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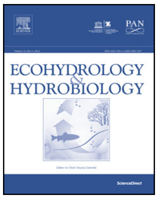

Original Research Article

The need to enforce minimum environmental flow requirements in Tanzania to preserve estuaries: case study of mangrove-fringed Wami River estuary

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ABSTRACT

The importance of restoring and maintaining environmental flows for sustaining the ecosystem integrity of rivers has been recognized in policies and legal frameworks in many countries. However this is routinely not implemented in Tanzania as exemplified by the case of the Wami River estuary, which plays a vital role in processing riverine nutrients, trapping sediment, recycling nutrients in the mangroves, and supporting the ecology of the Saadani National Park and the livelihood of the local communities. Our study reveals that currently the estuary is ecologically healthy but it is threatened by both increasing sedimentation and declining freshwater flow caused by decreasing rainfall – possibly linked with climate change – and by increasing water demand in the watershed for artisanal and large scale agriculture and irrigation schemes. Environmental flow assessment for the Wami River (with exclusion of estuary) has been done and the minimum flows were recommended but they are not enforced. We recommend that the responsible authority (Wami-Ruvu Basin Water Office) enforce its own environmental flow recommendations in order to maintain a healthy estuarine ecosystem and regulate water usage in the watershed. A similar recommendation also holds for all other rivers and estuaries in Tanzania.

1. Introduction

Many rivers in the world are suffering from hydrological alterations which result in degradation of aquatic habitats. The recognition of the importance of maintaining the natural flow regime for sustaining the ecosystem integrity of rivers and estuaries has led to development of environmental flow (EF) concept and national and international organizations are emphasizing the EF as key element of integrated water resources management (Dyson et al., 2008). Various definitions of environmental flow exist; the Brisbane declaration of 2007 (http://www.watercentre.org/news/declaration) defines EF as "the quantity, timing, and quality of water flows required to sustain freshwater and estuarine ecosystems and the human livelihoods and well being that depend on these ecosystems".

In Tanzania, EF assessments are supported by policy and legal frameworks such as National Water Policy of 2002 (URT, 2002), Environmental Management Act of 2004

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(URT, 2005) and The Water Resources Management Act of 2009 (URT, 2009). EF studies have been conducted in several Tanzania rivers including the Wami River (Dickens, 2011; GLOWS-FIU, 2014). The required minimum flows for Wami River for both dry and wet years were recommended. However, both studies ignored the freshwater needs of the estuary.

Estuaries are known to play an important role in human well-being and the economy, but they are increasingly threatened and, as a response, science-based management and restoration strategies are continuously evolving (Costa et al., 1994; Lindeboom, 2002; Uncles et al., 2002; Wolanski et al., 2004; Wolanski and Elliott, 2015). Much of the available knowledge is derived from large estuaries where the response to changing land and water use in the watershed is slower than that of small estuaries (Swaney et al., 2011).

The Wami River is managed by Wami-Ruvu Water Basin Office (WRWBO) while the estuary is managed by Saadani National Park (SANAPA). The estuary is a lifeline for SANAPA wildlife and people during the dry season where most of the water sources inside the park are dry. It is also the main source of income to Saadani village and adjacent coastal communities through fishery as well as through tourism. Prior to gazetting of the National Park in 2005, the estuarine condition was threatened by increased destruction of mangroves which were heavily exploited for charcoal, fuel wood, poles and salt production pans. Local communities have been complaining about decreasing catch of prawn and fish, local extinction of some fish species, changing water quality, particularly increasing water salinity in the estuary, and increasing sedimentation at the mouth of the estuary and in near shore waters where the fisheries are located. However, the majority of their claims were based on anecdotal information, with no scientific evidence to justify the claims.

In this paper we show that the Wami River estuary plays a vital role in processing riverine nutrients, in trapping fine sediment, in recycling nutrients in the mangroves, in supporting wildlife and the ecology of the National Park as well as the livelihood of the local communities. Nevertheless, this is now threatened both by increasing sedimentation and by declining freshwater flow in the Wami River due to decreasing rainfall – possibly linked with climate change – and by increasing water demand in the watershed. We show how the inclusion of the estuary to SANAPA in 2005 safeguarded the mangroves which help in trapping sediments and nutrient recycling by crabs as well as in protecting other estuarine wildlife such as hippopotami of which their populations have been observed to increase. We also indicate that the trapping of sediment by the mangroves helps buffer the seagrass meadows in coastal waters from excessive sediment load, although whether this is enough to preserve the seagrass is unknown and requires further research. Therefore, this study seeks to answer the main two questions – (i) What is the current status of Wami River estuary and (ii) What are the potential negative impacts to the estuary if recommended minimum environmental flows are ineffectively implemented.

2. Methods

2.1. Study area

The catchment area of the Wami River basin in Tanzania is about 40,000 km^2. The Wami River estuary is located between 06°07′213 S, 038°48′965 E and 06°07′155 S, 038°48′886 E (Mosha and Gallardo, 2013). The tides are semi-diurnal with a strong diurnal inequality, with spring tides reaching 4 m at the mouth. The tidal influence extends up to 8 km upstream. The average depth in the estuary is 2.5 m and 3.5 m during dry and wet seasons respectively. It supports extensive mangrove ecosystems and their associated inter-tidal organisms (TANAPA, 2003; Tobey, 2008). The main fringing vegetation types along the estuary are mangroves, palms and Acacia woodland mixed with grassland. There are eight species of mangroves but the dominant species are *Sonneratia alba*, *Avicennia marina*, *Xylocarpus granatum*, *Rhizophora mucronata* and *Heritiera littoralis*. Patchy seagrass meadows occur in coastal waters all along the coast (Fig. 1).

Hippopotami, crocodiles, and water birds are common along the estuary, while numerous wild animals such as ungulates and colobus monkeys access the upper estuary for drinking freshwater. Though small, the estuary supports one of the important prawn fisheries in Tanzania (TANAPA, 2003).

2.2. Hydrology data

Wami River discharge data from the Mandera hydrometric station (located about 50 km upstream) were obtained from WRBWO. Local rainfall data were obtained from Tanzania Meteorological Agency. Evaporation data were obtained from Nyenzi et al. (1981).

2.3. Environmental variables

Physical, chemical and biological data were obtained along a transect from the river to offshore at five sites shown in Fig. 1 at different times during dry (July–October) and wet (March–June) seasons between 2007 and 2015. Water samples were collected using a Niskin bottle near the surface, at mid-depth and near the bottom at each sampling site. From these samples, water salinity, temperature, dissolved oxygen and pH were measured *in situ*. Different instruments were used depending on the availability such as the HORIBA model U-10 and BANTE 900P portable multiparameter meters. Salinity was measured using a hand-held refractometer. A Secchi disk of 20 cm diameter was used for measurement of water visibility.

2.4. Nutrients and total suspended solids (TSS)

Water samples for nutrient and TSS analysis were collected using a Niskin bottle and stored in acid washed 1 L plastic bottles, rinsed with distilled water and re-rinsed with water from the sampling site two to three times. All samples were immediately stored in an iced cool box. In the laboratory, these samples were filtered using BOECO glass-microfibre discs (filters) grade MGC with 0.45 μm

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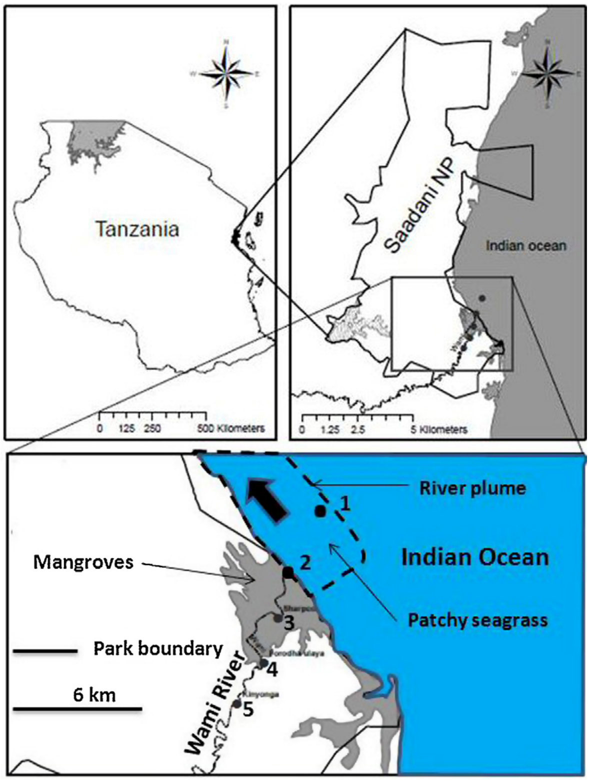

Fig. 1. Location of study area and sampling sites 1–5. The arrow indicates the direction of the prevailing net longshore northward current (http://www.gloss-sealevel.org/publications/documents/tanzania_gex2007.pdf). Patchy seagrass meadows occur all along the coast and they are readily apparent in satellite images although they have not been mapped in detail (http://www.seagrasswatch.org/Shop/SG_atlas.pdf). The outline of the river plume (dashed line) is sketched from visual observations.

pore size and GF/C Whatmann glass-microfibre filters of 4.7 cm diameter. A volume of 300–400 mL was filtered depending on how turbid the water was. Filtrate was used for nutrient analysis while filter papers containing residue were used for TSS analysis.

Dissolved Inorganic Phosphate (DIP) was determined by using the ammonium molybdate method. The procedures followed were adapted from Murphy and Riley (1962). Dissolved Inorganic Nitrogen (DIN) determination was done following the cadmium reduction method described by Parsons et al. (1984). TSS analysis was performed following the protocol described by APHA (2005).

2.5. Residence times and the fate of riverine nutrients

The residence time of water in the estuary and the fate of riverine nutrients in the estuary were calculated using the muddy LOICZ model of Xu et al. (2013) for the dry season when the estuary was vertically well-mixed, and of Xu et al. (2015) during the wet season when the estuary was vertically stratified. The data obtained on salinity, DIN, DIP and TSS were used in the LOICZ model to calculate the Net Ecosystem Metabolism (NEM; also called (p–r), where p is the production and r is the respiration) and the Nitrogen fixation rate minus the denitrification rate (Nfix – Denit).

2.6. Sediment trapping in mangroves

Sediment trapping in mangroves was measured using the method of Golbuu et al. (2003). PVC traps 20 cm long and 2.5 in. diameter closed at the bottom were deployed on four transects within the mangrove forest. Each transect had 4 traps deployed at a distance of 10 m from the river bank to up to 800 m inside the forest depending on the width of the mangrove forest strip. A hole was dug and a trap was put in up to 15 cm leaving the other 5 cm above the ground level. After a month, all traps were removed, sediments put in a container, dried and weighted.

2.7. The role of crabs in recycling mangrove litter

The role of crabs in recycling mangrove litter was measured using the method of Smith et al. (1991) and Lindquist et al. (2009). Three plots of 10 m × 10 m were established, species identified, counted, height estimated and diameter at breast height (dbh) measured. In each plot 100 new leaves were picked from trees and each leaf was tightly tied with a 1 m string. The leaves were spread evenly throughout the mangrove floor within the plot. This was done at low tide. We returned at low tide again after a tidal cycle and looked for the strings that remained. While a few leaves remained at the surface, most of the leaves either were in crab holes or were absent, having been exported to the estuary by the tides. The mean value of the number of leaves exported to the river for all three plots was calculated.

2.8. Movement of hippopotami in different seasons and their impact on mangroves

Physical observation of hippopotami movement during wet and dry season was done to see if they shift their local territories with changing river flows. We also measured their impact on the vegetation by locating their tracks along a 2 km stretch along the mangrove-fringed river banks. Whenever tracks were seen, GPS coordinates were taken following the tracks after every 10–20 m intervals for a distance of about 150–200 m. All tracks were then mapped.

3. Results

3.1. Hydrology

The rainfall varies strongly seasonally and inter-annually (http://www.wmo.int/pages/prog/wcp/wcdmp/documents/Tanzania.pdf). Rainfall is bimodal with long rainy (wet) seasons occurring between March and June and the short rainy season occurring between November and December. The long dry season occurs between July and October and the short dry season between January and February. Mean annual rainfall varies between 900 and 1000 mm (WRBWO, 2008). As a result, the Wami River discharge also varies seasonally and inter-annually.

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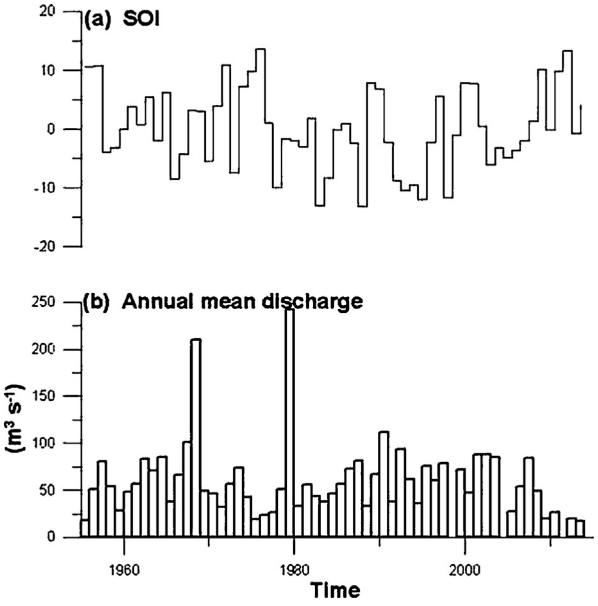

Fig. 2. Time-series plot of the annual mean (a) Southern Oscillation Index and (b) Wami River annual mean discharge.

From 1954 to 2014, the mean annual discharge varied-inter-annually between a maximum value of 241.9 $m^3 s^{-1}$ and a minimum discharge of 16.9 $m^3 s^{-1}$ and this discharge was not correlated ($r^2 = 0.04$) with the Southern Oscillation Index (SOI; Fig. 2).

The residence time of water in the estuary is very short (a few days; see later); thus the daily mean discharge determines the flushing rate. Historical data shows that during extremely wet years the discharge exceeded at times 600 $m^3 s^{-1}$, but in dry years that discharge was much reduced to the minimum values varying between 0.2 and 5 $m^3 s^{-1}$ during dry and wet years respectively (Fig. 3a). However in the last two there is a decreasing trend in the minimum dry season discharge for both wet and dry years (Fig. 3b).

3.2. Environmental variables

The Wami River estuary is a warm system throughout the year with temperature between 27.5 °C and 31.9 °C (not shown). Dissolved oxygen varied between 6.4–11.9 mg/L during the dry season and 5.4–6.7 mg/L during the wet season (not shown). The estuary was very turbid as the Secchi depth varied from 0.025 to 0.04 m during the wet season and 0.2 to 0.7 m during the dry season. By contrast the Secchi depth at site 1, in coastal waters, was typically about 4 m. The minimum value for pH during both wet and dry seasons was 7.6 and the maximum values varied from 8.1 in the dry season to 8.9 in the wet season (not shown). Higher values of pH were observed in the upper reaches of the estuary.

During the dry season, the estuary was vertically well mixed, with salinity of about 30 ppt at the mouth, and up to 7 at the tidal limit (Fig. 4a), *i.e.* the whole estuary was saline.

In contrast, during the wet season the estuary was highly stratified in salinity with surface salinity at the mouth of less than 7 ppt and bottom salinity of 35 ppt at high tide. This salinity extended only 1–2 km upstream from the mouth and the remaining part of the estuary was freshwater (Fig. 4b). At low tide the water was fresh at the mouth and a 1 m thick river plume extended up to 2 km offshore in the Indian Ocean and during our observations it was always deflected northward alongshore by the prevailing net currents sketched in Fig. 1.

3.3. Nutrients and TSS

In dry season, DIN values show high variation where low values were obtained in the upper reaches of the

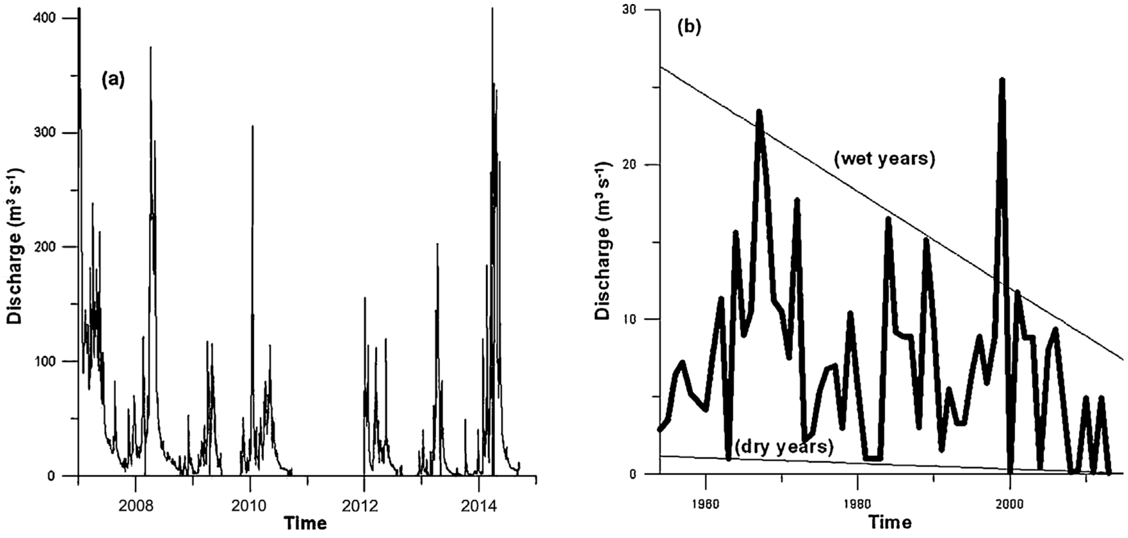

Fig. 3. Time-series plot of (a) the Wami River daily discharge during the study period and (b) the minimum daily discharge from 1954 to 2014 together with the suggested trend lines for wet and dry years.

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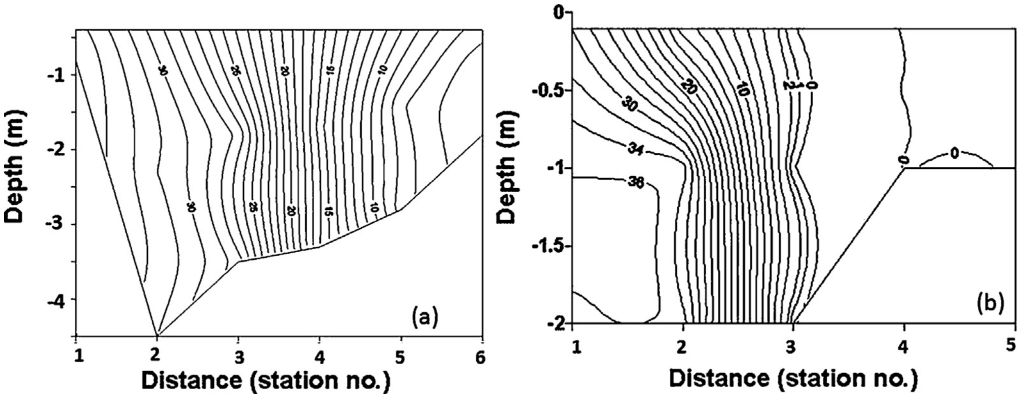

Fig. 4. Typical salinity distribution in the estuary during (a) the dry season (October 2010) and (b) during the wet season (March 2015).

estuary (0 μM), increased toward the mid estuary (17.9 μM) and decreased toward the ocean (9.2 μM). On contrary, in wet season the variation is very low compared to dry season with lower values in the upper estuary (0.036 μM) and slightly increased in mid estuary (0.049 μM) and the ocean (0.042 μM). A similar trend was observed for DIP in dry season with low values in the upper estuary (6 μM), higher values in mid estuary (26.7 μM) and decreasing values toward the ocean (16.9 μM). In wet season, the DIP values showed a decreasing trend with higher values in upper estuary (0.283 μM), and decreasing values in the mid estuary (0.174 μM) and (0.045 μM) toward the ocean.

TSS varied between 0 and 68.56 mg/L in dry season with low values in the upper estuary while in wet season TSS varied between 50 and 427 mg/L with low values in the ocean and higher values in the mid and upper estuary.

3.4. Residence times and the fate of riverine nutrients

The residence time of water, calculated using the LOICZ model, was about 6.9 days during the dry season during dry years and 0.5 days during the wet season during wet years. The fate of riverine nutrients is indicated in the Net Ecosystem Metabolism (NEM) which was positive (98.3 mmol C/m^2/day) in the wet season and negative (−10179.3 mmol C/m^2/day) in the dry season. Moreover, the Nitrogen fixation rate minus the denitrification rate (Nfix − Denit) was positive (15.07 mmol DIN/m^2/day) in the wet season and negative (−1532.84 mmol DIN/m^2/day) in the dry season.

3.5. Sediment trapping in mangroves

In the wet season, the Wami River supplied fine sediments at a rate of about 3763 tons day^{-1} and about 452 tons day^{-1} was trapped in mangroves. In the dry season, the riverine fine sediment inflow decreased to about 18 tons day^{-1}, and the fine sediment trapped in mangrove was about 195 tons day^{-1}. Also in recent years sedimentation has been observed in the Wami delta, and in turn this promoted the expansion of mangroves (Fig. 5).

3.6. The recovery of the mangroves under protection

Though the mangroves were in theory protected by law since 1994 under the Mangrove Management Project (Masalu, 2009), in practice the mangroves of the Wami River estuary continued to degrade due to imbalance between effective law enforcement and increased mangrove harvesting mainly for charcoal and building materials which were exported to Zanzibar. From 1990 to 2005 the mangrove forest cover was reduced by 27% (27.3 ha/y; McNally et al., 2011). This rate was reduced to 1.8 ha/y in 2005–2010 as the National Park protection laws were progressively implemented by effective law enforcement within the park's boundaries. As a result, at present the mangroves are regenerating quickly and naturally as we observed new mangroves growing in previously clear-felled areas and 2–3 m long branches sprouting from old cuts (Fig. 6).

3.7. The role of crabs in recycling mangrove litter

High percentage of the mangrove litter (57%) was consumed and recycled by crabs in their holes in the mangrove soil while 32% of the remaining litter was exported to the estuary and the 11% remained on the ground to decompose in the mangrove floor to contribute to soil nutrient.

3.8. Movement of hippopotami in different seasons and their impact on mangroves

Hippopotami are territorial animals in water and they graze on land especially during the night. During the dry season hippopotami were observed to stay in six groups (schools) within the estuary with the first school located in between sampling stations 2 and 3. In wet season when the estuary is mainly freshwater dominated, hippopotami groups were observed to split, form temporary schools and disperse throughout the estuary including near the river mouth.

Hippopotami and other wildlife (principally elephants and buffaloes) may contribute to bank erosion (Fig. 7a) but only at a few specific points. These are the points where the

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Fig. 5. Mangrove growth in the delta due to increasing sedimentation. North is up the page. Note the growth of the small mangrove island (in the ellipse) and the narrowing of the tidal channel around the large mangrove island to the east.

hippopotami crossed the mangrove forest on their way to grazing land but they did not destroy the mangrove vegetation (Fig. 7b). Their tracks were fairly straight, indicating that they choose to rapidly cross the mangrove forest to reach the grazing areas; by doing so they created paths which were then used by other animals (Fig. 7c).

4. Discussion

There has been increasing demand on water resources within the Wami River watershed for large scale agriculture, irrigation, industrial production and drinking water supply projects (Madulu, 2005; WRBWO, 2008; GLOWS-FIU, 2014). This is reflected in declining river flows to the estuary. Four of the six smallest river flows recorded in any year since 1954 occurred in the last five years (Fig. 2). Also, there is a decreasing trend of the minimum flows in both wet and dry years (Fig. 3). In dry years at present the salinity reaches 7 ppt at the tidal limit. This is a crisis for the wild animals in the estuary as they cannot drink the high salinity water and thus they either moved in the extremely shallow (depth of the order of a few cm) waters of the river upstream of the estuary to drink during the dry season in dry years, or they moved in the upper estuary to drink at low tide during 'normal' years, and other animals migrated out of the park in search of water and some were killed.

Before 2007, the estuary was only moderately turbid with dry season turbidity of about 75 mg/L (Anderson et al., 2007). Present turbidity is about 300 mg/L and higher

Fig. 6. Mangroves recovering in the Wami River estuary since the National Park was gazetted in 2005. Note the tree that has grown by 2015 from the trunk left by loggers in 2003.

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Fig. 7. Hippo tracks (a) in the banks of the estuary and (b) in the mangrove forest. (c) Tracks of a small ungulate within a hippo track.

within the estuary. The main causes of high turbidity in the estuary could be increased sediment load from the watershed from changing land-use and road constructions in the catchment, as well as re-suspension of bottom sediments by hippopotami, but the data are unavailable to quantify the relative importance of these processes. There is no doubt however that the estuary is silting (Fig. 5). There were also recent changes in the pH (GLOWS-FIU, 2014; Baumann et al., 2015). However, all other environmental variables and nutrients are within the acceptable levels recommended in the EF assessment of Wami River to sustain a healthy aquatic ecosystem (GLOWS-FIU, 2014).

The decreasing trend of minimum flows in the Wami River results in increasing dry season salinity in the estuary. In turn this impacts on the estuarine ecosystem because salinity influences the reproduction, growth, abundance, distribution and diversity of estuarine species ecosystem (Bidwell and Gorrie, 2006; Brown et al., 2006; Kefford et al., 2006). While the fluctuations in salinity within the estuary are a common phenomenon (Leroy et al., 2007), different estuarine organisms tolerate differently with these fluctuations and most of them can survive within very narrow ranges of salinities (Dunlop et al., 2008; Wolf et al., 2009; Wolanski and Elliott, 2015). This impacts also on the fish composition and distribution in the estuary (GLOWS-FIU, 2014). The changes in the salinity in the Wami River estuary can be expected to modify the species distribution, the composition and abundance, the mortality of sensitive species, the replacement of freshwater species by salt tolerant species, and the spawning, embryonic development, larvae development and hatching success of some species (Brown et al., 2006; Kefford et al., 2006; Song et al., 2008; Muylaert et al., 2009). Studies on the effect of salinity for specific groups of aquatic biota of Wami River estuary need to be done in the future to better understand the impacts of changing salinity patterns.

EF studies conducted in 2007 and 2011 for the Wami River recommended minimum environmental flows for different selected sites, but excluded the estuary. The recommendations were based on ecological and geomorphological flows in the driest years (Table 1). The commonly observed flow of $1\,m^3\,s^{-1}$ during the dry season during this study was less than 30% the recommended environmental flow, showing that environmental flow requirements were not respected.

During the wet season, the Wami River estuary is flushed in less than a day and the ecosystem appears healthy with no apparent stress to fauna or flora. Such is not the case, however, in the dry season when the water residence time is typically ~7 days and thus the health of the estuarine ecosystem depends on the daily river discharge. In particular short periods of river discharge less than $1\,m^3\,s^{-1}$, a common occurrence in the dry season (Fig. 3), result in excessively high salinity (see Fig. 4).

Though the estuary was rapidly flushed in the wet season, the estuary was autotrophic as the system produced more than it consumed (NEM = 98.32 mmol C/m^2/day). In dry season, when EF was reduced, the flushing time was much longer than in the wet season but the estuary consumption was higher than production

Table 1

Recommended environmental flow ($m^3 s^{-1}$) of the Wami River at Mandera. (RAD = recommended average discharge; AAD = available average discharge; RIP = recommended instantaneous peak discharge.).

Month	Driest year			Maintenance year			Wettest year		
	RAD	AAD	RIP	RAD	AAD	RIP	RAD	AAD	RIP
Oct	3.0	4.3		13.3	13.3		23.0	65.0	
Nov	3.0	5.9		14.0	26.0		23.0	265.9	
Dec	7.7	15.9		27.3	54.6		59.8	503.9	
Jan	7.7	10.1		32.8	65.7		96.5	412.9	
Feb	7.7	12.3		24.6	49.2		133.3	325.1	
Mar	5.6	5.6		52.4	69.9		170.0	466.6	
Apr	21.7	102.1	48 ($T < 1$ yr)	65.0	192.9	53 ($T < 1$ yr)	170.0	1240.5	170 ($T = 1.1$ yr)
May	21.7	261.7		65.0	145.4		170.0	465.9	
Jun	15.5	42.6		37.5	49.9		91.4	182.8	
Jul	9.2	27.9		20.8	27.7		30.1	60.3	
Aug	3.0	15.4		14.0	21.1		23.0	51.3	
Sept	3.0	10.4		14.0	15.5		23.0	61.5	

Source: GLOWS-FIU (2014).

(NEM = −10179.290 mmol C/m^2/day). Moreover, Nfix − Denit was negative in dry season (−1532.84 mmol DIN/m^2/day) and positive in wet season (15.07 mmol DIN/m^2/day) indicating that net denitrification occurred in the dry season and net Nitrogen fixation occurred in the wet season. These results suggest that if the EF will continue to decline in the future, the estuary may become unproductive.

The effect of estuarine water residence time τ_x on NEM has been studied by Swaney et al. (2011) for more than 200 estuaries worldwide using the LOICZ model; a strong negative correlation exists between NEM and τ_x (Fig. 8). The results indicate a decreasing Net Ecosystem Metabolism as the residence time increases, because estuaries that are quickly flushed do not have sufficient time to develop non conservative signal (Swaney et al., 2011). However, the Wami River estuary data did not follow well that trend line. We suggest that this is because these 200 estuaries plotted in the graphs did not include many small estuaries with very small flushing times, neither did they have mangroves and hippopotami. Our study thus suggests that the contribution of mangroves and hippopotami to nutrient cycling in the estuary is not negligible.

Mangroves in estuaries are known for their contribution to nutrient cycling in the estuary by absorbing some nutrients from water and releasing nutrients through leaf litter as detritus (Boehm et al., 2011). Detritus derived from mangrove leaf fall provides important source of food for macro-invertebrates such as sesarmid crabs. Sesarmid crabs are well known for their ability to transport, retain and consume large quantities of mangrove leaves in their burrows (Cannicci et al., 2008). Our data support these findings. The remaining mangrove leaves are outwelled to the estuary and may increase primary productivity, particularly so in the dry season when the residence time is large enough for mangrove litter to decompose and contribute to nutrient cycling before they are flushed out. However no definite answer can be given because no studies have been done in Wami mangroves to measure the rate of decomposition of mangrove plant litter. Hippopotami may also add nutrients to the estuary by their defecation in water after grazing on land. All this may help to explain why the absolute value of the Net Ecosystem Metabolism in the estuary is about ten times larger in the dry than in the wet season.

Suspended sediments transported by river flows are an important source of organic and inorganic matter in estuarine ecosystems (Santschi et al., 1990; Hedges and Keil, 1998). They also create microhabitats for aquatic organisms, allow other metals to attach in sediment particles and provide habitats for pathogens (Labelle et al., 1980). However the recent increase supply of suspended sediments to the Wami River estuary is so large that it significantly reduces light penetration and photosynthesis, and is likely to smother benthic organisms, replace seagrass by algae, impair predator–prey interaction, and alter macro-invertebrates and fish spawning habitats (Cloern, 1987; Alpine and Cloern, 1988; Abal, 1994; Wilber and Clarke, 2001; Uncles and Stephens, 2010; Wolanski and Elliott, 2015). In turn this may reduce prawn and fish catches by the villagers, but no data are available.

In the wet season, about 12% of the riverine fine sediment inflow was trapped in mangroves. During the dry season the riverine fine sediment inflow accounted for only about 10% of the sedimentation rate in the mangroves; thus most of that sediment originated from the muddy delta as well as, possibly, bottom resuspension caused by the hippopotami in the estuary. All the riverine sediment is trapped in the mangroves during the dry season, and about 88% of the riverine fine sediment is flushed out of the estuary during the wet season; from visual observations we suggest that much of that sediment settles in a submerged delta off the river mouth while the remaining fine sediment is transported northward long shore in the river plume and presumably deposits over the patchy seagrass beds in coastal waters (Fig. 1). No studies have been done to trace the origin of the fine sediment in the estuary and mangroves in the dry season. However there is negligible riverine inflow of fine sediment at that time. It seems reasonable thus to assume that the source of sediments in the dry season is the sea. Thus, to account for the observed sediment trapping in mangroves, a simple mass balance calculation then leads to the conclusion that about 60% of the fine sediment exported from the estuary in the wet season

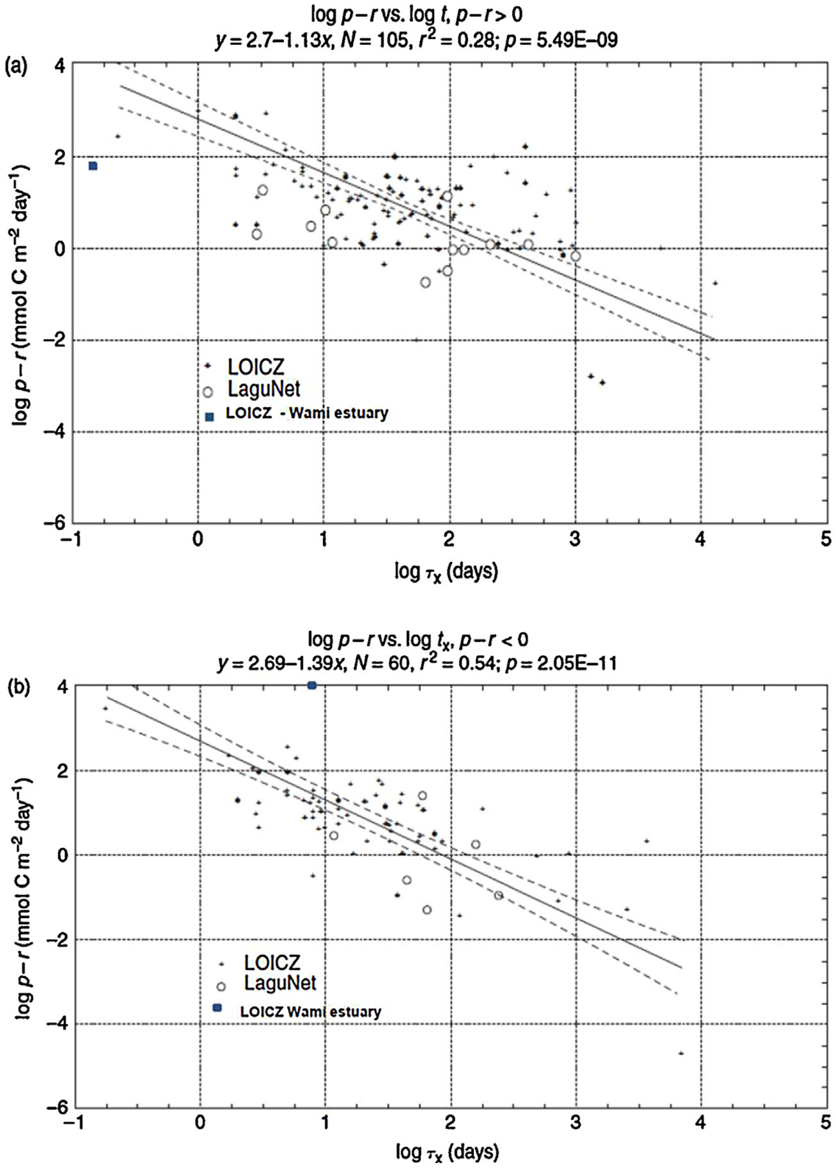

Fig. 8. Scatter plot of the Net Ecosystem Metabolism *versus* the estuarine water residence time τ_x for (a) autotrophic systems (p–r > 0) and (b) heterotrophic systems (p–r < 0). (■ = Wami River estuary; adapted from Swaney et al., 2011).

returns in the estuary to be trapped in the mangroves in the dry season.'' The expansion of mangroves results in increased trapping of fine sediment in the Wami River estuary during a year. Thus on the one hand the riverine sediment load is increasing, and on the other hand some of that load is trapped in the mangroves; the remaining load is exported to coastal seagrass and can damage the seagrass meadows that support the prawn fisheries. Studies are needed on the status of those seagrass meadows.

The hippopotami, all refugees from outside the National Park, are an important tourism attraction, and thus important to the local economy, but at the same time they modify the environment. Hippopotami contribute to nutrients cycling from terrestrial land (where they graze) to the estuary (through defecation). While there are no census data, visual observations suggest an increasing population of hippopotami after protection of the estuary in 2005. The hippopotami are not destructive of the mangrove forest, but they do create paths which are then used by other animals (Fig. 7). They also contribute to bank erosion (Fig. 7) and stirring the bottom and this increases the turbidity. Distribution and movement of hippopotami in the estuary also depends on EF as their movements have been observed to change with changing salinity patterns in the estuary. However, if the EF recommendations continue to be ignored and there is no enough freshwater, hippopotami may leave the estuary to find freshwater. If this situation happens the SANAPA will lose one of its main tourist attractions and the hippopotami may be killed if they leave the Park in search of freshwater.

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On the other hand, the mangroves are more tolerant of salinity fluctuations (Takemura et al., 2000). However, they require regular flushing with freshwater to balance salinity levels that can be tolerated. If the present trends lead to hypersaline conditions in the Wami River estuary in the future, then mangrove growth will be impeded and in turn this will prevent fruiting and seed (Ball, 1998, 2002; Aziz and Khan, 2001; Mitra et al., 2010) and consequently fisheries will be affected.

Changing uses of the land and water resources in the Wami River watershed decrease the freshwater flow and increase the sediment load to the Wami River estuary, and this is particularly ecologically important during the dry season to the level that the whole Wami River estuary ecosystem seems to be at a tipping point. This has enormous consequences for the ecology of SANAPA and thus its tourism potential, as well as for coastal fisheries; and in turn this impacts the local communities and their economy. Climate change may exacerbate this crisis because it is predicted to result in increasing frequency of droughts in Tanzania (Boko et al., 2007; Tierney et al., 2010; Wolff et al., 2011; GLOWS-FIU, 2014).

Maintaining minimum EF is crucial for the Wami River and its estuary but so far it has not been effectively implemented due to various reasons including insufficient resources and capacity (Dickens, 2011). Because of this neglect, the Wami River estuary ecosystem is now in crisis in the dry season in dry years, and will be increasingly so in the future if EF requirements continue to be ignored.

5. Conclusion and recommendation

At present, minimum environmental flow requirements are not effectively enforced in Tanzania (Elisa et al., 2010; Dickens, 2011). Our study shows that the results of this benign neglect are disastrous for the Wami River estuary. This estuary itself falls under the authority of SANAPA, which is enforcing its regulations. As a result the estuary is ecologically healthy but during the dry season it is threatened by increasing salinity intrusion due to decreasing freshwater flow in the Wami River. The estuary needs freshwater flow in the Wami River which falls within the mandates of Wami-Ruvu Basin Water Office (WRBWO). We recommend that WRBWO enforce its own environmental flow recommendations in order to maintain a healthy estuarine ecosystem and regulate water usage in the watershed. A similar recommendation also holds for all other rivers and estuaries in Tanzania.

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