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The changing hydro-ecological dynamics of rivers and deltas of the Western Indian Ocean: Anthropogenic and environmental drivers, local adaptation and policy response

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ABSTRACT

The rivers flowing into the Western Indian Ocean have steep headwater gradients and carry high sediment loads. In combination with strong tides and seasonal rainfall, these rivers create dynamic deltas with biodiversity-rich and productive ecosystems that, through flooding, have sustained indigenous use systems for centuries. However, river catchments are rapidly changing due to deforestation. Hydropower dams also increasingly alter flood characteristics, reduce sediment supply and contribute to coastal erosion. These impacts are compounded by climate change. Altogether, these changes affect the livelihoods of the delta users. Here, based on prior works that we and others have conducted in the region, we analyse the drivers of these hydro-ecological changes. We then provide recommendations for improved dam design and operations to sustain the underlying delta-building processes, the ecosystem values and the needs of the users.

1. Introduction

1.1. Background

When a river slows down, the balance between the turbulent forces in the water column and gravity changes, and this change leads to the sediment it carries being deposited. This happens at many scales and under many circumstances but most prominently where a river meets the ocean. Here, the river gradient approaches zero and any significant change in river flow results in floodwaters spreading over a wide area and offloading its sediment. As the regularly flooded areas build up as new sediment deposits and adjacent areas sink because of sediment compaction, dewatering and oxidation of organic matter, the flooded areas will shift position and the process restarts elsewhere. Typically, this creates a triangular or fan-shaped delta. However, depending on the balance between river and ocean dynamics, other delta types exist, e.g., wave or tide dominated (Anthony, 2015; Reading, 2009).

Unique and highly productive ecosystems have developed in these deltas, primarily flooded grasslands and salt-adapted vegetation such as mangroves at the marine fringes. These ecosystems support diversified livelihoods

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adapted to the flooding patterns. Traditionally these include fishing, livestock keeping, flood-recession agriculture and tidal rice cultivation, hunting and gathering, utilization of woody and non-woody forest products and beekeeping among others (Hamerlynck et al., 2017). Deltas are important, well beyond their physical perimeter, as carbon sinks, as coastal defence and land-building systems and as nursery areas where the juveniles of fish and crustaceans grow before entering neighbouring coastal waters where they are the targets of valuable fisheries (e.g., Lee et al., 2014). The total economic value of all the services provided by coastal wetlands including deltaic systems with mangroves is estimated around 200,000 US$/hectare/year (de Groot et al., 2012). This is the second most valuable ecosystem globally, only surpassed by coral reefs valued at around 350,000 US $/hectare/year, mostly because of tourism.

Being wet, flat and fertile, deltas have been targeted for large-scale land conversion including the building of embankments to establish large-scale irrigation or aquaculture. Such human interventions interfere with the very processes that form deltas, causing them to become vulnerable to oceanic salt water intrusion compounded by sea-level rise and the capture of sediments by upstream dams (Syvitski et al., 2009). Thus, under these pressures, coastal wetland systems are rapidly losing their value: between 1997 and 2011 swamps and floodplains lost 64% of their surface area while tidal marshes and mangroves lost 22% globally. With additional losses of flood-dependent ecosystem services, the total decline in the aggregated flow of services from these two wetland types characteristic of the lower reaches of river basins amounts to 9.9 trillion US$ per year corresponding to about 13% of global Gross Domestic Product (GDP) (Costanza et al., 2014).

For various reasons, including comparatively low investment into hydraulic infrastructure in the postcolonial era, the deltas of the Western Indian Ocean (Fig. 1) have, until recently, maintained many of their ecosystem values (Scheren et al., 2016) as well as the traditional use systems dependent on them. However, this is set to change as several new hydropower dams and irrigation systems, including for biofuel production, are under consideration or implementation as Africa, following over a decade of high GDP growth rates, is being promoted as the next investment frontier (Taylor, 2016). Unfortunately, these new investments are primarily targeting provisioning services such as food, water and energy to be developed in the short term (within the next 5 years). They fail to support the underlying flood-dependent regulatory services that need to be maintained or enhanced. Additionally, at a global policy level, the 17 goals of the 2030 Agenda for Sustainable Development, adopted at the UN summit in September 2015, promote a sectoral approach. In order to mitigate these two weaknesses (short-term vision and sectoral approach) a more evidence-based and functional approach, integrated across sectors has been proposed by Griggs et al. (2013). This requires an improved understanding of the changes affecting the Western Indian Ocean deltas and a thorough analysis of the conditions under which ecosystem functions can sustainably benefit the delta users.

This paper focuses on the area between the Equator and the latitude 25° South (slightly south of the tropic of Capricorn) (Fig. 1). We endeavour to describe the common characteristics of the rivers flowing into the Western Indian Ocean as well as their specificities, the changes affecting their hydro-ecological rhythms and their consequences downstream, especially in the deltas.

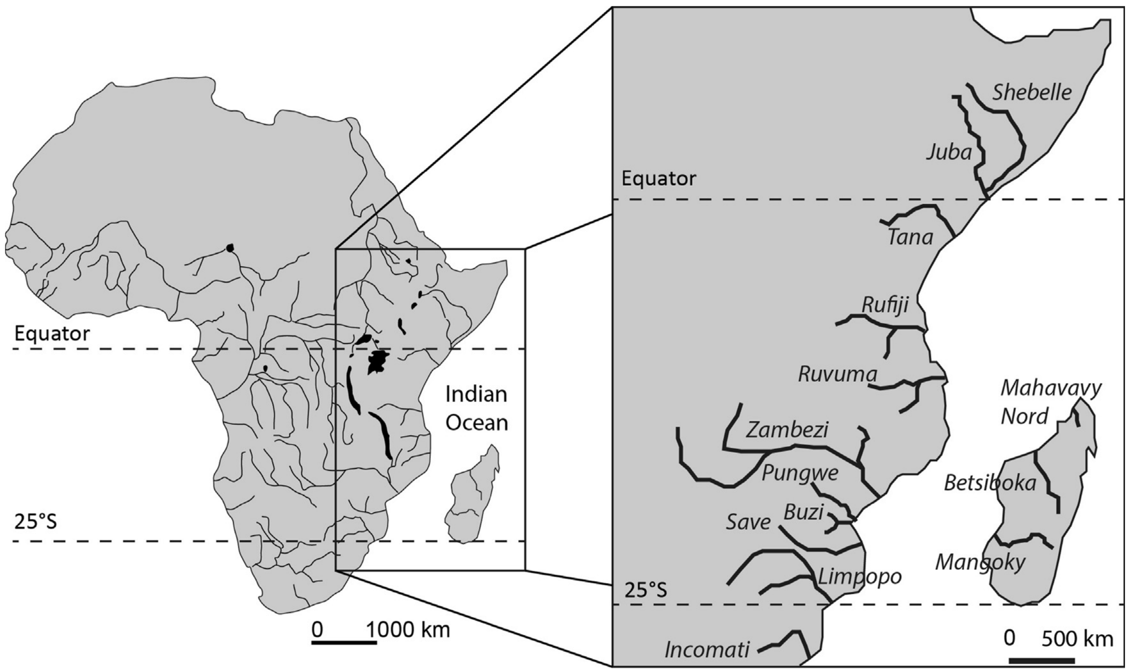

Fig. 1. Map of main rivers of the Western Indian Ocean.

2. Material and methods

2.1. Conceptual framework

The conceptual framework (Fig. 2) is derived from observations and results we obtained from our research experience predominantly acquired in three African coastal deltas since the early 1990s (Senegal, Tana, and Rufiji deltas) focusing on the local user adaptation strategies to flood variability i.e. the inter-annual differences in the timing, height, and duration of flooding (cf. "flood characteristics" that feature centrally in Fig. 2). These hydrological rhythms largely determine ecosystems productivity in natural floodplains and deltas (Opperman et al., 2013) and thus the local economies based on farming, fishing, livestock keeping, hunting, gathering and forestry (Hamerlynck et al., 2017).

In Fig. 2, above the flood characteristics, the main drivers of change are represented along a scale from the global (climate change) to the river basin level (land use change, infrastructure building such as hydropower dams or large-scale irrigation schemes that subtract significant volumes of water from the system). These two drivers can also operate at a more local scale (conversion to irrigation with embankments, road or other infrastructure crossing a delta, etc.). Still in Fig. 2, below the flood characteristics are the impacts on the deltas, geomorphology, ecosystem services and local user strategies.

Three main scenarios are considered. The natural variability in the flood characteristics is depicted in the central part of Fig. 2. Under such conditions, the deltas geomorphologically build themselves up, compensating for their natural subsidence and the ecosystem provides services with a productivity which is higher when substantial floods occur. When flooding is low the ecosystems still produce services but to a lesser extent. The rural users have learned to cope with this variability and are adapting their food production strategies. For example, they switch their main activity and source of income to fishing during high flood years and to forestry during low flood years. When geomorphology, ecosystems and user strategies are within their resilience spectrum (Gunderson, 2001; Holling, 1973), the Socio-Ecological Systems (Berkes and Folke, 1998) can bounce back.

To the left and to the right of this resilience spectrum are the situations that disrupt the functioning (Fig. 2). To the left are the disruptions happening when flood extent is reduced: less water is covering the deltaic floodplain and/or less sediment is being deposited. The delta is eroding, groundwater is becoming more saline, trees are

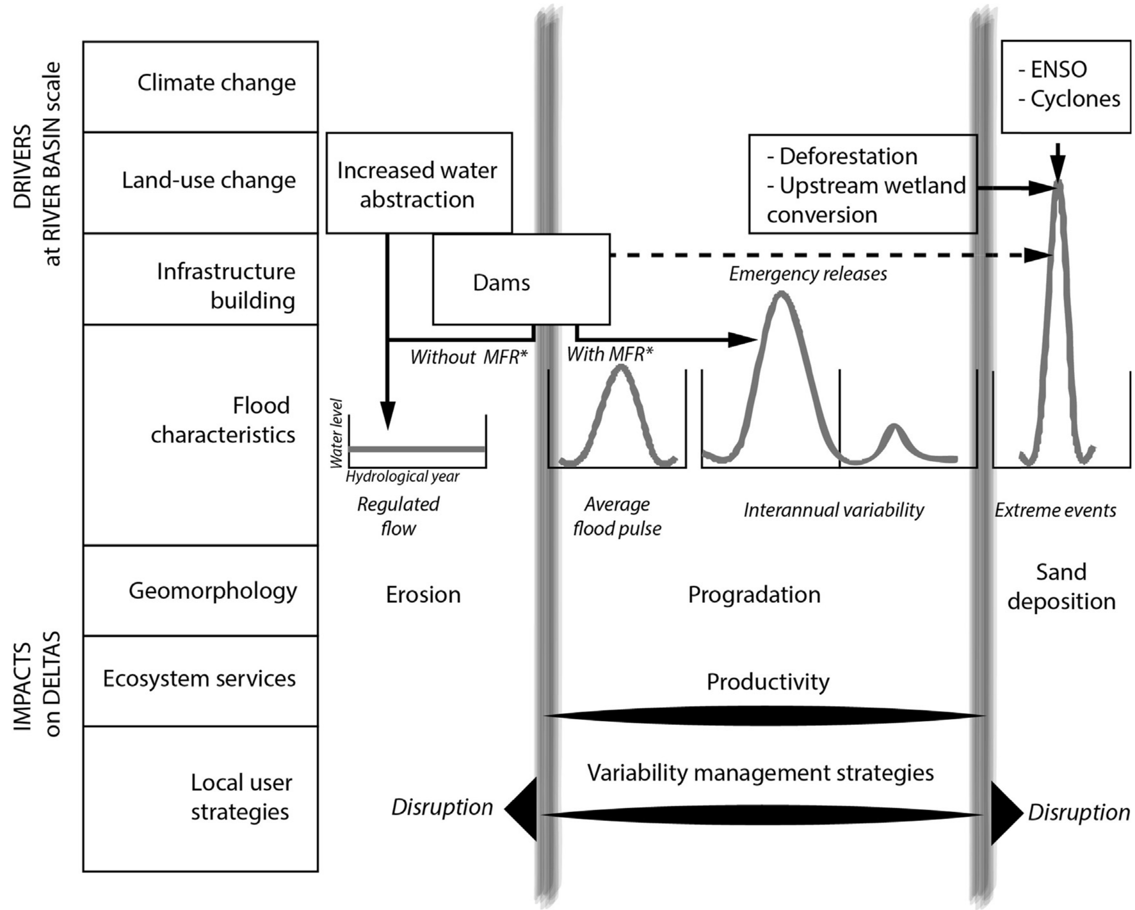

Fig. 2. Conceptual framework of the changing dynamics of the Western Indian Ocean deltas. *MFR: Managed Flood Releases.

establishing in the grasslands, etc. To the right are the disruptions when extreme floods are occurring (cyclones, ENSO events, emergency releases from dams, extreme deforestation or wetland drainage upstream), well beyond what was previously experienced. Extreme floods can bring down vast amounts of sand that cover parts of the normally fertile clay. The floods are rising too fast for the ecosystems (growth of the vegetation, fish migration to the spawning grounds) to react. The floods can also subside too fast, allowing insufficient time for the juvenile fish to grow to a size large enough to escape predation in the river bed, for groundwater to recharge to allow for recession agriculture and for palatable grasses to develop for livestock and wild grazing animals. The reproductive cycles of fish-eating birds are also negatively affected as they need a size spectrum of different fish life stages to feed their growing young. Managed flood releases (MFR) from dams are defined as "a controlled release of water from a reservoir to inundate a specific area of floodplain or river delta downstream to restore and maintain ecological processes and natural resources for dependent livelihoods undertaken in collaboration with stakeholders" (Acreman et al., 2000). They have the potential to maintain the socio-ecological systems within the resilience spectrum.

In order to confront this conceptual framework with the processes at work in the other deltas of the Western Indian Ocean, we have compared some of the characteristics of the Tana and Rufiji deltas to other deltas in the Western Indian Ocean. For the deltas analyzed, morpho-physical features (such as river slope), hydrological rhythms and a flow regulation index (as a measure of the impact of dams) were calculated and compared.

2.2. Data sources

River slopes (in m/km) were calculated from the altitude (in m) of the summit of the mountain range at the apex of the drainage basin, as available from open sources such as Wikipedia and verified on Google Earth, divided by the length of the river (in km) either from the refereed papers cited or from open sources.

For Kenya and Tanzania, we used the hydrological data collected in the framework of the GEOPAR project, which aimed at describing the link between flooding patterns and the user strategies (Duvail et al., 2013; Leauthaud et al., 2013). For the other countries, hydrological data were sourced from the refereed papers cited or, for those for which no refereed papers were located e.g., the Madagascan rivers, from the global river discharge database (Vörösmarty et al., 1998), always using the data from the measurement location closest to the river mouth. Mean tidal range was derived from the Global Sea Level Observing System Africa (GLOSS, 2017).

For the rivers equipped with large dams we have calculated a regulation index as the ratio between total storage capacity taken from the FAO Aquastat database (FAO, 2017]) and the average annual discharge. Rivers without large dams have a ratio of zero while a ratio of one means the entire flow of an average year can be stored. The ratio can exceed one for very large dams. A similar approach was used by Nilsson et al. (2005) using the database of the International Commission on Large Dams (ICOLD). Nilsson et al. (2005) introduced a correction factor of 0.5 $\times$ the maximum reservoir capacity to account for dead storage. However, it is difficult to obtain reliable information on dam storage capacity and on annual discharge. Conflicting numbers are found in the literature: for example, for the Limpopo an average pre-dam flow of 2000 m^3/s and 5% regulation (Nilsson et al., 2005) in contrast with a flow of between 174 and 232 m^3/s and a storage capacity of 7000 mm^3 (Mohamed, 2014), which is equivalent to an average flow of 222 m^3/s. It is likely that the Limpopo flow in Nilsson et al. (2005) is a typing error (2000 m^3/s instead of 200 m^3/s). Nilsson et al. (2005) also report an average flow of 7070 m^3/s for the Zambezi which is about twice the generally agreed flow of 3250 to 3960 m^3/s (Schleiss et al., 2017).

Population densities in the deltas were derived from the Socio-Economic Data and Application Center (SEDAC) database (CIESIN -Center for International Earth Science Information Network 2005).

3. Results: The Western Indian Ocean Deltas' changing hydro-ecological dynamics

3.1. River and sediment dynamics

The Western Indian Ocean receives freshwater inputs from the African continent and Madagascar mainly through many fairly large permanent rivers with average flows over 64 m^3/s (corresponding to a Mean Annual Discharge of 2000 mm^3). The Zambezi has the highest flows followed by the Rufiji, then the intermediate Mangoky, Ruvuma, and Save, and finally a series of smaller ones (Fig. 1 and Table 1).

In East Africa, most of the rivers take their source in the high-elevation ridge that bisects the African continent from the southern Red Sea coast through the Ethiopian relief and along the eastern branch of the Great Rift Valley (GRV) down to the southern shores of Lake Malawi. Further south many smaller east-flowing rivers take their sources in the mountainous areas of Lesotho and Swaziland and reach the Ocean through Maputo Bay. The notable exceptions are the Zambezi, which takes its main sources to the west of the GRV and reaches the Indian Ocean at the southern end of the GRV and the Limpopo which has it sources on the central plateaus of Botswana and South Africa. These two rivers have comparatively mild slopes (Table 1) though still steeper than, for example, the Nile (0.08 m/km) or the Niger (0.36 m/km). In Madagascar, all the rivers take their sources in the high altitude central plateau, but considering the dissymmetry characterizing the island, the rivers flowing to the Mozambican channel are longer and less steep than the rivers flowing toward the eastern part of the island (Chaperon et al., 1993).

Where these rivers meet the Western Indian Ocean, the sediments they carry are deposited and form deltas that vary in their shape. The deltas of the Rufiji, the Zambezi, the Mangoky and the Mahavavy are protruding into the Ocean and are characterized with significant areas of coastal mangrove. Where wave and wind action are the

Table 1
Major Rivers of the Western Indian Ocean.

Name	Average Flow (m^3/s)	Length (km)	Altitude Source (m)	Average Slope (m/km)	Regulation Index 2014
Shebelle (Eth-Som)	76	2526	4230	1.67	0.32
Juba (Eth-Som)	171	1808	4373	2.42	0.14
Tana (Ken)	99	1000	5199	5.20	0.32
Rufiji (Tan)	800	910	2400	2.64	0.01
Ruvuma (Tan-Moz)	450	800	1560	1.95	0
Zambezi (Zam-Ang-Nam-Bot-Zim-Moz)	3424	2574	1524	0.59	2.24
Pungwe (Zim-Moz)	120	400	2592	6.48	0
Buzi (Zim-Moz)	79	250	2436	9.74	0.81
Save (Zim-Moz)	440	400	1500	3.75	0.21
Limpopo (Bot-SAf-Zim-Moz)	170	1750	2300	1.31	1.31
Incomati (Swa-SAf-Moz)	111	480	1800	3.75	0.82
Mangoky (Mad)	484	740	1600	2.16	0
Betsiboka (Mad)	271	525	1755	3.34	0.02
Mahavavy Nord (Mad)	142	160	2200	13.75	0

Main Rivers entering the Western Indian Ocean from the African continent (from North to South) and Madagascar (from South to North) with their average flow, length, altitude of the source, average slope and regulation index (= total storage capacity of the dam reservoirs/mean annual discharge). Country codes are Ang: Angola; Bot: Botswana; Eth: Ethiopia, Som: Somalia; Ken: Kenya; Tan: Tanzania; Moz: Mozambique; Nam: Namibia; SAf: South Africa; Zam: Zambia; Zim: Zimbabwe; Swa: Swaziland and Mad: Madagascar.

dominant driving force, the deltas are non-protruding deltas (Anthony, 2015), as it is the case for the Betsiboka delta with its internal mangrove, or the Tana delta which is delimited by a high coastal dune on Ungwana Bay. In these situations, the mangroves are confined to the estuarine part and protected from direct wave action. A similar situation is encountered at the mouth of the Juba River with tiny mangrove fringes occurring along the river several kilometers upstream behind the ancient red dunes (Carbone and Accordi, 2000).

High sediment yields (measured in tonnes per km^2 per year) are strongly correlated to Mean Local Relief (MLR) which is a proxy for slope in the catchment. However, slope is not the only component in the dynamics of a river and its propensity to build a deltaic floodplain system: other factors such as the lithology play an important role. For instance, the metamorphic rocks typical of the African Precambrian Craton have a much lower erodibility, in general, than the volcanic rocks in the source areas of the major rivers feeding into the Western Indian Ocean (Vanmaercke et al., 2014).

The Western Indian Ocean, because of the constraining influence of Madagascar and the wide continental shelf in Mozambique, is characterised by a mesotidal regime with a tidal range of between 2 and 4 m. Tidal amplitudes are highest in the central part of the study area between Mozambique and Madagascar, weakening towards the north and the south. Tidal currents can be strong (over 2 m/s) in estuaries and creeks. The tidal influence can stretch far inland, for example 80 km in the Zambezi. Because of the stratification with the denser salty water forming a wedge below the fresh water, tidal freshwater wetlands are a common feature of these deltas. This allows the cultivation of tidal rice, often on areas cleared of mangrove. It should be noted that such mesotidal conditions are rare under tropical latitudes dominated by coral reef and mangrove lined coasts), the only other examples globally being Northwestern Australia and between the southwestern parts of Central America and the northwestern parts of South America.

3.2. Annual floods and inter-annual variability

In the river systems of the Western Indian Ocean, the flood pulse (Junk et al., 1989) is the engine of the productivity through a direct relationship between flood extent and ecosystem production (Drijver and Marchand, 1985; Opperman et al., 2013). This is especially true when the river takes its sources in the high-altitude areas of Sub-Saharan Africa and in its lower course runs through drier lowland. The strong rainfall gradient between the river sources and the lower course and the strongly seasonal pattern accentuate the contrast between the riverine wetlands and their drier surroundings.

For the studied area, the flood pulse ranges from semi-annual (Shebelle, Juba, Tana River and marginally for the Rufiji) to single annual (from the Ruvuma southwards and in Madagascar). For example, in the Tana, very close to the Equator, floods peaks occur in November and May. In the Rufiji there is a (generally small) rise of the water level in November related to the short rainy season and the main flood peak occurs in May. The flood peak in the Zambezi occurs in March or April and in February in the Limpopo and Betsiboka.

In Table 2, we calculated the inter-annual variability as a ratio of the maximum mean annual flow to the minimum mean annual flow. Given the difficulty of finding continuous historical data for overlapping time periods in the various countries, we did not consider the actual flood peaks. For example, in the Tana delta the two most extreme events were recorded in 1961 and 1998 but these do not show up as the highest annual mean flows. Still, Table 2 provides a raw indication of the variability range from one river to another and shows that the inter-annual variability is high throughout the area, ranging from a ratio of 2 to 6. The Tana and Zambezi have a high inter-annual variability, with for the Zambezi, a distinct 20 year period of higher flow from 1951–1981 (Frossard and Garros-Berthet, 2003). The Rufiji variability ranges from 1 to 4 though the time series is incomplete, especially for the post structural adjustment period during which river

Table 2
Minimum and Maximum Mean annual flows for several rivers of the Western Indian Ocean. In this table the mean annual flow is the average flow for each individual calendar year.

River	Station	Period of available data	Mean annual flow min (m^3/s)	Year of min. annual flow	Mean annual flow max (m^3/s)	Year of max. annual flow	Ratio Max/Min	Source
Tana	Garissa	1943–2009	57	1949 and 2000	356	1968	6.2	WRMA, calculated by authors
Rufiji	Stiegler's gorge	1951–1984	435	1975	1734	1962	4.0	Ministry of Water, calculated by authors
Zambezi	Victoria falls	1908–1996	424	1996	2528	1958	6.0	Frossard and Garros-Berthet, 2003
Betsiboka	Ambodiroka	1958–1968	157	1966	442	1959	2.8	Vörösmarty et al., 1998

monitoring was stopped (Duvail and Hamerlynck, 2007). Similarly, in Madagascar, recent time series are incomplete in comparison to those from the 1950s and 1960s (Vörösmarty et al., 1998). Still, for the Mangoky river there may be an increase in flows, possibly related to the high deforestation and land degradation in its catchment. For the 17 years with almost complete data between 1952 and 1968 the average flow is 440.9 m^3/s (95% confidence limits: 386.4–495.5) while for the 9 later years (1969 to 1975 and 1982–1983) the average flow is 700.9 (95% confidence limits 599.8–802.1). The fact that the flows were significantly different over the two periods should be tested in comparison with rainfall on the catchment to be able to prove the cause may be catchment degradation. Interestingly, from the analysis of coral reef cores, a strong covariance between forest cover, population density, river flow and sediment load was found for the Onihaly River just further south from the Mangoky River (Maina et al., 2012).

3.3. Extreme weather events and flooding

Extreme flood events from the Shebelle to the Rufiji can, in some years, be linked to positive El Niño-Southern Oscillation (ENSO) events (Erftemeijer and Hamerlynck, 2005) as happened in 1998 with a recorded flood peak of over 13,000 m^3/s, but not consistently so because of the complex influence of the Walker circulation (Tierney and Ummenhofer, 2015). The highest floods recorded so far in the Tana Delta occurred in 1961 (Leauthaud et al., 2013), with a recorded peak flow of 1585 m^3/s on the 20th of November 1961 and an average monthly flow of 1323 m^3/s over the month of November, even if it was not an El Niño year.

Further south on the continent, extreme flooding is generally linked to cyclone landfall (Carmo Vaz, 2000) which is more frequent in the opposite La Niña years combined with locally high Sea Surface Temperatures (Vitart et al., 2003). The landfall of two subsequent cyclones in the same general area in February 2000 led to the dramatic flooding of the lower Zambezi, Save, Buzi, Incomati, and Limpopo despite the existence of large dams on most of these rivers. Madagascar is also subject to cyclones that contribute to flooding events in the deltas.

3.4. Traditional use systems coping with hydro-climatic variability

In comparison to the world average population densities in deltas, estimated at around 500 inhabitants/km^2 (Overeem and Syvitski, 2009), the deltas of the Western Indian Ocean have low or average population densities. They are between 25–249 inhabitants/km^2 for the deltas on the East African coast from Somalia to the Zambezi (included) and 250–999 inhabitants/km^2 for the Madagascan deltas and those on the continent south of the Zambezi (apart from the Save delta which has a lower population density). The traditional use systems in the deltas and lower floodplains are adapted to the floods, in summary – for the dominant activities: fishing during the floods, farming during flood recession and grazing by livestock afterwards. In some deltas these activities are partitioned between ethnic groups but in the past 50 years users have diversified their livelihood portfolio, becoming fisher-farmers or livestock-keeper farmers, etc. (Hamerlynck et al., 2017). Within each activity there is also diversification as a risk avoidance strategy to cope with the inter-annual variability in flood height, extent and duration. Thus, in anticipation, a household will plant in a small number of plots positioned at different elevations within the floodplain and even within each plot plant different crops, typically rice in the deeper parts and maize on the edges so at least one plot will provide a harvest under the most common rainfall-flood combinations. There is also flexibility in the time spent on various activities as the flood characteristics of the year become clear with active instead of passive fishing becoming very important when recession agriculture has failed (Hamerlynck et al., 2011) and also for immediate cash to cope with social needs such as for example school fees (Paul et al., 2011). The low capital cost of the tools (a dug-out canoe, a nylon net and a paddle) partly explains the flexibility with which farmers can engage in fishing (Hamerlynck et al., 2017). Policies trying to constrain the multiple and flexible use systems e.g., through the forced settlement of nomadic livestock keepers or by block farming on predefined fixed plots (therefore situated at a single elevation) are ill adapted. The use systems expect high floods to occur at least every 3 or 4 years to provide fertile silt for the farming activities (Hamerlynck et al., 2010) and many other ecosystem services such as groundwater recharge, forest regeneration and flowering of trees essential for honey production.

3.5. Changes in river catchment hydro-dynamics

Various drivers of change are operating in the river catchments with impacts on the rivers and their deltas. One important driver is the conversion of natural, mostly tree-dominated, vegetation to more open land used for agricultural crops or as rangelands for livestock (Foley et al., 2005, Jackson et al., 2016). Such large-scale conversions result in faster run-off with higher sediment loads and thus more dynamic geomorphological changes in the river beds as well as increased deltaic deposition, as occurred in the Mangoky river basin (Anthony, 2015). This also results in shorter, higher and potentially more damaging flood peaks with less time for the beneficial groundwater recharge, fish reproduction and pasture development to take place in the floodplains.

Traditional hydropower or multi-purpose dams have the opposite effects with reduced flood peaks and a decline in sediment loads. This negatively affects the functioning of deltas and can lead to their sinking, soil salinization and coastal erosion as has been observed for the Nile (Abd-El Monsef et al., 2015) and the Volta (Anthony et al., 2016) rivers.

Hydropower or multipurpose dams have been constructed in most basins in East Africa, strongly regulating the flows especially for the rivers from the Zambezi southwards. Over the next few years, many additional dams, with hydropower production as their main objective and large reservoirs capable of storing over one year of average flows, are either planned or under construction on the major rivers flowing to the Western Indian Ocean (Duvail and Nyingi, 2016). Unfortunately, their design does not take recent findings on impacts of hydropower dams on downstream socio-ecosystems into account. The planned High Grand Falls dam on the Tana River (Duvail et al., 2012) and the Stiegler's Gorge dam on the Rufiji River (Duvail et al., 2013) have inadequate managed flood release provisions while proposals on how to fundamentally revise the operations of the existing dams on the Zambezi River in order to re-establish flooding dynamics have been formulated (Beilfuss and Brown, 2010; Fanaian et al., 2015).

Somewhat paradoxically, hydropower storage dams can also increase flood peaks if they are operated at maximum storage levels to increase hydropower production and thus unprepared to accommodate high seasonal inflows. Since the building of the Mtera and Kidatu dams on the Great Ruaha, a tributary of the Rufiji, peak flows have increased downstream (Yawson et al., 2006). With some dams in the Western Indian Ocean catchments having reached or passed their intended lifespan there are also increasingly issues with leakage, ongoing repairs and dam stability related to downstream river bed degradation, as is the case with the Kariba dam (Noret et al., 2013). This can push the dam operators to practice large releases when substantial inflows are occurring. The high loss of life and livelihoods in the Lower Zambezi, after the construction of Cahora Bassa, has been caused partly by inadequate dam operations such as in 1989 due to insufficient communication between Kariba dam operations and Cahora Bassa (Isaacman, 2005) but also by people moving into the floodplains expecting to be "protected" by the upstream dam.

Water abstraction upstream, usually in combination with the establishment of multipurpose dams, can also impact on the flooding dynamics that are maintaining the deltas. Thus, for the Tana, a large scale irrigated project (known as the "one-million-acre scheme"), in combination with the High Grand Falls Dam and the possible drinking water supply to the new Lamu harbour as part of the Lamu Port-South Sudan-Ethiopia Transport Corridor (LAPSSET), would eliminate all flooding in the delta and reduce outflow to the Indian Ocean to a trickle.

In river systems that are highly regulated by dams, such as the Tana and the Incomati, upstream dams favour increased saltwater intrusion in the estuaries. This has led to losses in tidal rice cultivation areas in the low-lying deltas of these rivers (Brockway et al., 2006), where a minimum flow of 35 m^3/s is required to push out the salt water: flows lower than this flow threshold are now lasting for several months a year. In the Zambezi also, soil salinization forced the move upstream of the Sena sugar estates.

In contrast to East Africa, no large hydropower dams have so far been established on the west-flowing rivers of Madagascar but plans to build dams on the Mangoky and Betsiboka are at an exploratory stage. On the Mangoky and Betsiboka, irrigated agriculture infrastructure was established during colonial times but has deteriorated, especially during political turmoil (Droy, 1998) but also punctually through cyclone damage. Through the intervention of numerous donor-funded rehabilitation projects, the Marovoay floodplains upstream of the Betsiboka delta are still the second most important paddy rice producing area of Madagascar. They have attracted large numbers of migrants from further south (Rakotonarivo et al., 2010) and the area is also targeted for large-scale cultivation of Jatropha for biofuel production (Medernach and Burnod, 2013). High sediment loads in the Betsiboka (Ralison et al., 2008) are interfering with the irrigation systems and are likely caused by catchment degradation and erosion (Raharimahefa and Kusky, 2010).

4. Discussion: policy responses

Here we discuss how the various nation-states consider the specificities of the deltas in their policies and how the current drivers of change are considered.

4.1. Contradictory delta land management policies

The deltas of the Western Indian Ocean are under pressure for the conversion of their extant land use with often incompatible development paths proposed by different ministries, private companies and civil society groups. Public policies and private initiatives formulated about the deltas encompass two opposite and even contradictory visions of the land management.

A first model is the conversion of the delta into an irrigated agro-fuels monoculture. This agro-industrial project echoes in the various countries with pre-WW2 colonial projects. In this view of the deltas, flooded land is considered as empty land to be developed into large commercial projects: well-watered, flat, with fertile soils from the riverine silt deposits deltas are seen as ideal for irrigated agriculture, including biofuel production (Mwansasu and Westerberg, 2014) but also, because of their proximity of the Ocean, for shrimp farming (Rönnbäck et al., 2002), salt production or tidal rice cultivation on cleared mangrove.

These large-scale conversions rarely achieved economic success in the deltas and floodplains where they were implemented. For example, in the 16,800 ha of the Tana Delta Irrigation Project (TDIP), funded from 1987 by the Japanese cooperation, yields were very low (a maximum of 800 ha cultivated and less than 2 tons of paddy per hectare produced) and hampered by corruption and were abandoned after the destruction of the main dike by the heavy floods of 1998 (Lebrun et al., 2010). 2000 ha were rehabilitated between 2008 and 2012, but the deficiencies inherent in the centralized state farm model have not been resolved.

For the deltas of the region, there is a renewal of large-scale projects for the past 10 years with two new characteristics: they are participating in a wider movement of global capitalism that invests in land in the South (Anseeuw et al., 2012) including irrigation aimed at the production of agro-fuels; secondly, they are carried by private, national or international companies, rather than through bilateral cooperation. So far, these projects, even if they were technically viable on the irrigation design, overestimated the water availability in the rivers and did not take the dynamic water needs of the area downstream into account, especially the mangrove areas and the loss of its high ecosystem services values.

A second vision of the delta land management is based on the protected area model in compliance with a series of International Conventions such as the Ramsar Convention on Wetlands (1971) (e.g., Tana Delta in Kenya, Rufiji Delta in Tanzania, Zambezi Delta in Mozambique) and the Convention on Biological Diversity (1993). The objective is to conserve biodiversity and to allow "wise use" of natural resources (as defined by the Ramsar Convention). The delta wetlands and associated ecosystems are also often designated as Forest Reserves, National Parks (Ankarafantsika National Park with dry forest and wetlands) or Marine Parks (Ruvuma Delta in Tanzania). The proponents of this vision envisage a revitalization of local economies through diversification of local activities, better access to the market for geographically localized products (e.g., mango, weaved mats, honey, fish) and the promotion of ecotourism. Local populations are encouraged to maintain fisheries, recession agriculture, and extensive use of forests without building infrastructure, enabling wetland landscapes to conserve all the biodiversity associated with recurrent flooding. Some parts of the deltas are designated for strict conservation or for carbon storage under "Reducing emissions from deforestation and forest degradation" (REDD +) schemes (Beymer-Farris and Bassett, 2012).

Protected areas can combine positive conservation and socioeconomic outcomes especially under co-management regimes where local people are empowered, economic inequalities reduced and cultural and livelihood benefits maintained (Oldekop et al., 2016). But several risks are also attached to these projects: such designations can be controversial, for example, the creation of a pendant in Mozambique for the Ruvuma Delta Marine in Tanzania (Rosendo et al., 2011) as, even under the guise of community-based conservation, protected areas can lead to elite capture of benefits while the losses accrue to the vulnerable traditional users (Benjaminsen and Bryceson, 2012).

In the Tana delta, the competition for donor money by various organisations and government institutions has led to confusion among the locals as each actor creates its own management plan. The associated maps delimit fixed land use areas (e.g., conservation, agriculture, livestock keeping, fishing, etc.) that are oblivious to the natural delta and river dynamics (Duvail, 2017). The "participatory processes" are also often lacking the essential elements of prior and informed consent as captured in the United Nations Declaration on the Rights of Indigenous Peoples (UNDRIP), adopted by the General Assembly in 2007.

4.2. Managed flood releases

Whatever management model is chosen for the delta, conservation or conversion, one of the key elements for success is the maintenance of flood rhythms yet these rhythms are often ignored in the management plans.

Managed flood releases from hydropower dams to restore, maintain or improve ecosystem service delivery have been inscribed in the water laws of many countries under the label of "environmental flows" and are supported by World Bank guidelines (Hirji and Davis, 2009). Such releases, though they have a cost by reducing hydropower output, if correctly timed and sufficiently large, have the potential of reviving floodplain and deltaic processes that sustain and enhance biodiversity and thus the services it provides. Initially confined to a restricted eco-hydrological scientific community, managed flood releases are now advocated by a broad base in civil society and it has been modelled and tested on various scales world-wide (Acreman et al., 2014). This shift from science into policy, benefited from the progress in the economic valuation of ecosystem services (Emerton and Bos, 2004) and their incorporation into the global Millennium Ecosystem Assessment (MEA, 2005).

There is however a time-lag to implementation of managed flood releases and this is particularly the case for the rivers flowing into the Western Indian Ocean for which the existing and planned dams, such as the High Grand Falls dam on the Tana and the Stiegler's Gorge dam on the Rufiji, were designed between the WWII and the publication of the Report of the World Commission on Dams (World Commission on Dams, 2000). Thus, dams generally do not have dedicated managed flood release infrastructure and dam management procedures also lack inclusive governance processes that would take the needs of downstream ecosystems and their users into account.

Though many countries, including Kenya and Tanzania have adapted their water laws and regulations according to the South African example, the emphasis has been on guaranteeing a minimum reserve flow, which is compatible with maximising hydropower production. Thus, for the shared river basins, such as the Incomati (Swaziland, South Africa, Mozambique) an agreement of 2002 only specifies that a minimum reserve flow of 5% of the mean annual discharge needs to be guaranteed throughout the year.

Under the auspices of the Southern African Development Community (SADC), agreements on other transboundary basins are being developed.

Very few systems, if any, implement a dynamic flooding pattern to simulate the natural hydrograph and maintain flood-dependent ecosystem services delivery. Managed flood releases have been tested on the Phongolo River that drains part of South Africa and Swaziland and joins the Maputo River some 25 km south of the mouth of the Incomati (Fig. 1). Before the construction of the Pongolopoort dam, designed primarily for irrigation, the flows peaked in February with mean monthly flows around 70 m^3/s but they are only around 40 m^3/s in the post dam period leading to a decline in fish production from around 500 tonnes to 40 tonnes annually (Dube et al., 2015). It is thought that flood releases of around 700 m^3/s are needed to entirely cover the 130 km^2 floodplain but through an agreement with Mozambique the flows entering the Maputo River cannot exceed 250 m^3/s to secure embankments and other water infrastructure (Mwaka et al., 2003). Managed flood releases scenarios have been explored for the three main dams on the Zambezi River at Kafue Gorge (in Zambia), the Kariba dam (between Zambia and Zimbabwe) and the Cahora Bassa dam in Mozambique (Fanaian et al., 2015, Liechti et al., 2015) including cost-benefit analyses with regard to power production (Nyatsanza et al., 2015). Similarly, for the Tana a conceptual model that allows the exploration of trade-offs between various dam uses, including an easy-to-understand visualisation accessible to decision-makers, was developed (Hurford and Harou, 2014) but it lacks inputs from the deltaic ecosystem services.

Such managed flood releases should also seek to reproduce the natural inter-annual flood variability. Indeed, applying for several consecutive years a standard scenario with an average pre-dam flooding surface area and duration would result in vegetation changes that would negatively affect productivity. Ideally, high flood years should alternate with low flood years. High floods are required to prevent the establishment of flood-intolerant dry acacia-dominated savannah in the floodplain and to maintain the high biodiversity riverine forests that require flood return periods of between 4 and 28 years (Hughes, 1990). Thus, in years of high water availability, such a flood release corresponding to the highest historical floods perceived as beneficial by the users could be implemented at least every 10 years. In contrast, low floods are useful to prevent the dominance of perennial sedges, less palatable to grazers including livestock. However, because they negatively affect the fish and agriculture productions, it is recommended that such a low flood should not be implemented more than 3 years in a row. This is based on the observation by the Rufiji farmers of a diminishing yield in recession agriculture plots that have not flooded for 3 consecutive years flooding (Hamerlynck et al., 2010).

As the ecosystem response to this theoretical flood release scenario is hard to predict, stakeholders could agree on a learning period during which close monitoring of ecosystem service delivery is collectively assessed and evaluated through intensive feedback sessions with the delta users. With the input from these feedback sessions the scenarios can be adapted to achieve a negotiated equitable optimisation of ecosystem service delivery to different user groups. Such an approach was implemented in the Senegal delta (Duvail and Hamerlynck, 2003) resulting in positive environmental, social and economic impacts. Wintering waterbird numbers increased over tenfold, the young able-bodied men that had migrated to the capital returned for permanent residency in the delta. The fisheries expanded from being practiced by only a handful, fishing for subsistence, to several dozen men producing over 300 tonnes of fish annually. The fishers earned over 20 $ a day during the flooding season, to be compared to the 70% of the Delta inhabitants living below the poverty line of 1.25 $ a day (Hamerlynck and Duvail, 2008).

Finally, in addition to being able to cater for the managed flood releases described above, the dam design needs to be adapted to events more extreme than those in the current hydrological record. Both cyclones and ENSO events are likely to change in frequency and intensity as the climate warms.

5. Conclusion

Large dams are a reality and over the next few decades more will be built along rivers entering the Western Indian Ocean. The current standard dam operating procedures are dominated by or, more commonly under the exclusive control of, the electricity companies whose primary task is to produce and sell hydropower. Such an approach, releasing small quantities of water through the turbines to respond to the daily power demands, results in the general flattening of the river hydrographs, the decline in seasonal and inter-annual hydraulic variability and, as sediments are stored in the reservoir, the loss of the delta-building dynamics. This mainly benefits the rapidly expanding cities inland, the countries' industrial outlay and the large-scale irrigation schemes while the small-scale deltaic users lose the biodiversity and ecosystem productivity on which they depend for their livelihoods.

However, on a multi-decadal time scale, the current standard approach is not sustainable as the biophysical processes that build and maintain the deltaic systems are undermined which, in combination with climate induced sea level rise and the expected increased frequency and intensity of extreme weather events, enhances their subsidence, salinization, and erosion. Those, in turn, have tremendous environmental, social and economic implications. The deltas of the comparatively steep and highly dynamic rivers flowing into the mesotidal Indian Ocean from the African continent and Madagascar are especially susceptible to this. Their characteristic mangrove systems are vital in coastal defence, sensitive to the hydraulic and sediment load changes. Mangroves are also a key hub in ecosystem productivity well beyond their physical limits because of their nursery function for the fish and invertebrates on which coastal and deltaic user communities depend. Future work will need to compare the changes observed in the Western Indian Ocean deltas.

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