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# Ecological classification of estuaries along the Tanzanian mainland: a tool for conservation and management

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## Abstract

Estuaries are unique and important coastal ecosystems providing significant and diverse services to ecosystems and human kind. Worldwide, estuaries are overwhelmed by human disturbance and over utilization of their resources which threatens their existence. This study aimed to develop a classification framework for Tanzanian mainland estuaries using abiotic variables (ecoregion, latitude and catchment size) and validate the resulting estuary types using biota (fish and prawns). Biota were sampled from five selected estuaries (Manyema, Lukuledi, Matandu, Rufiji and Ruvuma) using a seine net and identified to species level. Multivariate analyses including analysis of similarities, cluster analysis, Bray-Curtis, Pairwise and similarity percentage analysis were used to analyse biota data. Ecoregion, latitude and catchment size resulted in two (Pangani and Central East African), three (Lower (5°- 6°S), Middle (> 6°S- 8°S), Higher (> 8°S)) and five (Smaller (<1000km$^2$), Small (1000-10000km$^2$), Medium (10000-50000km$^2$), Large (50000-100000km$^2$), Larger (>100000km$^2$)) classes of estuary, respectively. Two classification options; latitude-catchment size and ecoregion-catchment size, have been proposed. The latitude-catchment size classification produced nine estuary types while the ecoregion-catchment size classification produced seven estuary types. The latitude-catchment size produced estuary types with higher significant differences (global R=0.926, $p$=0.01) than ecoregion-catchment size (global R=0.659, $p$=0.03).

**Keywords:** estuary classification, validation, estuary type, ecoregion, latitude, catchment size

## Introduction

Estuaries have significant ecological and socio-economic importance, and are a major focus for human activities (Saenger, 1995). Their importance has compromised the integrity of estuarine ecosystems resulting in large scale alterations of their natural communities (Graham *et al.*, 2000). Estuaries are influenced by human activities at a local scale (e.g. through mangrove harvesting, salt pans, industrial and urban waste disposal, dredging of shipping channels, and construction of port facilities) and at a broader scale in the upper catchment (e.g. through agriculture, livestock keeping, deforestation and water abstraction for hydroelectric power production and water supply). Local and large-scale stressors on estuaries create complexity for their conservation and management resulting in unsustainable resource utilization and ecosystem services provision.

The existence of an estuary depends on hydrological features such as freshwater inflow from inland areas and tidal inundations from the sea (Kennish, 1986). Hydrological and environmental variations in estuaries include variations in tidal range, freshwater availability, salinity, temperature, dissolved oxygen and turbidity, which together have an influence on the biota. Therefore, biodiversity and ecosystem integrity of estuaries are directly determined by the prevailing hydrological and environmental characteristics which vary among estuaries. Consequently, the occurrence and distribution of biota are expected to differ across estuaries. Ecosystem responses to various

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conservation and management interventions are also expected to vary across different estuaries. Conservation of estuaries also requires an understanding that different estuaries are subjected to particular types and levels of human impacts.

Estuary classification refers to the grouping of similar estuaries into estuary types. An estuary type is defined as 'a group of estuaries with similar abiotic and biotic characteristics which shows distinct characteristics from another estuary type'. Estuary classification can be used as a tool for efficient conservation and management of estuary ecosystems (Bucher and Saenger, 1991; Saenger, 1995). Classification of estuaries could also serve as a tool for identifying potential Estuary Protected Areas to serve as estuary conservation units. Estuary classification as a management tool has been globally applied, for example in Australia (Saenger, 1995, Graham *et al.,* 2000), New Zealand (Hume *et al.,* 2007; NIWA, 2013), South Korea (Jang and Hwang, 2013), UK (Davidson *et al.,* 1991) and South Africa (Colloty *et al.,* 2002; Harrison and Whitfield, 2006). Although the Tanzania National Water Policy (URT, 2002) requires classification of all water resources including estuaries, Tanzanian estuaries have not yet been classified. Therefore, this study aimed to develop a classification framework for Tanzanian estuaries using abiotic variables and to validate the developed classification framework in selected estuaries using biota (fish and prawns).

## Materials and Methods

### Study area

Classification of estuaries was carried out for the entire Tanzanian mainland coast, which extends for a length of 1424km from the border with Kenya in the north to the Ruvuma estuary in the south. The Tanzania coastline is intersected by numerous estuaries, which vary from large, permanently open systems to small systems that are only occasionally connected to the ocean (Kimirei *et al.,* 2016). Validation of the classified estuary types was done on the selected estuaries of Manyema creek, Lukuledi, Matandu, Rufiji and Ruvuma.

### Study sites (estuaries)

Manyema creek is a tidal inlet on the Msasani-Kunduchi shoreline in the Dar es Salaam seascape formed by the northward accretion of 3km of sandy shore. The creek is flushed by semi-diurnal tides which have a maximum spring tide range of about four metres and a neap tide range of about one metre. Lukuledi creek is located at the southern border of Lindi Urban District. The estuary is surrounded by a fringing mangrove forest. Matandu estuary is found in Lindi region at Kilwa Kivinje. It has a funnel-shaped river mouth and surrounded by a fringing mangrove forest. Rufiji estuary occurs in Rufiji District, Pwani Region. The estuary has a deltaic formation. The delta extends some 24km inland (tides influence the river for some 40km upstream) and has eight major branches. Ruvuma estuary is located in Mtwara on the border with Mozambique. This estuary has a deltaic formation made up of tidal creeks rather than river tributaries. It is the second largest estuary in Tanzania with a large area of mangroves, sand banks and mud flats, and many channels and tributaries.

### Classification of estuaries using abiotic characteristics

Estuaries along the Tanzanian mainland coast were identified on maps and reviewed in the literature. A desktop study was used to review information on physical features that could be potentially useful for estuary classification. Key reviewed information for each estuary included latitude, ecoregion and catchment size. Additional reviewed information included climatic data, rainfall and temperature, which were obtained from the Tanzania Meteorological Agency using weather stations near the estuaries. In this study, a two-level framework, which allows integration of climatic, hydrological and other catchment features, was used to classify Tanzanian estuaries. A two-level classification provides different levels of resolution and options for selection of the most appropriate level of resolution, as per different objectives (Frissel *et al.,* 1986). The two proposed levels in this study were 'latitude' and 'ecoregions' as the first level and 'catchment size' as the second level. Both levels of characteristics have previously been used in ecosystem classification and are considered as good reflectors of biotic communities (Chaves *et al.,* 2005; Dodkins *et al.,* 2005). Freshwater ecoregions which have been previously described for Africa by Thieme *et al.,* (2005) were adopted for this study to classify the Tanzania coastline at level one classification. To incorporate climatic characteristics as defined by latitudinal difference, a latitudinal zonation along the Tanzania coastline was also developed and used at level one. Furthermore, a catchment size classification was developed and used at level two. Catchment size further allows the classification to capture hydrological and ecological features which influence estuaries socio-ecological characteristics and their management.

### Validation of classified estuary types using biotic characteristics

A total of eleven sites from five estuaries; namely Manyema creek (3), Lukuledi estuary (3), Matandu estuary (1), Rufiji estuary (2) and Ruvuma estuary (2) were selected for biotic validation. These five estuaries are distributed among three and four estuary types for ecoregion-catchment size and latitude-catchment size classifications, respectively, as classified in this study. Fish and prawn species were sampled for use in the biotic validation of the classified estuary types.

### Fish and prawn sampling procedure

Fish and prawns were collected by dragging a 35m seine net with a 3m drop and 13mm mesh onto the shore. Samples at each site were recorded and counted to obtain abundance. Samples which could not be identified at the site were preserved and transported to the University of Dar es Salaam for further taxonomic identification.

### Data analysis: validation of estuary types

Estuary types were validated using combined biotic data for fish and prawn samples at each site. Analysis of similarity (ANOSIM) was used to test whether or not there were significant differences in biotic (fish and prawns) assemblages amongst classification classes of both ecoregion-catchment size and latitude-catchment size classification frameworks. The Pairwise analysis was then carried ou to ascertain strength in differences among estuary types. Non-metric multidimensional scaling (NMDS) was used to visualise biotic patterns using Bray–Curtis analysis. Cluster analysis was carried out to show group similarities among estuaries for both ecoregion-catchment size and latitude-catchment size classification frameworks. A similarity percentage (SIMPER) analysis was undertaken to show average similarity and dissimilarity within groups based on taxa.

## Results

### Classification of estuaries using abiotic characteristics

*Level I: Ecoregions and latitude*

Ecoregions

Ecoregion classification developed by Thieme *et al.* (2005) and latitudinal differences of the Tanzania freshwater ecosystems were used in the level I classification of Tanzanian estuaries. Ecoregion classification divides the Tanzanian mainland coastline into two ecoregions: the Pangani Ecoregion on the northern side, and the Central East Africa Ecoregion on the southern side. This resulted in two estuary classes being identified; the Pangani estuary type and Central East Africa estuary type. The Pangani estuary type includes the estuaries of Pangani, Msangazi, Mkulumuzi and Sigi. The Central East Africa estuary type includes the estuaries of Msimbazi, Mzinga, Mpiji, Tegeta, Manyema, Wami, Ruvu, Matandu, Rufiji, Mbwemkuru, Mavuji, Lukuledi and Ruvuma (Table 1).

Latitude

The latitudinal range of the Tanzanian mainland coast is from 5°S in Tanga region to 10°S in Ruvuma region. Three latitudinal classes were proposed as the lower latitude estuary type (≤6°S), middle latitude estuary type (6°-8°S) and higher latitude estuary type (>8°S). The lower latitude estuary type includes estuaries occurring from 6°S northwards, namely Pangani, Msangazi, Mkulumuzi and Sigi estuaries. The middle latitude estuary type includes the Msimbazi, Mzinga, Mpiji, Tegeta, Manyema, Wami, Ruvu and Rufiji, while the lower latitude estuary type includes the Mavuji, Matandu, Lukuledi, Mbwemkuru and Ruvuma estuaries.

*Level II: Catchment Size*

Catchment size was used as a level II classification factor to further divide either ecoregions or latitude classes proposed in level I. Catchments draining the Tanzania mainland estuaries range in size from small (<50km$^2$), for example Manyema and Tegeta creeks, to large (about 183,79km$^2$) in the case of the Rufiji delta. Five size classes of catchments were suggested, which ranged from smallest (<1,000km$^2$), small (1,000 to 10,000km$^2$), medium (>10,000 to 50,000km$^2$), large (>50,000 to 10, 0000km$^2$), and largest (>10, 0000km$^2$) catchments.

*Estuary classification framework*

A two-level classification framework is proposed for defining estuary types on the Tanzanian mainland. Three abiotic attributes, *viz*: Ecoregion, latitude, and catchment size, were used to produce classification options as ecoregion–catchment size classes and latitude-catchment size classes (Fig. 1).

The advantage of the two classification options is that ecoregion-catchment size classification can be used as a broader class while latitude-catchment size classification can be used for a zoomed- in classification. The option for ecoregion-catchment size classification produces 7 estuary types, while the latitude-catchment size classification produces 9 estuary types (Table 1).

Table 1. Estuary types following the Ecoregion-Catchment size and Latitude-Catchment size classifications.

| | | Estuary Type | Description | Estuaries |
|---|---|---|---|---|
| 1 | Ecoregion-Catchment size (7) | Estuary Type 1 | Pangani Ecoregion – smaller catchment size (<1000 Km²) | Mkulumuzi |
| 2 | | Estuary Type 2 | Pangani Ecoregion – small catchment size (1000-10000 Km²) | Sigi and Msangazi |
| 3 | | Estuary Type 3 | Pangani Ecoregion – large catchment size (>50000-100,000 Km²) | Pangani |
| 4 | | Estuary Type 4 | Central East African Ecoregion – smaller catchment size (<1000 Km²) | Mpiji, Msimbazi, Mzinga, Tegeta and Manyema |
| 5 | | Estuary Type 5 | Central East African Ecoregion – small catchment size (>1000-10000 Km²) | Mavuji |
| 6 | | Estuary Type 6 | Central East African Ecoregion – medium catchment size (>10000-50000 Km²) | Wami, Ruvu, Matandu, Mbwemkuru and Lukuledi |
| 7 | | Estuary Type 7 | Central East African Ecoregion – larger catchment size (>100000 Km²) | Rufiji and Ruvuma |
| 8 | Latitude-Catchment size (9) | Estuary Type 1 | Lower latitudes – very small catchment size (5°- 6°S - <1000 Km²) | Mkulumuzi |
| 9 | | Estuary Type 2 | Lower latitudes – small catchment size (5°- 6°S - >1000-10000 Km²) | Sigi and Msangazi |
| 10 | | Estuary Type 3 | Lower latitudes – large catchment size (5°- 6°S ->50000-100,000 Km²) | Pangani |
| 11 | | Estuary Type 4 | Middle Latitudes – smaller catchment size (>6-8° S - <1000 Km²) | Mpiji, Msimbazi, Mzinga, Tegeta and Manyema |
| 12 | | Estuary Type 5 | Middle Latitudes – medium catchment size (>6-8°S -10000-50000 Km²) | Wami and Ruvu |
| 13 | | Estuary Type 6 | Middle Latitudes – larger catchment size (>6-8°S - >100000 Km²) | Rufiji |
| 14 | | Estuary Type 7 | Higher latitude – small catchment size (>8°S - >1000-10,000 Km²) | Mavuji |
| 15 | | Estuary Type 8 | Higher latitude – medium catchment size (>8°S - 10000-50000 Km²) | Matandu, Mbwemkuru and Lukuledi |
| 16 | | Estuary Type 9 | Higher latitude – larger catchment size (>8° S - >100000 Km²) | Ruvuma |

### Validation of estuary types using biota (fish and prawns)

A total of 42 fish and 4 prawn species were identified from the five studied estuaries. Across the five estuaries, higher abundances of *Encrasicholina heteroloba* (516), *Sardinella gibbosa* (156), *Upeneus vittatus* (103), *Valamugil seheli* (48), *Upeneus sulphureus* (45), *Penaeus indicus* (41), *Penaeus monodon* (32) and *Gaza minuta* (28) were apparent. Highest catches in terms of abundance were recorded for *Encrasicholina heteroloba* (346) and *Upeneus sulphureus* (96) in Lukuledi estuary, and *Sardinella gibbosa* (120) in Ruvuma estuary. Prawn catches were highest in the Rufiji delta. Higher abundance was recorded in Lukuledi estuary (727), Rufiji estuary (333), Ruvuma Estuary (108), Matandu estuary (53) and Manyema estuary (25).

Analysis of similarity (ANOSIM) for ecoregion-catchment size estuary type showed a significant difference between the estuary types (global R = 0.659, $p$ = 0.03). Pairwise analysis showed strongest separation between Estuary Type 6 and Estuary Type 4 (R=1, $p=0.001$), Estuary Type 7 and Estuary Type 4 (R=0.927, p=0.001)

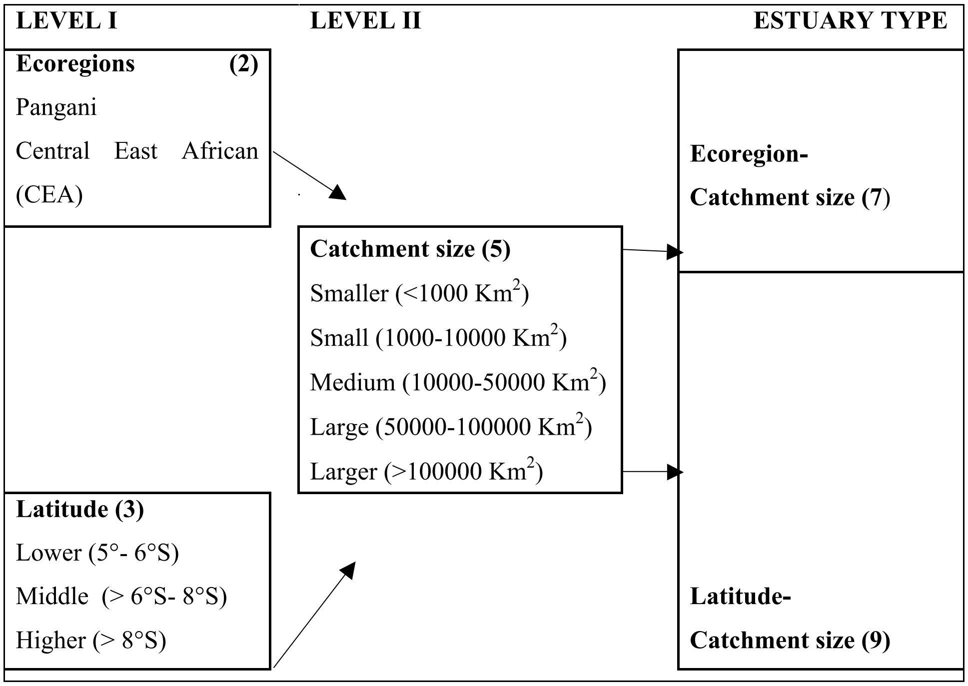


**Figure 1.** Classification framework for Tanzanian mainland estuaries.

and weakest separation between Estuary Type 6 and Estuary Type 7 (R=0.406, p=0.001) (Table 2). ANOSIM showed a strong significant variation of species among the nine latitude-catchment size groups (global R=0.926, $p$=0.01), based on latitude-catchment size classification. Strongest variations were obtained between all groups and were slightly less significant between Estuary Type 8 and Estuary Type 9 (R=0.607).

Cluster analysis for the two classification options (Fig. 2) shows the percentage levels at which samples are similar to form a group; that is, estuary type based on fish samples. In ecoregion-catchment size classifications, abiotic factors grouped the five estuaries into estuary types 4, 6 and 7 where estuary type 7 comprised of the Ruvuma and Rufiji estuaries. Biological validation, however, grouped the five estuaries into four groups separating Rufiji and Ruvuma estuaries. The Ruvuma and Rufiji estuaries together show a 20% similarity, while when separated, samples from Rufiji and Ruvuma showed a similarity of about 40% and 20%, respectively. Cluster analysis of the latitude-catchment size classification validated biotic differences between Ruvuma and Rufiji estuaries which belong to different estuary types.

Patterns of fish assemblages were visualized using a non-metric multidimensional scaling (MDS) for the latitude-catchment size classification. The MDS analysis showed a clearer separation of estuary types in latitude-catchment size than ecoregion-catchment size classification with a 2D stress value of 0.09. The MDS was overlaid with the cluster analysis to emphasize the biota grouping pattern (Fig. 3).

**Table 2.** Pairwise test for ANOSIM statistics of estuary groups based on Latitude-Catchment size classification.

| Estuary Types Groups | R significant, p=0.001 |
|---|---|
| Estuary Type 8 and Estuary Type 9 | 0.607 |
| Estuary Type 8 and Estuary Type 4 | 1 |
| Estuary Type 8 and Estuary Type 6 | 0.907 |
| Estuary Type 9 and Estuary Type 4 | 1 |
| Estuary Type 9 and Estuary Type 6 | 1 |
| Estuary Type 4 and Estuary Type 6 | 1 |

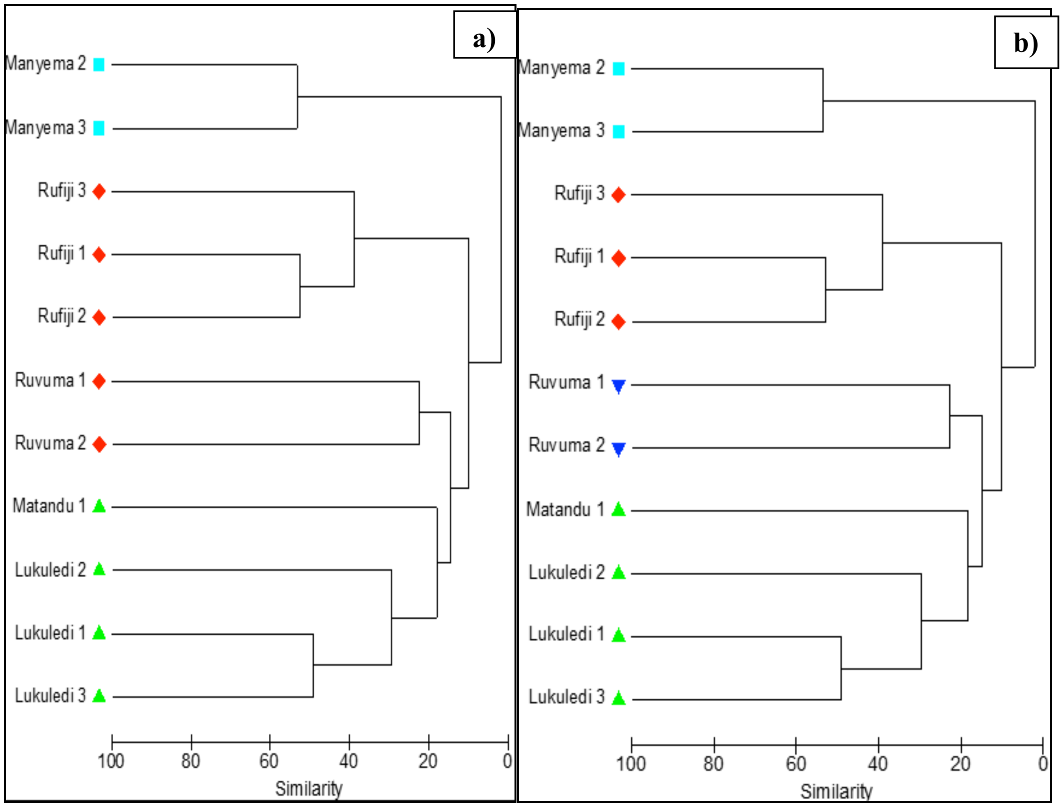


**Figure 2.** Cluster analysis of fish samples for a) ecoregion-catchment size and, b) latitude-catchment size classifications from estuaries along the Tanzania mainland, 2016.
(Ecoregion-catchment size: ■= Estuary Type 4; ▲= Estuary Type 6; ♦= Estuary Type 7 and latitude-catchment size; ■= Estuary Type 4; ▲= Estuary Type 8; ▼= Estuary Type 9; ♦ = Estuary Type 6).

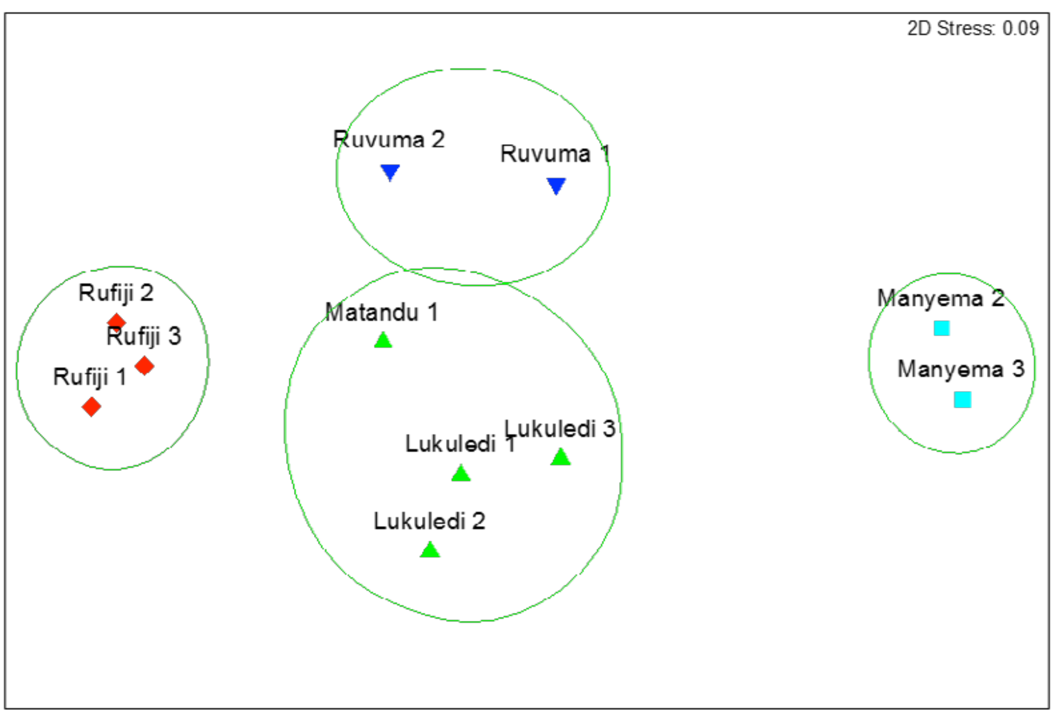


**Figure 3.** Non-metric multidimensional scaling plots showing grouping of estuaries based on biota assemblages overlaid on the cluster analysis for the latitude catchment size classification.

**Table 3.** Analysis of similarity percentage (SIMPER) of fish samples from four estuary types on the Tanzania mainland, 2016. Percentage of contribution by fish and prawn species for each estuary type are presented.

| Latitude-size Estuary Type | Sample | Average similarity (%) | Species | Contribution (%) | Cumulative contribution (%) |
|---|---|---|---|---|---|
| Estuary Type 8 | Lukuledi 1 | 27.11 | *Penaeus monodon* | 29.74 | 29.74 |
| | Lukuledi 2 | | *Encrasicholina heteroloba* | 21.87 | 51.60 |
| | Lukuledi 3 | | *Gerres acinaces* | 15.70 | 67.31 |
| | Matandu 1 | | *Alectis ciliaris* | 9.69 | 76.99 |
| Estuary Type 9 | Ruvuma 1 | 22.47 | *Sardinella gibbosa* | 84.77 | 84.77 |
| | Ruvuma 2 | | *Penaeus indicus* | 15.23 | 100.00 |
| Estuary Type 4 | Manyema 2 | 53.34 | *Leiognathus equlus* | 55.05 | 55.05 |
| | Manyema 3 | | *Etelis carbunculus* | 44.95 | 100.00 |
| Estuary Type 6 | Rufiji 1 | 43.51 | *Penaeus monodon* | 28.11 | 28.11 |
| | Rufiji 2 | | *Rastrelliger kanagurta* | 9.84 | 37.95 |
| | Rufiji 3 | | *Penaeus semisulcatus* | 8.32 | 46.27 |
| | | | *Johnius dussumieri* | 7.83 | 54.10 |
| | | | *Thryssa vitrirostris* | 7.80 | 61.90 |
| | | | *Macrobranchium rude* | 7.44 | 69.34 |
| | | | *Lutjanus argentimaculatus* | 7.00 | 76.34 |
| | | | *Valamugil seheli* | 6.75 | 83.09 |
| | | | *Arius africanus* | 6.44 | 89.53 |
| | | | *Penaeus indicus* | 5.51 | 95.05 |

A similarity percentage (SIMPER) analysis for the latitude-catchment size samples based on fish taxa showed that average similarity was 53.34%, 43.51%, 27.11%, 22.47% for Estuary Type 4, Estuary Type 6, Estuary Type 8 and Estuary Type 9, respectively. *Leiognathus equlus* contributed 55% of group similarity in Estuary type 4. In Estuary type 6, 28.11%, 9.84%, 8.32% and 7.83% of group similarity was contributed by *Penaeus monodon, Rastrelliger kenagurta, Penaeus semisulcatus* and *Johnieops sinain*, while in Estuary type 8, 29.74% and 21.87% was contributed by *Penaeus monodon* and *Encrasicholus heterolobus*, and in estuary type 9, 84.77% and 15.23% was contributed by *Sardinella gibbosa* and *Penaeus indicus* (Table 3).

## Discussion

Estuaries are coastal ecosystems which are among the most productive biomes globally, and support important and diverse life forms, including humans (Day *et al.*, 1989, Constanza *et al.*, 2014). Diverse provisioning and servicing by estuaries increasingly contributes to the disappearance and loss of some of the functional value and importance of these systems. Classification of estuaries is considered important for conservation and management purposes (Durr *et al.*, 2011; Ramos *et al.*, 2016; Mahoney and Bishop, 2018). Estuary classification may be useful in identifying groups of ecologically similar estuaries, for which common conservation strategies might be developed or adopted. Mahoney and Bishop (2018) summarised various schemes of estuary classification developed in different countries including Australia, Canada, Europe, New Zealand, United Kingdom, USA, South Korea and South Africa, where most schemes have used hydrological, geomorphological and physical-chemical classification variables (Mahoney and Bishop, 2018). Estuarine habitat mosaic and geomorphic classes can be influenced by the size of drainage basins, hydrology and climate through wave action and runoff. Climatic influence results in latitudinal zonation of estuaries following light, temperature and precipitation distribution patterns (Harris *et al.,* 2002).

The classification scheme developed in this study for Tanzania estuaries has used ecoregion, latitude and catchment size classification variables which pulls together the combined effect of climate, hydrology and drainage basin size. These classification variables were considered to have an influence on naturally partitioning of estuaries into estuary types. In this study, a classification option based on the combination of latitude and catchment size produced stronger differences between estuary types and stronger similarities among estuaries within the same estuary type than the ecoregion and catchment size classification. Latitudinal zonation is an important factor influencing the occurrence and distribution of living organisms along coasts (Engle and Summers, 1999). Fish occurrence and diversity in estuaries has specifically been described to be latitudinally influenced (Harrison and Whitfield, 2006). For example, in South Africa, estuarine fish diversity declines with decreasing latitude (from the east coast to the west coast) (Day *et al.,* 1981; Whitfield, 1992). In this study, fish composition separated Estuary type 6 and 9 of the latitude catchment size classification which occurs in the same Central East African ecoregion (Thieme *et al.,* 2005), but distinguished by latitude, Estuary type 9 (10°28'27.82"S) is further to the south than Estuary type 6 (7°49'28.77"S).

The size of the catchment draining into the estuaries contributes to the amount of freshwater discharge and sediment loads entering the estuary and has a significant impact on estuary productivity. Estuary type 8 and 9; and Estuary type 4 and 6 occur within similar latitudinal zones but showed significant differences between each other. This is attributed to the difference in catchment sizes forming the estuary types under comparison. This emphasizes the importance of the size of the draining catchment and its resulting abiotic characteristics. On the same note, the extent of human disturbance, ecosystem resilience and management options are influenced by catchment size. The upstream-downstream effect on estuaries is also influenced by the size of the catchment. Larger catchments are more susceptible to complex multi-sectoral impacts and conflicts than smaller catchments; however, they have higher potentials for economic importance and revenues than smaller catchments. Therefore, classifying similar types of estuaries allows for collective management of individual estuaries under a common entity (estuary type) (Mahoney and Bishop, 2018), thus facilitating extrapolation, adoption and comparison among estuaries of the same type.

Based on the validation and performance of classification options, it is suggested that the latitude-catchment size estuary types are used. Looking at the cluster analysis, the relationships between estuary types may be visualized. Estuary type 8 is more like Estuary type 9, while together they are similar to Estuary type 6, and the three groups are similar to Estuary type 4. This relationship may be related to their latitudinal locations.

## Conclusion

This study proposes a classification framework for Tanzania mainland estuaries using abiotic variables (ecoregion, latitude and catchment size). The framework gives options of using either an ecoregion-catchment size classification or latitude-catchment size classification.

The latitude-catchment size classification produced nine estuary types, while the ecoregion-catchment size classification produced seven estuary types along the Tanzania mainland coast.

The biotic validation of estuary types using biotic composition (fish and prawns) showed that latitude-catchment size classification was significantly stronger in partitioning estuary types than ecoregion-catchment size classification.

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