

Supplemental Information, Tables and Figures

For publication “Determination of Environmental Flows in data-poor estuaries – Wami River Estuary in Sadaani National Park, Tanzania”

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Contents:

The Supplemental Information document has been arranged into three sections:

1. Hydrology – summary of data (measured, historical, known water users), flood frequency analysis, tidal backwater measurements, channel cross-sections and bathymetry, hydrologic model performance and result summaries, water quality measurements.
2. Ecosystem – Riparian vegetation community zonation along estuary, list of fish species encountered in our catch efforts and market surveys, Wildlife water requirements, birds and reptiles encountered over field campaigns along with habitat use in estuary, local human community water needs, summary of current and projected threats to the estuary.
3. Environmental Flows Determination – results of minimum flow determinations for wet and dry seasons for ‘normal’ and ‘drought’ years, confidence assessment of the flow determinations.

Table S1: Physical Description of the EFA sites for hydrological field observations

Site Name	Site ID	Coordinates (WGS 1984)	Locality	Physical description
Matipwili	BBM 1	E 468513.17 N 9311004.92 UTM Zone: 37	It is located in Matipwili village, at the pump house of the irrigation scheme	Freshwater; ungauged; meandering with a short straight reach; low lying vegetated right bank; elevated and collapsing left bank; sand and gravels are material forming the channel bed; runs, pools and sand bars are present
Gama	BBM 2	E 475213.32 N 9314427.88 UTM Zone: 37	It is located at the Saadani National Park gate in Gama	Sea water backflow upstream limit; Abandoned gauging station; meandering with a short straight reach; elevated vegetated stable banks with isolated collapsing banks; bridge could be used as platform for flow sampling; runs, pools and sand bars occur instream

Table S2: Summary of measured discharges at three locations in August 2015

Station Name	Date	Mean Depth (m)	Width (m)	Mean Velocity (m/s)	Max Velocity (m/s)	Cross-sectional Area (m ²)	Discharge (m ³ /s)
Gama Gate	22 - 08 - 2015	1.34	36.5	0.105	0.329	62.92623	6.598
Matipwili Village	22 - 08 - 2015	1.53	30.0	0.121	0.375	59.15303	7.131
Wami Mandera	22 - 08 - 2015	2.10	45.0	0.059	0.109	118.7769	7.013

Table S3: Known water users between Matipwili and Gama Gate (used to estimate water withdrawals and thereby available flows at Gama Gate)

Water User	Village	Type of use	Type of Infrastructure	Date established	Amount (m ³ /d)	Amount (m ³ /s)	Remarks
Saadani village Water supply project	Saadani village	Domestic	Intake	10/1/2013	163.3	0.0019	
Sea salt industry	Saadani village	Domestic	Dozer	1977	24.0	0.0003	
Saadani National Park	Saadani village	Domestic	Dozer	2005	342.3	0.0040	
Kitame village water supply project	Kitame village	Domestic	Intake	10/1/2013	140.6	0.0016	
Zakaria Musa Farm	Gama -Kitame	Irrigation	pump	1997	40.0	0.0005	Based on estimates
Sabina Nyoni Farm	Gama -Kitame	Irrigation	pump	2014	60.0	0.0007	Based on estimates
Hamis Makenza Farm	Gama -Kitame	Irrigation	Pump	2015	60.0	0.0007	Based on estimates
"Mchugaji" Farm	Gama -Kitame	Irrigation	pump	2015	60.0	0.0007	Based on estimates
Sanctury River lodge	Gama -Kitame	Domestic	pump		15.0	0.0002	
H.J Stanley & Sons LTD (Utondwe salt work)	Kitame village	Domestic	Bulzers		25.0	0.0003	
Chalinze Water Supply	Chalinze area				9600.0	0.1111	
Total water used/abstracted					10530.2	0.1219	

Flood Frequency Analysis

Frequency analysis was carried out for annual maximum extracted from available daily data. The Generalized Extreme Value type 1 (GEV-1) and the Log-Pearson Type III probability distributions were fitted to the data. The best fit probability distribution was Log-Pearson Type III. The results of frequency analysis using the best fit probability distribution at the EFA sites are presented in Figure 1 while 4 presents a summary of flood quantiles. It is important noting that substantial amount of uncertainty is expected in the quality of data used, based on the unreliability of the higher flows estimates at gauging station (high flows not normally recorded at gauges) and are subject to the availability of data (ca.27years), which may not reflect present conditions as records end in the 1980s. The increase in deforested areas in the Basin since the 1980s (Yanda & Munishi 2007, FIU-GLOWS 2014a) suggests the possibility of a corresponding increase in high flows responding to large rainfall events because of lower rainfall interception by forests; however the existence of large discharge data gaps since the 1980s, together with the absence of the collection of high flow data by manual staff gage readings suggests an underestimation of flood frequency.

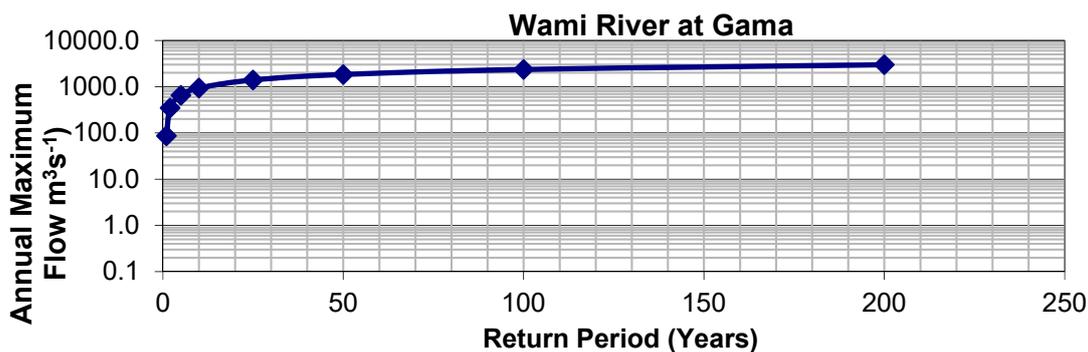


Figure S1: Annual Flood Frequency Analysis for Wami River at Gama EFA Site using Log-Pearson Type III (Analysis using Annual Maximum Flow: 1955-1981)

Table S4: Summary of maximum flow quantile for the Wami River at Gama

River Name	Q _T							
	1.0101	2	5	10	25	50	100	200
Wami River at Gama	86.4	346.8	654.3	936.8	1399.6	1835.1	2359.1	2989.3

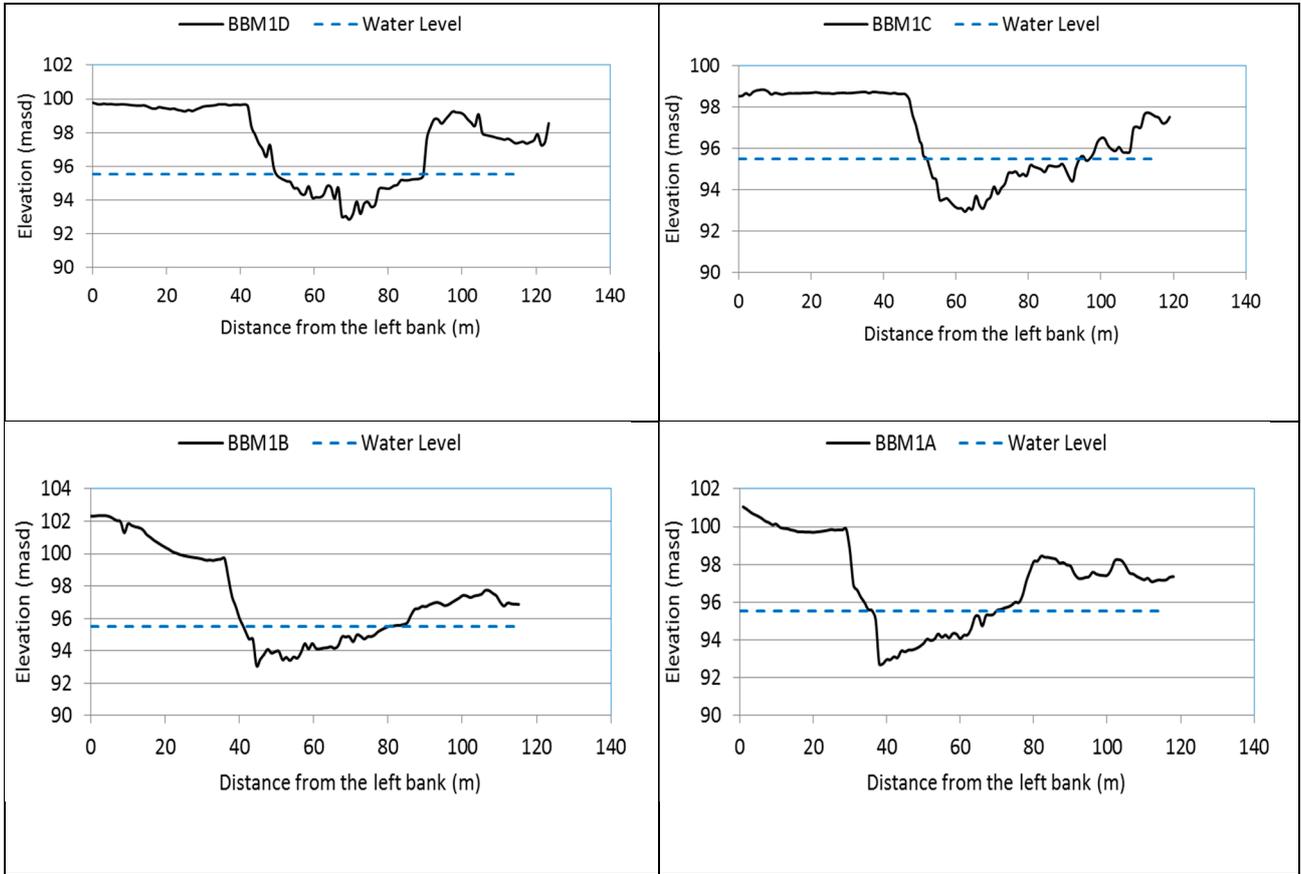


Figure S2: Cross-sectional channel profiles of the Wami River ar BBM1-Matipwili

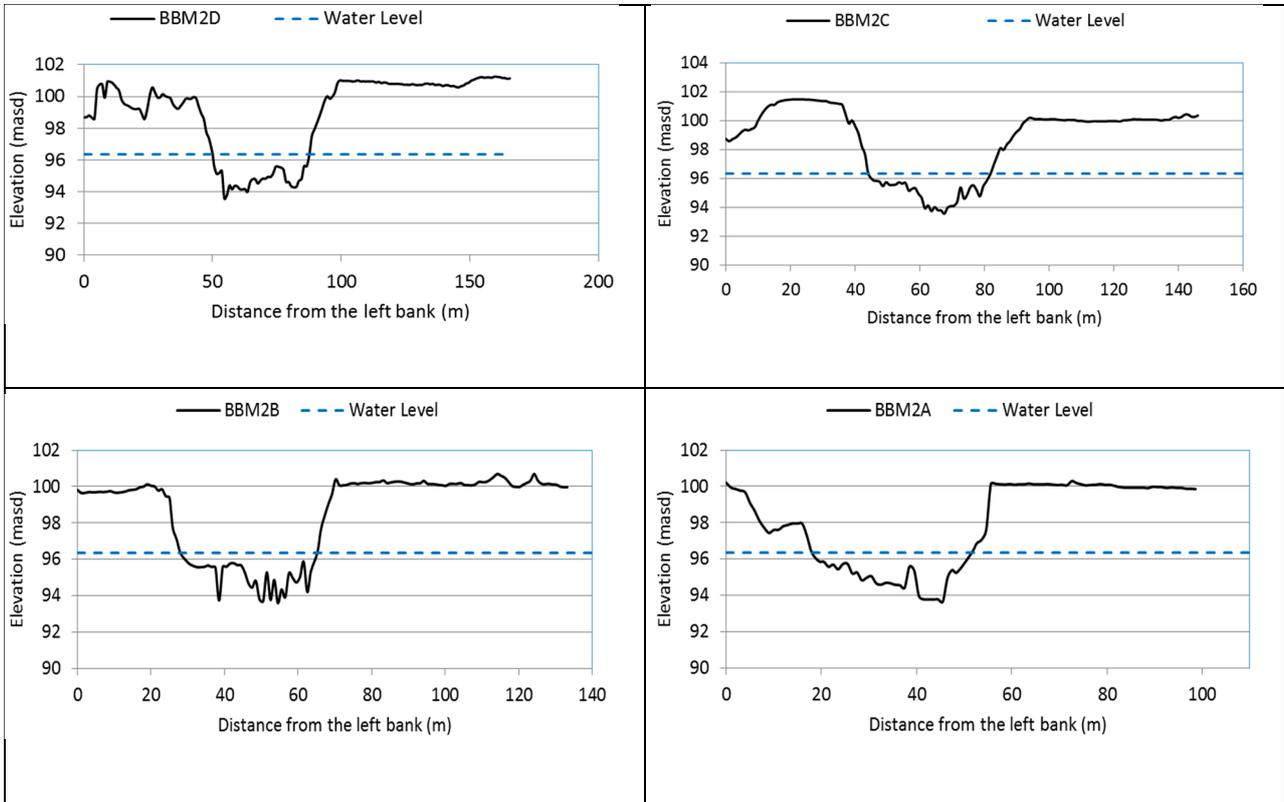


Figure S3: Channel cross-sectional profile of the Wami River at BBM2-Gama

Tidal backwater measurements:

The plot for Gama Gate shows that the flow speed dropped from 10 am to around 2 pm, and thereafter began to increase once again. The higher speeds occur when the water level is low, and as the water level rose from midmorning to mid afternoon, most probably as a consequence of being backed up by the incoming high tide at the estuary mouth, the speed of flow slackens. At Kinyonga, only the flowspeed was recorded between 11.30 am and 5 pm (Figure 24). Unlike the situation at Gama Gate (11.7 km upstream), the flow velocity appeared to increase from noon until mid afternoon. This was perhaps due to the river at Kinyonga experiencing low tide effects earlier than at Gama Gate. To understand the effect of tides on water level and flow in the estuary, it is clear that locations differed in tide conditions at an instant in time, and that there are lag effects that vary with distance upriver.

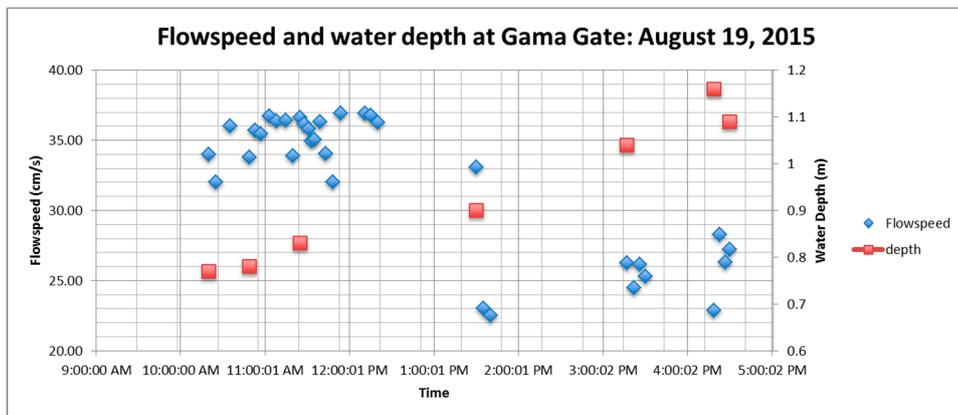


Figure S4: Flow speed and water depth at Gama Gate

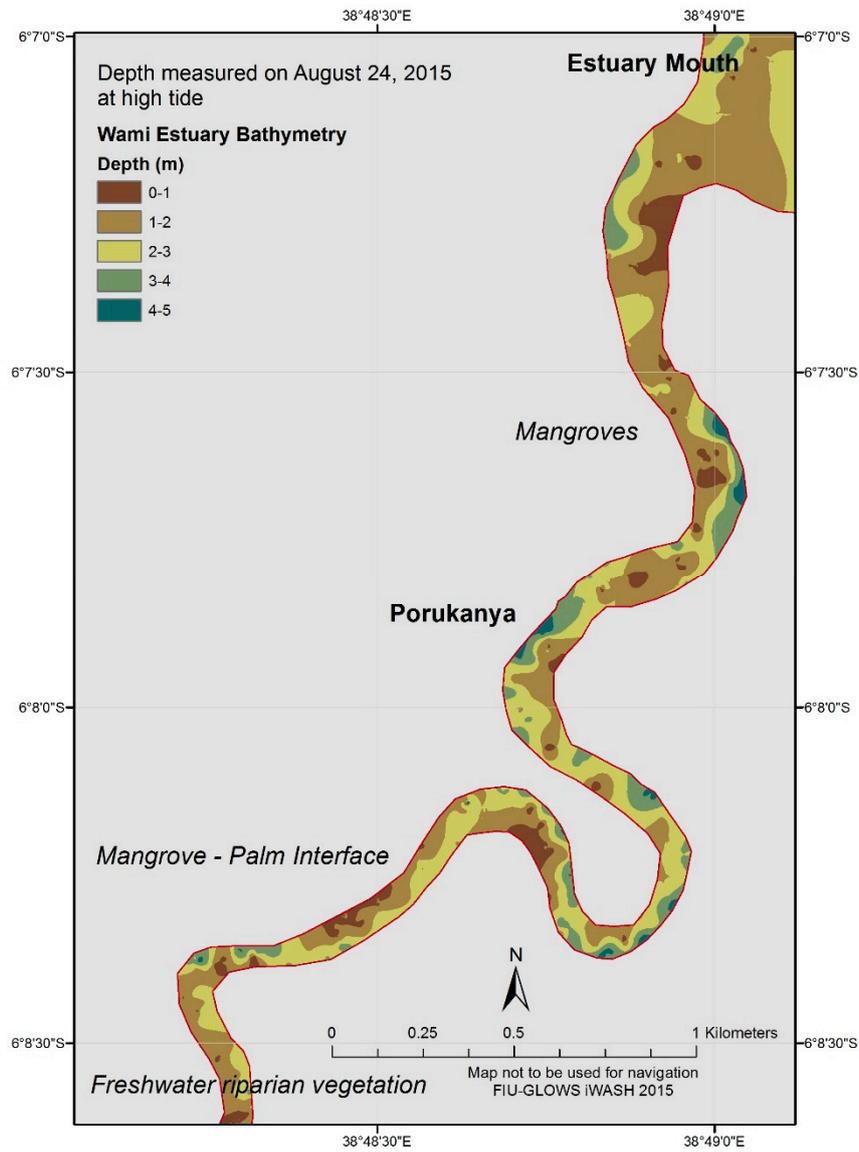


Figure S5: Wami Estuary Channel bathymetry upto freshwater vegetation section.

Channel bathymetry measurements give an idea of the channel geometry and depths along the course of the estuary from upriver to mouth, along with sediment deposits and sandbars. A bathymetry unit was attached to the stern of a boat which then travelled along the river downstream from Kinyonga campsite in a zigzag manner to get as many channel cross-sections as possible, given the need to traverse the entire estuary under a range of similar tidal conditions. The unit consists of a submerged ultrasonic depth finder sensor connected to a Goldilocks microprocessor board that recorded the depth to the river bottom at 1 second intervals and records the data on an SD card. The system is powered by a 12V motorcycle battery.

The map shows the expected channel depth morphology with scour sections (deep) and depositional sections (shallow) at opposite ends at channel bends. The depositional sections are colonized by hippo populations.

Table S5: Performance of hydraulic model at BBM1 site – Matipwili

Data Type	Transect	Mean Velocity (m/s)	Water Surface Elevation (masd)	Flow Area (m ²)	Flow Top Width (m)	Max. Water Depth (m)	Average Depth (m)
Observed	BBM1D	0.13	95.45	76.68	38.50	2.59	1.00
Simulated		0.16	95.42	38.21	39.12	2.53	0.98
Relative Error in %		20.6	0.03	50.2	1.6	2.3	2.0
Observed	BBM1C	0.17	95.50	82.16	40.00	2.54	1.23
Simulated		0.12	95.50	50.72	42.96	2.54	1.18
Relative Error in %		27.4	0.00	38.3	7.4	0.0	4.1
Observed	BBM1B	0.16	95.55	65.08	39.20	2.43	1.20
Simulated		0.13	95.52	45.06	39.07	2.41	1.15
Relative Error in %		16.8	0.03	30.8	0.3	0.8	3.9
Observed	BBM1A	0.13	95.60	72.74	35.00	2.88	1.48
Simulated		0.12	95.55	50.15	34.92	2.82	1.44
Relative Error in %		9.5	0.05	31.1	0.2	2.1	2.9

Table S6: Performance of hydraulic model at BBM2 site - Gama

Data Type	Transect	Mean Velocity (m/s)	Water Surface Elevation (masd)	Flow Area (m ²)	Flow top width (m)	Max. Water depth (m)	Average depth (m)
Observed	BBM2D	0.12	96.33	67.39	37.50	2.73	1.48
Simulated		0.12	96.28	55.18	36.86	2.67	1.50
Relative Error in %		3.7	0.05	18.1	1.7	2.2	1.2
Observed	BBM2C	0.11	96.33	72.04	37.80	2.77	1.31
Simulated		0.18	96.29	35.87	36.59	2.38	1.00
Relative Error in %		63.3*	0.04	50.2	3.2	14.1	23.8
Observed	BBM2B	0.12	96.34	60.24	37.20	2.74	1.22

Simulated		0.19	96.31	34.81	36.00	2.44	0.98
Relative Error in %		57.7*	0.03	42.2	3.2	10.9	19.9
Observed	BBM2A	0.15	96.35	58.21	33.60	2.71	1.38
Simulated		0.14	96.34	45.66	33.63	2.72	1.36
Relative Error in %		4.8	0.01	21.6	0.1	0.4	1.2

**Large velocity errors at the bridge approach and exist cross sections may be attributed to the ineffective flow areas.*

Table 7: Global summary statistics of hydraulic model performance and performance rating for both EFA sites

EFA Site	Relative error (%)				Remarks	Recommended transects	Performance rating 1-5
	Minimum	Maximum	Mean	Median			
Matipwili	0.00	50.17	10.51	2.58	<p>Simulated hydraulics matched well with field data/observations in most of the transects.</p> <p>The spotted errors in some of the transects could be attributed to both uncertainty in discharge measurements and complexity of the river geometry.</p> <p>The hydraulic model is based on only one sampling event.</p>	BBM1A	3
Gama Gate	0.01	63.3	14.32	3.48	<p>Simulated hydraulics matched well with field data/observations in most of the transects.</p> <p>The bridge approach and exit transects did not perform well.</p> <p>The spotted errors could be attributed to uncertainty in discharge measurements, lack of bridge design data, influence of the sea water backflow and complexity of the river geometry.</p> <p>The hydraulic model is based on only one sampling event.</p>	BBM2D	2

Water Quality

Turbidity

Wami Estuary is generally a turbid system because; first, it is tide- dominated estuary where strong tidal currents re-suspend fine sediments; second it has large population of hippopotami which re-suspend bottom sediments through their movements in water and; third, the high erosion from weak river banks add sediment to the river. During survey, turbidity was measured using a Secchi disk. The Secchi depth indicates the depth of the water column through which light can penetrate and the disk seen clearly. Hence, higher turbidity results in smaller values for Secchi depth. Values varied from 0.26 to 0.87 m with lowest value recorded at site 3 and highest value at site 2 (**Error! Reference source not found.**). Site 3 was more turbid than other sites because of presence of large group of hippo and significant river bank erosion. Also it is a place where elephants cross the river, swim and drink water (Visual observation by Kiwango). The similar pattern of water clarity was observed during both flood and ebb tides. However in shallow depths of less than 1 m. the water was clear enough to see the bottom of the river.

On a later visit to the estuary (September 13-14, 2015), the water level at Gama Gate had dropped by 25 cm when measured, and was much clearer.

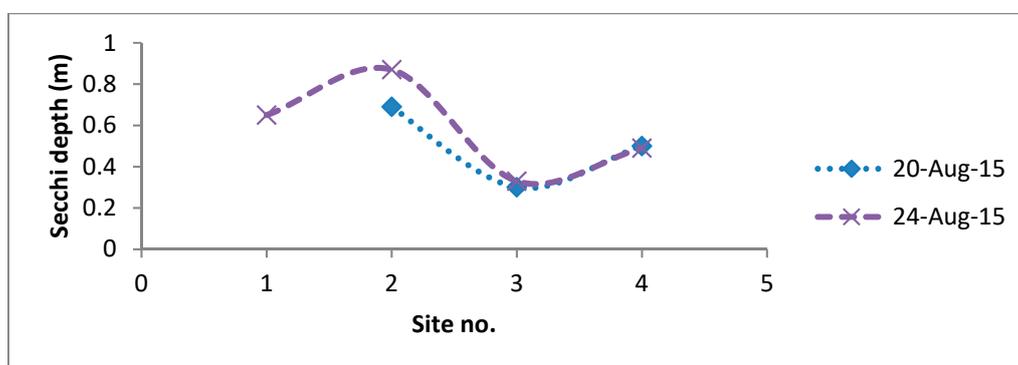


Figure S6: Water clarity during ebb (20 -Aug-15) and flood (24- Aug-15) tides.

Dissolved Oxygen (DO)

DO concentrations varied between 6.28 - 7.57 ppm (78.1 and 93.7 % saturation) and 6.74 - 7.66 ppm (80.7 - 95.4 % saturation) during flood and ebb tides respectively. High DO levels were detected at the surface and low level at the bottom. Moreover, values recorded during ebb tide were relatively higher than flood tide values, possibly a consequence of faster freshwater flows at ebb tide. Site 2 and site 3 which had hippopotami had lower values compared to site 1 and 4 at both flood and ebb tides. This could be because of high consumption of oxygen by microbial activities for decomposition of hippo feces. Generally the DO concentration is similar to that recorded in August 2007.

pH

pH in Wami Estuary throughout the sampling survey varied between 8.23 - 8.54 and 7.67 to 8.54 during ebb and flood tides respectively. Though the normal pH within estuaries may vary from 7 - 9, for Wami Estuary it appears as this parameter has more fluctuations compared to other parameters. For example in October 2003 at high tide pH was between 7.9 and 8.7, January 2004 at high tide it was between 8.3 and 8.6, October 2007 was 7.1 - 8 and 7.8 - 8.1 at low and high tide respectively (Kiwango unpublished). Factors that may cause pH fluctuation include salinity, freshwater and groundwater inflows and primary productivity. However, it is difficult to pinpoint the reasons for pH change in Wami Estuary since there are no detailed studies of ecological and biogeochemical factors affecting pH in the system.

Temperature, Total Dissolved Solids and Electrical Conductivity

Other water parameters such as water temperature, TDS and electric conductivity may provide some additional physicochemical properties of water. For instance, electrical conductivity (EC) of water indicates the presence of ions that are charged. Salt dissociates into sodium anions and chlorine cations; similarly many other inorganic chemicals from agriculture, industrial discharge and runoff also dissociate. Hence a higher EC indicates the presence of more ions in water. In this case, higher EC in flood tide, correlated with higher salinity readings stems from higher salt ions. Similar values of temperature and TDS were also recorded in August 2007. A summary of these water quality parameters observed during our sampling survey is indicated in the table below:

Table S8: Water quality parameters

Date	Tide	Water temperature (°C)	TDS (mg/L)	Electric conductivity (µS)
20-Aug-15	Ebb	26.2 - 27.2	105.7 - 439.4	162.7 - 677
21-Aug-15	Ebb	25.6 - 27.4	112.2 - 287.1	172.2 - 443
23-Aug-15	Flood	25.2 - 26.4	126 - 33940	197.8 - 52100
24-Aug-15	Flood	24.4 - 26.4	138 -90000	211 - 47450

ECOSYSTEM

Table S9: Distance along riverbank occupied by the different plant communities in the Wami River Estuary.

Habitat	Distance (km)
Mangrove forest	4.72
Mangrove-Palm ecotone	0.73
Palm forest	2.71
Palm-Riparian ecotone	0.51
Riparian vegetation	14.57
Total distance covered	23.24

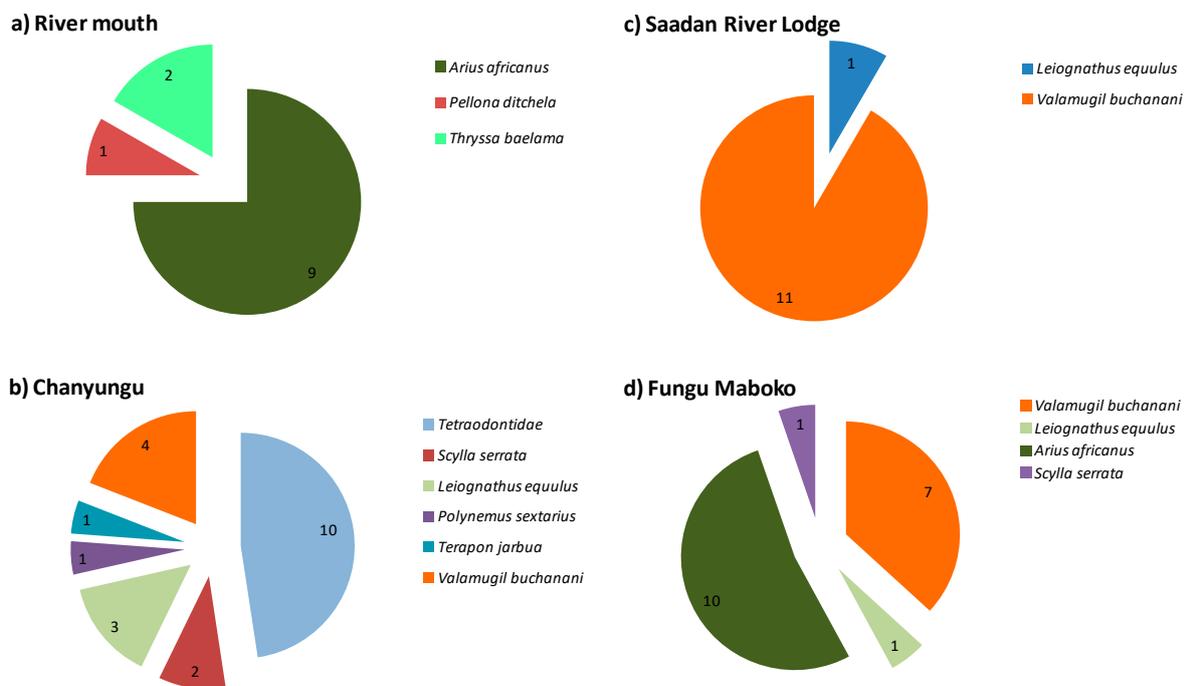


Figure S7: Catch composition of fish species at different locations in the Wami River estuary and within 2 kilometers offshore (Chanyungu). Numbers indicate number of individual fish species caught.

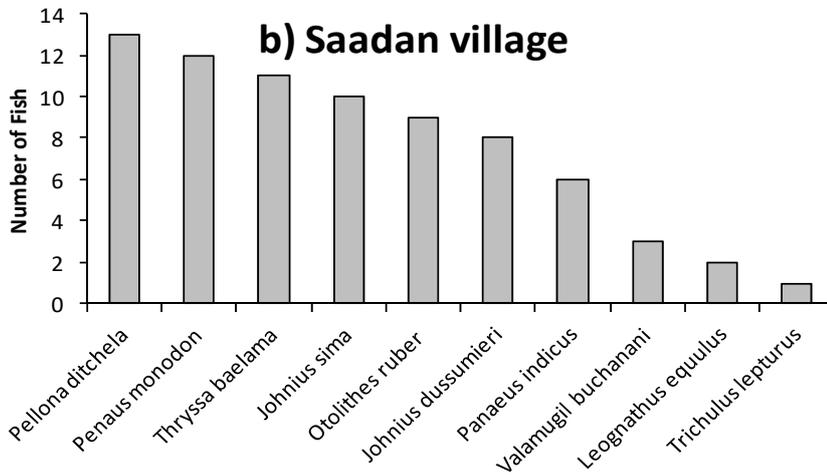
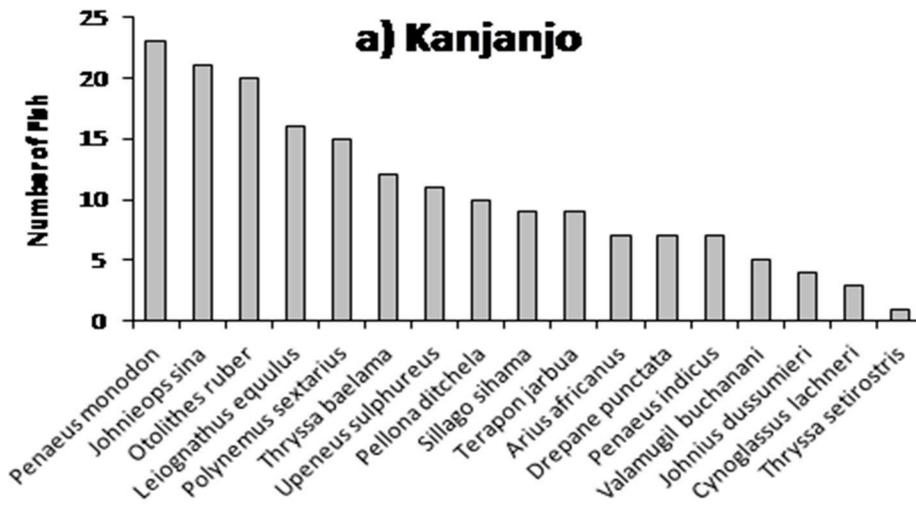


Figure S8: Number of fish caught in one day (August 2015) by fishermen at Kanjanjo and Saadan village landing sites

Table S10: Fish species encountered in the Wami Estuary Study

Area	Lat	Long	Species	Number
River Mouth	-6.11694	38.81704	<i>Arius africanus</i>	9
			<i>Pellona ditchela</i>	1
			<i>Thryssa baelama</i>	2
Chanyungu	-6.13457	38.83628	<i>Tetraodontidae</i>	10
			<i>Crabs (Scylla serrata)</i>	2
			<i>Leiognathus equulus</i>	3
			<i>Polynemus sextarius</i>	1
			<i>Terapon jarbua</i>	1
			<i>Valamugil buchanani</i>	4
Saadani River lodge	-6.15968	38.80814	<i>Jellyfish</i>	1
			<i>Leiognathus equulus</i>	1
Fungu Maboko			<i>Valamugil buchanani</i>	11
			<i>Valamugil buchanani</i>	7
			<i>Leiognathus equulus</i>	1
			<i>Arius africanus</i>	10
Kajanjo(Morning Fishers Catch)	-6.09474	38.79898	<i>Scylla serrata</i>	1
			<i>Otolithes ruber</i>	6
			<i>Pellona ditchela</i>	8
			<i>Thryssa baelama</i>	11
			<i>Polynemus sextarius</i>	15
			<i>Leiognathus equulus</i>	16
			<i>Johnius dussumieri</i>	4
			<i>Johnieops sina</i>	21
			<i>Penaeus indicus</i>	5
			<i>Upeneus sulphureus</i>	11
Kajanjo (Evening- Fishers Catch)	-6.09474	38.79898	<i>Penaeus monodon</i>	7
			<i>Penaeus indicus</i>	2
			<i>Penaeus monodon</i>	16
			<i>Arius africanus</i>	7
			<i>Pellona ditchela</i>	2
			<i>Thryssa baelama</i>	1
			<i>Cynoglossus lachneri</i>	3
			<i>Otolithes ruber</i>	14
			<i>Terapon jarbua</i>	9
			<i>Drepane punctata</i>	7
SaadaniVillage Landing Site Fishers Catch	-6.04534	38.78051	<i>Valamugil buchanani</i>	5
			<i>Sillago sihama</i>	9
			<i>Thryssa setirostris</i>	1
			<i>Trichulus lepturus</i>	1
			<i>Otolithes ruber</i>	9
			<i>Penaeus monodon</i>	12
			<i>Pellona ditchela</i>	13
			<i>Leiognathus equulus</i>	2
			<i>Penaeus indicus</i>	6
			<i>Thryssa baelama</i>	11
<i>Johnius sima</i>	10			
	<i>Johnius dussumieri</i>	8		
	<i>Valamugil buchanani</i>	3		

Mammals

Hippos are the most abundant mammal in the estuary (N=153) and constitute around 66% of all mammals observed while yellow baboon, black and white colobus monkey and blue monkey comprised 20%, 8% and 5% respectively, see appendix). Mammal distribution is influenced by habitat type and water quality. Primates appeared to avoid mangrove and seawater environments. Most primates were found in palm and freshwater riparian forests. The majority of individuals of Black and White Colobus monkeys and Blue monkeys appeared to prefer palm forest environment while yellow baboons were seen in the more open Acacia-savannas alongside the river. Most hippos were observed in freshwater, although a family was observed in brackish water on two days, where the salinity ranged from 2 ppt at the surface to 10 ppt at the bottom. That hippos prefers fresh water environment rather than sea water has been specified in the literature, showing hippos are greatly depends on freshwater environment which makes them susceptible to drought, agricultural and industrial developments (Lewison and Oliver, 2008). Hippos observed were ranging from 5-31 individuals; two large groups were seen in mangrove forest environment were of 31 and 25 individuals, palm had two large groups as well of 28 and 23 individuals, palm-riparian group has 4 individuals and 15 individuals group at riparian environment. Although small groups of hippos observed ranged from 1-5 individuals, the normal range is from 20 to 100 individuals (Barklow, 2004). Several trails have been seen along the river channel; these trails also constitute sub-channels during high tide and wet season, when they provide lagoons and side pools that small fish retreat during drought (Eltringham, 1999; Mosepele, et al., 2009). Other wildlife in the park, such as elephants, giraffes, lions, warthogs, ungulates and antelopes were encountered in the savanna part of SANAPA on our way to the estuary; however, since our observations were largely restricted to the estuary, we do not have any direct observation of these animals in the short time frame of the study.

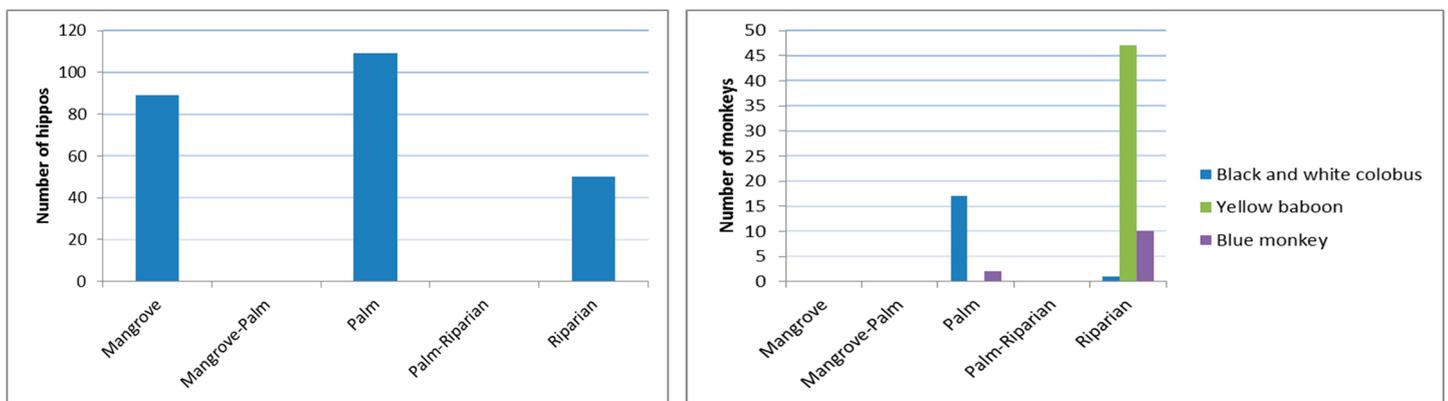


Figure S9: Number of hippos (left) and primates (right) in different habitats. Errata: left graph should read 59, 51, 4 and 39 individuals of hippopotami.

Table S11: Estimated population size of terrestrial mammals, their maximum water consumption per day per individual species and per whole population

EPS=Estimated Population Size (Source: Ismail *et al.*, 2015); EWC=Estimated Water Consumption

Terrestrial mammal Name	EPS	Maximum estimated water consumption per individual (Litre/day)	Amount required per population (Litre/day)
Yellow baboon	6546	2	13092
Common waterbuck	2710	20	54200
African buffalo	2560	55	140800
Masai Giraffe	894	80	71520
Bohor Reedbuck	753	20	15060
Hartebeest	683	40	27320
Sable antelope	673	40	26920
African elephant	633	300	189900
Common warthog	442	20	8840
Wildebeest	210	40	8400
Eland	90	50	4500
Lion	90	10	900
Harvey's duiker	80	10	800
Bushbuck	70	10	700
Zebra	70	50	3500
Bush pig	70	20	1400
Greater Kudu	60	30	1800
Suni	30	10	300
Grey duiker	20	10	200
Side stripped jackal	20	5	100
Spotted hyaena	20	5	100
African civet	10	2	20
Leopard	10	10	100
Blue monkey	12	2	24
Black and White colobus monkey	18	2	36
Total	16774	843	14140482

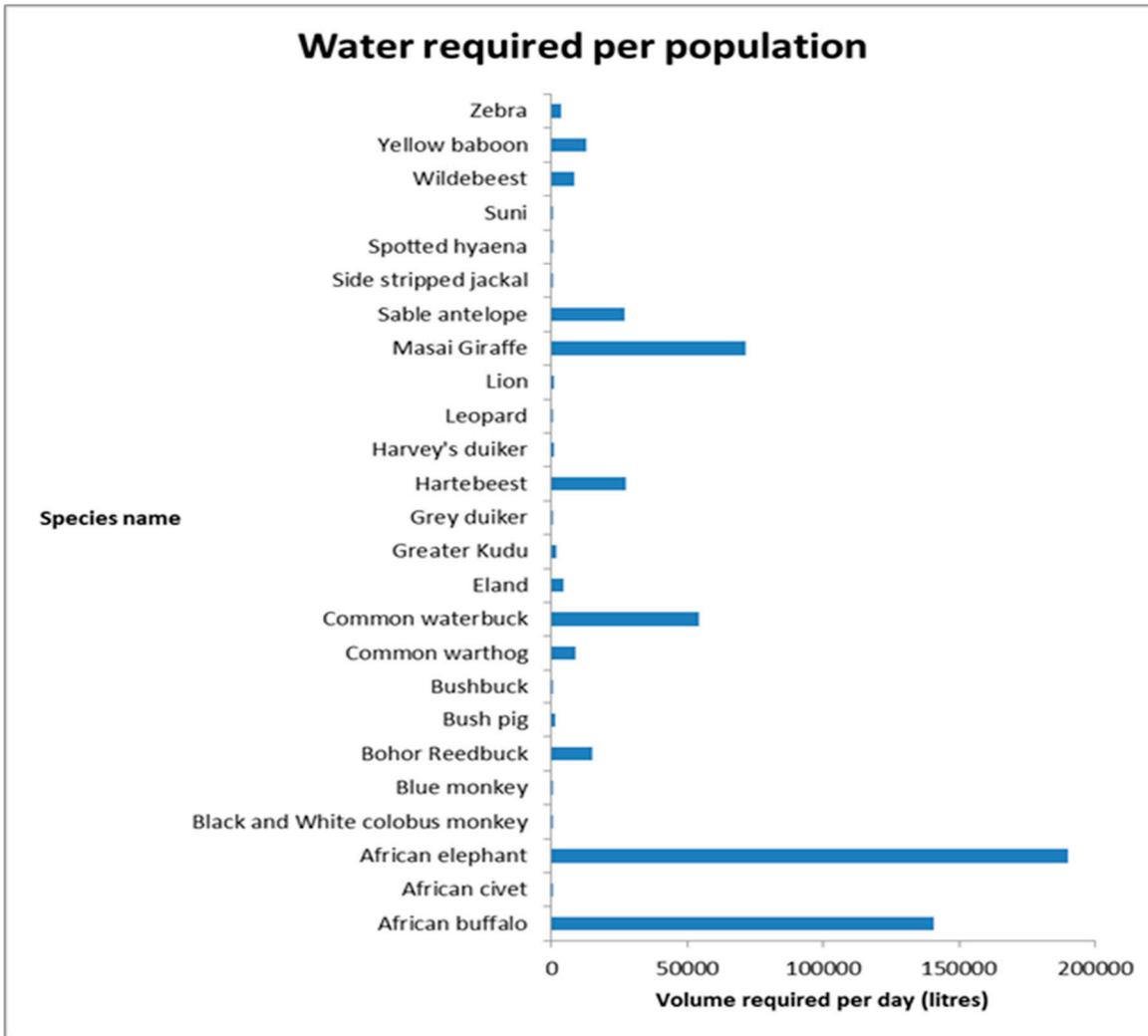


Figure S10: Water required per population of terrestrial wildlife species in Sadaani National Park

Birds:

About 28 bird species have been identified (Supp Info); an increase in abundance and species diversity of birds was observed as one travelled upstream, with the largest and most diverse assemblages occurring in the freshwater riparian environment. In freshwater riparian environment (salinity 0.08 ppt as measured), some birds such as Golden Weavers build nests hanging over the river, some kingfisher species excavated holes in high cliffs at points where water level cannot reach even during spring tide and on top of this steep sandy river bank mostly topped by *Acacia zanzibarica* species. Woolly-necked storks, Little bee-eaters, Intermediate Egrets, Pink-backed pelican, African Golden Weaver, African Spoonbills and Pied kingfisher were observed in every habitat of the estuary except weavers as they inhabited at the tall grasses found in riparian environment.

Table S12: Name, composition and habitat of water birds observed in Wami Estuary

Avians	Scientific name	Number observed	%	Mangrove	%	Mangrove-Palm	%	Palm	%	Palm-Riparian	%	Riparian	%
African Pied Wagtail	<i>Motacilla aguimp</i>	2	0.4376368	0	0	0	0	0	0	0	0	2	0.7407407
Little bee eater	<i>Merops pusillus</i>	46	10.065646	0	0	0	0	0	0	0	0	46	17.037037
Long-tailed Cormorant	<i>Phalacrocorax africanus</i>	8	1.750547	8	10	0	0	0	0	0	0	0	0
Crested Guinea fowl	<i>Guttera pucherani</i>	2	0.4376368	0	0	0	0	0	0	0	0	2	0.7407407
Woolly-necked Stork	<i>Ciconia episcopus</i>	54	11.816193	19	23.75	7	87.5	8	13.793103	16	39.02439	4	1.4814815
Black Kite	<i>Milvus migrans</i>	1	0.2188184	0	0	0	0	0	0	0	0	1	0.3703704
Little Egret	<i>Egretta garzetta</i>	6	1.3129103	6	7.5	0	0	0	0	0	0	0	0
Intermediate Egret	<i>Mesophoyx intermedia</i>	37	8.0962801	8	10	1	12.5	11	18.965517	3	7.3170732	14	5.1851852
Eurasian Swift	<i>Apus apus</i>	27	5.9080963	16	20	0	0	0	0	0	0	11	4.0740741
African Fish Eagle	<i>Haliaeetus vocifer</i>	1	0.2188184	1	1.25	0	0	0	0	0	0	0	0
Pallid Harrier	<i>Circus macrourus</i>	2	0.4376368	0	0	0	0	0	0	0	0	2	0.7407407
Grey heron	<i>Ardea cinerea</i>	18	3.9387309	8	10	0	0	5	8.6206897	2	4.8780488	3	1.1111111
Hamerkop	<i>Scopus umbretta</i>	8	1.750547	0	0	0	0	0	0	2	4.8780488	6	2.2222222
Crowned Hornbill	<i>Tockus pallidirostris</i>	3	0.6564551	0	0	0	0	0	0	0	0	3	1.1111111
Malachite Kingfisher	<i>Alcedo cristata</i>	2	0.4376368	0	0	0	0	0	0	0	0	2	0.7407407
Mangrove Kingfisher	<i>Halcyon senegaloides</i>	14	3.0634573	8	10	0	0	6	10.344828	0	0	0	0
Palm-nut vulture	<i>Gypohierax angolensis</i>	3	0.6564551	0	0	0	0	0	0	1	2.4390244	2	0.7407407
Africa Paradise Flycatcher	<i>Terpsiphone viridis</i>	1	0.2188184	0	0	0	0	0	0	0	0	1	0.3703704
Pink-backed pelican	<i>Pelecanus rufescens</i>	45	9.8468271	0	0	0	0	0	0	0	0	45	16.666667

Great White pelican	<i>Pelecanus onocrotalus</i>	26	5.6892779	0	0	0	0	0	0	0	0	26	9.6296296
Pied Crow	<i>Corvus albus</i>	1	0.2188184	0	0	0	0	0	0	0	0	1	0.3703704
Pied Kingfisher	<i>Ceryle rudis</i>	11	2.4070022	6	7.5	0	0	0	0	0	0	5	1.8518519
Common Sandpiper	<i>Actitis hypoleucos</i>	25	5.4704595	0	0	0	0	25	43.103448	0	0	0	0
African Pygmy Kingfisher	<i>Ispidina picta</i>	2	0.4376368	0	0	0	0	0	0	0	0	2	0.7407407
Sacred ibis	<i>Threskiornis aethiopicus</i>	5	1.0940919	0	0	0	0	3	5.1724138	0	0	2	0.7407407
African Spoonbill	<i>Platalea alba</i>	37	8.0962801	0	0	0	0	0	0	17	41.463415	20	7.4074074
Water Thick knee	<i>Burhinus vermiculatus</i>	17	3.7199125	0	0	0	0	0	0	0	0	17	6.2962963
African Golden Weaver	<i>Ploceus subaureus</i>	53	11.597374	0	0	0	0	0	0	0	0	53	19.62963
Total birds		457	100	80	100	8	100	58	100	41	100	270	100

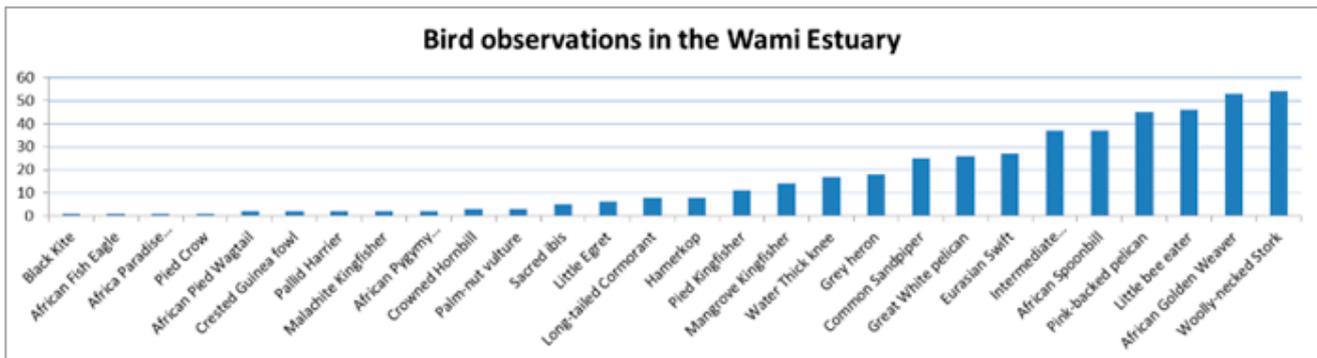
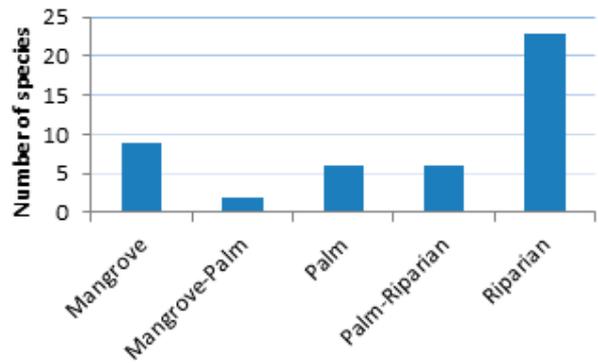
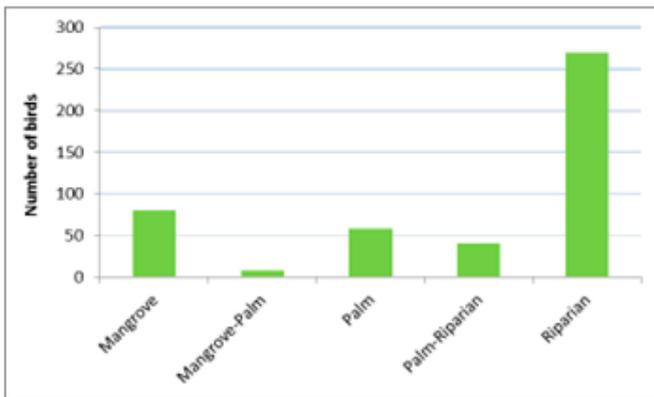


Figure S11: Number of individuals and number of bird species encountered in different habitat types

Large Reptiles

During this study, the Nile crocodile (*Crocodilus nilotica*) was the dominant reptile throughout the Wami Estuary, and was the most abundant in the freshwater section, from palm-riparian transition zone to riparian forests. About 47 % of crocodiles were sighted in the freshwater riparian environment, followed by 24% in palm-riparian transition zone, thus indicating a preference for riparian and palm environment. As salinity increased in the river, the number of crocodiles decreased: the palm zone (salinity, 0.1 ppt) and mangrove-palm transition zone held 11.77% while mangrove (salinity, 0.26 ppt) held 6% of all sighted crocodiles. A few green monitor lizards were seen in palm habitat along the riverbank (salinity, 0.1 ppt). This study being boat-based was able to observe only large reptiles, hence, lizards and snakes were not seen, apart from a green mamba in the riparian forest at Kinyonga Camp.

Human water use

Pastoralists use areas with shallow water for their cattle to drink; these shallow areas are also preferred by Nile crocodiles. When water tide is very low, they bask on the river banks on sand beaches and short small patches of grasses but when water surface level increases they return in river channel to feed on fishes coming from the ocean. The salinity changes of water in riparian to palm forest environment is low (0.1 ppt) compared to mangrove forest environment (ranging from 0.2-5 ppt) and at river mouth is very high up to 20 ppt during medium tide level and crocodiles preferred to stay on 0.1 to 0.2 ppt as observed in the field.

Table S13: Water uses by human communities around the Wami Estuary

Water User	Village	Ward	Location (Gps)	Population	Type Of Use	Water Source	Amount	Water Use Permit	Type Of Infrastructure	Major Production	Year Established	Remarks
Saadani village Water supply project	Saadani village	Mkange	S 06° 10.779" E 038° 47.258"	1,609	Domestic	Wami River	163.3m ³ /day	No	Intake	NA	Oct. 2013	
Sea salt industry	Saadani village	Mkange	S 06° 01.556" E 038° 46.654"	500	Domestic	Wami River	24m ³ /day	No	Water Bowser	Salt	1977	
Saadani National Park	Saadani village	Mkange			Domestic	Wami River		No	Water Bowser	NA	2005	
Kitame village water supply project	Kitame village	Makulunge	S 06° 10.779" E 038° 47.529"	1452	Domestic	Wami River	140.6m ³ /day	No	Intake	NA	Oct. 2013	
Zakaria Musa Farm	Gama - Kitame	Makulunge	S 06° 12.465" E 038° 46.841"	Aprox. 5 ha	Irrigation	Wami River	40m ³ /day	No	Pump	Vegetable farming	1997	Based on estimates
Sabina Nyoni Farm	Gama – Kitame	Makulunge	S 06° 12.465" E 038° 46.840"	Aprox. 7 ha	Irrigation	Wami River	60m ³ /day	No	Pump	Vegetable farming/ Fishing	2014	Based on estimates
Hamis Makenza Farm	Gama - Kitame	Makulunge	S 06° 10.779" E 038° 47.529"	Aprox 2 ha	Irrigation	Wami River	60m ³ /day	No	Pump	Water melon Fruits	2015	Based on estimates
"Mchugaji" Farm	Gama - Kitame	Makulunge		Aprox 10 ha	Irrigation	Wami River	60m ³ /day	No	Pump	Vegetables	2015	Based on estimates
Sanctury river lodge	Gama - Kitame	Makulunge		60	Domestic	Wami River	15m ³ /day	No	Pump	Hotel		
Santuary Saadani Safari Lodge	Saadani village	Makulunge		90	Domestic	Borehole		No	Borehole	Hotel		Not applicable
H.J Stanley & Sons LTD (Utondwe salt work)	Kitame village	Makulunge		100	Domestic	Wami River	25m ³ /day	No	Water Bowser	Salt	1960s	

Major threats to the estuary and its ecosystem services

- Clearing of mangroves for salt pans, charcoal, timber, settlements (fishing camp)
- Increased water abstraction upstream/ downstream - decreasing water flows
- Increase migrating livestock
- Inefficiency use of water or irrigation
- Cultivation along the buffer zone
- Use of pesticides
- Siltation due catchment degradation
- Sea water intrusion at increased rate
- Huge investments along the river; hotels etc
- Climate change

Sustainable utilization and management of resources at the Wami Estuary should be emphasized to avoid future catastrophe. The currently situation in resources utilization positions the basin at great risk due to escalating emerging threats at the Estuary and surrounding areas. The growing population, increased abstraction, and clearing of mangrove are some of the detected threats as discussed below:

Increased population growth

With rapid population increase, there is also an increased demand on environment services. As people struggle to improve their livelihood much pressure is invented to exploitation of natural resources. Studies indicate that there has been a rapid population growth over past two decades, between 1988 -2002, the growth rate was 6.1% compared to that of 1.0% in past 10 years (URT, 2004). This has been due to the influx of people migrating to the area mainly for fishing. However, the increase has been escalating by the presence of salt industries employing large number of workers and pastoralist migrating to adjacent villages with large number of livestock. Increasing human populations result in increased pressures on resources of the Wami River Estuary to support their livelihoods.

Clearing of mangroves

McNally et al (2011) describe the effects of prohibiting indiscriminate mangrove treecutting in the Sadaani National Park upon resources availability to local communities. While firewood costs increased, as this had to be sourced from further away, the newly granted protection to the mangrove forests benefitted prawns, molluscs, crabs and fish populations, with subsequent increases in fish catch across all economic groups in the villages. The clearing of mangrove was noted back in 1990s, caused by destructive activities happening along the coast. The establishment of salt pans largely involves clearing of vegetation, and has an impact on mangroves. The current expansion of salt pans within the estuary and coastal areas has greatly reduced mangrove coverage along the coast of Bagamoyo. While the existing salt works provide revenue benefits to SANAPA, and income to the local community, they also constitute a very important permanent habitat for a wide variety of aquatic birds including several species of flamingoes (Omary 2015). A balance is necessary between the benefits from salt pans and the loss of benefits resulting from the destruction of mangroves.

The following human activities have also been mentioned by interviewed communities; illegal cutting of mangroves for firewood, charcoal and timber. It was revealed that Zanzibar has been a good market for charcoal and firewood. Establishment of settlements at the fishing camp within the mangrove forest in Saadani village was another noted threat calling for an immediate sustainable Environmental Management strategy.

Increased human activities upstream/ downstream the Wami

Water abstraction in the Wami is largely for irrigation, domestic and industrial use. Of recent, there has been an increase in the number of users abstracting from the Wami River both upstream and downstream leading to management challenges for the Wami/Ruvu Basin Water Board, Many are unlicensed water abstractions. The largest water users in the Wami include, Mtibwa Sugar Company, Chalinze Water projects, Dakawa Irrigation scheme and the recently established Eco-Energy project just upstream if the Sadaani National Park. A decrease in water flows in the Wami was cited as a result of increased water abstraction although further studies are required to assess the validity of this argument.

The present study revealed that despite of the presence of the WRM Act 2009, the component of enforcement is still a challenge. This was also observed at the Wami Estuary, where the buffer zone has been encroached by human activities, including cultivation within 60 meters from river banks. It was also noted that water is inefficiently used for irrigation purposes, as users do not pay the real value of the water and abstractions are not monitored. The widespread use of pesticides also impacts the quality of water and on living organisms depending on the river. Another issue of concern is increased sedimentation due to catchment degradation and soil erosion, resulting from deforestation, poor agricultural practices,

livestock, encroachment of river banks and wetlands. Of great interest was the increased rate in sea water intrusion impacting on water quality. According to interviews with communities in Saadani, salt water intrudes further compared to the past. The impact was felt after the establishment of a water project where they claimed to have been pumping salt water during high tides. Another significant environmental threat would be the expansion of salt pans which impacts the sustainability of mangroves.

Conclusion

The socioeconomic component of the study highlights the major human uses of resources offered by the Wami estuary – freshwater as well as fisheries, forest resources and wildlife tourism-based economic opportunities. The study provides a baseline overview to integrate information already available through other studies. It further points the major environmental threats to the estuary. Human water use is dominated by irrigation and domestic uses which account for about 90% of the water withdrawn from water sources within the basin. With increased population growth and socioeconomic development, the demand for water is likely to double in a few years. A sustainable approach to water management is sought to be achieved through an integrated water resources management. Such an approach is also necessary for maintaining the ecosystem that has provided the basic services supporting the lives and livelihoods of local communities, as well as resources for people living further away from the Wami estuary, by providing assets such as mangrove poles and others, as well as benefiting fisheries and tourism activities.

Additional reading for the Wami Basin

Gritzner, J., & Jemison, R. (2009). USDA Forest Service Technical Assistance Trip Report. https://www.crc.uri.edu/download/USFS_Wami_Wetlands_Gritzner_Jemison_2009.pdf

McNally, C. (2007). A follow-up dry season rapid ecological assessment of the Wami River Estuary, Tanzania. *Coastal Resources Center, University of Rhode Island*. Accessed https://pdf.usaid.gov/pdf_docs/PNADN808.pdf

Environmental Flows determination

Table S14: Maintaining the dry season low flows for drought years (November)

Component	Depth (m)	Flow at Gama Gate (m ³ /s)	Motivation	Consequences of not providing this flow
Fish	0.5	1	SURVIVAL, maintain habitat within channel, <i>P. Indicus</i> sensitive	Lose juveniles as November is beginning of spawning period, loss of critical habitat, lifespan 2 years, multiyear drought = population disappearance
Wildlife	1.5	6.6	SURVIVAL, only source of freshwater in SANAPA, hippos, crocs and water birds; water source for other wildlife	Lower diversity and abundance, chance of local extinction of water-dependent wildlife, fishkills resulting from very low oxygen in hippo pools, if flow is very little.
Riparian vegetation	1	3.3	SURVIVAL of trees, prevent cavitation and mortality, maintain annual vegetation on river bend beaches	Tree mortality from extreme water stress, dry soil + understory promotes fires in riparian zone from inland farms
Water quality	1.5	6.6	Maintain sufficient mixing and circulation of water for survival of estuary species, particularly phytoplankton; maintain water residence time < 10 days	Hypersaline water inhibits survival of estuarine organisms; eutrophication and harmful algal blooms can occur; anoxia due to decomposition of hippo dung leads to fishkills
Social	1.5	6.6	Water supply projects to be able to pump water (at low tide); insuring water security for domestic use; also ensures fishing downstream (estuary) for food and income; provision of water for livestock; sufficient flow for water quality; flushing pollutants and salt dilution	Watersecurity and availability negatively impacted; livelihood, health, revert to unimproved sources, and income negative impact; Increased potential for conflict between groups over access to water
Geomorphology			Keep water flowing	Prevent pools and excess sedimentation
Agreed Hydraulics	1.5	6.6	0.5 is disastrous as large part of estuary saline, saltwater intrusion far upriver, while 2 m ³ /s is sometimes unattainable from inflows; maintain water quality, enough for hippos, fish, water uptakes	

Table S15: Maintaining the wet season low flows for drought years (April)

Component	Depth (m)	Flow at Gama Gate (m ³ /s)	Motivation	Consequences of not providing this flow
Fish	2	11	Spawning for marine fish; catadromous fish (live in ocean and come to spawn in freshwater – eels, hilsa); to inundate more bank area where aquatic vegetation grows, more habitat, shelter and feeding, leading to greater productivity	Loss of hydrologic connectivity; water remains in channel and adjacent vegetation covered banks are not inundated, so fish do not have access to prey and shelter
Wildlife	3	24	More breeding activities, training juveniles how to defend themselves, gather prey; increased foraging, hippos can get more food closer to river channel and not have to wander further offshore, in competition with livestock; Elephant and buffalo movements in corridors during wet season; migration route crossing river; Banw colobus monkeys feed on invertebrates in riparian trees	Reduced abundance and diversity of aquatic biodiversity because of breeding being impaired; riparian gallery forest habitat
Riparian vegetation	2	11	Maintain water and nutrient uptake for photosynthesis and growth	Growth of trees can be interrupted or hampered if insufficient water is available in soil (capillary and root uptake of groundwater from river source)
Water quality	3	24	Maintain normal ecosystem function and adequate flushing of materials (particularly nutrients and sediment) to the sea	Inadequate flushing can lead to increase in sediment and nutrient loading to the estuary
Social	3	24	Guarantee water security for domestic use; river condition for fishing (fish spawning for instance) for food and income; not concerned with water for livestock and irrigation; sufficient flow to maintain water quality	Water security may be negatively impacted, as also incomes and health; <i>peneus indicus</i> (marine) prawn catch is related to good freshwater inflow
Agreed Hydraulics	3	24	9.1 is available, max available is 80 cumecs (historical data – natural flows)	

Table S16: Maintaining the dry season low flows for maintenance years (October)

Component	Depth (m)	Flow at Gama Gate (m ³ /s)	Motivation	Consequences of not providing this flow
Fish	1.5	6.6	Dry period, survival, more nutrient uptake, better growth, hydrologic connectivity between diff parts of estuary, more flushing	Fitness of fish can be affected, especially if following year may be a drought; also
Wildlife	2	11	Hippos need particular amount of water for reproduction (males and females need to be submerged, so below 1.5 m cannot submerge; april – nov is mating season, gestation 8 months), crocs and water birds (prey availability – fish); maintaining water quality and quantity is needed for aquatic biodiversity	Low reproduction;
Riparian vegetation	1.5	6.6	Support leaf flush, flowering and fruiting in some woody species; food source for wildlife using riparian habitat; herbaceous/graminoids on bank	Plant water stress; dry conditions promote fires spreading from interior adjacent farms; pest outbreaks possible under dry conditions
Water quality	2.4	15	Maintain adequate water to support primary and secondary productivity; maintain salinity intrusion within the tidal limit area (Kinyonga)	Decreasing estuary primary/secondary productivity; saline intrusion may exceed tidal limit area and affect composition and abundance and distribution of estuarine biota
Social	2	11	Same as dry low in drought year – ensure water supply, fishing (major occupation for people), livestock, irrigation (vegetables), tourism (boating); guarantees sufficient flow to maintain water quality (dilution and flushing of pollutants	Water security negatively impacted; livelihoods health and income may be impacted negative; tourism negatively affected
sediment	2	11	Minimize excess deposition of sediments on convex bank	
Agreed Hydraulics	2.4	15	5.5 is available from historical data	

Table S17: Maintaining the wet season low flows for maintenance years (April)

Component	Depth (m)	Flow at Gama Gate (m ³ /s)	Motivation	Consequences of not providing this flow
Fish	3	24	Spawning period; excess freshwater provides reproductional cues for freshwater fish that spawn in the sea (catadromous);	Affect reproductive success and recruitment for next season; loss of migration corridors and less fish abundance
Wildlife	4	45	Diversifying aquatic habitats; diversity of foraging and grazing grounds; maintains adequate depth for boat safari; migration and immigration happens in wet season; enhancing mangrove community ecosystem productivity and dependant wildlife	Reverse of motivations elements; animals would be constrained for foraging, reducing genetic variation on account of inhibited ranging;
Riparian vegetation	3	24	Wet season = season of growth because of high water and nutrient availability.	Suboptimal growth during wet season reduces fitness (for flowering, fruiting) in ensuing dry season; if drought follows, trees do not have adequate storage of nutrients and carbohydrates
Water quality	3.5	33	Same as wet season low flow in drought year	Same as wet season low flow in drought year
Social	3	24	Ensure water security for domestic, fisheries, water quality (dilution and flushing of pollutants)	Water security and availability and livelihoods will be impacted negatively
Agreed Hydraulics	4	45	18.2 is available, max available from historical naturalized flows is 96 cumecs.	

Table S18: Maintaining the wet season high flows for drought years (April)

Component	Depth (m)	Flow at Gama Gate (m ³ /s)	Motivation	Consequences of not providing this flow
Fish	6	147	Spawning; especially for marine fish; isolated peaks as this is a drought year; at least one peakflow for a week; inundating floodplain transports nutrients from the floodplain to the river	Affects successful recruitment of floodplain spawners such as clarias
Wildlife	5	88	Same as wet season low flow in drought year; moving of drowned trees downstream, flushing the most tolerant invertebrates that have established during prior dry season, allowing for recolonization of greater aq. invertebrate diversity	Same
Riparian vegetation	5	88	Adequate nutrient uptake; suppressive invasive herbaceous vegetation; not more than a weeklong consecutive flooding period, replenish soil moisture that can be low in a drought period	If floodplain not inundated, less nutrients and sediment comes in (for trees) .But, if more than a week, 2 weeks, then trees get flood stressed.
Water quality	5	88	Maintain flushing of materials; enhance nutrient cycling between mangroves/vegetation and adjacent waters; few days to a week of continual inundation	Low productivity; turbidity and sedimentation increases; reduces light penetration for photosynth and predator-prey visibility
Social	5	88	Floods required for moisture within floodplain, recharging water table (boreholes and ponds); duration: 1 week	Livelihoods, health and income negatively impacted if flood event does not occur that replenishes water and nutrients in floodplain
Agreed Hydraulics	6	147	available	

Table S19: Maintaining the wet season high flows for maintenance years (April)

Component	Depth (m)	Flow at Gama Gate (m ³ /s)	Motivation	Consequences of not providing this flow
Fish	6	147	Spawning; removal of excess sediment/mud in channel; Two peaks – one in march/april, other in may/june of duration 2 weeks each (for spawning of labeo and repeated spawners)	Affects spawning, same as above
Wildlife	7	200	Actually Recommends 10 m because – oxbow lake (garuka) is filled only when this level of flooding happens (in good years, wet years); but 10 m will flood the bridge at gama gate. So 7m once every two years.	No oxbow lake (hippo and elephant and other wildlife incl fish and birds)
Riparian vegetation	6	147	Sediment and nutrient transfer to floodplain via inundation and transport; suppress invasive herbaceous vegetation. Flooding duration NOT exceeding 2 weeks at a stretch. Two flood events preferable.	Impoverished floodplain in terms of nutrients and soil; invasive vegetation establishing;
Water quality	6	147	Same as above	Same as above
Social	6	147	Same as above; inundation over wider areas (max 100 m away from bank); a week of continual flooding; only in the long rains (march-may)	
Agreed Hydraulics	7	200	6m depth twice per year AND 7 m depth once every alternate year. This also flushes river of deposits on scouring bank	

Confidence estimates of the assessments

The assessments were made from a combination of literature findings, the professional knowledge of the experts, the experience of the SANAPA staff, field observations over the 5-10 day period and interviews with local village communities. It thus represents an attempt to collect the best available knowledge, both technical and anecdotal about the estuarine ecosystem, its interconnections with hydrology and the services it provides to wildlife and local communities, and thereby add to the scientific knowledge base for the region. As mentioned before in various chapters, there is very little in-depth scientific literature for the ecosystem, nor is there any time series data on water quality and hydrology in the estuary. Furthermore, the fieldwork was carried out in the mid dry season only, missing out on the ecosystem responses to different flow conditions in other periods of the year. In some cases, professional experience can be relied upon to infer ecosystem structure and function with respect to hydrology; for instance, the boundary between herbaceous annual / wetland vegetation and woody trees can indicate the usual extent to which the river level reaches in most years. Hence, a confidence assessment was carried out for the team’s EFA recommendations. The results are expressed as a confidence rating from 1 to 5, with 1 being the highest level of confidence and 5 the lowest. The motivation for a particular expert’s self-assessment is also included in Table 28.

Table S20: Confidence levels of the different ecosystem component assessments

Component	Confidence Rating: 1 (highest) – 5 (lowest)	Motivation	Research gap/proposed future research
Aquatic community	2	<p>Observations in only mid-dry season (low flow), as species distribution and abundance changes during the wet season (experience in Tanzanian rivers and wetlands) when the area of inundation and connectivity between different water bodies increases.</p> <p>Flow guidelines for species were determined elsewhere in tropical Africa and not for the conditions prevalent in the Wami River.</p>	<p>Additional sampling during the wet season; using electrofishing is recommended;</p> <p>species and community studies understanding the life cycle and foodweb positions.</p>
Riparian Vegetation	2	<p>Knowledge of phenology (leaf flush and fall, flowering and fruiting) with respect to water availability is needed to better understand the fate of riparian forests, as well as to manage them to preserve biodiversity (given that they are degraded or absent in many areas).</p>	<p>Study water level-plant ecophysiology and phenology; mapping species composition of gallery forests to enable monitoring; riparian-aquatic ecosystem interactions</p>
Terrestrial wildlife	2	<p>While Park staff have 10 year + continuous knowledge, understanding wildlife water use requires year-round focused studies; many animals are hard to monitor or regularly observe, such as chameleons, also population sizes of big mammals refer to that in the whole park and not just those near the river</p>	<p>requiring other observation methods such as traps for reptiles, camera traps, scat studies along transects; settle the uncertainty about the southern boundary; both banks of the river must be included within SANAPA</p>
Water quality	2	<p>Data collected just for few days, at neap tide, that too, some days in flood tide, other days in ebb tide.</p>	<p>Continous sampling can yield time series data at a fixed location, to infer both tidal and seasonal changes; turbidity meter; seasonal and tidal observations of biological properties like phytoplankton, the base of the estuarine foodweb; sediment and nutrient budgets related to discharge</p>
Hydrology	2	<p>Missing climate aspect and sea level rise effects;</p> <p>Data time series at mandera, upriver of the estuary had to be extrapolated to the estuary head; and this data too had gaps; amount of</p>	<p>Need endpoints of driest and wettest times of the year.</p>

		abstractions all along the estuary, and between mandera and matipwili is not known;	Propose gauging station at Gama.
Hydraulics	2	Limitations of Q-liner tool: minimum operating depth is 0.5 m but in many places the river channel had depths < 0.5, even 0.1-0.2 m, so this can cause error in flow readings.	Developing an accurate hydrological model requires the use of RTK for elevation measurements in the floodplain, especially because being inside a national park, vegetation cannot be cleared for the line of sight required by traditional survey methods; besides more time spent onshore increases danger of attack by hippos and crocs.
Human communities	2	Interviewing local communities, officials and other stakeholders is a long and time consuming process taking more than the allotted 5-8 days	Socioeconomic valuation of ecosystem services; estimate amount of unauthorized water abstraction; effects of increasing livestock in area; longer study period;