshwater runoff and increases sediment loads in runoff water, resulting in downstream accretion and changes to estuarine, beach and nearshore morphology (Kitheka and Mavuti, 2016). The seasonal (or even permanent) closure of river mouths due to sedimentation and the formation of sandbanks is common in smaller estuaries in eastern South Africa, with major implications for their ecological functioning (Whitfield et al., 2012). At a regional scale, disrupted connectivity between estuarine and marine environments result from upstream water abstraction, higher sediment loads and droughts.

Local scale: At a local scale (within and around individual estuaries) pressures are a reduced freshwater discharge, seasonally altered flood-cycles from dam releases and increasing coastal populations (Table 3). Economic growth and building of urban infrastructure are gradually replacing traditional (or subsistence) livelihood systems which are based on seasonal flood cycles. WIO estuaries have supported subsistence livelihoods over many centuries, with interactions relying on timely societal adaptations and natural biophysical resilience (Leauthaud et al., 2013). Fishing for food, use of mangroves and other wood for fuel and construction, flood-recession planting of rice and other crops, and seasonal grazing of livestock all contributed to livelihoods in flexible traditional-use systems (Hamerlynck et al., 2010).

Coastal livelihoods around estuaries are now threatened by human population growth and a greater demand for biological resources than that which can be obtained from estuarine ecosystems (UNEP-Nairobi Convention and WIOMSA, 2015). Unplanned urban and industrial development around estuaries is accompanied by overharvesting of nearby natural resources (fish and mangroves), pollution, and altering estuarine water flow through canalization or infilling. Threats from human activities include loss of critical habitats, loss of core estuarine processes and functions, reduced water quality and lowered food security through destructive fishing (Table 3). Increasing upstream salinity and salt intrusions affect wetlands and vegetation, with implications for biodiversity, agriculture and traditional livelihood systems. Loss of traditional livelihoods is expected to accelerate urbanization, followed by increased unemployment and socio-economic stress. The loss of the estuarine protection function against climatic events (ie -mangrove barriers and stabilized banks of estuaries) further increases the vulnerability of local inhabitants and infrastructure to storms and floods.

Commented [A4]: Author to please check these adjectives are correctly placed.

State of the WIO estuaries

The WIO estuaries were all data deficient relative to the key aspects of distribution of critical habitats, ecological processes, and historical trends in freshwater and marine in influences. A formal assessment against the IUCN Ecosystems categories and criteria (IUCN, 2015) could therefore not be undertaken. In its place, a simple qualitative index was developed to assess the present status of 12 WIO estuaries for placement into one of five categories (Table 4). None of the 12 estuaries qualified for the 'excellent' (least concern) category because all of them are increasingly affected by human activities in catchments or in the estuarine functional zone.

Commented [A5]: Duplicated text. See comment on same on page 2.

Estuary status relative to their condition 50 years ago (default assumption of pristine, except where contrary evidence exists) was assessed against six indicators, selected to represent the condition of critical habitats (core and support), functioning of estuarine processes, water quality, biodiversity and to what extent freshwater discharge into estuaries is affected by upstream dams (Table 5).

Assessment by estuary (Table 6):

Tana: Estuary state = Poor (Endangered)

The Tana delta is comprised~~s~~ of four estuaries of which the northern-most one has been channelled to form the main river mouth into Ungwana Bay (Scheren et al., 2016). Construction of hydroelectric power (HP) plants and dams in the Upper Tana basin has reduced runoff and affected the seasonal flood cycle. Water abstraction is increasingly affecting run-off to the estuary. Impacts of land-use change, damming and climate variability are high turbidity, heavy sedimentation, changes in beach morphology, and degradation of mangrove forests and marine ecosystems (Kitheka and Mavuti, 2016). The surface area and longevity of flood-supported riverine forests, wetlands and mangroves have been reduced, and the abundance and diversity of fish are diminished. Kipini village at the junction of the main estuary and Ungwana Bay remains small.

Athi-Sabaki: Estuary state = Poor (Endangered)

There are no upstream dams, but urbanization in the headwaters have led to water abstraction and reduced infiltration of rainfall, manifesting as a diminished base flow and more rapid and short-lived flooding events (Scheren et al., 2016). Higher sedimentation loads because of land use change to agriculture have negatively impacted nearshore corals, but have led to an increased area colonized by mangroves (Kitheka and Mavuti, 2016). The estuary remains important in terms of biodiversity, providing habitats and nursery grounds for prawns and feeding grounds for birds. It plays an important role in sustaining the productivity of Ungwana Bay, but is threatened by heavy accretion.

Rufiji: Estuary state = Poor (Endangered)

The Rufiji is the largest river in Tanzania, and its delta extends 65 km across and 23 km in length, with a surface area of 1200 km^2. Sediment carried by the river has caused accretion with a seaward shift of the shore-line over millennia. It supports the largest mangrove area in Tanzania (approx. 50 000 ha), which, together with nearby seagrass beds, coral reefs and small islands form an interacting seascape which provides invaluable ecological services to the WIO (Wagner and Sallema-Mtui, 2016). Erosion and loss of mangroves at the seaward edge of the Rufiji delta have been attributed to sea-level rise; the loss at the seaward edge is counter-balanced by inland migration of mangroves at the landward edge (Wagner and Sallema-Mtui, 2016). Livelihoods are traditionally based on agriculture and fishing. Agriculture, particularly rice farming, has increased significantly over the past two decades, and is associated with clearing of mangrove areas (Tumbo et al., 2015). The invasive giant freshwater prawn *Macrobrachium rosenbergii* has established a population in the delta and is occasionally fished and sold on markets (Kuguru et al., 2019). There are no major dams in the catchment basin, but large-scale conversion to agricultural land and increasing water abstraction for farming and hydroelectric power generation are increasingly contributing to water stress in the delta (Shaghude, 2016). Human population density in the delta is low, although projected to increase steeply based on census data from the past 30 years (Tumbo et al., 2015). Improved road access has attracted external traders, potentially increasing the extraction of natural products (fish, timber) for markets in Dar es Salaam. Whereas the Rufiji delta retains its core and support estuarine habitats intact, with most key estuarine processes in place, there has been loss of habitats and water quality, which is set to accelerate if a planned upstream dam in the main river at Stiegler's Gorge is built (Tumbo et al., 2015).

Ruvuma: Estuary state = Good (Near threatened)

The Ruvuma is a transboundary estuarine system, protected by the Mnazi-Bay Ruvuma Estuary Marine Park in Tanzania and the Quirimbas National Park in Mozambique. There are no major dams in its catchment basin and the human population density in the parks is low. The estuary is well-known for its beaches, mangroves and tropical coastal marine resources (Scheren et al., 2016). A recent bird survey showed high diversity, including palearctic migrants, species restricted to the East African biome and a globally threatened heron species (Borghesio et al., 2009). Large land mammals occur, and turtles nest on beaches. Locals rely mainly on farming and fishing, but also harvest mangroves for tannins, fuel wood, medicine, boat-building and carpentry. Some activities are not allowed within the park boundaries (Mangora et al., 2014). Based on Landsat imagery, the area of mangrove cover remained similar between 1995 and 2005 (Ferreira et al., 2009). The Ruvuma retains its core estuarine and support habitats, estuarine processes are in place, water quality is good and species diversity high – and protected. Although well preserved, the delta is threatened by expanding agriculture, hunting, planned oil and gas drilling and illegal timber extraction.

Zambezi: Estuary state = Poor (Endangered)

The Zambezi is the largest delta along the East Africa coast, and is 100 km long and 120 km wide at the coast, covering about 15 000 km^2 (Chenje, 2000). Its ecological functions include the support and maintenance of the Sofala Bank habitats and their rich nearshore fisheries, through the discharge of vital nutrients and organic matter into the sea (Hoguane and Armando, 2015). It supports nursery areas for penaeid prawns, the target of nearshore trawl fisheries and of artisanal fishers on intertidal mudflats, and productive feeding areas for many fish species, which are also harvested. The delta supports large mangrove forests, which appear to be in a good conservation status, showing increased coverage between 1994 and 2013 (Macamo et al., 2016). The human population density in the delta is relatively low, and local livelihoods rely on farming, fishing and harvesting mangroves for fuel and construction. The construction of the Kariba (1959) and Cahora Bassa dams (1974) for hydro-electric power generation did not take downstream impacts of a change in flood regime into account, and has led to “reduced artisanal fisheries and shrimp industry productivity, reduced silt deposition and nutrient availability, severe coastal erosion, soil salinization, salt water intrusion, replacement of wetland vegetation by invasive upland species, reduction in coastal mangroves, failure of vegetation to recover from grazing, and disrupted or mistimed reproductive patterns for wildlife species" (Beilfuss, 1999). Biodiversity and the abundance of wild animals have declined, following loss of habitats. From a socio-economic perspective, the dams reduced the land available for flood-recession agriculture and grazing practices. Based on the literature, there is little doubt that the Zambezi core and supporting habitats have been substantially reduced and altered by upstream dams, and that there has been a loss of estuarine processes. Biodiversity and abundance of terrestrial and marine species have been reduced – as reflected by reduced distribution and numbers of large mammals, and by lower fish and prawn catches by the Sofala Bank fisheries.

Pungue: Estuary state = Poor (Endangered)

The Pungue catchment basin is characterized by a low degree of development, few abstractions, diversions or regulation. There are no large dams, but a water pipeline transfers approximately 22 million m^3 per year to supply Mutare in Zimbabwe (Van der Zaag, 2000). It also supplies freshwater to Beira (pop. 500 000 in 2017), located on the north bank of the estuary where it meets the ocean with fresh water. Water shortages in the Pungue basin are uncommon (Droogers and Terink, 2014), but during low flow conditions, the upstream fresh water intake for Beira is affected by salt intrusion. Large amounts of sediments discharged by the river minimizes the effects of coastal erosion. The rate of mangrove deforestation in Beira is high (Barbosa et al., 2001). Prawn aquaculture takes place in the estuary. The Port of Beira is situated on the north bank of the Pungue near the river mouth and is an important centre for shipping and logistics in the central Mozambican and Central African regions. The river mouth is dredged. Rural livelihoods rely on small-scale agriculture in flood plains, and some fishing. Since 2013, an invasive prawn, called 'rainbow prawns', make up a large portion of artisanal catches in the estuary – it is unclear whether they escaped from prawn farms in the estuary, or were brought by ballast water. The Pungue displays impacted core and estuarine support habitats, impairment of key estuarine processes, reduced water quality as a result of the port and city, and loss of biodiversity, reflected by the presence of invasive species. Interestingly, its endangered status results from a port and urbanization near the estuary mouth, as opposed to damming and water abstraction in catchment basins, which affects several other deltas in the region, for example the Zambezi and Tana.

Limpopo: Estuary state = Poor (Endangered)

Although not dammed, the river drains catchments in three countries and flows through the economic hub of southern Africa – resulting in high abstraction of water for domestic use and agriculture, and a high pollution load (Earle et al., 2006). The river experiences high streamflow variability, including very low conditions during droughts, and devastating floods that occur every few years after torrential rainfall in catchments. A severe flood in 2000 temporally increased the width of the estuary from 200 m to several square kilometres~~km~~, causing sediment transformation, mangrove forest degradation, uprooting and dieback, and affecting around 2 million people. Two mangrove species, *Xylocarpus granatum* and *Ceriops tagal* disappeared from the estuary after the 2000 flood but have since been replanted (Bandeira and Balidy, 2016). Severe flooding events over the past 70 years occurred in 1955, 1967, 1972, 1975, 1977, 1981, 2000 and 2013. Climate is therefore the major driver of the Limpopo estuary status (Bandeira and Balidy, 2016). The estuary also provides a nursery ground for fish and prawns, and its flood plains are under extensive agricultural cultivation (Louw and Gichuki, 2003). Core and support estuarine habitats have been substantially reduced by farming and recurrent floods, and water quality is low. Mangrove rehabilitation through replanting seedlings is underway to improve estuarine health.

Incomati: Estuary state = Degraded (Critically Endangered)

The Incomati River is shared by Mozambique, Swaziland and South Africa, and is intensively used for irrigation in South Africa (Hoguane and Antonio 2016). It is of high ecological importance for the maintenance of the Maputo Bay ecosystem and fisheries. The Incomati estuary is located near a major urban centre (Maputo) and therefore suffers high anthropogenic pressure. The estuary is about 40-50 km long and meanders within the coastal plain separated from the ocean by a narrow sand dune. It has reduced freshwater inputs and is shallow, with islands and sandbars. Mangrove deforestation (Le Marie et al., 2006) and severe degradation (Paula et al., 2014) have been attributed to overharvesting for fuelwood and construction, and modifications to river flow resulting from damming. The estuary remains a sanctuary for breeding colonies of aquatic birds, and a nursery ground for fish and crustacean species (Sengo et al., 2005). The estuary contributes approximately 20 per cent~~%~~ of the overall prawn catch in Maputo B~~b~~ay (Anon., 2001). The reduction of estuarine core habitats (mangroves), impairment of key estuarine processes because of reduced freshwater input and polluted water endanger the ecological role of the estuary.

Maputo: Estuary state = Fair (Vulnerable)

The Maputo estuary is small with most of its catchment in Swaziland and South Africa, where its tributary (Pongola River) is dammed. The estuary is of high ecological importance for the maintenance of the Maputo Bay ecosystem and fisheries. It is located further from Maputo city than the Incomati and suffers less from anthropogenic pressures – with parts of the estuary located in the Maputo Special Reserve. Mangroves are in a good, though not pristine condition (Paula et al., 2014). Most core estuarine and support habitats are intact, and key estuarine processes are in place, with biodiversity receiving protection in the reserve.

Thukela: Estuary state = Poor (Endangered)

The Thukela River rises in the Drakensberg Mountain Range and has a steep gradient. It is highly impounded, with >600 smaller dams in its tributaries, seven major dams, and several inter-basin transfers that supply water to South Africa's economic hubs. Freshwater inflow is highly seasonal, with summer rains and dry months in winter – and variable with occasional major floods. The estuary has large mud flats, and although open to the sea, sand bars have occasionally closed the mouth in recent years. The Thukela estuary is small, without mangroves, but has high ecological importance as a source of organic material, nutrients and sediments to the nearshore Thukela Bank (Turpie and Lamberth, 2010; de Lecea and Cooper, 2016), which forms the southernmost prawn trawl grounds in the WIO. It is also an important habitat for resident and non-resident birds, fish and crustaceans. Water quality is affected by upstream industries and pesticides used in extensive sugarcane monoculture.

Umgeni: Estuary state = Degraded (Critically Endangered)

The Umgeni River flows through a dense urban metropolis (Durban) and the mainstream is impounded by a major dam within 30 km of its mouth. The estuary is severely affected by loss of habitat, sedimentation, freshwater deprivation, chemical and organic pollution, and modifications to its mouth (Forbes and Demetriades, 2008). The estuary has a dense mangrove stand on its north bank, and a diverse fish community, possibly because of its permanently open mouth. It also has an abundant and diverse bird community, because of intertidal sand / mud banks.

Betsiboka: Estuary state = Degraded (Critically Endangered)

The Betsiboka is Madagascar's largest river stretching 600 km from the high central plateau to the northwest coast, where it discharges into Bombetoka Bay (Scheren et al., 2016). The city of Mahajanga (pop. 220 000 in 2013) with a port is located on its northern bank. The Betsiboka transports lateritic soils and sediments derived from the highlands of central Madagascar to the sea, colouring the river a blood-red hue. The evolution of the bay, coastline, delta, and change detection results derived from Landsat satellite images recorded in 1973, 1989, 1999, 2000 and 2003, show that sedimentary transport and suspension in Bombetoka Bay has increased dramatically over the past 30 years, attributed to increased erosion following large-scale deforestation, bush fires, and overgrazing in the river basin (Raharimahefa and Kusky, 2010). These changes have adversely affected core estuary habitats, estuarine processes and water quality – as reflected in negative changes in agriculture (rice paddies and shrimp pens), fisheries and transportation.

Other estuaries: Estuary state = Not assessed

Numerous other rivers and estuaries discharge into the WIO from eastern Africa and Madagascar, and it is unlikely that many of them have escaped the dual influences brought by human activities and climate change effects. For example, the 98 km coastline of the Ethekwini municipality around Durban incorporates 16 estuaries, of which 13 are temporarily open / closed estuaries, two are permanently open and one is an estuarine bay (Forbes and Demetriades, 2008). Apart from the estuarine bay (Durban Bay), they are small estuaries (<10 to 230 ha), and their current health status range from highly degraded to good (Forbes and Demetriades, 2008).

Existing Protection

International frameworks

Rivers that cross borders between countries are shared resources subject to equitable utilization by riparian states, and they are therefore fundamentally part of international and national watercourses governance and laws (Birnie et al., 2009). As a part of this, common management models include the creation of international institutions in which all riparian states cooperate in formulating and implementing policies for the development and use of a water course. In the past, these institutions focussed mainly on the access and allocation of water between upstream and downstream states, but in recent years, more attention has been given to broader ecological implications, within a legal framework more attuned to sustainability and water shortage (Momanyi, 2016). For example, Article 23 (protection and conservation of the marine environment) of the 1997 Watercourses Convention makes specific mention of the preservation of estuaries, as follows:

"*Watercourse States shall, individually and, where appropriate, in cooperation with other states, take all measures with respect to an international watercourse that are necessary to protect and preserve the marine environment, including estuaries, taking into account generally accepted international rules and standards".*

Several deltas and estuaries in the WIO have Ramsar status, as part of an international agreement for the protection and wise use of wetlands (1971 Wetlands Convention), which imposes conservation and management duties and responsibilities on states. Three examples of estuarine Ramsar sites in the WIO are the Tana delta (since 2012), the Marromeu complex in the Zambezi delta (2003) and the Kosi Bay complex (1991) in eastern South Africa, which is composed of four interconnected tidally influenced lakes (Momanyi, 2016).

WIO regional frameworks and Nairobi Convention (www.unep.org/nairobiconvention/)

The estuarine ecosystems of the WIO have a strong regional legal framework for protection and sustainable use, grounded in various river basin organizations throughout the region, and in the provisions of the 1985 Nairobi Convention and the 2010 Amended Nairobi Convention (Momanyi, 2016). River basin organizations, such as the Incomati Basin Water Authority (South Africa, Mozambique, Swaziland) and the Zambezi River Authority (Mozambique, Zambia and Zimbabwe) operate according to clearly defined mandates for a specific purpose, such as shared dam construction or operation, hydropower generation or irrigation, but do not engage in interstate negotiations or policy formulation.

The 2010 Amended Nairobi Convention defines 'Convention Area' to include WIO estuarine ecosystems, as well as watersheds, and has provisions on pollution from various sources, including from ships (Article 5), by dumping (Article 6) and from land-based sources and activities (Article 7). In particular, Article 7 exhorts contracting parties to:

"… take all appropriate measures to prevent, reduce and combat pollution of the Convention area caused by coastal disposal or by discharges emanating from rivers, estuaries, coastal establishments, outfall structures, or any other land-based sources and activities within their territories"

The 2010 Land Based Sources and Activities (LBSA) Protocol to the Nairobi Convention has detailed provisions regarding measures to control, reduce and prevent downstream pollution, physical alterations and habitat destruction emanating from land-based sources (www.unep.org/nairobiconvention/).

Overall, there appears to be an elaborate framework of regional, national and local legal, policy and institutional arrangements in WIO riparian countries, but they treat estuaries as a part of international watercourses or river basin systems. Because the framework does not specify or isolate estuaries, they generally fall short of effective protection of estuarine ecosystems (Momanyi, 2016). Main challenges regarding the conservation of estuarine ecosystems *per se* are therefore policy and legislative inadequacies, limited institutional capacities, inadequate awareness, inadequate financial resources and mechanisms, and poor knowledge management (UNEP/Nairobi Convention Secretariat and WIOMSA, 2009).

Integrated Coastal Management Act (South Africa)

The Integrated Coastal Management Act (ICM; Act No. 24 of 2008) of South Africa has made some progress towards providing a more specific and integrated environmental management framework for estuaries (de Villiers, 2016). As in other WIO countries, South Africa has a mass of legislation that applies to estuaries at all levels of government (local, district, provincial, national and international) and because of multiple-use of land and water resources – from the catchment to the coast – the responsibility for their management and development falls under various government departments and acts, often with conflicting objectives. To deal with the complexity, the ICM A~~a~~ct includes a section that deals specifically with estuaries and estuary management.

The ICM A~~a~~ct prescribes that estuary management plans are developed for individual estuaries, by independent service providers, and with multiple stakeholder engagements, where government departments are represented to outline / discuss official management mandates. A Generic Framework for Estuary Management Plans (van Niekerk and Taljaard, 2007) provides broad guidelines to follow when developing individual estuary management plans, including structure and content, and ensures that all aspects are taken into account, including biodiversity value, social and economic values, goods and services, and environmental flow requirements. After stakeholder approval, the plan is submitted to a management authority for adoption. The management authority is a government department, mandated according to the National Estuary Management Protocol (Gov. Gazette No. 36432, 10 May 2013). Each estuary management plan includes an implementation plan, which reports to the management authority, where it can be audited. The formation of multiple stakeholder fora~~ums~~ for individual estuaries improves the efficiency of estuarine management plans.

It is envisaged that sufficient data will be collected to develop a 'State of the Estuaries' report that can be used to assess South African estuaries each year. The 2011 National Biodiversity Assessment (Driver et al., 2012) was the first such assessment that linked the states of estuaries and catchments.

Priority options for conservation

The over-riding importance of changes in catchment areas

The conservation of estuaries is a complex matter because their health and functioning depend not only on activities within the estuarine functional zone, but also on upstream land-use activities and water abstraction in catchment areas, which may span more than one country. Energy (dams for hydroelectric power generation), food security (water abstraction for irrigation), and clean water for urban and industrial growth are fundamental raw materials of economic development. Throughout the WIO region, upstream water abstraction to satisfy these demands has overshadowed initiatives to conserve downstream estuarine ecosystems. A first conservation priority is to increase awareness of the importance of changes in catchment basins on downstream ecosystems – especially at a political level.

Flood-pulses are a part of natural cycles and cannot be ignored

Damming and water abstraction in catchment basins affect estuaries by reducing freshwater runoff into estuaries, and by disrupting seasonal flood regimes. Reduced freshwater runoff changes the dynamics of tidal and fluvial influences, allowing for erosion, salt intrusion, and changes in habitat distribution. The disruption of seasonal flood-pulses causes radical changes in the floodplain ecology, leading to multiple environmental problems, as well as loss of biological productivity. Several studies (Drijver and Marchand, 1985; Junk et al., 1989; Opperman et al., 2013) have shown a direct relationship between flood extent and ecosystem production. Managed flood releases from hydropower dams to restore, maintain and improve estuarine ecosystem service delivery or "environmental flows" is a key conservation priority (Duvail et al., 2017), supported by World Bank guidelines, best scientific practices, and a broad base in civil society (Acreman et al., 2014). The timing and volume of flood-releases – to fit with seasonal cycles and interannual variability – is critical.

Coastal communities, traditional livelihoods and socio-economic consequences

Socio-economic consequences of changes to estuarine and coastal ecosystems are fundamentally important in the WIO region (Leauthaud et al., 2013; Duvail et al., 2017), where flood-recession agriculture and fishing are important livelihood activities. Direct impacts of a loss of ecosystems goods and services on coastal communities are an increased vulnerability to climate change and other natural causes, including erosion, reduced fish catches, declining water quality for drinking and domestic use, and the loss of traditional livelihoods, farming systems and food security. Loss of estuarine ecosystems and their associated unique habitats and high biodiversity has also occurred, with long-term impacts on livelihoods, and on the economic growth potential of the region, through tourism development. Conservation of estuarine ecosystems, with a focus on their specific supporting, regulating, provisioning and cultural goods and services, is fundamental in maintaining traditional livelihoods over a longer term, to facilitate local socio-economic stability.

Mangroves are critical habitats in the WIO

Mangroves are a key component of WIO estuarine ecosystem productivity with influence well beyond their physical limits. They recycle nutrients which can be exported to marine ecosystems, provide habitats for many brackish water species, and nursery areas for marine fish and prawns, which support artisanal and commercial fisheries. They trap sediments and form barriers against storms and floods, stabilize mud- and sand banks against erosion, and provide fuel and construction wood to coastal communities. The conservation of mangroves and the hydrological systems that support them is therefore a high priority (see Chapter 9).

Marine Protected Areas – only a partial solution

Marine Protected Areas (MPA) in several WIO estuarine systems (Wami, Ruvuma) may protect critical habitats and biodiversity in and around estuaries from human activities in the estuaries, but these MPAs remain exposed to changes in land and water use in catchment basins. The habitats and ecosystems that the MPAs are meant to protect are increasingly vulnerable to salt-water intrusions, especially when freshwater flow has been reduced. The situation is exacerbated by rising sea level and more frequent storms resulting from climate change. Water stress originating from outside MPA boundaries is therefore likely to disrupt ecological processes and degrade critical habitats within their boundaries. Ensuring the maintenance of "environmental flow", originating in catchment basins far removed from the MPA jurisdiction, is therefore also a key conservation priority.

Further, MPAs often face challenges in translating the accrued resource protection benefits into enhanced livelihoods of local communities in and around areas of their jurisdiction (Mangora et al., 2014). In the Mnazi Bay-Ruvuma Estuary Marine Park, traditional access and user rights have been reduced by MPA operations, thus affecting livelihoods of local communities, without providing commensurate alternative livelihood strategies (Mangora et al., 2014). Finding a way to redress the cost of denied access to livelihood resources, by provision of alternative livelihood means accepted by stakeholders, is therefore a priority when establishing MPAs.

Integration of ecological considerations into development politics, planning and design

From the above, the conservation of WIO estuaries and multiple ecosystems goods and services that they provide can only be approached in a true cooperative manner, with stakeholder participation. Stakeholders should include government departments with relevant mandates (agriculture, fisheries, water provisioning, environmental affairs, industrial development, energy, forestry, rural development and coastal protection), local jurisdictions and municipalities, NGOs, the private sector and local communities. The catchment basin, estuary and nearshore marine environment all need to be considered in planning and design – which will need to take ecological considerations, such as maintaining seasonal environmental flows, into account.

Treat estuaries individually – with specifically designed estuary management plans

Individual estuaries differ substantially in size, flow regime, anthropogenic impacts, geomorphology, habitats and ecosystem services that they provide. Managing them successfully requires individual estuary management plans, designed according to specific circumstances and characteristics. The South African Integrated Coastal Management Act (Act No. 24 of 2008) prescribes that estuary management plans are developed for individual estuaries, by independent service providers, and with multiple stakeholder engagements. The design and implementation of individual estuary management plans in South Africa is transformative, and the strategy can easily be adapted for use in other WIO countries (Momanyi, 2016).

Recommendations

1.) Increase awareness of the importance of changes in catchment basins to the health and functioning of water-dependent downstream ecosystems, especially estuaries. Increase the awareness of the ecosystems goods and services provided by estuaries, and how important they are to the socio-economies of coastal communities. An awareness campaign should target multiple levels (political, executive, middle management, field officers and affected communities).
2.) Treat estuaries individually, within a specific estuaries framework that takes a broad spectrum of environmental, ecological, socio-economic, and economic development indicators into account. An example of an operational framework is provided by the South African Integrated Coastal Management Act (Act No. 24 of 2008).
3.) Individual estuary management plans and implementation plans must be built on wide stakeholder participation, by identifying common ground, areas of mutual interest and shared concerns among stakeholders, while also recognizing potential tensions among them. A final plan must be acceptable to all affected parties, where possible.
4.) "Environmental flow", or the volume and seasonality of freshwater discharge into estuarine systems, to restore or maintain critical habitats, ground-water reserves and ecosystem functioning, needs to be determined for individual estuaries. Managed flood releases from upstream hydropower dams must be used to maintain natural environmental flow conditions through estuaries.
5.) Mangrove forests are a key habitat of the WIO estuaries with multiple ecological functions which affect marine ecosystems and commercial fisheries. They are also a key source of fuel and construction material for coastal communities. The coverage and condition of mangroves should be monitored, potentially with a time series of remote sensing images backed up by ground-truthing, and where changes exceed a threshold, restorative actions should be taken, for example replanting (Bandeira and Balidy, 2016).
6.) Human encroachment through building or flood plain agriculture also needs to be monitored, potentially with comparative remote sensing images backed up by ground-truthing. They can be managed to remain within specific estuary management plans.
7.) Estuarine MPAs are a useful tool for managing exploitation of natural resources and reducing degradation of habitats within a protected area, thus conserving biodiversity and natural habitats. Nevertheless, they fall short when freshwater flow and natural flood-cycles are disrupted. The design of MPAs should account for activities in catchment basins and nearshore marine influences, as part of individual estuary management plans.

References

Acreman, M., Farquharson, F.A.K., McCartney, M.P., Sullivan, C., Campbell, K., Hodgson, N., Morton, J., Smith, D., Birley, M., Knott, D. and Lazenby, J. (2000). Managed flood releases from reservoirs: issues and guidance. *Report to DFID and the World Commission on Dams*. Centre for Ecology and Hydrology, 2000, p. 86. Wallingford, UK

Agbenyega, O., Burgess, P.J., Cook, M. and Morris, J. (2009). Application of an ecosystem function framework to perceptions of community woodlands. *Land Use Policy* 26(3), pp. 551-557

Anderson, E.P., McNally, C., Kalangahe, B., Ramadhani, H. and Mhitu, H. (2007). *A Rapid Ecological Assessment of the Wami River Estuary, Tanzania*. Global Water for Sustainability Program, Florida International University

Anon. (2001). *Transboundary water management as an international public good – development financing 2000*. A report prepared for the Ministry of Foreign Affairs of Sweden. Department for International Development Cooperation, Ministry for Foreign Affairs/Norstedts, Stockholm. ISBN 91-7496-250-7

Arthurton, R. (2003). The fringing reef coasts of eastern Africa—present processes in their long-term context. *Western Indian Ocean Journal of Marine Science* 2(1), pp.1-14

Ayers, M.J., Scharler, U.M. and Fennessy, S.T. (2013). Modelling ecosystem effects of reduced prawn recruitment on the Thukela Bank trawling grounds, South Africa, following nursery loss. *Marine Ecology Progress Series* 479, pp. 143-161

Bandeira, S. and Balidy, H. (2016). Limpopo Estuary mangrove transformation, rehabilitation and management. In *Estuaries: A Lifeline of Ecosystem Services in the Western Indian Ocean*, pp. 227-237. Springer, Cham

Bandeira, S. and Paula, J. (eds.) (2014). *The Maputo Bay Ecosystem*. WIOMSA, Zanzibar Town, 427 pp.

Barbosa, F.M.A., Cuambe, C.C. and Bandeira, S.O. (2001). Status and distribution of mangroves in Mozambique. *South African Journal of Botany* 67(3), pp. 393-398

Beilfuss, R. (1999). Can this river be saved? Rethinking Cahora Bassa could make a difference for dam-battered Zambezi. *World Rivers Review* 14(1), pp. 8-11

Birnie, P.W., Boyle, A. and Redgwell, C. (2009). *International Law and the Environment*. Third Edition, Oxford University Press, 579 pp.

Borghesio, L., Armakobe, B., Bakari, S., Balidy, H., Biasol, D. and Menomussanga, M. (2009). A bird survey of the Ruvuma Delta, northern Mozambique. *Bulletin of the African Bird Club* 16(2), pp. 197-203

Bosire, J., Mangora, M., Bandeira, S., Rajkaran, A., Ratsimbazafy, R., Apadoo, C. and Kairo, J.G. (eds.) (2016). *Mangroves of the Western Indian Ocean: status and management*. WIOMSA, Zanzibar Town, 161 pp.

Chenje, M. (2000). State of the environment in the Zambezi Basin 2000. SADC / IUCN / ZRA / SARDC, Maseru / Lusaka / Harare

Cyrus, D., Jerling, H., MacKay, F. and Vivier, L. (2011). Lake St Lucia, Africa's largest estuarine lake in crisis: combined effects of mouth closure, low levels and hypersalinity. *South African Journal of Science* 107(3-4), pp. 1-13

Cyrus, D.P., Vivier, L. and Jerling, H.L. (2010). Effect of hypersaline and low lake conditions on ecological functioning of St Lucia estuarine system, South Africa: An overview 2002–2008. *Estuarine, Coastal and Shelf Science* 86(4), pp. 535-542

de Lecea, A.M. and Cooper, R. (2016). The importance of the Thukela River Estuary, East Coast of South Africa, for the biology of the near-shore environment and associated human aspects: a review. In *Estuaries: a lifeline of ecosystem services in the Western Indian Ocean*, pp. 53-65. Springer, Cham

de Villiers, P. (2016). Estuary management in South Africa – An overview of the challenges and progress made to date. In *Estuaries: A Lifeline of Ecosystem Services in the Western Indian Ocean*, pp. 301-311. Springer, Cham

Diop, S., Scheren, P. and Machiwa, J.F. (eds.) (2016). *Estuaries: A Lifeline of Ecosystem Services in the Western Indian Ocean*. Springer International Publishing, 322 pp.

Drijver, C.A. and Marchand, M. (1985). Taming the floods: Environmental aspects of floodplain development in Africa. agris.fao.org

Driver, A., Sink, K.J., Nel, J.L., Holness, S., van Niekerk, L., Daniels, F., Jonas, Z., Majiedt, P.A., Harris, L. and Maze, K. (2012). *National Biodiversity Assessment 2011: An assessment of South Africa's biodiversity and ecosystems*

Droogers, P. and Terink, W. (2014). Water Allocation Planning in Pungwe Basin Mozambique. *Future Water Report*, 129

Duvail, S., Hamerlynck, O., Paron, P., Hervé, D., Nyingi, W.D. and 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), pp. 269-279

Earle, A., Goldin, J., Machiridza, R., Malzbender, D., Manzungu, E. and Mpho, T. (2006). Indigenous and institutional profile: Limpopo river basin. Working Paper no. 112. International Water Management Institute, Colombo

Elliott, M. and McLusky, D.S. (2002). The need for definitions in understanding estuaries. *Estuarine, coastal and shelf science* 55(6), pp. 815-827

Ferreira, M.A., Andrade, F., Bandeira, S.O., Cardoso, P., Mendes, R.N. and Paula, J. (2009). Analysis of cover change (1995–2005) of Tanzania/Mozambique trans-boundary mangroves using Landsat imagery. *Aquatic Conservation: marine and freshwater ecosystems* 19(S1), pp. S38-S45

Forbes, A.T. and Demetriades, N.T. (2008). *Estuaries of Durban*. Report for the Environmental Management Department, eThekwini Municipality

Forbes, A.T., Demetriades, N.T., Bosman, C., Leuci, R., Sinclair, D., Smith, A.M., Fennessy, S., Robertson, W.D., Sink, K., Kruger, A. and Everett, B.I. (2002). Impacts of proposed dams on the Thukela estuary and inshore marine environment, Kwa-Zulu-Natal, South Africa. *African basins: LOICZ global change assessment and synthesis of river catchment-coastal sea interaction and human dimensions, LOICZ reports and studies* (25), pp. 168-173

Hamerlynck, O., Duvail, S., Hoag, H., Yanda, P. and Paul, J.L. (2010). The large-scale irrigation potential of the lower Rufiji floodplain: Reality or persistent myth. *Shared waters, shared opportunities: Hydropolitics in East Africa*, IFRA, pp. 219-234. Nairobi

Hatziolos, M., Gustaf, C. and Alm, A. (1996). Africa: A framework for integrated coastal zone management. *The World Bank*, pp. 150. Washington DC

Hill, B.J. (1975). The origin of Southern African coastal lakes. *Transactions of the Royal Society of South Africa* 41(3), pp. 225-240

Hirji, R., Partorni, F.M. and Rubin, D. (1996). Seminar on integrated water resources management in Kenya. Proceedings sponsored by government of The Netherlands and the World Bank. *The Economic Development Institute of the World Bank* 227 pp.

Hoguane, A.M. and Antonio, M.H.P. (2016). The hydrodynamics of the Incomati Estuary–An alternative approach to estimate the Minimum Environmental Flow. In *Estuaries: A Lifeline of Ecosystem Services in the Western Indian Ocean*, pp. 289-300. Springer, Cham

Hoguane, A.M. and Armando, E.V. (2015). The influence of the river runoff in the artisanal fisheries catches in tropical coastal waters – The case of the Zambezi River and the fisheries catches in the northern Sofala Bank, Mozambique. *Journal of Integrated Coastal Zone Management* 15(4), pp. 443-451

IUCN (2015). *Guidelines for the application of IUCN Red List of Ecosystems categories and criteria, version 1.0* (eds. L.M., Keith, D.A., Miller, R.M., Murray, N.J. and Rodríguez, J.P.). Bland, 93 pp. Gland, Switzerland

Junk, W.J., Bayley, P.B. and Sparks, R.E. (1989). The flood pulse concept in river-floodplain systems. *Canadian Special Publication of Fisheries and Aquatic Sciences* 106(1), pp. 110-127

Kennish, M. J. and Paerl H. W. (2010). Coastal lagoons: critical habitats of environmental change. In *Coastal lagoons: critical habitats of environmental change* (eds. M. J. Kennish and H. W. Paerl). USA: Marine science series, CRC Press, pp. 1-16

Kimirei, I.A., Igulu, M.M., Semba, M. and Lugendo, B.R. (2016). Small estuarine and non-estuarine mangrove ecosystems of Tanzania: overlooked coastal habitats? In *Estuaries: A Lifeline of Ecosystem Services in the Western Indian* Ocean, pp. 209-226. Springer, Cham

Kitheka, J.U. and Mavuti, K.M. (2016). Tana Delta and Sabaki Estuaries of Kenya: Freshwater and sediment input, upstream threats and management challenges. In *Estuaries: A Lifeline of Ecosystem Services in the Western Indian* Ocean, pp. 89-109. Springer, Cham

Kitheka, J.U., Ochiewo, J., Nthenge, P. and Obiero, M. (2004). Land use changes and climatic variability in the Tana and Athi-Sabaki River Basins and associated impacts on coastal resources in Kenya. In *Paper for START-LOICZ AfriCAT workshop*, pp. 18-21

Kiwango, H., Njau, K.N. and Wolanski, E. (2015). The need to enforce minimum environmental flow requirements in Tanzania to preserve estuaries: case study of mangrove-fringed Wami River estuary. *Ecohydrology & Hydrobiology* 15(4), pp. 171-181

Kjerfve, B. (1994). Coastal Lagoons. In *Coastal Lagoon Processes* (ed. Kjerfve, B.). Elsevier Oceanography Series 60, pp. 1-8

Kuguru, B., Groeneveld, J., Singh, S. and 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), pp. 379-391

Leauthaud, C., Duvail, S., Hamerlynck, O., Paul, J.L., Cochet, H., Nyunja, J., Albergel, J. and Grünberger, O. (2013). Floods and livelihoods: The impact of changing water resources on wetland agro-ecological production systems in the Tana River Delta, Kenya. *Global Environmental Change* 23(1), pp. 252-263

LeMarie, M., Van der Zaag, P., Menting, G., Baquete, E. and Schotanus, D. (2006). The use of remote sensing for monitoring environmental indicators: the case of the Incomati estuary, Mozambique. *Physics and Chemistry of the Earth, Parts A/B/C* 31(15-16), pp. 857-863

Lotze, H.K., Lenihan, H.S., Bourque, B.J., Bradbury, R.H., Cooke, R.G., Kay, M.C., Kidwell, S.M., Kirby, M.X., Peterson, C.H. and Jackson, J.B. (2006). Depletion, degradation, and recovery potential of estuaries and coastal seas. *Science* 312(5781), pp. 1806-1809

Louw, A. and Gichuki, F. (2003). *Limpopo Basin Profile: Strategic research for enhancing agricultural water productivity*. Baseline reports. Colombo, Sri Lanka, CGIAR Challenge Programme on Water and Food

Lugendo, B. (2015). Mangroves, salt marshes and seagrass beds. In *The Regional State of the Coast Report: Western Indian Ocean* (ed. Paula, J.) pp. 49-64. UNEP-Nairobi Convention and WIOMSA, Nairobi, Kenya

Macamo, C.C.F., Massuanganhe, E., Nicolau, D.K., Bandeira, S.O. and Adams, J.B. (2016). Mangrove's response to cyclone Eline (2000): What is happening 14 years later. *Aquatic Botany* 134, pp. 10-17

Mangora, M.M., Shalli, M.S. and Msangameno, D.J. (2014). Livelihoods of coastal communities in Mnazi Bay-Ruvuma Estuary Marine Park, Tanzania. In *Vulnerability of Agriculture, Water and Fisheries to Climate Change*, pp. 271-287. Springer, Dordrecht

McNally, C.G., Gold, A.J., Pollnac, R.B. and Kiwango, H.R. (2016). Stakeholder perceptions of ecosystem services of the Wami River and Estuary. *Ecology and Society*, 21(3)

Miguel, L.L.A.J., Nehama, F.P.J. and Castro, J.W.A. (2017). Lagoon-barrier system response to recent climate conditions and sea level rise, Mozambique, Africa. *Estuarine, Coastal and Shelf Science* 216, pp. 71-86

Millennium Ecosystem Assessment (2005). *Ecosystem and human well-being: biodiversity synthesis. World Resources Institute.* Washington, DC

Miththapala, S. (2013). Lagoons and Estuaries. Coastal Ecosystems Series, Vol. 4, vi + 73 pp. IUCN Sri Lanka Country Office, Colombo

Momanyi, A. (2016). Re-thinking estuarine ecosystem governance in the WIO region. In *Estuaries: A Lifeline of Ecosystem Services in the Western Indian Ocean*, pp. 241-257. Springer, Cham

Mwaguni, S., Ruwa, R.K., Odhiambo-Ochiewo, J. and 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 *Estuaries: A Lifeline of Ecosystem Services in the Western Indian Ocean*, pp. 111-129. Springer, Cham

Opperman, J., Galloway, G.E. and Duvail, S. (2013). The multiple benefits of river-floodplain connectivity for people and biodiversity. In: *Encyclopedia of biodiversity* (ed. Levin, S.A.) vol. 7. Waltham: Academic Press, pp. 144-160. ISBN 978-0-12-384720-1

Overeem, I. and Syvitski, J.P.M. (2009). Dynamics and vulnerability of delta systems. GKSS Research Center, LOICZ International Project Office, Institute for Coastal Research. Geesthacht, Germany

Paula, J., Macamo, C. and Bandeira, S. (2014). Mangroves of Maputo Bay. In *The Maputo Bay ecosystem* (eds. Bandeira, S. and Paula J.). WIOMSA, Zanzibar Town, pp. 101-146

Raharimahefa, T. and Kusky (2010). T.M.J. Environmental monitoring of Bombetoka bay and the Betsiboka estuary, Madagascar, using multi-temporal satellite data. *J. Earth Sci.* 21, pp. 210-226. https://doi.org/10.1007/s12583-010-0019-y

Scheren, P., Diop, S., Machiwa, J. and Ducrotoy, J.P. (2016). The Western Indian Ocean: a wealth of life-supporting ecosystem goods and services. In *Estuaries: A Lifeline of Ecosystem Services in the Western Indian Ocean*, pp. 1-23. Springer, Cham

Sengo, D.J., Kachapila, A., Van der Zaag, P., Mul, M. and Nkomo, S. (2005). Valuing environmental water pulses into the Incomati estuary: key to achieving equitable and sustainable utilisation of transboundary waters. *Physics and Chemistry of the Earth, Parts A/B/C* 30(11-16), pp. 648-657

Shaghude, Y.W. (2016). Estuarine environmental and socio-economic impacts associated with upland agricultural irrigation and hydropower developments: the Case of Rufiji and Pangani Estuaries, Tanzania. In *Estuaries: A Lifeline of Ecosystem Services in the Western Indian Ocean*, pp. 169-182. Springer, Cham

Tansley, A.G. (1935). The use and abuse of vegetational concepts and terms. *Ecology* 16(3), pp. 284-307

Taylor, M., Ravilious, C. and Green, E.P. (2003). *Mangroves of East Africa*. UNEP-WCMC Biodiversity Series 13. Cambridge

Tumbo, M., Mangora, M.M., Pauline, N.M. and Kuguru, B. (2015). Review of literature for a climate vulnerability assessment in the RUMAKI Seascape, Tanzania

Turpie, J.K. and Lamberth, S.J. (2010). Characteristics and value of the Thukela Banks crustacean and linefish fisheries, and the potential impacts of changes in river flow. *African Journal of Marine Science* 32(3), pp. 613-624

UNEP (2001). *Eastern Africa atlas of coastal resources*. UNEP and BADC (Government of Belgium), Nairobi, pp. 111. Tanzania

UNEP / Nairobi Convention Secretariat and WIOMSA. (2009). *Regional synthesis report on the review of the policy, legal and institutional frameworks in the Western Indian Ocean (WIO) region*. UNEP. Nairobi, Kenya

UNEP-Nairobi Convention and WIOMSA (2015). *The Regional State of the Coast Report: Western Indian Ocean*. UNEP and WIOMSA, pp. 546. Nairobi, Kenya

Van der Zaag, P. (2000). *The Pungwe River Basin*. SADC Water Sector. ICP collaboration Portal. http://www.icpconfluence-sadc.org/riverbasin/102

Van Niekerk, L. and Taljaard, S. (2007). Proposed generic framework for estuarine management plans. *CAPE Generic Estuary Management Plan*. Version 1, pp. 114

Vanmaercke, M., Poesen, J., Broeckx, J. and Nyssen, J. (2014). Sediment yield in Africa. *Earth-Science Reviews*. 136, pp. 350-368

Wagner, G.M. and Sallema-Mtui, R. (2016). The Rufiji Estuary: climate change, anthropogenic pressures, vulnerability assessment and adaptive management strategies. In *Estuaries: A Lifeline of Ecosystem Services in the Western Indian Ocean*, pp. 183-207. Springer, Cham

Whitfield, A.K., Bate, G.C., Adams, J.B., Cowley, P.D., Froneman, P.W., Gama, P.T., Strydom, N.A., Taljaard, S., Theron, A.K., Turpie, J.K. and van Niekerk, L. (2012) A review of the ecology and management of temporarily open/closed estuaries in South Africa, with particular emphasis on river flow and mouth state as primary drivers of these systems. *African Journal of Marine Science* 34(2), pp. 163-180

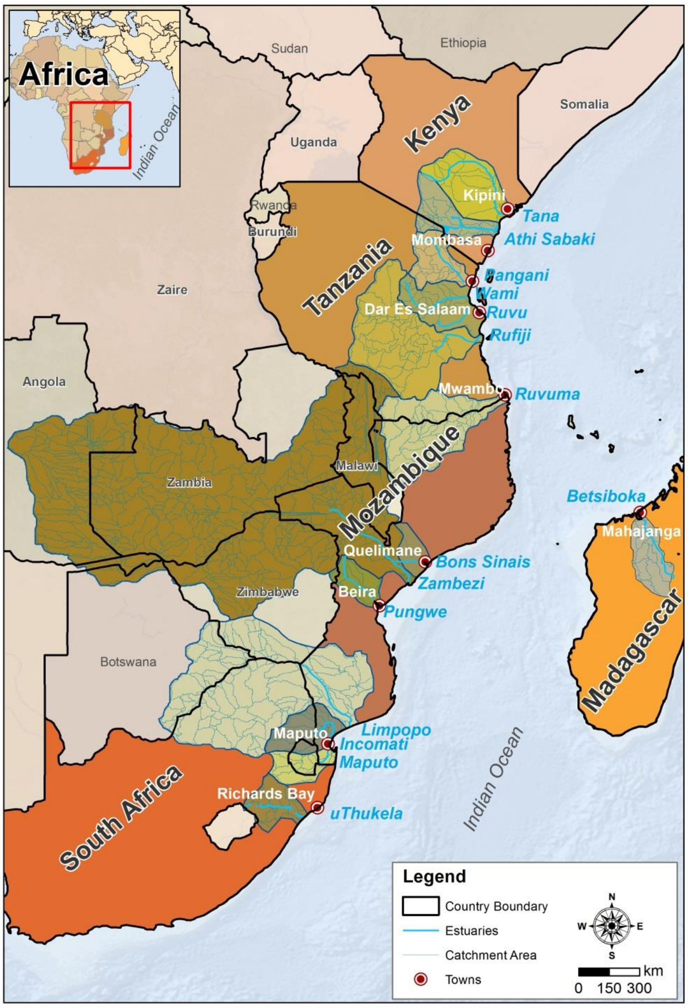

Figure 1: Representative estuaries selected for this study, showing their locations and catchment basins.

Table 4: A simple qualitative index for assessment of WIO estuaries (adapted from Forbes and Demetriades 2008), based on an evaluation of key indicators (see Table 5). No estuaries qualified for the Least concern (Excellent) category because all of them are increasingly affected by human activities in catchments or in the estuarine functional zone.

Description of 5 categories used	
Least concern (Excellent)	Estuaries with high level of habitat integrity, good water quality, high diversity and high provision of goods and services
Near threatened (Good)	Estuaries with most core estuarine habitats and support habitats still present, good water quality, high diversity of species, estuarine processes in place
Vulnerable (Fair)	Estuaries with core estuarine habitat intact, some estuarine support habitats, impacted water quality, some loss of diversity, key estuarine processes in place
Endangered (Poor)	Estuaries with impacted core estuarine habitat. Substantially reduced or no estuarine support habitats, polluted water, substantial loss of diversity and/or abundance and key estuarine processes impaired
Critically endangered (Degraded)	Estuaries which have major impacts on core estuarine habitats through infilling, canalization and pollution, substantially reduced or no estuarine support habitats and major loss of key estuarine processes.

Table 5: Key indicators used to evaluate the status of individual estuaries, for placement into categories defined in Table 4.

Indicators used for assessment of estuaries		
Core estuarine habitats	Mesohaline pelagic- or benthic habitats that support brackish water species; mangrove forests	
Estuarine support habitats	Intertidal and freshwater wetland habitats	
Water quality	Levels of organic pollution, eutrophication, salt intrusion	
Species diversity	Diversity and abundance of brackish water plants; birds; mammals; fishes; crustaceans	
Estuarine processes	Seasonal and inter-annual flood cycle; high productivity, nutrient cycling, erosion/accretion, water storage processes retained	
Freshwater supply from catchment basins	Regulation index (total storage of dam reservoirs/mean annual discharge for 2014) (Table 1)	
Colour code in Table 6: The present (2018) status of the indicator is similar / worse / much worse relative to the status 50 years ago		
Similar	Worse	Much worse

Table 6: Estuary status inferred from qualitative scoring of key indicators, based on information obtained from available literature.

	Core habitat	Support habitat	Water quality	Species diversity	Estuarine processes	Catchment dams	Overall status
Tana							Poor
Athi-Sabaki							Poor
Rufiji							Poor
Ruvuma							Good
Zambezi							Poor
Pungue							Poor
Limpopo							Poor
Incomati							Degraded
Maputo							Fair
Thukela							Poor
uMngeni							Degraded
Betsiboka							Degraded