CHO Chapter 6

Appraising tropical coastal watersheds and connected habitats: implications for integrated land-sea management in the Western Indian Ocean

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Summary

One of the key management strategy outcomes for the conservation of coastal ecosystems in the tropical world is maintaining ~~a~~ sustainable sedimentation and nitrification regimes. Elevated sedimentation causes mortality on coral reefs and sea~~-~~grasses, while depleted sedimentation leads to the loss of mangroves. Yet, human land cover modification, coupled with climate change, continue to drive changes in the types and amount of sediment and nutrients that are deposited on mangroves and coral reefs. The success of this strategy hinges on generating understanding of land-sea connectivity dynamics, including the drivers and the magnitude of associated pressures impacting on specific catchments, and on identifying catchments that are socio-ecologically sensitive to enable prescription of actions that could potentially mitigate impacts on adjacent coral reefs, sea~~-~~grass beds and mangrove forests. In this report, ~~we review~~ land-sea linkages and connectivity pathways are reviewed, based on published information describing the hydrogeology of coastal catchments, climate variability and linked ecosystems in the Western Indian Ocean (WIO) region. Further, ~~we review~~ the processes that link the drivers of land-use change to management responses required to sustain coastal ecosystem services, during a period of accelerating climate change are investigated, and the ~~. We also explore~~ freely available coastal topography and river network data to illustrate the spatial distribution of coastal catchments and the nodes (or estuaries) connecting them to the o~~O~~cean through rivers and streams are explored. Lack of understanding of the complex, spatially explicit, processes linking land-use change to change in coastal processes hinders effective integrated land-sea planning. Overcoming this limitation can be facilitated through efforts to integrate models from the drivers of land-use change to management responses for marine ecosystems.

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Background

The WIO coastal zone region ~~is~~ includes~~the site of~~ major cities, harbors, industries and other social and economic infrastructure increasingly affecting the marine environment (Celliers and Ntombela, 2015). Approximately 30 per cent~~%~~ of the estimated 100 million inhabitants of the ~~western Indian Ocean (~~WIO~~)~~ live on the coastal zone (Ngoile, 2002). The mainland states with large catchments adjoining the coast, and with major cities along the coast are the most ~~susceptible~~ prone to the ecological footprints of urbanization. These cities include Mombasa (Kenya), Dar es Salaam (Tanzania), Maputo (Mozambique) and Durban (South Africa), each of which support populations of 2 to 4 million people (Diop et al., 2016). Among other pressures, urbanization and forest conversion for agriculture continue to alter hydrological processes and regimes ~~occurring~~ within~~on~~ coastal catchments. These processes underpin land-sea connectivity and all ecological functions and water quality outcomes, which are directly linked to the health of the adjacent marine environment.

Coastal marine ecosystems have developed on a coastline that for centuries have delivered low-moderate nutrient concentrations and suspended sediment (Figure 1). Therefore, the ecosystems have adapted to a specific range of sediment and nutrient conditions as influenced by the linked coastal watersheds. Human forest conversion on coastal watersheds to other land uses has altered the annual load of nutrients and suspended sediment exported from the coastal catchments flowing into marine environment, with detrimental impact on marine ecosystems (Fleitmann et al., 2007; Maina et al., 2013) (see Fig. 1). For example, reports from Kenya's Sabaki R~~r~~iver have estimated an increase in sediment discharge into the Indian Ocean from 1900 to 1990's to be between five and six~~5-6~~ times (Fleitmann et al., 2007). Increased suspended sediment concentrations have been linked with changes in land-use and soil erosion in the Sabaki basin, with the actual increases strongly dependent on the type of land-use change (Fleitmann et al., 2007).

Despite the ongoing changes occurring ~~on~~ to coastal land and pollution impacts on marine ecosystems, implementing the Integrated Coastal Zone Management (ICZM) approach is complicated due to lack of knowledge on historical trends and baselines of nutrient and sediment emanating from land. With no understanding of the key baselines at discharge locations in the ~~Western Indian Ocean~~WIO, ICZM is handicapped, owing to attribution challenges for ecosystem condition to changes on land among other drivers of change. Considering that few catchments in the region are gauged for river flow, let alone sediment load, a key priority for the respective national ICZM and basin management agencies is to set upestablish a sediment and river flow monitoring system. Furthermore, catchments should be subjected to appraisal and evaluation of the amount of nutrients and sediment flowing into the ocean, potential impacts on biodiversity, and how different activities on land, such as agriculture, mining and land clearing in general, and climate change may impact on the fluvial ecology and sediment budget. Another challenge is to link the land-based activities and sediment effluent to changes in marine ecosystems. For example, it is of paramount importance that knowledge on sediment and nutrient thresholds is established for the different linked ecosystems, and the social and ecological response behaviour pattern is mapped. Attribution of the changes in habitats to pollution can not only create awareness and provide scientific support and a basis necessary for the formulation and implementation of land sea policy and management actions, but also it would lead to the establishment of key targets for sediment reduction and measure of success of the management actions.

Land-Sea connectivity in the WIO

The concept of land-sea connections in the WIO is dependent on several factors but is primarily driven by hydrological connectivity between freshwater, estuarine and coastal ecosystems (Figure 1). The interface between the coastal, estuarine and freshwater system is a very productive component of the food chain as well as a critical corridor for movement between ecosystems (Wolanski, 2007; Sheaves et al., 2015). Several marine and estuarine fish species use the freshwater systems for part of their life cycle. For example, mangroves and estuaries are vital habitats that support the life cycle of many shrimp species (eg Munga et al., 2007; Fulanda et al., 2011; Abreu et al., 2017), reflected in the d. Detailed studies from Kenya (Munga et al., 2007; Fulanda et al., 2011) that demonstrated the significance of land sea connectivity to shrimp species diversity and fisheries in Kenya's Tana and Sabaki Estuaries. Also in Mozambique there is evidence of the link between catchment discharges and shrimp commercial catches in several estuaries, such as the Zambezi delta (Gammelsrød, 1992) and the Maputo Bay catchments (Bacaimane and Paula e Silva, 2014; Nordez, 2014).The freshwater flows from the various waterways also serve as the primary delivery mechanism for materials that runoff the catchment including a range of pollutants. These physical exchanges underpin the functional land-sea connectivity. Therefore, understanding the physical connectivity, in terms of catchment dynamics, outlets, sediment and flow volumes, and sensitivity to climate and land uses is of critical importance to managing the functional connectivity.

Depending on each catchment characteristics and type of land-sea (estuarine) interface, the mixing of waters of different origin occurs with associated transformation of matter from land origin through diverse biogeochemical processes (eg Meybeck and Dürr, 2009; Dürr et al., 2011). The coastal interfaces are strongly affected by the whole catchment, and freshwater runoff, erosion and biogeochemical processes at basin scale modulate downstream characteristics and their variability at varying temporal scales, as seen for instance for coastal resources within the Maputo Bay in Mozambique (eg Monteiro and Marchand, 2009). The inherent optical and chemical characteristics of the terrestrial sourced plume entering the ocean, such as nutrients, salinity and sediment load, and associated organisms, influence the adjacent marine environment through the transformation of dissolved and particulate materials (eg Frankignoulle et al., 1998; Dagg et al., 2004). Although most evidence of continental drainage effects on the coastal zone comes from rivers and associated coastal interfaces, diffuse groundwater flows are still largely unknown.

River basins in the tropical world can broadly been classified based on climate, primarily rainfall, as wet tropics basins (WTBs) and dry tropics basins (WTB's) (Latrubesse et al., 2005). WTB are characterized by wetter climates with average annual rainfall exceeding 3000 mm, and the presence of intensive agricultural land uses and their associated fertilizer and pesticide loads. In the WIO, examples include regions in the low-mid latitude including northern Mozambique, Tanzania, Kenya and the southern parts of Somalia that receive high intensity rainfall during the wet season from March through May (Scheren et al., 2016). On the small Oceanic islands, such as those of the Seychelles and other island states, receive high intensity rainfall that is strongly influenced by the monsoon (FAO, 2005). Changes in rainfall patterns coupled with human activities in both the wet and dry tropics have contributed to changes in sediment regimes on along the WIO coastlines. In contrast, catchments in dry tropical areas, for example southwestern Madagascar and drier parts of southern Kenya (Lower Tana basin), have average annual rainfall in the 500–750 mm range. Such areas tends to be and are dominated by unimproved original savannah/woodland rangeland grazing.

While the flow volume determines the transport capacity of the river-borne sediment, the rainfall intensity influences the erosion potential and dislodgement of soil particles. Thus, rivers draining high and intense rainfall watersheds exhibit higher flow and sediment discharges. Reports indicate that catchments in the wet tropics are very sensitive to deforestation, with minimal forest decline leading to large amounts of river runoff and sediment discharge (Maina et al., 2013). In dry catchments, however, sedimentation is less sensitive to forest decline, as is the case in south western Madagascar where large degree of deforestation led to marginal decline in sediment discharge (Maina et al., 2013). According to Scheren et al. (2016), in the northern parts of the WIO region (eg Somalia and Kenya), the estimated total annual river discharge is in the range 1.8–4.95 km^3/yr. River discharge volume along the WIO coastline (eg Tanzania, Mozambique and South Africa) is estimated to be in the range of 2.9–106 km^3 (Hatziolos et al., 1996; Scheren et al., 2016). These large sediment loads discharged to the Ocean have generated estuarine formations, particularly in the southern parts of the WIO region (Mozambique) with extensive mangrove forest development (Taylor et al., 2003; Scheren et al., 2016).

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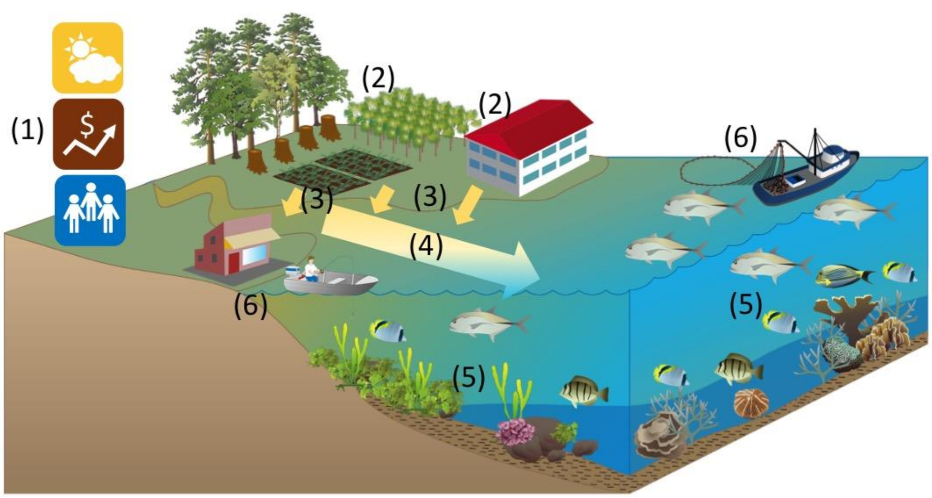

Figure 1 - Land-sea connections. (1) climate, economic and societal drivers of land-use change; (2) human activities that change pollutant run-off, including forestry, agriculture and urbanisation; (3) sediment and nutrient run-off from activities on land enter streams and eventually the ocean;

(4) resulting changes in water quality as pollutants are dispersed and transformed in the ocean; (5) changes in marine ecosystems and fished populations, including interactions between predators, prey and between fished species and their habitats; and (6) impacts of ecological change on fisheries and social and economic responses to change in fisheries. (source: Brown et al., 2019)

Hydrological landscape

Rivers discharge nodes are the main features that connect coastal catchments to marine ecosystems. These could be large perennial all-season rivers, or seasonal rivers that are active during flash floods or during the wet season. Similarly, the watersheds that are drained by these rivers could be large basins, or smaller watersheds within the larger basin. Most national water management bodies are based on a basin scale, for example, Tanzania's Rufiji Basin Water Office, and Kenya's Tana Basin Corporation in Kenya manage the water at the basin level. Consequently, hydrological reports and data are aggregated at the basin level, which in most cases can be too coarse for their consideration as land-sea connectivity units. Small-medium catchments within larger basins are the ideal unit for land-sea management, given the scale at which activities on land takes place (e.g. small scale farming) and the significance of smaller sub-catchment in erosion and transportation of sediment.

Despite the ecological significance of smaller catchments, the management focus has been on larger basins and estuaries. In the estuarine chapter, twelve large river basins are described and presented as the main estuaries in the WIO (Scheren et al., 2016). However, many estuariesne that are not considered large but are of significance nevertheless are largely undocumented. Small estuaries are mainly fed by seasonal rivers and are distributed all across many WIO countries. They are characterized by inactivity during the dry season, but they discharge large amount of runoff during the wet season. The freshwater flows from the various rivers have a profound effect on the coastal marine ecosystems in the region, driving various ecological processes and providing nutrients for many biota (Kairu and Nyandwi, 2000). Given their significance to of land-sea connectivity, we interrogated freely available topography data was interrogated to determine the spatial distribution of all estuaries including those that are small and seasonal in nature.

To characterize the catchment ecosystem in the region to a scale relevant for diverse features of physical and biological connections, ~~we downloaded~~ spatial data on watersheds was downloaded from the Hydrosheds website (http://www.hydrosheds.org). This database was delineated from the Remote Sensing derived elevation data (Shuttle Radar Topographic Mission-SRTM) (Lehner et al., 2008). ~~We obtained~~ T~~t~~he data obtained was~~and~~ used it to evaluate the number and size of catchments and main rivers draining the catchments. ~~For small islands in the WIO, catchment and rivers' data were not available in the SRTM watershed product.~~ From these, a total of 83 river discharge points were delineated for continental WIO and Madagascar, draining a total of 72 (sub) watersheds (Figure 2). For small islands in the WIO, catchment and rivers' data were not available in the SRTM watershed product.

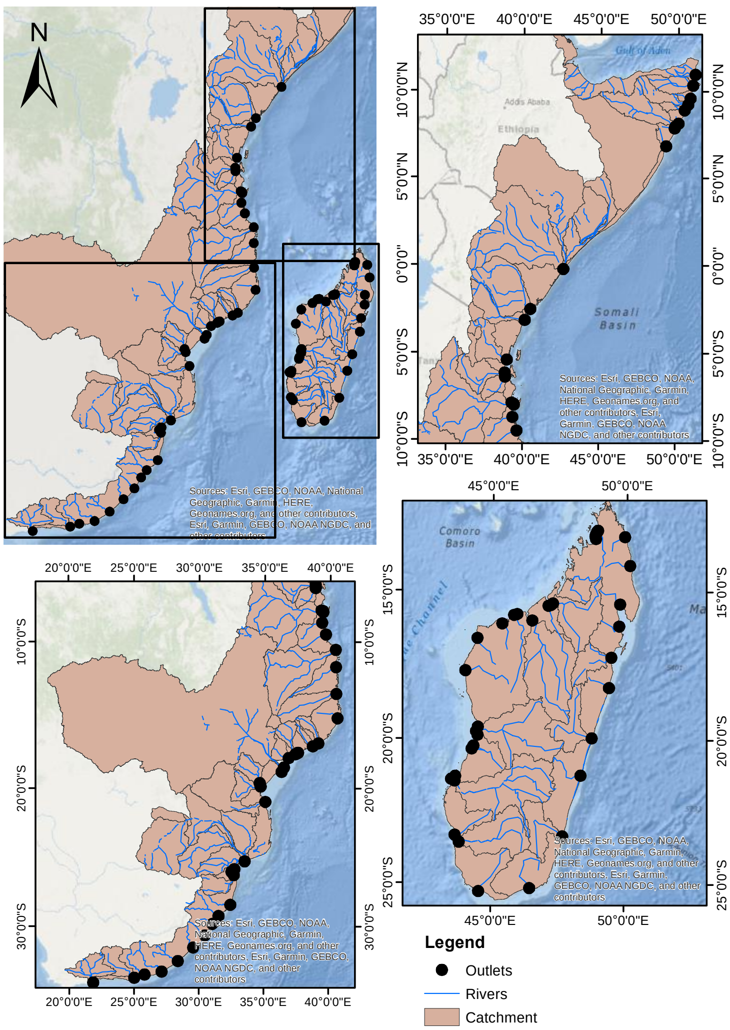

Figure 2. Distribution of 83 discharge points from all types of rivers in the continental WIO and Madagascar.

Linked marine ecosystems

Coral reefs

Coral reefs are described in detail in the coral reefs chapter 12. Natural land-ocean linkages through runoff and sedimentation have been altered as a result increased sediments and pollutants being deposited in the coastal waters to the detriment of coral reefs. Among the main causes of the global coral decline, terrestrial sourced pollutants rank as one of top causes (Gardner et al., 2003). Modification of terrestrial sediment fluxes can result in increased sedimentation and turbidity in receiving waters, with detrimental impacts on coral reef ecosystems. Preventing anthropogenic sediment reaching coral reefs requires a better understanding of the specific characteristics, sources and processes generating the anthropogenic sediment, so that effective watershed management strategies can be implemented. This information, however, is unavailable for most catchments. At the basic level, linkages between sedimentation and coral reef decline at the region need to be demonstrated empirically, so that thresholds could be established. Establishing sediment concentration thresholds at which coral reefs begin to deteriorate is necessary for management intervention.

Assessments of impacts of sediment on reefs, and of linkages between catchments and coral reefs have been undertaken for various locations in the region. In a study in Kenya, coral diversity and evenness decreased, and the dominance index increased due to selective survivorship of coral species resistant to elevated sediment (for example *Millepora* sp.) (McClanahan and Obura, 1997). Another study revealed high sedimentation rates on Malindi reef emanating from Sabaki River, which did not have impact on coral recruitment and general coral health (Mwachireya et al., 2015). However, increased hydrodynamics and enhanced flushing rates have been credited for the nuanced observations of impacts of sediment on reefs. A more recent threat, however, is the synergy between global and local stressors. The global coral decline has been attributed to interacting multiple global and local disturbances (Darling et al., 2019). These include terrestrial sourced pollutants (Gardner et al., 2003; Wilkinson, 2004); overfishing and loss of herbivores (Mumby et al., 2006); and climate-related changes in sea surface temperature and acidity (Fabricius et al., 2011; Hoegh-Guldberg et al., 2007) among others. These compound drivers may interact with varying consequences in different coral reef systems. Furthermore, they operate at different spatial scales, where local factors may exacerbate the effects of global processes, and at different temporal scales, where longer-term trends may be obscured by short-term, inter-annual or seasonal variability (Chabanet et al., 2005; Habeeb et al., 2005). Simultaneous assessments of drivers of change may provide an insight into the inter-linkages and relationships between physical and biological processes in coastal watersheds and the adjacent coral reefs.

Mangroves

Mangrove forests are described in detail in chapter 9. The WIO mangroves, with estimated coverage of 1 million hectares represents 5 per cent~~%~~ of the global mangrove coverage (Bosire, 2016). The dense distribution of mangrove forests in the WIO occurs in deltas and estuaries (Spalding, 2010; Hamilton and Casey, 2016). The nature of mangrove distribution and easy accessibility has exposed them to unprecedented human pressure in recent years. Human activities such as reclamation for expansion of residential housing~~es~~, tourist installations and agriculture; commercial or artisanal extraction of wood for timber, fuelwood~~,~~ and poles;~~,~~ and freshwater diversion are happening to the detrimental of mangrove ecosystems. Deforestation of coastal watersheds occurring throughout the WIO has altered the transport of water, nutrients and sediments to mangrove estuaries and coastal oceans. This occurs because of powerful couplings linking land-use changes on upland watersheds to receiving aquatic ecosystems down the topographical gradient.

Eutrophication is one of the major causes of coastal ecosystem degradation. Eutrophication leads to an increase of the occurrence of algal blooms (Paerl, 1997), degradation of coral reefs (Lapointe, 1997) and reductions in seagrass cover (Van Katwijk et al., 2011). Persistent eutrophication can also adversely affect mangroves, which have the potential to assimilate nutrients in eutrophicated coastal environments (Robertson and Phillips, 1995). Lovelock et al. (2009) have suggested that nitrogen enrichment may reduce the resilience of mangroves to environmental stress, thereby increasing mortality. Nitrogen enrichment of terrestrial and coastal ecosystems produces similar effects. In a terrestrial system with little or no harvesting, for example wooded ~~(Lovelock et al., 2014)~~ semi-natural terrestrial systems, nitrogen may be taken up into the local nutrient cycles. Nitrogen enrichment of the terrestrial forest floor usually increases growth and nutrient (soil and foliar) levels (Lovelock et al., 2014). Similar effects have been found in mangrove ecosystems. Mangroves showed enhanced growth and in- creased foliar nitrogen (N) and phosphorus (P) concentrations under conditions of N and P enrichment. Addition of N and P (each 300 g/tree) to mangrove soils resulted in increases of up to 30 % per cent for foliar N and 40–100 % pre cent for foliar P levels. In a similar study, Boto and Wellington (1983) reported that addition of N and P (each 100 kg/ha) increased mangrove foliar N and P levels by 22 and 7 %, per cent, respectively.

Estuarine Wetlands

Estuaries are assessed in detail in Chapter 14. Estuarine habitats may include: forests (mangroves), coastal saltmarshes (grass, sedge and herb swamps), salt flats and saltpans, mudflats and intertidal seagrass ecosystems. Beneath the water, estuarine habitats can include soft-bottom communities, hard-bottom communities, and ecosystems dominated by coral and seagrass. Estuaries are located at the terminus of coastal catchments and receive run-off and contained loads of sediment, nutrients and other contaminants from contributing catchment areas. Due to these biophysical linkages, the condition of an estuary is mediated by the condition of its catchment to varying degrees. Estuaries are therefore susceptible to catchment land use and development that alter freshwater flows or elevate loads of sediment, nutrient and other contaminants exported downstream (see Chapter 14). This affects their susceptibility to water quality impacts associated with run-off contaminant loads in runoff.

Estuarine ecosystems in the WIO are exposed to extreme environmental conditions, from large freshwater flows during the wet season leading to hyposalinity, to hypersaline conditions caused by cessation of flows and evaporation during the dry season. Estuarine ecosystems have adapted to these conditions but are dependent on connectivity and tidal exchange for ongoing health and resilience. Changes to river flow regimes and tidal connectivity between individual habitat components can cause phase shifts in estuarine communities. Recovery time from disturbance can be as long as 20 years. Saltmarsh communities are generally more susceptible to human disturbance than mangrove areas.

Planning for land-use change

It is inevitable that with competing demand for land and ~~the~~ ongoing climatic change, optimal land allocation will increasingly become complicated and will require decision support planning tools for prioritisation. Marine management in the ~~Western Indian Ocean~~WIO, like elsewhere in the world, will need to plan for conservation amid the ongoing global environmental changes, including climate change and conversion of forest land to agriculture and economic development i~~o~~n coastal catchments. Decision support tools, including the land-sea models are indispensable tools to assist in conservation planning (Brown et al., 2017). Given the multidisciplinary nature of the land-sea environment, different tools will need to be coupled to cover different sectors of the land-sea continuum. For example, hydrological modelling may need to be linked with coastal hydrodynamics to determine where the sediment comes from and where it disperses to post-discharge. Similarly, socioecological and economic models would be required quantify the impacts of sediment on ecosystems and the socioeconomic consequences. Incorporating this information into a quantitative planning framework provides a transparent and repeatable approach to land-sea planning (Game et al., 2013).

A review of studies across the region reveal that there is precedence on coupled integrated land-sea spatial planning, which exposes ~~a~~ key knowledge and management gaps. Elsewhere in the tropical world, land-sea planning has been applied in the management of the G~~g~~reat B~~b~~arrier R~~r~~eef (GBR) catchments in Australia, in a bid to ~~take~~ reduce sedimentation ~~of~~ from impacting the ~~great barrier reef~~GBR (Dale et al., 2017). Table 1 ~~(adapted and contextualized for WIO from Brown et al., 2017)~~ provides examples of research studies along the land-sea continuum in the WIO. From this review, it is clear that most of the studies in the region are on establishing the impacts of sediment on ecosystems, and on quantifying the amount of river flow and/or sediment discharge from catchments. The table also highlights the gaps, especially on integrating all the datasets for spatial planning.

Table 1 Examples of quantitative studies along the land-sea continuum, that have linked land-use change to coastal ecosystems and fisheries. Blue boxes indicate steps where a specific quantitative model was used. Empty boxes indicate that no quantitative model was used, though that step may have been considered conceptually (Adapted and contextualized for the WIO after Brown et al., 2017).

Example	Drivers of land-use change	Human activities that cause land-use change	Fresh water and pollutants run-off	Dispersion of pollutants in the ocean	Ecosystem response	Socio-economic response	Land-Sea Spatial Planning	Reference(s)
Madagascar, coral reefs								Maina et al., 2012; Maina et al., 2013
Rufiji Basin, mangroves								Reference?
Athi/Sabaki basin (Malindi) Coral Reefs								McClanahan and Obura 1997; Fleitmann et al., 2007
Tana Basin, Mangroves								
Pangani Basin (Tanga)								Ndomba, 2010

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Conclusion and future directions

The strong linkages between land-based activities and nearshore marine ecosystems and associated socioeconomics demand that marine resource management evolve to consider human activities on land. The complexity of processes linking basin land-use change to change in coastal ecosystems hinders effective integrated land-sea planning. Overcoming this complexity can be facilitated through efforts to integrate models from the drivers of land-use change to management responses for marine ecosystems. Based on the key knowledge gaps identified in this review, ~~we provide~~ the following future research directions for connecting land and sea models and actions that could be taken that will assist integrated land-sea planning are proposed:

1. A thorough scientific assessment of the hydrological processes within the coastal catchments in the ~~Western Indian Ocean~~WIO to be carried out, including: the seasonal to annual water balances, streamflow and hydrograph characteristics, the role of land-use in runoff processes, ground and surface water interactions from the hillslopes to the lower

floodplains, overland flow extent and floodplain inundation frequencies, the role of in-stream storages (dams and weirs) in the catchment hydrology, and the dependence of event scale variability on various synoptic processes (for example, ENSO and dipole).

2. An analysis of climatic and streamflow trends within the coastal catchments of the WIO, including statistical tests for non-stationarity is needed.

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3. The undertaking of a~~A~~n analysis of the sensitivity of streamflow to other changes in the catchment water and energy balances especially precipitation and vegetation, and the feedbacks between them.
4. A detailed analysis of the overland flow (floodplain) transport pathways where nutrient addition is of primary concern, including their inundation, flow hydraulics, infiltration, changes in water quality, and the subsequent return flow to river channels or the coast. This would also consider the relation of these processes to the river channel hydrograph, and the relative contribution of return flow from floodplains to flood plumes which ultimately reach the nearshore marine ecosystems.
5. A comprehensive study on the coupling between nutrient kinetics and the hydrological transport processes in the landscape in selected watersheds. This would include key biogeochemical kinetic factors (organic matter, dissolved oxygen, microbial processing), the role of event and seasonal hydrology in nutrient export, and how this links with the surface, hyporheic zone, and groundwater exchanges and flow paths.
6. Establish the impact of sediment and nutrient pollution (or lack of) on marine ecosystems and determine the socioeconomics and livelihoods consequences ~~on~~ of sediment pollution. This would facilitate the tradeoff ~~of~~ between land-based activities based on the potential impacts on ecosystems and livelihoods.
7. Finally, for long term management effectiveness, it is important to establish a robust monitoring network, preferably where streamflow records are already continuously monitored, that would determine surface, groundwater and hyporheic zone water exchanges, continuously monitor key kinetic determinants of nutrient concentrations (organic matter fluorescence, dissolved oxygen). Monitoring sites would also~~, and~~ serve as locations for surface water and groundwater sampling.

Each of these actions provides the critical information necessary to understand how catchment processes impact on the marine nearshore environments. However, they also proceed in a logical independent order: with actions 1 – 3 enabling areas of *critical hydrological function* within the WIO coastal catchments to be effectively identified, and actions 4 – 5 enabling areas of *critical biogeochemical function* to be identified. If these can be achieved in combination, then it is possible to establish areas requiring further investigation as an *immediate priority for marine biodiversity protection*, and which would therefore be the target of action 7. Finally, the complexity of comprehensive modelling of linked land-sea processes should not hold back the development of management plans. A pragmatic way to proceed in the absence of planning tools that account for land-sea impacts is to devise plans using expert input and then evaluate ecological and socio-economic outcomes post-hoc using existing modelling tools. Quantitative planning for the impacts of land-use change on coastal fisheries requires linking models across a multitude of disciplines. Doing so can be a challenge for the small teams often tasked with developing land-sea plans. Addressing the research challenges outlined above should help those teams develop plans that focus on outcomes, like fish yield, rather than more abstract objectives of reducing threat. Outcome-driven planning is likely to be more effective for driving land-sea plans and evaluating competing trade-offs.

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Targeted review on gGround-water linkages to nearshore marine areas in the WIO

While rivers form one of the main land-sea connectivity pathways on the surface, another important pathway connecting coastal land and sea realms is the submarine groundwater discharge (SGD). SDG is a hydrogeological process by which groundwater enters coastal waters. The global sub-surface flux is estimated at approximately 10 per cent% of the gross fresh river discharge (Taniguchi ~~and others~~et al., 2002). This process, which is increasingly becoming recognized as nutrient and pollutant pathway from land to coastal oceans, transports bioactive solutes, including but not limited to nutrients (nitrogen, phosphorous, silica), gases (methane, carbon dioxide), and trace metals (iron, nickel, zinc) (Moosdorf and Oehler, 2017). Nutrient addition to nearshore marine ecosystems through SGD can be beneficial because nutrient availability largely controls primary productivity (Duarte et al.~~and others~~, 2010). However, changes in salinity due to SGD may also undermine productivity, considering that salinity is important physiochemical attribute for nearshore biodiversity. Consequently, the distribution and abundance of marine organisms may also be directly affected by changes in salinity (Krause-Jensen et al.~~and others~~, 2008). On terrestrial coastal areas, coastal aquifer salinization as a result of seawater intrusion is a common phenomenon in many cities located in coastal areas. When groundwater is pumped from coastal aquifers, potential SGD is intercepted. This disrupts the natural equilibrium, causing the fresh-water - salt-water interface to locally migrate landward and/or vertically ~~locally~~ upward (Manivannan and Elango, 2019). This targeted review focuses on both terrestrial groundwater discharging into the sea (terrestrial fraction or fresh SGD) and marine fractions (SSaline SGD), and the environmental and biological impacts as reported in different studies in the WIO.

In the WIO region, few case studies of SGD exist. Among them are studies in the small island of Mauritius on the impacts of the micro-environmental conditions caused by SDG on reef fishes (Povinec et al.~~and others~~, 2012,; Lilkendey et al.~~and others~~, 2019). They found that physiologically favorable conditions created by the SGD elevates the survival potential of marine fish (Lilkendey et al.~~and others~~, 2019). Given the observed benefits, their study highlights the need for ground water fluxes to be included in the environmental management plans, in particular with regards to addressing potential future challenges such as tradeoffs between anthropogenic freshwater needs and coastal fisheries productivity. In the neighboring volcanic island of Reunion, ground-water discharge onto coral reefs, in particular La-Saline reef was discovered in early 1980's (Naim, 1993). Subsequent studies have reported coral cover decline in La-Saline reef and algal overgrowth (e.g. Chabanet et al.~~and others~~, 2002,; Chazottes et al.~~and others~~, 2002). This has been attributed to nutrients issued from SGD, which have caused eutrophication on this reef that is comprised of reef-flat and a backreef of deeper reefs. This can complicate the management of coral reefs, considering that nutrient reduction on reefs is one of the commonly recommended strategy for enhancing coral reef resilience to climate change.
At a global scale, a recent high-resolution estimate of SGD flux indicated that 23~~%~~ per cent of the global coastline is at risk of eutrophication by terrestrially derived ground water (Luijendijk et al.~~and others~~, 2020). Based on the report, some of the high-risk areas in the WIO include nNorthe-Eastern Madagascar, central Mozambique and Dar as Ssalaam in Tanzania and parts around Durban in South Africa (Luijendijk et al.~~and others~~, 2020)

As the coastal cities along the WIO bulge with increasing population, the demand for water increases and, in most cases, surpasses the governments capacity for water provision within the city. As a consequence, coastal cities along the WIO experience high groundwater exploitation due to population growth and industrial developments (Bakari et al., 2012). The intensive use of coastal aquifers often results in its salinization from sea water intrusion. A case study for Dar es Salaam in Tanzania simulated the different pathways of salt-water intrusion and found that intrusion depended on depth of the wells and their distance from the coastline (Van Camp et al., 2014). The study demonstrated the importance of formulating and enforcing evidence-based recommendations when drilling new wells for a better monitoring of the salinization process along the coast (Van Camp et al., 2014). The overdependence on SGD, and its active use by coastal populations demonstrates its role for coastal societies (Luijendijk et al., 2020). In the WIO, fresh submarine groundwater discharge is widely valued as a water resource for drinking, hygiene, agriculture, and culture, among other uses. For example, in Quissico, Mozambique, locals use intertidal springs for bathing and laundry (Moosdorf and Oehler, 2017).

Despite the wide-ranging benefits (Moosdorf and Oehler, 2017; Luijendijk et al., 2020), the region lacks adequate policy measures for safeguarding the integrity of the SGD. Furthermore, hydrogeological knowledge is fragmented, groundwater lacks a long-term monitoring infrastructure and information transfer from stakeholders to users is limited. A logical step towards sustainable use of SGD is to incorporate it within the Integrated Coastal Zone system and as part of the environmental flow, such that its role in the system is clearly outlined and considered in the formulation of ~~the~~ relevant policies.