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ORIGINAL

Geomorphology of a tropical river delta under pressure: the Rufiji delta, Tanzania—context, channel connectivity and alongshore morpho-sedimentary and hydrodynamic variability

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Abstract

The geomorphology of the Rufiji River delta was investigated with emphasis on the influence of the delta's context, including the river basin, and remote-sensed delta-plain channel connectivity and shoreline morphological, sedimentary and hydrodynamic variations. The Rufiji is influenced by its East African Rift Valley tectonic context, high inter-annual water discharge variability and large mud-dominated sediment supply. The delta exhibits 14 distributary channels, only five of which are currently functional and all debouching presently in a low-energy muddy north sector, probably in response to NE tectonic tilting of the coastal basin of Tanzania. The south sector is characterized by a clear loss of distributary connectivity with the main stem but this appears to have occurred gradually over time, and is not a product of sudden avulsion. This loss is manifested by stronger meandering and numerous meander cut-offs indicative of a weaker overall delta-plain gradient, and may reflect the influence of the aforementioned tilting. This sector also has more abundant beach-ridge deposits than the north sector. The difference in shoreline facies between the dominantly muddy north sector and the dominantly sandy south sector appears to reflect primarily exposure to wave energy determined by an archipelago fronting the delta, and this difference is presently reinforced by preferential channel sediment routing to the north and sectorial sediment sequestration. The Rufiji River basin and its delta represent important stakes in the development of Tanzania under the country's rapid demographic growth, hydropower dam development and climate change. Eventual expected delta retreat caused by fluvial sediment shortage from the basin due to current and projected hydropower dams could be temporarily mitigated by sediment release by deforestation and by the relatively sheltered hydrodynamic setting of this delta.

Introduction

Deltas are complex landforms characterized by low topography and are thus particularly vulnerable to catastrophic river floods, tsunami, cyclones, subsidence and global sea-level rise (Anthony 2016). They are attracting diverse and cross-disciplinary research in response to concerns regarding their increasing vulnerability to human activities, notably as a result of reduction of sediment flux from rivers (Besset et al. 2019a).

The eastern seaboard of Africa between Somalia and Mozambique comprises numerous river deltas that have formed at the outlets of catchments with headwaters in the Eastern Arc Mountains associated with the Great Rift Valley (Duvail et al. 2017). Among these, the Rufiji delta (Fig. 1) is a particularly important coastal depocentre and the largest delta in Tanzania. The Rufiji delta is a rich biodiversity hotspot of environmental and economic significance and a RAMSAR wetland of international importance. The delta,

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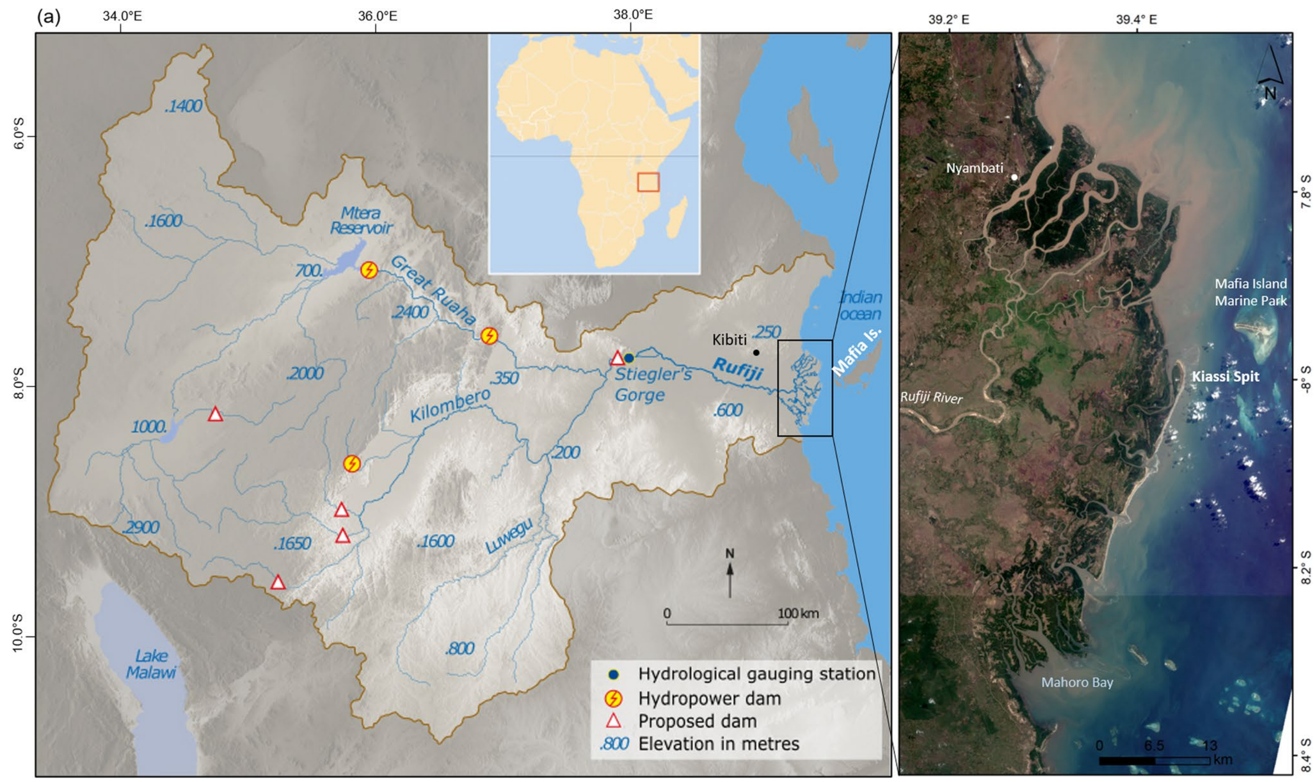

Fig. 1 The Rufiji River basin with main tributaries (**a**), and 2020 Sentinel-2 satellite image of the delta (**b**)

like the catchment of which it is a part, is an important food basket for Tanzania and crystallizes factors related to environment and water management, climate, rapid economic and social development and land-use changes in Tanzania (Duvail et al. 2007; Ellison 2015; TEEB 2018; Doggart et al. 2020; Geressu et al. 2020). The Rufiji delta has been a hotspot of research on mangrove dynamics, ecology and geochemistry (Erftemeijer and Hamerlynck 2005; Wagner and Sallema-Mutti 2010; Ellison 2015; Shaghude 2016; Minu et al. 2020a, b; Punwong et al. 2012, 2018; Mwevura et al. 2021) and at the cross-roads of a complex relationship between Reduced Emissions from Deforestation and Degradation (REDD+) policies involving mangrove conservation and socio-nature relations (Beymer-Farris and Bassett 2012). Little is known, however, of its geomorphology. Acquiring a better understanding of the geomorphology of this large delta should be an important objective with high relevance for the future development of Tanzania, especially in the light of the operation of important hydro-ecological changes that will be compounded by the impact of current and future dams (Duvail et al. 2017) on the sediment supply issue, which is particularly pertinent to delta sustainability.

The aim of this letter is to characterize the geomorphology and sediment dynamics of the Rufiji delta based essentially on remote sensing. The results show that the Rufiji delta is a particularly interesting illustration of delta-plain and shoreline morphological diversity, a potential indicator of resilience in a time of important on-going changes due to both natural drivers in delta dynamics and the impacts of human activities in the Rufiji River basin.

The Rufiji River basin and delta

The Rufiji River basin (Fig. 1a) has an area of 177,420 km^2, i.e. about 20% of Tanzania (Mwalyosi 1990), and is the largest in the country. The basin and present delta (Fig. 1b) are set in an extremely complex tectonic setting related to the uplift chronology associated with the East African Rift system and attendant sedimentation in the coastal basin of Tanzania (Said et al. 2015; Maselli et al. 2020; Scoon 2020). The regional geological history of faulting, uplift and seismic activity and the relatively elevated basin relief of the Rufiji River (Fig. 1a) have been drivers for important fluvial sediment supply to the Indian Ocean, culminating notably in significant past landslide activity off the delta (Maselli et al. 2020). The present delta has developed in the shelter of an archipelago comprising a Mafia Island (394 km^2), an outcrop of uplifted Pleistocene coral up to 20 m high, overlying, like the mainland delta, much older deposits originating from the superimposition of the Cenozoic East African rifting event and uplifts during the Late Eocene (Mpanda

1997). The Rufiji River basin experiences a humid tropical climate comprising two seasons. Pressure gradients between the Intertropical Convergence Zone and anticyclones in the Indian Ocean generate, respectively, hot and humid monsoon winds from a north to northwest sector during the rainy season and cool, dry south to southeast trade winds from May to November that are dominant during the dry season (Mahongo et al. 2012). Data on the Rufiji River's water discharge at the only gauging station on the river at Stiegler's Gorge (Fig. 1a) are incomplete, spanning 1954–1978, but with significant gaps (Fig. 2a). The mean annual water discharge of the Rufiji River is about 800 m^3/s with maximum flows occurring during the rainy season between March and May and the minimum in late October and November during the dry season. Inter-annual variability is high (Fig. 2a). The sediment yield of the Rufiji is estimated, based on the coarse global riverine water discharge and suspended sediment transport model WBMsed v.2.0 (Cohen et al. 2014), at about 29 MT/yr. The Rufiji's solid load is presumably largely dominated by mud, as for most large tropical deltas, an assumption supported by the volcanic source rocks, the tropical chemical weathering regime of Tanzania, and the mud-dominated facies of the delta.

Winds in the coastal zone of Tanzania are characterized by moderate speeds that peak in July between 3.7 and 6.0 m/s. In the absence of local wave data, data culled from the ERA5 wave reanalysis (see the 'Methods' section) have been used to document the wave regime (Fig. 2b, c, d) off the Rufiji delta. The wave climate is closely related to the seasonal wind regime, but also to the sheltered geomorphic context of the delta, fronted by a relatively shallow lower shoreface (10–30 m) in the lee of Mafia Island and archipelago, and seaward of which lies the Tanzanian continental shelf. Monsoon winds from N to NW generate moderate waves, with a tendency towards relatively calm conditions at the end of the monsoon season. The highest and most frequent offshore waves are from ESE to SE, in response to the highly regular and sustained trade winds from May to November. The mean offshore significant wave height (Hs) is 1.25 m based on ERA5, and 65% of all waves are between

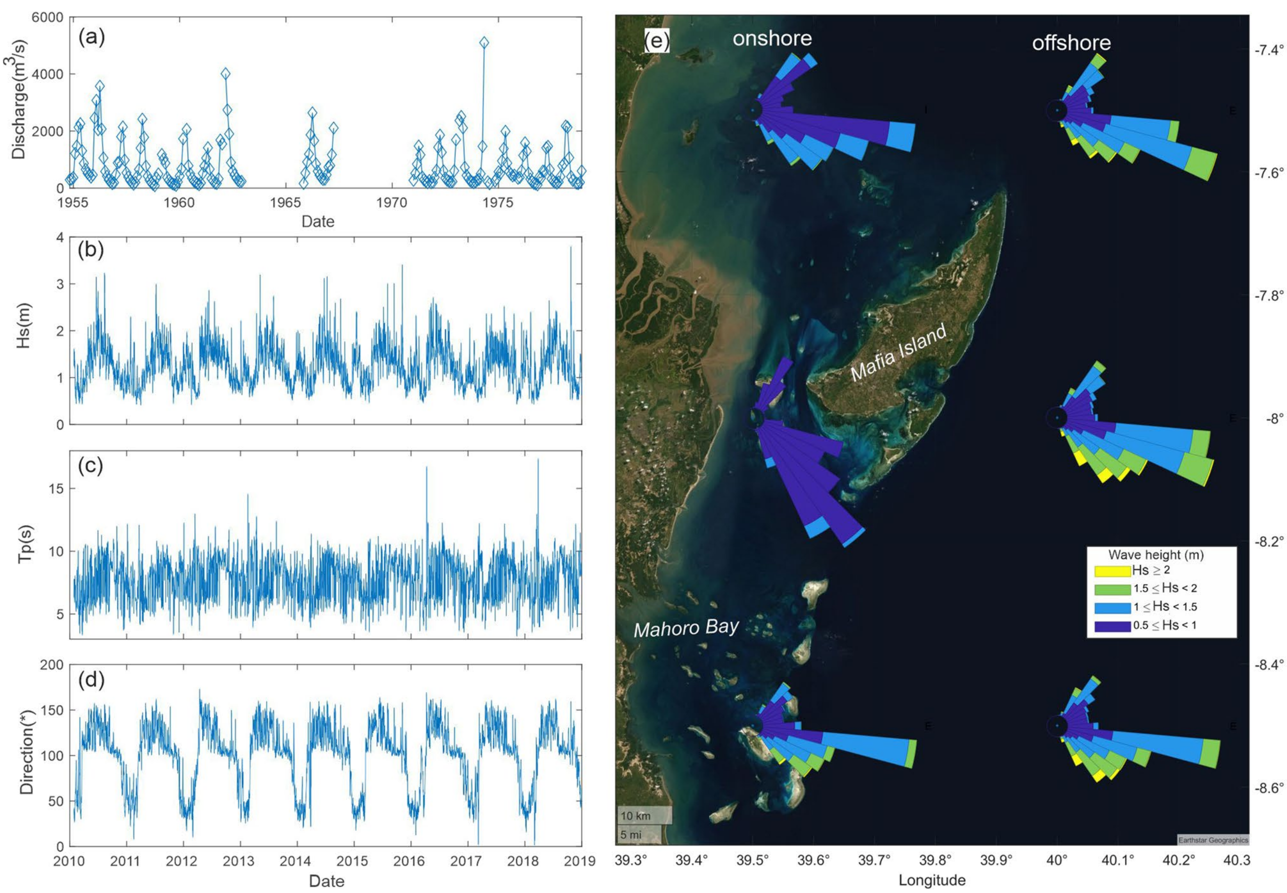

Fig. 2 River discharge and wave data for the Rufiji delta: **a** monthly water discharge; **b**, **c**, **d** significant wave heights (Hs), peak wave periods (Tp) and direction for the offshore location directly east of Mafia Island based on ERA5 reanalysis; **e** Era5 wave roses offshore and inshore of Mafia Island. Waves may be even more strongly refracted and dissipated by the archipelago than what the coarse ERA5 model shows

1 and 2 m, 5% above 2 m. The highest waves are occasionally close to 4 m at the height of the trade wind season. Waves attaining the delta shoreline refract to SW to SSW, and have lower heights, in the lee of Mafia Island. There are no tidal gauges in the vicinity of the delta. The average tidal range is about 2–2.5 m and approximately 3.3–4.3 m at high spring tides (Francis 1992; Richmond et al. 2002). Tides influence the river for some 40 km upstream (Kayaa 2019).

The Rufiji delta lies in the track of tropical storms and cyclones, although none has made landfall over the delta in recent years (Cyclone Kenneth, set to hit the coast of southern Tanzania in April 2019, changed course to make landfall in Mozambique, notably over the Zambezi delta). The Rufiji's tectonic setting also involves faulting and earthquakes associated with the flanks of the East African Rift System, including a branch, the Pangani rift, that runs offshore into the Indian Ocean just north of the present Rufiji delta (Scoon 2020). This setting has been associated with remobilization of sediment through submarine landslides, including one of the biggest landslides ever on Earth: the Mafia mega-slide (Maselli et al. 2020). This recent finding indicates that the coastal region of East Africa is therefore also potentially susceptible to regional tsunami, in addition to distant tsunami in the Indian Ocean (e.g., the 2004 Indian Ocean tsunami which attained the East African coast).

Materials and methods

Delta-plain morphology and land–water changes

The morphology of the Rufiji delta was analysed from a high-precision MERIT global digital elevation model (DEM) (Yamazaki et al. 2017) at 3 arc second resolution (~ 90 m at the equator). MERIT DEMs eliminate major errors from existing DEMs, such as the NASA SRTM, and separate absolute bias, stripe noise, speckle noise and tree height bias using multiple satellite datasets and filtering techniques. After error removal, land areas mapped with 2 m or better vertical accuracy were increased from 39 to 58%. Significant improvements are found in flat regions where height errors are larger than topography variability, and features such as river networks become clearly represented, useful for landscape analysis (Yamazaki et al. 2017). Delta areas converted from land into water and vice versa can now be estimated from existing datasets in the literature. Among these is the Global Land Analysis and Discovery (GLAD) dataset (Pickens et al. 2020), which uses a probability sample-based assessment and consists of Landsat 5, 7, and 8 scenes between 1999 and 2019. The data are derived for each pixel (30 × 30 m) of satellite image, and also show seasonal patterns of conversion for each pixel. Several categories were identified over the 20-year period of observation: (1) new permanent water surfaces (land into permanent water), (2) loss of permanent water (permanent water into land). We also retained 3 stable categories: (3) water dominant, (4) land dominant, and (5) seasonal water (wet and dry periods).

River discharge and waves

The river water discharge data shown in Fig. 2a were retrieved from The Global Runoff Data Centre (GRDC, Koblenz, Germany) for Stiegler's Gorge station (Fig. 1a). Wave data (Fig. 2b, c, d) were retrieved from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5 model, a state-of-the-art climate reanalysis (Hersbach et al. 2018), and have a 0.5° horizontal resolution. The following parameters were used: significant height of combined wind waves and swell (Hs), mean wave direction (Dir) and peak wave period (Tp). Three-hourly time series were obtained for six grid points corresponding to north, central, south and onshore/offshore locations of the Rufiji delta.

Delta shoreline morphology and multi-decadal changes

Data on shoreline mobility and area change were obtained from a comparison of two high-resolution 2020 Sentinel-2 satellite images (10-m pixel size) and two 1989 Landsat 8 images all taken at high tide. Following previous work on similar delta shorelines in the Mekong (Anthony et al. 2015), the shoreline markers used correspond to the mangrove fringe in muddy mangrove-dominated sectors and dry sand, brush or plantation fringe in sandy, beach-dominated sectors. These shoreline markers were confirmed in the course of field observations in the Rufiji delta on June 3, 2019. Shoreline variations were calculated by overlaying the coastal areas extracted in 1989 and 2020. Using ArcGIS®10.6, surface area differentials were determined to obtain annual area gains and losses. A relatively large uncertainty shoreline change band of ± 20 m was retained, which is much more than commonly used in the literature. The reader is referred to Besset et al. (2019b) for the complete error computation methodology.

Results

The lower floodplain of the Rufiji River is up to 30 km wide, more or less delimited, as it merges with the delta, by a relatively sharp change in the orientation of the river from W-E to S–N (Fig. 3a). The delta plain has an area of about 1400 km^2 and may be considered in terms of two sectors, north and south, on either side of a protrusion point at Kiassi spit (Fig. 3a). The plain is characterized by about 14

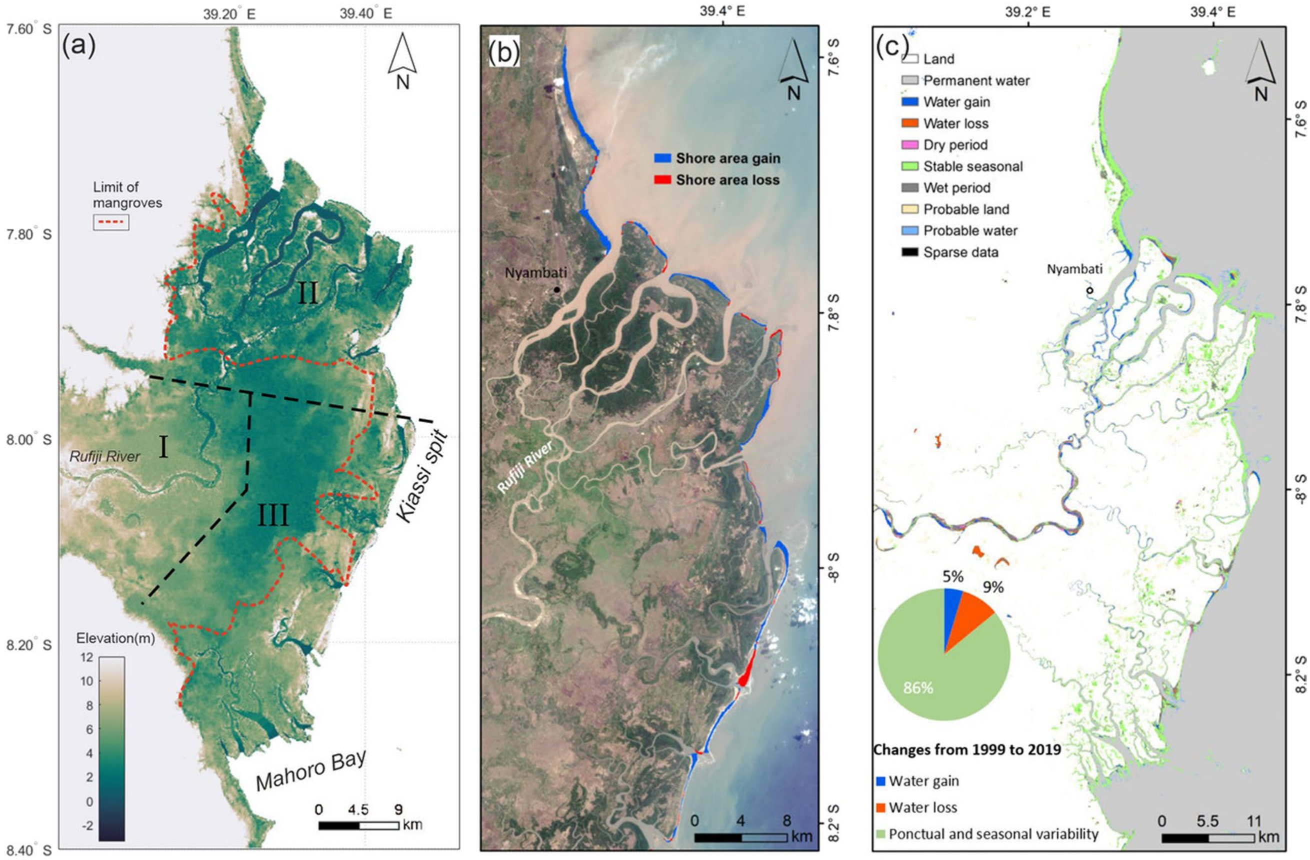

Fig. 3 Morphology and dynamics of the Rufiji delta: **a** MERIT digital elevation model (DEM) with delimited sectors corresponding to (I) the lower floodplain; (II) the north sector of the delta plain; and (III) the south sector of the delta plain. Light brown (non-green) areas along the coast correspond to beach ridges; also shown are the limit of mangroves; **b** shore area changes retrieved from a comparison of Landsat 8 (1989) and Sentinel-2 images (2020); **c** surface water classes and their stability or change from the GLAD database (1999–2019)

inter-distributary channels. Surface water change over the period 1999–2019 shows that none of the channels in the delta south of Kiassi spit is currently connected to the main stem which essentially feeds five relatively parallel distributaries running roughly SW-NE (Fig. 3a). The delta plain in the south sector is studded with numerous abandoned meander belts. The delta comprises about 530 km^2 of mangroves, the largest mangrove stand in East Africa (Erftemeijer and Hamerlynck 2005; Duvail and Hamerlynck 2007). The delta shows traces of beach ridges between inter-distributary channels that attest to wave reworking of open sandy shoreline deposits. These beach ridges are more abundant in the south sector (Fig. 3b) and many have been truncated by past channel mobility. Beach ridges also bound the coast north of the delta. Interior delta-plain changes revealed by the GLAD database (Fig. 3c) show an increase in land area of 0.4 km^2/yr for the northern, active delta plain, and only 0.056 km^2/yr for the southern decoupled plain, clearly indicating reduced sedimentation in this sector of the delta.

The north sector shoreline, mainly oriented SE-NW, is dominantly bounded by large mudflats commonly backed by mangroves, and, more rarely, narrow and alongshore-discontinuous sandy upper beach deposits in places. This shoreline morphology differs from that of the south sector which is oriented SW-NE and dominated by sandy shorelines, except in Mahoro Bay in the southern extremity where muddy shorelines prevail again in the shelter of the numerous islets south of Mafia Island (Fig. 2e). The delta's shore area shows a net gain between 1989 and 2020 (Fig. 3b) exceeding 7.8 km^2, of which 80% associated with the north sector and 20% with the south sector. The shore area gain in the north sector is only partially captured in the water-land changes in Fig. 3c, probably because of the difference in the timing of the GLAD images (1999–2019) and the shore area change images (1989–2020). The wave-sheltered muddy southern extremity of the delta is not considered in this statistical estimate because of large intertidal variations, but its shoreline has been stable over time. There are no shoreline hotspots of massive land loss or gain. Positive (gain) or negative (loss) changes show a longshore pattern.

Discussion

The formation of the present Rufiji River delta is closely tied to a context of abundant Holocene fluvial sediment accumulation and wave and current redistribution in an initial triangular-shaped embayment up to 80 km wide at the present shoreline confines of the delta, and largely sheltered by the Mafia archipelago. Punwong et al. (2012, 2018) showed, from shallow cores (1.5 m) about 10 km from the sea in the north sector of the delta calibrated to mean tide level (MTL) relative to a benchmark at Kibiti (Fig. 1a), 14C ages ranging from modern (+ 3.22 m MTL) to 5711–5486 cal BP. (− 0.97 m MTL), and documented local accumulation rates of up to 3 mm/a. The cores show about 1.1 m of silt overlying sand. The discussion will focus on the following two overarching themes and their intermeshing with the particular environmental context of the Rufiji: (1) delta-plain channel changes and (2) delta shoreline facies.

Delta-plain channel changes

A distinctive feature of the Rufiji delta is the large number of its distributaries, indicative of abundant water and sediment routing, although nearly a third of these distributaries are no longer active. Many deltas develop resilience and adapt to changes in sediment supply, commonly through enhanced within-delta sediment sequestration notably by re-organizing their channels and, where possible, alongshore transport processes to limit alongshore export of sediment (Anthony 2015). Delta distributaries are often considered features tied in competition for water and liquid discharge in transit through the river main stem (Frazier 1967; Elliot 1986; Jerolmack 2009; Moodie et al. 2019), although they also provide pathways for the formation of new channel bifurcations and lobes (Tamura et al. 2012). The competition may culminate in the gradual downgrading of one distributary (or more) to the benefit of the other(s), notably through increasing diversion of discharge or through sudden and wholesale channel switches or avulsions (Jerolmack 2009), which are generally rare (Moodie et al. 2019).

Little is known of the history of the Rufiji delta distributaries in the absence of an established absolute geochronological framework. In addition to a complex and active geological setting, at a more contemporary scale, the Rufiji basin has been subject to significant fluctuations in water discharge (Fig. 2a) that, according to Minu et al. (2020a, b), have led to changes in the hydrology of the inter-distributary channels and their courses in recent history, with important implications of this flow routing for spatio-temporal variations in delta salinity gradients, mangrove geochemistry and probably agricultural choices. These recent changes are attested by the numerous meander belt cut-offs. Important hydrological fluctuations over the last five decades have been identified by Erftemeijer and Hamerlynck (2005) and Hamerlynck et al. (2011) who also associated them with significant changes in fluvial-plain hydrological connectivity and mangrove ecology. Beymer-Farris and Bassett (2012) have evoked the consequences, in terms of narratives on land-use of the delta at the expense of mangroves, of the exceptional flood event in 1968 (unfortunately a data-gap year, Fig. 2a) that was deemed to have resulted in a northward 'diversion' of the Rufiji's main stem discharge towards the five currently functional north-sector distributaries. Wagner and Sallema-Mtui (2010) argued that this change occurred in 1978, which is not a year of exceptional discharge (Fig. 2a). Beymer-Farris and Bassett (2012) have shown, in a compelling analysis of the complex competing views on agriculture and environmental protection in the delta, how the purported larger freshwater discharge has been tied up, in Tanzanian narrative, with increased human transformation of the north sector since the 1970s manifested by an upsurge in rice farming at the expense of mangroves.

The south sector of the Rufiji delta exhibits abundant abandoned channel meander belts but no evidence of wholesale channel avulsions. Abandoned inter-distributary delta lobes no longer sourced by fresh sediment inputs are commonly subject to marine reworking, and where waves are active, to shoreline straightening, often resulting in the formation of retreating sand barriers and spits as sand is concentrated into coherent bodies and ambient mud dispersed, eventually culminating in lobe demise (Anthony 2015). Although the dominant channelling of flow should be to the advantage of the north sector of the Rufiji delta, there is little evidence of large-scale erosion of the shorelines of the south sector (Fig. 3b). The changes in macroscale channel hydrology of the Rufiji delta embodied by main stem flow diversion to the north sector may simply reflect a threshold drop in competence of the south channels manifested by much stronger meandering (weaker gradient) and the influence of backwater dynamics resulting from past progradation. The distinct change in orientation of the Rufiji main stem from W-E to S–N in its connectivity with the north-sector distributaries (Fig. 3a) may, however, also reflect long-term tilting of the coastal basin of Tanzania. The abrupt change occurs at a point where the main stem is only 20 km away directly from the south-sector shoreline, compared to a more distant 30 km for the north-sector shoreline. This tilting hypothesis is consistent with the extensive tectonic activity that has had an overarching influence on river orientations and large sediment supply to the coast by the Rufiji River (Said et al. 2015; Maselli et al. 2020). This tilting appears to be consistent with an ocean dip of the eastern flank of the Pangani rift shoulder in Tanzania which runs SE seaward and intersects the coast of Tanzania just north of the Rufiji delta (Scoon 2020). Whatever the true reasons for the diversion of flow to the north sector channels, it would seem that both deltaic sectors prograded concurrently under multiple distributary channel activity, as attested by the limited 14C data (Punwong et al. 2012) available for the north sector.

Delta shoreline facies

The difference in shoreline facies between the dominantly muddy north sector and a dominantly sandy south sector may reflect (1) primarily exposure to wave energy determined by the archipelago fronting the delta (Fig. 2e), and this difference is probably presently reinforced by (2) preferential channel sediment routing to the north (Fig. 3a) and (3) sectorial sediment sequestration. Regarding condition 1, the Mafia Island and associated archipelago and the dominant provenance of the most energetic waves from the SE imply marked alongshore variations in wave energy from south to north: (a) a low-energy window for the muddy extreme-southern mouth in Mahoro Bay, presumably strongly tide-influenced corner with tidal pumping dominating the dynamics of the channels; (b) a more energetic wave-dominated window along much of the sandy south-sector shorelines between the archipelago and Mafia Island, again with tidal pumping maintaining the freshwater-disconnected distributary channels; and (c) dominantly muddy low-energy north-sector shorelines sheltered from direct SE wave influence by Mafia Island, and with distributary mouths strongly influenced by river discharge and subsidiary tidal pumping that presumably assumes more importance in the dry season. The SW-NE orientation of these muddy north-sector shorelines implies significant refraction and damping of the higher energy SE waves propagating through windows in the archipelago. Condition 2 corresponds to the current propensity of the north sector distributaries to convey much of the presumably largely mud-dominant sediment load of the Rufiji. Condition 3 refers to the capacity of shoreline sectors to sequester sediments exiting through distributary mouths.

An 1885 map of the delta dating back to the time when Tanzania was part of colonial German East Africa (Fig. 4a) shows much the same shoreline morphology as at present, thus suggesting relative overall delta plan-shape equilibrium, the southern shorelines being relatively straight and the northern more indented. In fact, the shoreline in the south sector shows a slight gain in area between 1989 and 2020. This may indicate the operation of episodic fluvial sediment supply to this sector and efficient sediment sequestration aided by net tidal sediment import. Inter-annual discharge variability is so high (Fig. 2a) in the Rufiji basin that temporary connectivity between the main stem and the ‘abandoned’ south-sector distributaries is probably established during very high-discharge years, enabling temporary resumption of water and sediment routing. This hypothesis needs, however, to be verified by much better monitoring and modelling of hydrological connectivity in the Rufiji basin and delta.

The overall morphological context of delta development in the shelter of Mafia Island and its archipelago and the moderate wave-energy setting of the Rufiji delta in the lee of this archipelago entail a high capacity for Holocene sediment sequestration. Sediment sequestration in the confines of deltas is considered a key element in their self-maintenance (Anthony 2015) and in tempering their vulnerability to sediment losses induced, for instance, by upstream dams (e.g. Besset et al. 2019a) or diversion of discharge. Clearly, there have been periods in the geological history of the Rufiji River when sediment supply directly to the shelf, with or without the sheltering effect of the Mafia archipelago, had been so massive as to source major landslides in the Indian Ocean, as epitomized by the early mid-Miocene Mafia landslide identified by Maselli et al. (2020).

Sediment sequestration concerns both fine-grained load that is fundamental to maintenance of the elevation of the delta plain, and bedload that forms the fringing sand beaches. The relatively straight sandy shorelines between the distributary mouths of the south sector may be responding to the shutdown of sediment supply concomitant with wave reworking of sand, but with no overall loss, due to the operation of several separate bidirectional drift cells separated by the distributary channel mouths (Fig. 4b). Under these conditions, sand is stored in river-mouth bars and redistributed alongshore under seasonally changing longshore transport directions induced by the Monsoon- and trade wind-generated waves off the coast of Tanzania. These transport patterns are commonly a manifestation of local delta shoreline sand sequestration (i.e., no alongshore sand leakage) that prevents the progressive demise of inter-distributary lobes (Anthony 2015).

From measurements of salinity and suspended sediment concentrations (SSC) throughout the Rufiji delta and along a transect from inter-distributary channels to 10-km offshore, Francis (1992) showed a clear separation of inshore and offshore waters, with significant trapping of low-salinity water and suspended sediment inshore and over mangrove swamps in the delta plain, and very little offshore transport of suspended sediment. This observation is confirmed by the well-defined inshore band of suspended sediment transport on satellite images (Figs. 1b and 2e). SSC ranged from less than 490 for waters in the lower estuarine reaches to about 1000 mg/l for the inshore waters and then very suddenly dipped to zero at the offshore location. Francis (1992) attributed this trapping to alongshore stretching of outflowing sediment-charged freshwater in the inshore zone under the influence of the East African Coastal Current, a monsoon-driven

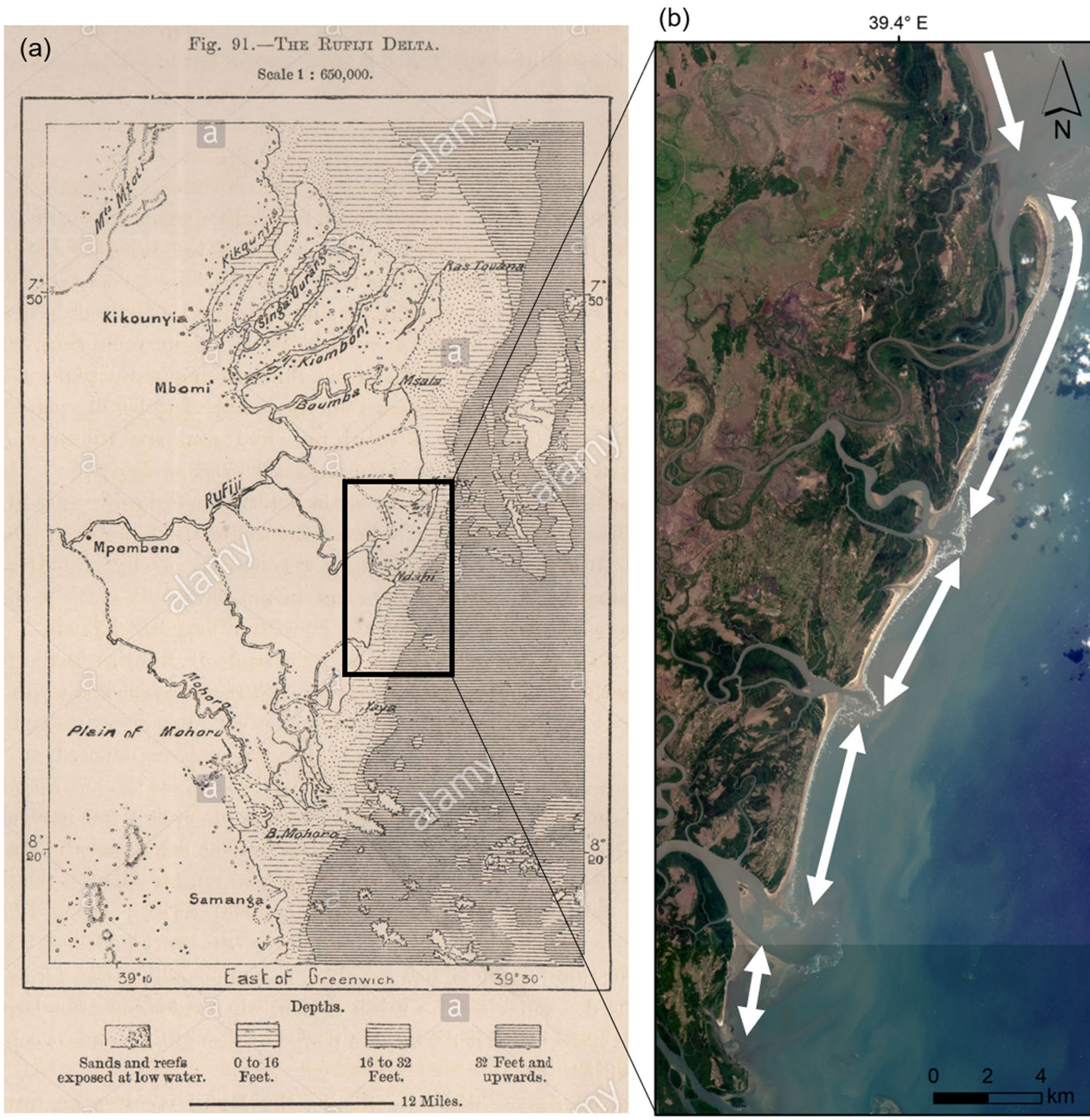

Fig. 4 1885 map of the Rufiji delta edited by the German colonial authorities (**a**), and bidirectional sediment cells on a Google-Earth image in the southern, strongly wave-influenced sector of the delta (**b**). 1885 map provenance: 'The Universal Geography' by Élisée Reclus, Ed. by A.H. Keane, Published by J.S. Virtue & Co., London. Credit: alamy.com

coastal current. This trapping of freshwater and suspended sediment may have favoured the high rate of accretion and significant mangrove development identified by Punwong et al. (2018) in the north sector of the delta, while inhibiting carbon export offshore (Francis 1992).

From the foregoing discussion, a number of the overarching elements of the varied geomorphology, channel connectivity, energy context and shoreline facies of the Rufiji delta, reflecting inferred tectonic influence, differential alongshore exposure to waves and water and sediment routing, are summarized in Fig. 5.

Perspectives

Beyond the foregoing aspects of delta geomorphology, some of which need to be verified and others bolstered by forthcoming studies, the future stability of the Rufiji delta, like that of many deltas worldwide, will be determined by sustained sediment

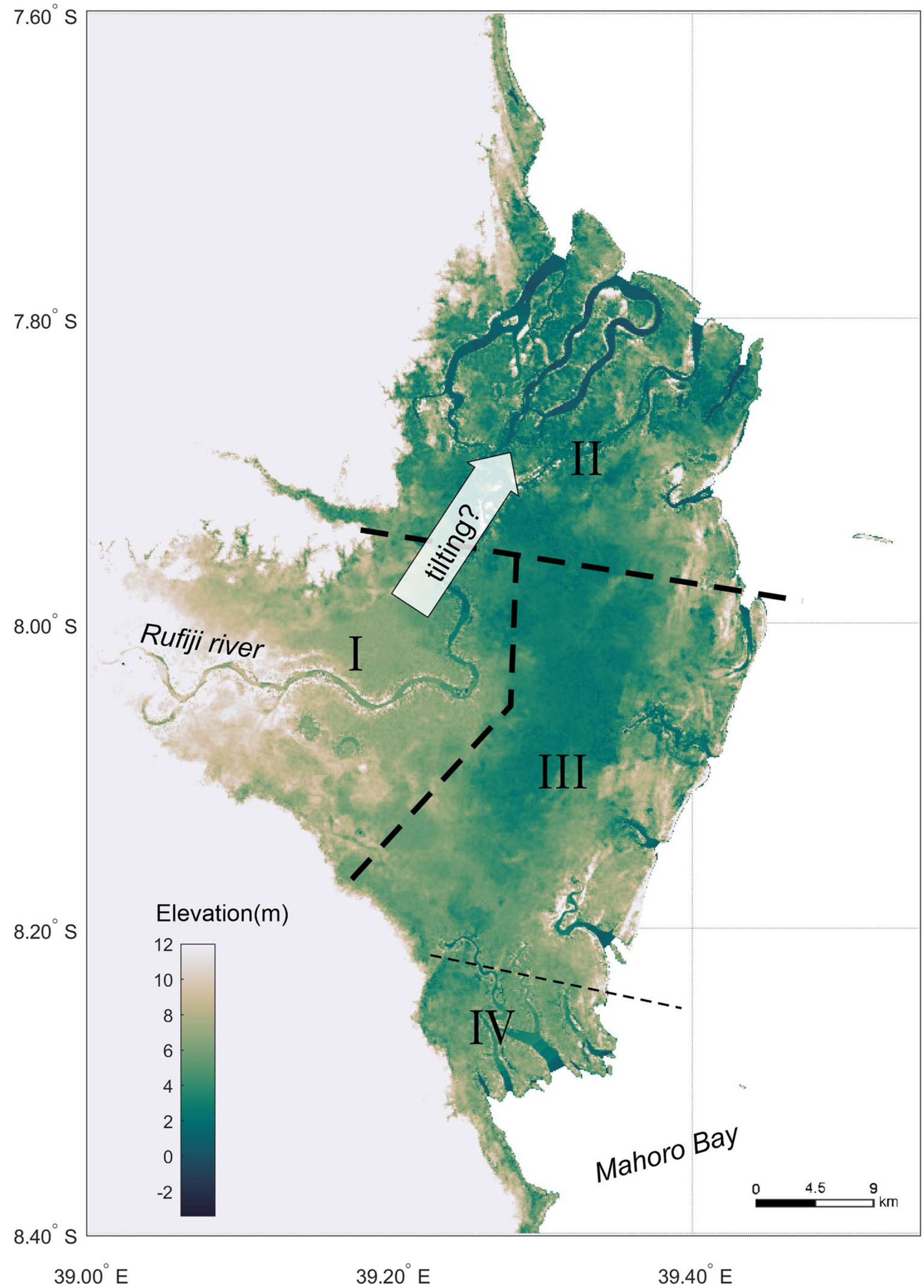

Fig. 5 A conceptualized synthesis of morpho-sedimentary, hydrological and hydrodynamic aspects of the Rufiji River delta superimposed on a DEM of the delta plain with indicative limits between units: (I) downstream part of the lower Rufiji River floodplain; (II) north delta-plain sector with currently active distributary channels and prograding muddy low wave-energy shorelines strongly influenced by river outflow and enhanced tidal pumping in the dry season; (III) south delta-plain sector with distributary channels disconnected from the Rufiji main stem, probably with episodic temporary hydrological connectivity with main stem during very high river discharge years, and subjected to tidal pumping, bounded by dominantly sandy shorelines strongly influenced by wave action but with bidirectional longshore transport cells that assure overall shoreline sand-budget stability; and (IV) muddy, wave-sheltered Mahoro Bay shoreline strongly influenced by tidal pumping. The relatively sharp northward turn of the Rufiji River may be a result of tectonic tilting

supply to counter sea-level rise (Anthony 2016; Besset et al. 2019a) and by delta resilience in the face of multiple environmental and human pressures (Hoitink et al. 2020). The Rufiji basin and its delta embody important stakes in the economic development of Tanzania, and these stakes will increasingly assume greater importance in a context of rapid demographic growth, hydropower development, deforestation and climate change. Much of the basin is targeted by the government of Tanzania for socioeconomic development as part of the Southern Agricultural Growth Corridor of Tanzania (SAGCOT) and is a major Tanzanian example of the interdependent water-energy-food-environmental (WEFE) 'nexus' sectors, supplying water for around 4.5 million people and generating 80% of Tanzania's hydropower (Geressu et al. 2020). The Rufiji basin is also subject, like the rest of Tanzania, to agriculture-driven deforestation (Doggart et al. 2020). Several new dams and run-of-river hydropower plants are planned in the Rufiji basin. Among these are the future Julius Nyerere Hydropower Project (JNHP) at Stiegler's Gorge (Fig. 1a) on the river's main stem that will potentially control 95% of the river's discharge in order to cater to hydropower production, export-oriented irrigation of several hundred thousand hectares of agricultural land in the lower Rufiji floodplain, and to assure flood control (Geressu et al. 2020). Depending on the dam operation mode, this major enterprise, coupled with the variability of the river's discharge, could radically transform the delta by curtailing sediment supply to the coast (Duvail and Hamerlynck 2007; Hamerlynck et al. 2011; Duvail et al. 2013; Shaghude 2016; WWF 2018). The expected sediment reduction could eventually impair the resilience of the delta, especially in a context of sea-level rise. Delta retreat caused by fluvial sediment shortage from the basin due to current and projected hydropower dams could be temporarily mitigated by sediment release by basin deforestation, which is being rapidly driven by agriculture in Tanzania (Doggart et al. 2020), and by the relatively sheltered hydrodynamic setting of this delta. More detailed studies of the geomorphology of the Rufiji delta should contribute to a better appreciation of these aspects, while throwing light on the environmental context in which human-nature relationships will play out in the future in a delta subject to demographic growth and pressure on mangroves, climate change and sea-level rise.

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Data availability All the open-source data can be retrieved by request or from the sites of the respective providers of data (Merit DEM, ERA5 wave data, GRDC discharge, GLAD surface water changes). The shoreline change data can be uploaded at Zenodo—Research. These data can be obtained on request from the authors.

Declarations

Conflicts of interest The authors declare no competing interests.

References

Anthony EJ (2015) Wave influence in the construction, shaping and destruction of river deltas: a review. Mar Geol 361:53–78

Anthony EJ (2016) Deltas. Oxford Bibliographies, Geoscience, Oxford University Press. http://www.oxfordbibliographies.com/view/document/obo-9780199363445/obo-9780199363445-0057.xml?rskey=g50miF&result=1&q=Deltas#firstMatch. Accessed 1 Feb 2021

Anthony EJ, Besset M, Brunier G, Goichot M, Dussouillez P, Nguyen VL (2015) Linking rapid erosion of the Mekong River delta to human activities. Sci Rep 5:14745. https://www.nature.com/articles/srep14745

Besset M, Anthony EJ, Bouchette F (2019a) Multi-decadal variations in delta shorelines and their relationship to river sediment supply: an assessment and review. Earth-Sci Rev 193:199–219. https://doi.org/10.1016/j.earscirev.2019.04.018

Besset M, Gratiot N, Anthony EJ, Bouchette F, Goichot M, Marchesiello P (2019b) Mangroves and shoreline erosion in the Mekong River delta. Estuar Coast Shelf Sci 226:106263. https://doi.org/10.1016/j.ecss.2019.106263

Beymer-Farris BA, Bassett TJ (2012) The REDD menace: resurgent protectionism in Tanzania's mangrove forests. Glob Environ Chang 22:332–341

Cohen S, Kettner AJ, Syvitski JPM (2014) Global suspended sediment and water discharge dynamics between 1960 and 2010: Continental trends and intra-basin sensitivity. Glob Planet Chang 115:44–58

Doggart N, Morgan-Brown T, Lyimo E, Mbilinyi B, Meshack CK, Sallu SM, Spracklen DV (2020) Agriculture is the main driver of deforestation in Tanzania. Environ Res Lett 15:034028. https://doi.org/10.1088/1748-9326/ab6b35

Duvail S, Hamerlynck O (2007) The Rufiji river flood: plague or blessing? Int J Biometeorol 52:33–42

Duvail S, Mwakalinga AB, Eijkelenburg A, Hamerlynck O, Kindinda K, Majule A (2013) Jointly thinking the post-dam future: exchange of local and scientific knowledge on the lakes of the Lower Rufiji, Tanzania. Hydrol Sci J 59:713–730

Duvail S, Hamerlynck O, Paron P, Hervé D, Nyingi WD, Leone M (2017) The changing hydro-ecological dynamics of rivers and deltas of the Western Indian Ocean: anthropogenic and environmental drivers, local adaptation and policy response. Comptes Rendus Geoscience 349:269–279. https://doi.org/10.1016/j.crte.2017.09.004

Elliott T (1986) Chapter 6: Deltas. In: Reading HJ (ed) Sedimentary environments and facies. Blackwell Scientific Publications, Oxford, pp 113–154

Ellison JC (2015) Vulnerability assessment of mangroves to climate change and sea-level rise impacts. Wetl Ecol Manag 23:115–137. https://doi.org/10.1007/s11273-014-9397-8

Erftemeijer PLA, Hamerlynck O (2005) Die-back of the mangrove *Heritiera littoralis dryand* in the Rufiji Delta (Tanzania) following El Nino floods. J Coastal Res 4:228–235

Francis J (1992) Physical processes in the Rufiji delta and their possible implications on the mangrove ecosystem. Hydrobiologia 247:173–179

Frazier DE (1967) Recent deltaic deposits of the Mississippi River: their development and chronology. Trans Gulf Coast Assoc Geol Soc 27:287–315

Geressu R, Siderius C, Harou JJ, Kashaigili J, Pettinotti L, Conway D (2020) Assessing river basin development given water-energy-food environment interdependencies. Earth's Future 7:e2019EF001464. https://doi.org/10.1029/2019EF001464

Hamerlynck O, Duvail S, Vandepitte L, Kindinda K, Nyingi DW, Paul JL, Yanda PZ, Mwakalinga AB, Mgaya YD, Snoeks J (2011) To connect or not to connect? Floods, fisheries and livelihoods in the Lower Rufiji floodplain lakes, Tanzania. Hydrol Sci J 56:1436–1440

Hersbach H, Bell B, Berrisford P, Biavati G, Horányi A, Muñoz Sabater J, Nicolas J, Peubey C, Radu R, Rozum I, Schepers D, Simmons A, Soci C, Dee D, Thépaut J-N (2018) ERA5 hourly data on single levels from 1979 to present. Copernicus Climate Change Service (C3S) Climate Data Store (CDS). https://doi.org/10.24381/cds.adbb2d47

Hoitink AJF, Nittrouer JA, Passalacqua P, Shaw JB, Langendoen EJ, Huismans Y, van Maren DS (2020) Resilience of river deltas in the Anthropocene. J Geophys Res Earth Surf 125:e2019JF005201. https://doi.org/10.1029/2019JF005201

Jerolmack DJ (2009) Conceptual framework for assessing the response of delta channel networks to Holocene sea level rise. Quat Sci Rev 28:1786–1800

Kayaa LT (2019) Ecological classification of estuaries along the Tanzanian mainland: a tool for conservation and management. WIO J Mar Sci 18:57–65. https://doi.org/10.4314/wiojms.v18i1.6

Mahongo SB, Francis J, Osima SE (2012) Wind patterns of coastal Tanzania: their variability and trends. Western Indian Ocean J Mar Sci 10:107–120

Maselli V, Iacopini D, Ebingern CJ, Tewari S, de Haas H, Wade BS, Pearson PN, Francis M, van Vliet A, Richards B, Kroon D (2020) Large-scale mass wasting in the western Indian Ocean constrains onset of East African rifting. Nat Comm 11:3456. https://doi.org/10.1038/s41467-020-17267-5

Minu A, Routh J, Machiwa JF (2020a) Distribution and sources of organic matter in the Rufiji Delta in Tanzania: variability and environmental implications. Appl Geochem 122:104733. https://doi.org/10.1016/j.apgeochem.2020.104733

Minu A, Routh J, Machiwa JF, Pamba S (2020b) Spatial variation of nutrients and primary productivity in the Rufiji Delta mangroves. Tanzania Afr J Mar Sci 42:221–232. https://doi.org/10.2989/1814232X.2020.1776391

Moodie AJ, Nittrouer JA, Ma H, Carlson BN, Chadwick AJ, Lamb MP, Parker G (2019) Modeling deltaic lobe-building cycles and channel avulsions for the Yellow River delta, China. J Geophys Res Earth Surf 124:2438–2462. https://doi.org/10.1029/2019JF005220

Mpanda S (1997) Geological development of the East African coastal basin of Tanzania. PhD thesis, Stockholm University, Faculty of Science, Department of Geology and Geochemistry

Mwalyosi RBB (1990) Resource potentials of the Rufiji River basin, Tanzania. Ambio 19:16–20

Mwevura H, Kylin H, Vogt T, Bouwman H (2021) Dynamics of organochlorine and organophosphate pesticide residues in soil, water, and sediment from the Rufiji River Delta, Tanzania. Reg Stud Mar Sci 41:101607. https://doi.org/10.1016/j.rsma.2020.101607

Pickens AP, Hansen MC, Hancher M, Stehman SV, Tyukavina A, Potapov P, Marroquin B, Sherani Z (2020) Mapping and sampling to characterize global inland water dynamics from 1999 to 2018 with full Landsat time-series. Remote Sens Environ 243:111792. https://doi.org/10.1016/j.rse.2020.111792

Punwong P, Marchant R, Selby K (2012) Holocene mangrove dynamics and environmental change in the Rufiji Delta, Tanzania. Veg Hist Archaeobotany 22:381–396

Punwong P, Selby K, Marchant R (2018) Holocene mangrove dynamics and relative sea-level changes along the Tanzanian coast, East Africa. Estuar Coast Shelf Sci 212:105–117. https://doi.org/10.1016/j.ecss.2018.07.004

Richmond MD, Wilson JDK, Mgaya YD, Le Vay L (2002) An analysis of smallholder opportunities in fisheries, coastal and related enterprises in the floodplain and delta areas of the Rufiji River, Tanzania. Rufiji Environment Management Project Technical Report 89, 25 pp

Said A, Moder C, Clark S, Abdelmalak MM (2015) Sedimentary budgets of the Tanzanian coastal basin and implications for uplift history of the East African rift system. J Afr Earth Sci 111:288–295

Shaghude YW (2016) Estuarine environmental and socio-economic impacts associated with upland agricultural irrigation and hydropower developments: the case of Rufiji and Pangani Estuaries, Tanzania. In: Scheren P, Diop S, Machiwa J, Ducrotoy J-P (eds) Estuaries: A lifeline of ecosystem services in the Western Indian Ocean. Springer, Cham, pp 169–182. https://doi.org/10.1007/978-3-319-25370-1_11

Scoon EN (2020) Geotourism, Iconic Landforms and Island-Style Speciation Patterns in National Parks of East Africa. Geoheritage 12:66. https://doi.org/10.1007/s12371-020-00486-z

Tamura T, Saito Y, Nguyen VL, Ta TKO, Bateman MD, Matsumoto D, Yamashita S (2012) Origin and evolution of interdistributary delta plains; insights from Mekong River delta. Geology 40:303–306

TEEB (The Economics of Ecosystems and Biodiversity) (2018) Managing ecosystem services in the Rufiji River basin: Biophysical modeling and economic valuation. Institute of Resource Assessment, University of Dar es Salaam, Tanzania

Wagner G, Sallema-Mtui R (2010) Change analysis of Rufiji-Mafia-Kilwa mangroves, Tanzania in relation to climate change factors and anthropogenic pressures. WWF Tanzania Country Office, Dar es Salaam, 158 pp

WWF (2018) WWF Statement on Decision to Build Stiegler's Gorge Dam in Selous Game Reserve, Press Releases, WWF. Retrieved January 16, 2020, from https://www.worldwildlife.org/press-releases/wwf-statement-on-decision-to-build-stiegler-s-gorge-dam-in-selous-gamereserve

Yamazaki D, Ikeshima D, Tawatari R, Yamaguchi T, O'Loughlin F, Neal JC, Sampson CC, Kanae S, Bates PD (2017) A high-accuracy map of global terrain elevations. Geophys Res Lett 44:5844–5853