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The Need to Enforce Minimum Environmental Flow Requirements in Tanzania to Preserve Estuaries: Case Study of the 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 and estuaries has been recognized and given proper attention in policies and legal frameworks in many countries including Tanzania. The Wami River estuary is small but it plays a vital role in processing riverine nutrients, in trapping sediment, in recycling nutrients in the mangroves, and in supporting the ecology of the Saadani National Park and the livelihood of the local communities. The proper functioning of this estuary to a large extent depends on adequate supply of freshwater flows. Our studies reveal 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. However, like in many other rivers in the country, effective implementation of recommended environmental flows remains to be a challenge. In order to maintain a healthy estuarine ecosystem in the future, it is the obligation of the WRBWO now to stick to and enforce the recommendations of its own environmental flow assessment to regulate water usage in the watershed. A similar recommendation also holds for all other rivers and estuaries in Tanzania.

Keywords: Minimum environmental flow requirement; Salinity; Sedimentation; Mangroves; Fisheries; Wildlife; Local economy.

Introduction

Many rivers in the world are suffering from hydrological alterations which result in degradation of aquatic habitats. Changing hydrological regime of the river affect water quality, sediments, nutrients supply and biotic interactions within the river and their associated estuaries. 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 international organizations such as World Conservation Union (IUCN) are emphasizing on the EF as key element of integrated water resources management Dyson et al., [1]. There are various definitions of environmental flow but 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 estuarine environments, EF plays a major role in salinity gradients, mixing patterns and water quality, flushing time (residence time), productivity as well as distribution and abundance of estuarine biota. In Tanzania, EF assessments are supported by policy and legal frameworks such as Tanzania Water Policy of 2002 [2], the Environmental Management Act of 2004 [3] and Water Resources Management Act of 2009 [4]. EF studies have been conducted in some rivers such as Pangani, Wami, Ruvu, Rufiji and Mara [5]. For the Wami River, the study was done in 2007 and 2011 [5,6]. The required minimum flows for both dry and wet years were recommended. However, both studies ignored the freshwater needs of the estuary.

Throughout the world 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 [7-12].

Furthermore, the functioning of estuarine ecosystems, and their responses to changing abiotic and biotic factors, are system-specific and strongly dependent on the size of the estuary, its latitude, watershed properties and human activities within [12]. Much of the available knowledge is derived from large estuaries where the response to changing environment is slower than that of small estuaries [13].

The Wami estuary falls under the management authority of Saadani National Park (SANAPA) and the whole Wami River under the management authority of the Wami-Ruvu Water Basin Office (WRWBO). 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, and poles, as well as destroyed for creating open inter-tidal areas used for salt production. Local communities have complained about decreasing catch of prawn and fish, local extinction of some fish species, changing water quality particularly increasing water salinity at the estuary as a result of

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decreasing EF, and increasing sedimentation at the mouth of the estuary and in near shore waters where the fisheries are located. However, majority of their claims were based on anecdotal information but there is no sufficient scientific evidence to justify the claims. 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, the Wami estuarine ecosystem, its fisheries, the National Park and the local economy are 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 mainly for artisanal and large scale agriculture and irrigation schemes.

In this paper we show how the estuary is/will be impacted as a result of changing EF and we give emphasis on the importance of effectively implementing the recommended flows by both SANAPA and WRBWO to sustain the estuary. We focus on changing water quality, salinity gradients and mixing patterns, sedimentation, flushing (residence time), nutrient budget and productivity with respect to changing hydrology of the river particularly during wet and dry seasons. We show how the inclusion of estuary to SANAPA in 2005 was important in safeguarding 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 show that the trapping of sediment by the mangroves help to buffer the sea grass meadows in coastal waters from excessive sediment load, although whether this is enough to preserve the sea grass is unknown and requires further research.

Methods

Study area

Wami River estuary is located in Northern coast of Tanzania between 06°07´213 S, 038°48´965 E and 06°07´155 S, 038°48´886 E [14]. The Wami-Ruvu basin covers an area of 72,930 km^2 but the Wami River drains about 40,000 km^2 of that area [15]. The tides are semi-diurnal with a strong diurnal inequality, with spring tides reaching 4 m. 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 [15,16]. 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 *Sonneratioa alba, Avicennia marina, Xylocarpus granatum, Rhizophora mucronata and Heritiera litoralis*. Patchy seagrass meadows occur in coastal waters all along the coast (Figure 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 [16].

Hydrology data

Wami River discharge data from the Mandera hydrometric station (located about 50 km from the estuary) were obtained from WRBWO. The data were processed and used to indicate changes in freshwater flow to the estuary. Local rainfall data were obtained from Tanzania Meteorological Agency while evaporation data were obtained from Nyenzi et al. [17].

Environmental variables

Physical, chemical and biological data were obtained along a transect from the river to offshore at five sites shown in Figure 1 at different times during dry (July-October) and wet seasons (March -June) 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 multi parameter meters. Salinity was measured using a hand-held refractometer. A secchi disk of 20 cm diameter was used for measurement of water visibility.

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 pore size and GF/C Whatmann glass-microfiber filters of 4.7 cm diameter. A volume

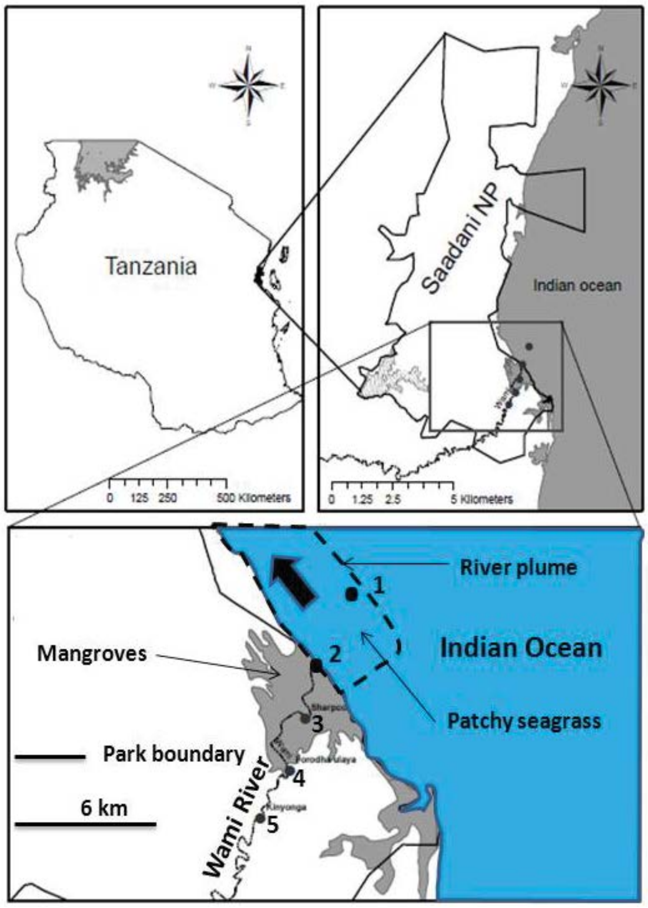

Figure 1: Location of study area and sampling sites 1-5. The arrow indicates the direction of the prevailing net longshore northward current (http://www.gloss-sealevel.org/publications/documents/tanzania_gex2007.pdf). Patchy seagrass meadows occur all along the coast and they are readily apparent in 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.

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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 [18]. Dissolved Inorganic Nitrogen (DIN) determination was done following the cadmium reduction method described by Parsons et al., [19]. TSS analysis was performed following the protocol described by APHA [20].

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., [21] for the dry season when the estuary was vertically well-mixed, and of Xue et al., [22] during the wet season when the estuary was vertically stratified. The model assumes steady state. The surface area of the estuary was estimated from Google Earth and the volume was calculated based on mean depth for wet season (3.5 m) and dry season (2.5 m). The rainfall and evaporation data together with 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).

Sediment trapping in mangroves

Sediment trapping in mangroves was measured using the method of Golbuu et al., [23]. PVC traps 20 cm long and 2.5" 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 weighed.

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., [24] and Lindquist et al., [25]. Three plots of 10 × 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.

Movement of hippo in different seasons and their impact on mangroves

Physical observation of hippos' movement during wet and dry season was done to see if they shift from their local territories during changing flows. We also wanted to know if their movements within the mangrove forest impact the vegetation. Therefore we located their tracks along a 2 km stretch along the mangrove-fringed river banks. Whenever tacks were seen, GPS coordinated were taken following the tracks after every 10-20 m intervals for a distance of about 150-200 m. All tacks were then mapped.

Results

Hydrology

Rainfall in coastal Tanzania varies strongly seasonally and inter-annually. 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 900-1000 mm [26]. As a result, the Wami River discharge also varied seasonally and inter-annually. From 1954 to 2014, the mean annual discharge varied inter-annually between a maximum value of 241.9 m^3s^{-1} and a minimum discharge of 16.9 m^3s^{-1} and this discharge was not correlated (r^2=0.04) with the Southern Oscillation Index (SOI; Figure 2).

Because the residence time of water in the estuary is very short, what controls the flushing of the estuary is not the mean annual flow but the daily mean discharge. Historical data shows that during extremely wet years the discharge exceeded at times 600 m^3s^{-1}, but in dry years that discharge was about 120-150 m^3s^{-1} (Figure 3a). However that discharge was much reduced during the dry season and, in recent years, the minimum discharge varies between 0.2 and 5 m^3s^{-1} during dry and wet years respectively (Figure 3b). Since the data were recorded starting in 1954, there is a decreasing trend in the minimum discharge for both wet and dry years (Figure 3b).

Environmental variables

The Wami Estuary is a warm system throughout the year with temperature range between 27.5°C and 31.9°C (not shown). Dissolved oxygen varies between 6.4 to 11.9 mg l^{-1} during the dry season and 5.4 to 6.7 mg l^{-1} during the wet season (not shown). The estuary was very turbid as the secchi disk readings varied from 0.025 to 0.04 m during

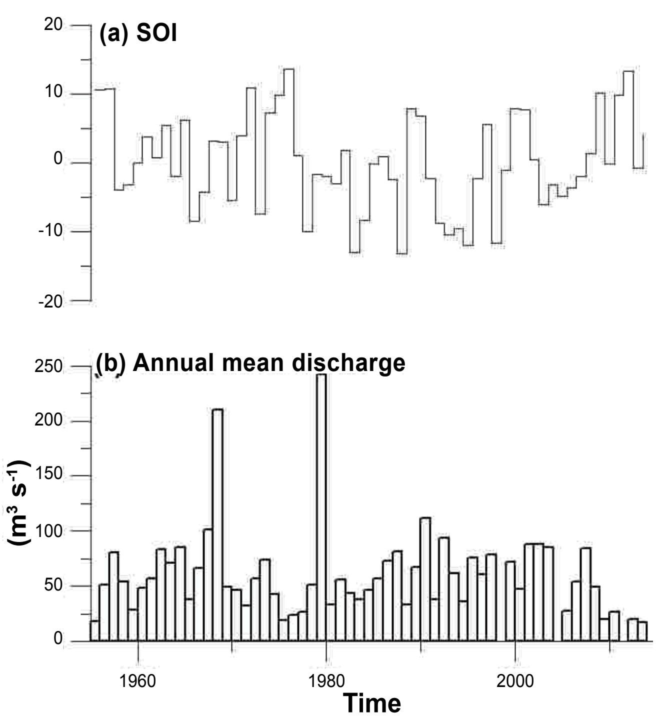

Figure 2: Time-series plot of the annual mean (a) Southern oscillation index and (b) Wami river discharge.

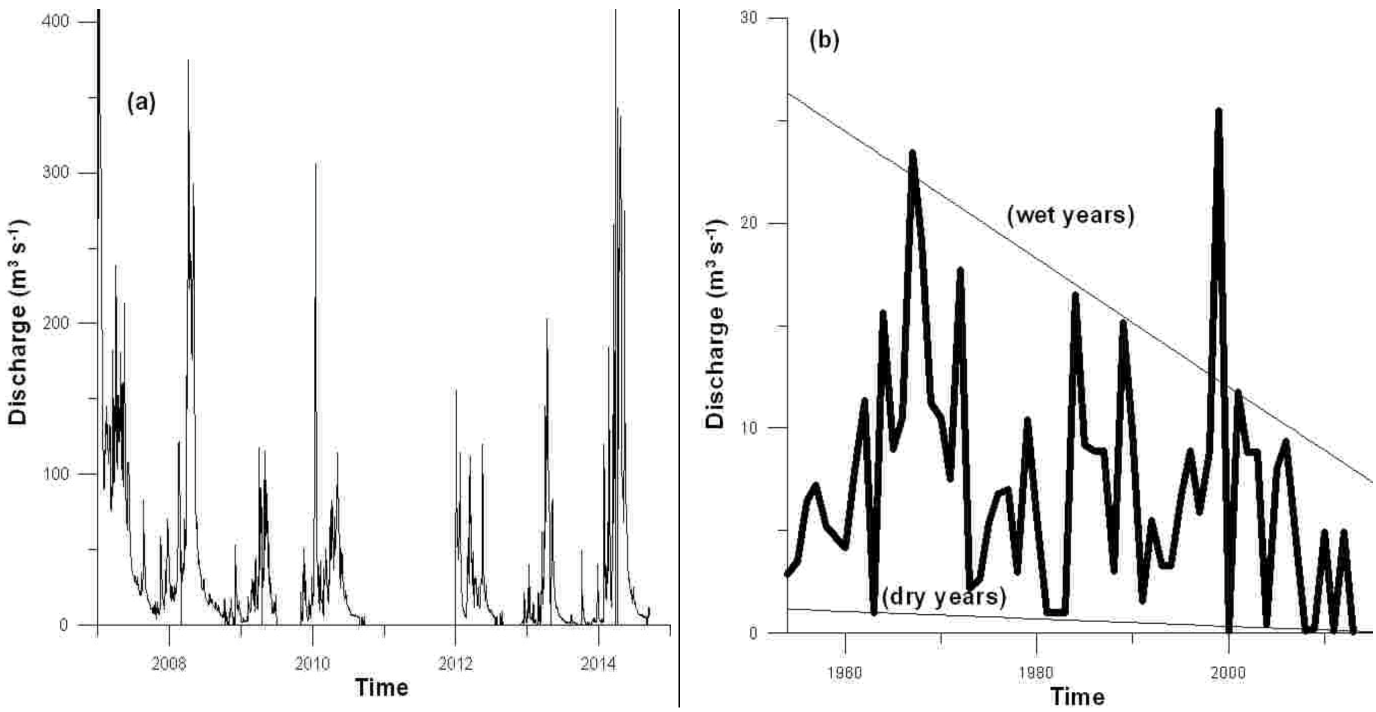

Figure 3: Time-series plot of (a) the daily Wami river discharge during the study period and (b) the minimum daily discharge from 1954 to 2014 together with the suggested trend lines for wet and dry years.

the wet season and 0.2 to 0.7 m during the dry season. By contrast the secchi disk reading 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 and followed a decreasing trend towards the river mouth. This trend coincides with increasing salinity towards the river mouth.

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

In contrast, during the wet season the estuary was highly stratified in salinity with surface salinity of less than 7 ppt and bottom salinity of 35 ppt at high tide at the mouth. This salinity extended only 1-2 km upstream from the mouth and the remaining part of the estuary was freshwater (Figure 4b). At low tide the water was fresh at the mouth and the 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 Figure 1.

Nutrients and TSS

In dry season, DIN values shows high variation where low values were obtained in the upper reaches of the estuary (0 µM), increased towards the mid estuary (17.9 µM) and decreased towards 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 towards 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) towards the ocean. TSS varied between 0-68.56 mg/L in dry season with low values in the upper estuary while in wet season TSS varied between 50-427 mg/L with low values in the ocean and higher values in the mid and upper estuary.

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 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.

Sediment trapping in mangroves

In the wet season, the Wami River supplied fine sediments at a rate of about 3,763 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 (Figure 5).

The role of crabs in recycling mangrove litter

High percentage of 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 small percent (11%) remained on the ground to decompose in the mangrove floor to contribute to soil nutrient.

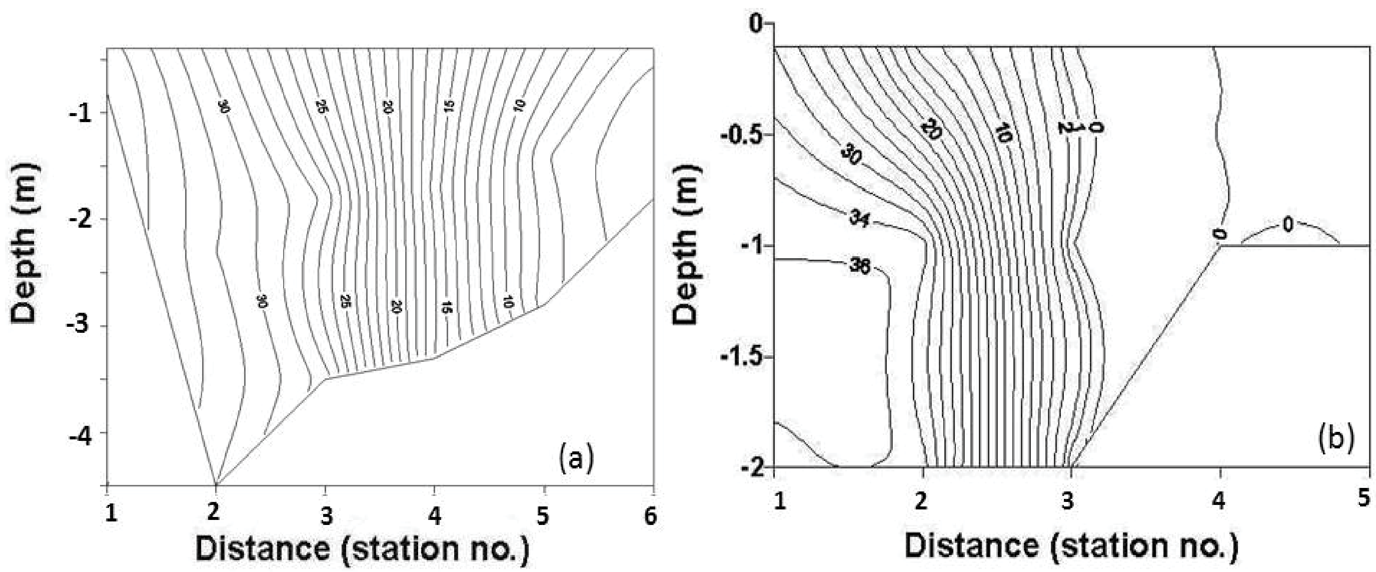

Figure 4: Typical salinity distribution in the estuary during (a) the dry season (October 2010) and (b) during the wet season (March 2015).

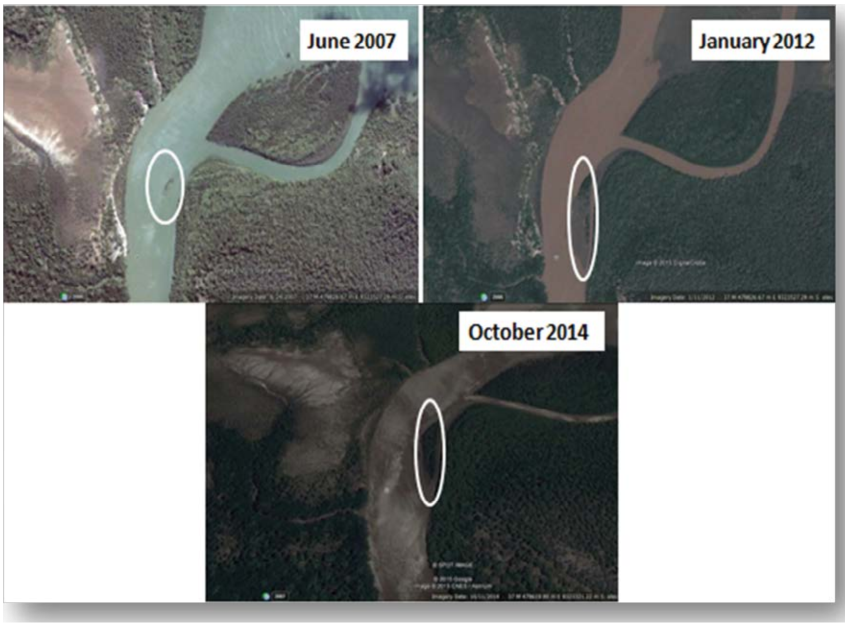

Figure 5: Mangrove growth in the delta due to increasing sedimentation. Note the growth of the small mangrove island (in the ellipse) and the narrowing of the tidal channel around the large mangrove island to the north.

Movement of hippo in different seasons and their impact on mangroves

Hippos are territorial animals only in water but not on land where they normally graze especially during the night. During the dry season hippo were observed to stay in six groups (schools) within the estuary with the first school located in between sampling station 2 and 3. In wet season when the estuary is mainly freshwater dominated, hippo groups were observed to split, form temporary schools and disperse throughout the estuary. Some hippos were located very close to the river mouth.

Hippos and other wildlife (principally elephants and buffaloes) may contribute to bank erosion (Figure 6a) but only at specific points. These are the points where the hippos crossed the mangrove forest on their way to grazing land but they didn't destroy the mangrove vegetation (Figure 6b). Their tracks were fairly straight, indicating that they choose short distances within mangroves and rapidly cross the mangrove forest before they reach the grazing areas; by doing so they create paths which are then used by other animals (Figure 6c).

Discussion

The hydrology of Wami River based on discharge data shows

Figure 6: 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.

a declining trend, yet 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 [6,26,27]. This declining trend together with increased upstream activities have contributed to the alteration of natural flow and water quality of the Wami River. Four of the six lowest river flows recorded in any year since 1954 occurred in the last five years (Figure 2). Also, there is a decreasing trend of the minimum flows in both wet and dry years (Figure 3). In dry years at present the salinity reaches 7 ppt at the tidal limit and this is a crisis for the wildlife as it cannot drink the water. As the animals in SANAPA could not drink this high salinity water, they either moved in the extremely shallow (depth of 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. There are also other indicators of change. Before 2007, the estuary was only moderately turbid with turbidity varying between 75 and 444 NTU during the dry and wet seasons respectively [28]. The turbidity has been increasing even after the EF studies in 2011, where TSS up to 300 mg/L was measured in the closest site to the estuary and in our study the highest value during wet season was about 427 mg/L within the estuary. The main causes of high turbidity in the estuary could be increased sediment load from the watershed from changing land-use, ongoing road constructions in upper regions of the catchment, bank erosion as well as re-suspension of bottom sediments by hippos, but the data are unavailable to quantify the relative importance of these processes. There is no doubt however that the estuary is silting (Figure 5). There were also changes in the pH, and these may be driven by the geochemistry of the Wami River [6,29] since the values of pH increased in the wet season when the system was autotrophic. However, other environmental variables and nutrients are within the acceptable levels as indicated in GLOWS-FIU (2014) [6].

The decreasing trend of minimum flows in the Wami River implies increasing dry season salinity in the estuary. In turn this will have an impact on the estuarine ecosystem because salinity influences the reproduction, growth, abundance, distribution and diversity of estuarine species [30-35]. While the fluctuations in salinity within the estuary is a common phenomenon [36], different estuarine organisms tolerate differently these fluctuations and most of them can survive within very narrow ranges of salinities [2,37,38]. For example, change in water quality is indicated by changing fish composition and distribution upriver as some of estuarine fish were caught in dry season at Matipwili approximately 20 km from the estuary [6]. The changes in the salinity in the Wami River estuary may have similar impacts to many studied aquatic environments and 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 [32,33,39-41]. Studies on the effect of salinity for specific groups of aquatic biota of Wami 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 required flows for different selected sites, but excluded the estuary. The recommendations were based on ecological and geomorphological flows in the driest years (Table 1).

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 – even short periods of river discharge less than 1 m^3s^{-1}, a common occurrence in the dry season (Figure 3), result in excessively high salinity.

Though the estuarine flushing rate was very high in wet season,

Month	Driest year			Maintenance year			Wettest year		
	RAD	AAD	RIP	RAD	AAD	RIP	RAD	AAD	RIP
Oct	3	4.3		13.3	13.3		23	65	
Nov	3	5.9		14	26		23	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	466.6	
Apr	21.7	102.1	48(T<1 yr)	65	192.9	53(T<1 yr)	170	1240.5	170 (T<1.1 yr)
May	21.7	261.7		65	145.4		170	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	15.4		14	21.1		23	51.3	
Sep	3	10.4		14	1505		23	61.5	

Table 1: Recommended EF ($m^3 s^{-1}$) of the Wami River at Mandera. (RAD: Recommended Average Discharge; AAD: Available Average Discharge; RIP: Recommended Instantaneous Peak Discharge) (Source: GLOWS – FIU, 2014).

where EF is high, the estuary was autotrophic as the system produces more than it consumes (NEM=98.32 mmol C/m^2/day). In dry season, when EF is reduced the flushing time was much longer than in the wet season but the estuary consumption was higher than production (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 indicate that if the EF will continue to decline, there is a high chance of the estuary to become unproductive.

The effect of estuarine water residence time τ_x on NEM has been studied by Swaney et al., (2011) [13] for more than 200 estuaries worldwide using the LOICZ model; a strong negative correlation exists between NEM and τ_x (Figure 7). The results indicate a decreasing net ecosystem metabolism as the residence time increases. However, the Wami River estuary data did not follow 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 do they have mangroves and hippos. Our study suggests that the contribution of mangroves and hippos 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 [42]. Detritus derived from mangrove leaf fall provides important source of food for macro-invertebrates such as sesarmid crabs. High concentrations of tannins in mangrove leaves prevents them from being eaten by many estuarine organisms except crabs since tannin interfere with protein digestion. Sesarmid crabs are well known for their ability to transport, retain and consume large quantities mangrove leaves in their burrows [43]. However, in the wet season the effective contribution of mangrove litter to nutrients in the estuary may be smaller than during the dry season because materials are quickly flushed out to the sea; by contrast in the dry season 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 and its likely seasonal variation.

Though the mangroves were in theory protected by law since 1994 under the Mangrove Management Project [44], 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.) [45]. 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 through regular patrols and arresting of any person who harvest mangrove within the park's boundaries. As a result, at present the mangroves are regenerating quickly and naturally as we observed during our study new mangroves growing in previously clear-felled areas and 2-3 m long branches sprouting from old cuts (Figure 8).

Suspended sediments transported by river flows are an important source of organic and inorganic matter in estuarine ecosystems [46,47]. They tend to settle in streambeds and create microhabitats for aquatic organisms, allow other metals to attach in sediment particles and provide habitats for pathogens [48]. However, the recent increase supply of suspended sediments to the Wami River estuarine systems is large and in most likelihood, by comparison with other estuaries worldwide, results in higher turbidity, which in turn may cause reduction of light penetration and photosynthesis, smothering of benthic organisms, replacement of seagrass by algae, impair predator-prey visibility, alteration of macro-invertebrates and fish spawning habitats [12,49-53]. 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. However during the dry season the riverine fine sediment inflow accounted for only about 10% of the sedimentation rate in the mangroves. We suggest that during dry season the sediments originated from the muddy delta as well as bottom resuspension caused by the hippos in the estuary. Thus it appears that during the dry season all the riverine sediment is trapped in the mangroves while during the wet season about 88% of the riverine fine sediment is flushed out of the estuary; 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 longshore in the river plume and presumably deposits over the patchy seagrass beds in coastal waters (Figure 1). During the dry season 60% of that exported fine sediment returns in the estuary to be trapped in the mangroves. The expansion of mangroves results in increased trapping of fine sediment in the Wami River estuary during a year. However because fine sediment is exported to coastal waters during the wet season, and from visual observations this appears to be increasing due to deforestation in the watershed, it is not known if the increased riverine sediment inflow degrades the

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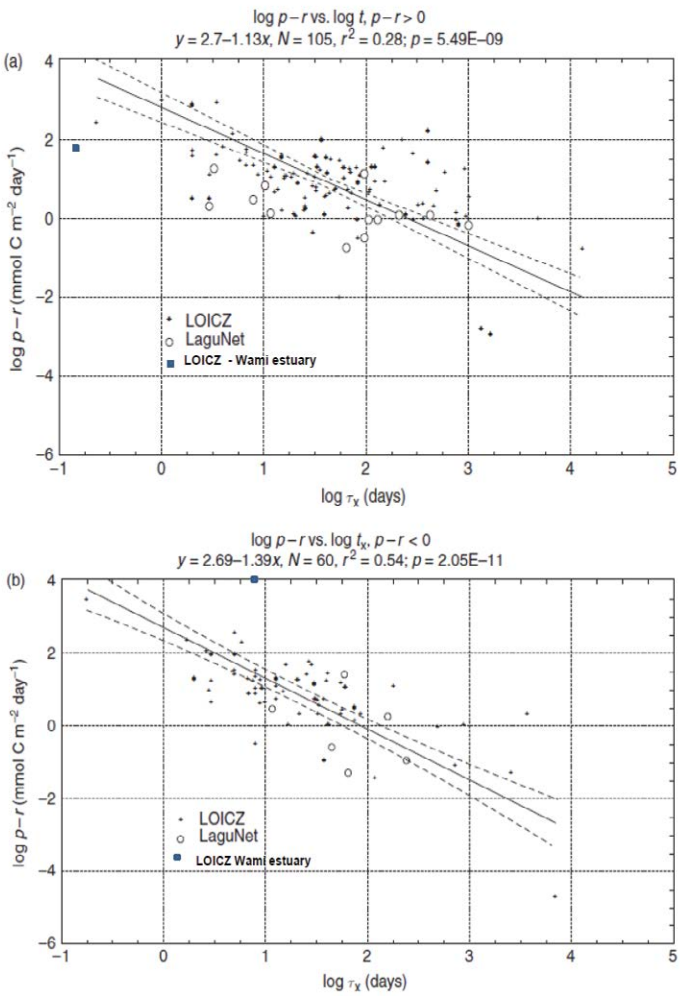

Figure 7: Scatter plot of the Net Ecosystem Metabolism versus the estuarine water residence time τx for (a) autotrophic systems (p-r>0) and (b) heterotrophic systems (p-r<0). (■=Wami River estuary; Swaney et al., [13]).

Figure 8: 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.

seagrass in coastal waters, which supports the local prawn fisheries. Studies are needed on the status of those seagrass meadows.

The hippos, 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 are new to the environment and they modify it. Hippos contribute to cycling nutrients from terrestrial land (where they graze) to the estuary (through defecation). While there are no census data, visual observations indicate an increasing population of hippo after protection of the estuary in 2005. The hippos are not destructive of the mangrove forest, but they do create paths which are then used by other animals (Figure 6). They also contribute to bank erosion (Figure 6) and stirring the bottom and this increases the turbidity. Distribution and movement of hippo in the estuary also depends on EF as their movements have been observed to change with changing freshwater flow in different seasons associated with changing salinity patterns within the estuary. However, these movements will only be sustained if the EF recommendations will be effectively implemented. Otherwise under worst case scenarios if there is no enough water, hippos will be forced to change from their territorial behavior and coexist in large groups within the uppermost reaches of the estuary where they may find residual freshwater or they may leave the estuary for other suitable places where they can find enough water. If this situation happens the SANAPA will lose one of its main tourist attractions in the park and consequently the economy of the park will be negatively affected.

On the other hand, the mangroves are more tolerant of salinity fluctuations. They have developed different mechanisms to deal with salinity [54]. However, they require regular flushing with freshwater to balance salinity levels that can be tolerated because excessive salinity is detrimental to mangroves. If the present trends lead to hypersaline conditions in the Wami estuary in the future, then mangrove growth will be impeded and in turn this will prevent fruiting and seed [55-58] 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 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 [6,59-61].

Estuary is a very complex ecosystem since its functioning is influenced by both river flow and sea water unlike other upriver sites which are influenced by freshwater flow only. Thus, determination of EF for the Wami estuary is very crucial as the requirement may be different from the river. Despite the fact that, the EF of the estuary has not been done, the recommended EF for upriver sites have not been effectively implemented due to various reasons including insufficient resources and capacity as indicated by Dickens (2011) [5].

The Wami River estuarine ecosystem is now in crisis in the dry season in dry years, and will be increasingly so in the future if effective measures are not taken.

Conclusion and Recommendation

At present, as reviewed by Elisa et al., [62] and Dickens [5] minimum environmental flow requirements are not effectively enforced in Tanzania. 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 due to decreasing freshwater flow in the Wami River. The estuary needs freshwater flow in the Wami River and the management of freshwater flows of the Wami River falls within the WRBWO. WRBWO has carried out EF assessments for the Wami River but it is not effectively enforcing its own recommendation. In order to maintain a healthy estuarine ecosystem it is the obligation of the WRBWO now to stick to and enforce the recommendations of its own environmental flow assessment to regulate water usage in the watershed. A similar recommendation also holds for all other rivers and estuaries in Tanzania.

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