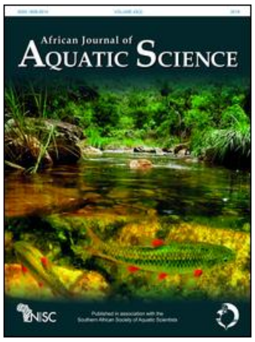

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An Estuary Ecosystem Classification that encompasses biogeography and a high diversity of types in support of protection and management

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For nearly three decades, the Whitfield (1992) characterisation scheme served as a reference framework to type South African estuaries. We outline a revised ecosystem classification scheme that incorporates biogeographical zonation and introduces new types. Coastal outlets were re-categorised as estuaries or micro-systems. For functional estuaries, the Estuarine Lakes, Estuarine Bays and Predominantly Open Estuary types were largely retained. New types are Estuarine Lagoons and Arid Predominantly Closed Estuaries. The numerically dominant, temporarily open/closed category was subdivided into Small and Large Temporarily Closed Estuaries, with a total habitat area of 15 ha, serving as threshold separating these two subdivisions. River mouths were renamed Fluvially Dominated Estuaries and divided into large and small size categories to reflect dissimilar catchment influences. Micro-systems were separated into micro-estuaries, micro-outlets, and waterfalls. South Africa's 290 estuaries were classified into 22 estuarine ecosystem categories arising from nine estuary types occurring across four biogeographical zones. In addition, 202 micro-systems were classified into nine ecosystem types, of which only the micro-estuaries (42) share possible functionality with estuaries. Estuaries subjected to functional shifts were also identified. The classification system provides a framework that integrates biogeography and the range of biophysical parameters evident in South Africa, and can be used for red listing of ecosystem types and determining estuarine sensitivity to pressures.

Keywords: arid, estuarine bays, estuarine lagoons, estuarine lakes, fluvially dominated estuaries, predominantly closed estuaries, predominantly open estuaries, South Africa, temporarily closed estuaries

Supplementary material: available online at https://doi.org/10.2989/16085914.2019.1685934

Introduction

Estuaries are difficult to classify, because they vary temporally in shape and size and encompass gradients in conditions from riverine to marine. Human interventions and morphological changes brought about by climate and sea level fluctuations further complicate the process. This paper recognises an estuary as a partially enclosed permanent waterbody that is either continuously or periodically open to the sea and that extends as far as the upper limit of tidal action, salinity penetration or back-flooding under closed mouth conditions. During high catchment flows or floods, an estuary can become a river mouth, with no seawater entering the formerly estuarine area or, when there is little or no fluvial input, an estuary can be isolated from the sea by a sandbar and become fresh or even hypersaline (CSIR 1992; modified from van Niekerk and Turpie 2012).

"Typology" refers here to the characterisation of estuary types according to shared key features, whereas "ecosystem classification" refers to the categorising of estuarine ecosystem types based on their abiotic constituents (e.g. climate, oceanic conditions, substrate, water, and all other non-living elements) and its biotic constituents, consisting of all its living members (Allee et al. 2000). Ecosystem classifications are complex, and often hierarchical or nested, whereas typologies tend to be more straightforward and based on general type. The level of classification depends mainly upon the number of criteria selected (e.g. biogeography, geomorphology and biology) and the spatial resolution required (e.g. local, regional or global). The greater the number of criteria and the wider the geographical scope, the more complex the classification

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becomes. Depending on the task or information required, a balance has to be established between the number of criteria and the level of detail selected (Whitfield and Elliott 2011).

Reflecting the high diversity of estuarine types globally, numerous estuary typology and classification schemes exist. These are usually specific to a geographic region (Whitfield and Elliott 2011). Traditionally estuaries have been typed based on key processes and features, such as tidal ranges, tidal prisms, topography, geomorphology, salinity characteristics and ecosystem energetics (Davies 1964; Nichols and Biggs 1985; Kennish 1986). Topographical typologies categorise them as drowned river valleys, fjords, bar-built estuaries and others (Pritchard 1952; Dyer 1997), whereas morphological typologies base groupings on physical features resulting from the interplay between catchment runoff and sediment loads, and tides, waves and other coastal processes (Dalrymple et al. 1992). Salinity-based approaches separate them according to the degree of mixing within the water column (Pritchard 1955; Cameron and Pritchard 1963) and stratification–circulation typologies using densiometric numbers from the fluid mechanics discipline (Hansen and Rattray 1966; Fischer 1972; Simpson et al. 1990). Most of these typologies require extensive in-field time-series and high spatial coverage data.

National or regional ecosystem-level classification schemes have to recognise environmental parameters often not strongly reflected in physical and morphology typologies, such as variations in climate or biogeography, vegetation and other biological aspects (see Whitfield and Elliott 2011 for the evolution of estuary classification). Examples include the comprehensive United States marine and estuarine ecosystem and habitat classification that moves from a biogeographical level to a habitat level at it smallest spatial scale (Allee et al. 2000). Regional schemes that explicitly include temporarily closed estuaries, common on the South African coastline, are those of Australia and California. Early Australian schemes identified seven geomorphology-based estuary types across five biogeographical regions under the influence of wave, tide and river energy (Boyd et al. 1992; Dalrymple et al. 1992; Kench 1999). Linking these to climate and rainfall characteristics allowed for the incorporation of freshwater- and evaporation-dominated types (Boyd et al. 1992; Heggie et al. 1999a, 1999b; Kench 1999). A more recent Australian classification described three intermittently open/closed estuary types (IOCE) based on the duration and frequency of mouth condition and estuary size (large, medium or small) (McSweeney et al. 2017). A typology of Californian estuaries distinguished eight closed-mouth states based on berm elevation and tidal exchange where river inflow rather than tidal influence controls mouth opening. This scheme recognised that mouth states prevail over multiyear to multidecadal periods (Jacobs et al. 2010). Over the past six decades estuary classification studies have therefore evolved from relatively simple "topology" schemes (defining estuary types based on a key process or feature), to more complex regional ecosystem-level classification schemes (regional schemes that include elements of climatic/biogeography, estuarine processes and biological responses).

The choice of classification system depends to some extent on its intended purpose. Ecosystem-level classification schemes have a wide range of potential application in research and natural resource management. National and regional ecosystem classifications are useful, because they can be applied to the International Union for Conservation of Nature (IUCN) Red List of Ecosystems (RLE) framework to assess risks and identify vulnerable ecosystems based on a set of criteria and thresholds (Rodríguez et al. 2011; Keith et al. 2013; 2015; Bland et al. 2017a, 2017b, 2018).The RLE requires clearly defined units of assessment (ecosystem types) that can be spatially delineated (Keith et al. 2013). Ecosystem classification is therefore one of the fundamental inputs for such global assessment processes.

South African national-level biodiversity assessments, and national and regional conservations plans also require an ecosystem-level classification that details similarities and differences between estuary types and describes their biogeographical occurrence (Turpie and Clark 2007; Turpie et al. 2012; van Niekerk and Turpie 2012). Classification is fundamental to estuary conservation planning to pinpoint important biodiversity areas and initiate the setting of targets for species, habitats and types to ensure that all species and the critical processes they depend on are conserved (Turpie and Clark 2007; Turpie et al. 2012). It is also essential for determining estuary flow requirements and water resource allocations where estuary type serves as an indicator of sensitivity to flow modification and declining water quality (van Niekerk et al. 2019a, 2019b). In a data-limited environment, such as South Africa, classifications can be used to signify system-specific ecosystem processes and associated biotic characteristics.

The aim of this paper was to develop an ecosystem-level national classification scheme for South African estuaries that incorporates key processes and patterns in different biogeographic regions and can inform broad-scale assessments of estuary resilience to anthropogenic pressures.

Material and methods

A detailed literature review of globally- (see Introduction) and locally-used estuary typologies was conducted to identify key parameters that support estuary classification at the ecosystem level. Parameters used most often in estuary typologies included: estuary size and geomorphology; catchment features (size and geology); river flow and tidal regimes; marine connectivity (mouth state or inlet stability); sediment processes; salinity structure; habitat diversity; and, biotic composition. In addition, common to most national or global ecosystem-level classification schemes were biogeographical, ocean processes (wave energy), or climatic elements.

Developing an estuarine ecosystem-level classification scheme for South Africa required a number of steps (Figure 1): revisiting the biogeographic organisation of South African estuaries to ensure that all climatic and oceanic processes are accurately reflected based on emerging research; evaluating existing typologies and revisiting, if needed, the high diversity of estuarine processes and responses that occur on the subcontinent. In addition, previously neglected very small outlet types that do not fully function as estuaries, collectively referred to here as micro-systems, were included. A "functional" estuarine system, even if very small (<2 ha or <200 m in length), was taken as any permanent coastal waterbody that supports significant estuarine processes and associated biological composition.

A significant effort was made to ensure all rivers and streams with outlets to the sea were identified and to address systems omitted from historical lists (>400 outlets were evaluated). Datasets consulted included the CSIR NRIO list (1981) and those of Harrison et al. (2000), van Niekerk and Turpie (2012), Whitfield and Baliwe (2013), Bate et al. (2017), Dalu et al. (2018) and Human et al. (2018). Micro-system types, previously omitted from formal classification schemes, were also identified through the literature and using satellite imagery (GoogleEarth™) and aerial photographs (1930s to 2000s). Where possible, a distinction was made between natural outlets and artificially created stormwater outlets (with the latter validated by site visits), with a focus on only including naturally occurring features in the landscape. Seven coastal outlets, not previously listed as estuaries, were deemed to be functional system types based on size, topography and vegetation cover and added to the formal list of estuaries. All larger outlets (>200 m) were delineated based on the 5 m topographical contour (obtained from the Department of Rural Development and Land Reform: National Geospatial Information) to determine how far they extend inland (Harris et al. 2019; van Niekerk et al. 2019c). Existing national and bioregional datasets were then scrutinised to establish what information was available on the physical features and processes of estuaries (e.g. size, mean annual runoff, mouth state) and biotic components (plants, invertebrates, fish and birds) to assist with classification (Harrison et al. (2000); van Niekerk and Turpie (2012); van Niekerk et al. 2015; van Niekerk et al. 2019d).

Using the collated information, all functional estuaries were evaluated by a panel of national experts in 2009 and again in 2018 (see author list), each expert having between 10 and 35 years' experience in estuarine physical processes, vegetation, invertebrates and/or fish (van Niekerk et al. 2013). The specialists assessed each dataset to identify estuary types that support key ecosystem processes and functions across biotic groups. Although published information was given preference, the panel also drew on the authors unpublished field data and personal field observations. The outcome was cross-validated by consulting historical data sources and published literature. Data and field observations were often lacking for very small estuaries and outlets, and classification for these systems relied on visual observations and expert judgements. Usually the panel participants' consensus view on a system's classification was adopted, with the few exceptions being resolved by a majority vote.

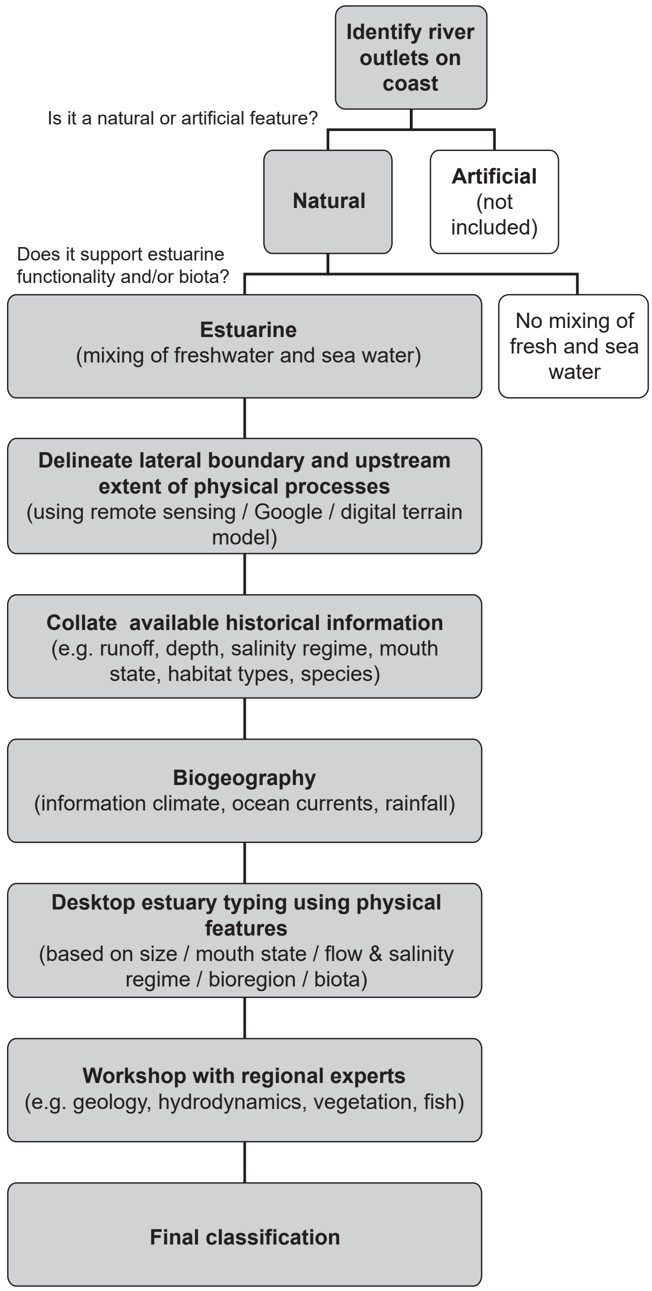

Figure 1: Flow diagram of estuary classification process

Results and discussion

South Africa's estuarine ecosystem-level classification

Currently, there are a number of typologies or classification systems recognised for estuaries in South Africa, largely based on geomorphological and/or physical characteristics. Early attempts described estuary types fairly loosely and with little scientific backing, e.g. temporarily closed estuaries were referred to as "lagoons" (Begg 1978), "blind estuaries" (Day 1980, 1981) or "seasonally open/closed estuaries" (Bennet1989). Whitfield (1992) typed South Africa's estuaries into five types based on their physiographic (tidal prism, size), hydrographic (mouth state and mixing process) and salinity characteristics (Table 1). A geomorphological system used by Harrison et al. (2000) recognised six main types based on mouth condition (open or closed), size and the presence of a sand bar at the mouth (or inlet). More recently, the NBA 2011 assessment (van Niekerk and Turpie 2012) proposed a typing based on estuary size, mouth state, salinity structure and catchment type. This resulted in 46 ecosystem types, which included three estuary size classes (large >100 ha, medium 10–100 ha and small <10 ha).

Whitfield's (1992) typology of estuaries has been most widely used to describe the estuaries on the subcontinent (Table 1). Most estuaries were classed as Temporarily Open/Closed systems, where connection to the sea is governed by a sand bar that builds across the mouth under conditions of low river flow and high coastal wave conditions. Floods cause the mouth to open by scouring large volumes of sediment to sea. Permanently open estuary types are controlled by marine and riverine processes that act together to maintain an open mouth. Estuaries categorised as river mouths are dominated by riverine processes, because strong outflow inhibits marine intrusion into the mouth area, allowing oligohaline conditions to persist, especially in the upper and middle reaches. Heavy silt loads are a common feature of river mouths, resulting in shallow estuaries and ebb tidal deltas. Estuarine Bays and Estuarine Lakes, the two remaining categories, are large open water systems uncommonly represented along the coast. The bays are permanently linked to the sea by deep mouths and have euhaline salinities in the lower and middle reaches whereas the lakes are usually drowned coastal systems filled by reworked sediments and separated from the sea by vegetated sand dunes. Estuarine Lakes can be either permanently or temporarily linked to the sea.

However, Whitfield's (1992) scheme omitted a large number of small estuaries and micro-systems from its original characterisation. The scheme also primarily covered functional estuary types and ignored regional biogeography. Atypical estuary types, such as coastal lagoons, where a river or stream is absent and where the groundwater provides only a limited freshwater signal, were also not represented. The scheme showed a bias towards estuaries important to fish, and therefore largely ignored the small, hypersaline systems along the west coast, which have few fish, but are important for plants and birds. Nearly 75% of all estuaries were classified as temporarily open/closed systems, and the scheme did not recognise the differences between the more habitat diverse/species-rich larger systems, and the relatively depauperate smaller examples of this type. Finally, the river mouth type encapsulated a diversity of fluvially dominated estuary types ranging from those being fed by large, sediment rich catchments to clear, smaller catchment, black-water systems with very limited suspended sediments.

The above limitations of the Whitfield (1992) estuarine classification necessitated the development of an expanded ecosystem-level classification scheme for South Africa's estuaries, although at the same time allowing for "cross walking" of historical studies and assessments. Developing a more comprehensive ecosystem-level classification scheme required three interlinked steps: 1) the formal biogeographic organisation of South African estuaries to reflect regional biotic responses; 2) the refinement of estuary types to reflect the high diversity of small and large estuary types that occur on the subcontinent; and 3) the inclusion and organisation of previously neglected micro-system types.

A new tropical biogeographic zone

The traditional biogeographic organisation of South African estuaries has included only three regions, viz. Subtropical, Warm Temperate and Cool Temperate (Emanuel et al. 1992; Turpie et al. 2000; Harrison 2002). However, the tropical distribution of some species recorded in the Kosi and uMgobezeleni Estuaries in the north, provides good motivation to subdivide the Subtropical region and include a tropical transition zone in the north-east of South Africa. Both of these systems, albeit differing in size, type and function, are unique clear water estuaries on a small section of tropical South African coast; the location also being characterised by the higher latitudinal limit of Western Indian Ocean coral reefs (Schleyer et al. 2008).

By way of example, the Kosi Estuary has a uniquely tropical flora amongst South Africa estuaries, indicated by presence of the seagrass *Halodule universis* and mangrove species *Lumnitzera racemosa*, *Ceriops tagal* and *Xylocarpus granatum* that are found in no other South African systems (DWS 2016). Recent records of tropical species, such as the snake sea cucumber, *Synapta maculata*, and pen shell, *Pinna muricata* in the Kosi Estuary point to a tropical influence on the system's invertebrate fauna (DWS 2016). The Kosi ichthyofauna comprises a particularly wide diversity of fish, including tropical species not reported from any other South African estuaries (Blaber and Cyrus 1981; DWS 2016). Although the presence of reef habitat at the mouth contributes to this, biogeographic considerations also play a role. Elements of the estuary-associated fish fauna in Kosi appear to reflect the unique (in a South African context) linkages between estuarine habitats, particularly clear water mangroves, and offshore coral reefs. This is evidenced by the abundance and large sizes of several members of the Lutjanidae (snappers) in the Kosi system. This family of fish includes many species that rely on linkages and strong connectivity between mangroves and coral reef habitats on tropical coastlines elsewhere in the world (e.g. Nagelkerken et al. 2000, 2002; Mumby et al. 2004).

In contrast, to the south, St Lucia Estuary supports invertebrate and fish assemblages common in Subtropical estuaries on the subcontinent (MacKay et al. 2010; Perissinotto et al. 2013). The new zone also aligns with marine biogeographic patterns evident for floral and faunal groups, such as benthic macroalgae (Bolton et al. 2004), intertidal invertebrates and algae (Sink et al. 2005), and shelf holothuroideans (Thandar 2015), and agrees with the recent marine biogeographic map that includes the Natal-Delagoa tropical region (Sink et al. 2019).

Therefore, the updated ecosystem-level classification scheme defined the biogeographical regions as the tropical from Kosi to uMgobezeleni, the Subtropical stretches from the St Lucia system in KwaZulu-Natal to the Mbashe Estuary in the Eastern Cape, the Warm Temperate from the Mendwana Estuary in the Eastern Cape to the Ratel Estuary near Cape Agulhas, and the Cool Temperate from the Uilkraals Estuary to the Orange Estuary on the Northern Cape coast (Emanuel et al. 1992; Turpie et al. 2000; Harrison 2002).

Revision of South Africa's estuarine types

Improved scientific understanding has resulted in necessary updates to Whitfield's (1992) classification, e.g.

adding two new estuary types, namely Estuarine Lagoon and Arid Predominantly Closed Estuaries. Langebaan is an example of an Estuarine Lagoon, whereas the Buffels, Swartlintjies and Spoeg Estuaries in the same region are examples of Arid Predominantly Closed Estuaries (Figures 2, 3 and 4, Supplementary material). The original "River Mouth" type was renamed "Fluvially Dominated" and divided into large and small systems, and according to river sediment inputs. The temporarily open/closed group was also divided by size into Large and Small Temporarily Closed Estuaries. The new types are further described in Figure 2 and Table 2, with key features and dominant physical processes that characterise these revised estuary types being summarised in Table 3. The listing and designation of all systems is provided in the supplementary material (Supplementary Table). Localities around the coast are shown in Figure 4.

Estuarine Lakes
Estuarine Lakes (also known as Intermittently Closed and Open Lakes and Lagoons or Coastal Lakes) comprise one or more typically large circular waterbodies connected to the sea by a constricted inlet channel (Figure 3, Table 3). Freshwater input can be from a single or multiple large rivers, groundwater or aquifers, or multiple small waterways or streams feeding into the basin; or a combination thereof. Maximum water levels are determined by berm height, mouth state and freshwater input. Marine connectivity varies from almost permanently open, to temporarily closed, on annual scales. Salinities are highly variable, ranging from fresh to hypersaline, because of differing freshwater input (surface and ground water), evaporation and the extent and duration of the marine connection. Mixing processes are dominated by wind and, to a lesser extent fluvial inputs, owing to their restricted mouths and relatively

Table 1: Whitfield's (1992) typology of South Africa's estuaries

Type	Tidal prism	Mixing process	Average salinity *
Estuarine Bay	Large (>10 × 106 m^3)	Tidal	20–35
Permanently Open	Moderate (1–10 × 106 m^3)	Tidal/riverine	10– >35
River Mouth	Small (<1 × 106 m^3)	Riverine	<10
Estuarine Lake	Negligible (<0.1 × 106 m^3)	Wind	1– >35
Temporarily Open / Closed estuaries	Absent	Wind	1– >35

* Expressed without units, because salinity is a ratio or according to a Practical Salinity Scale (seawater ~35).

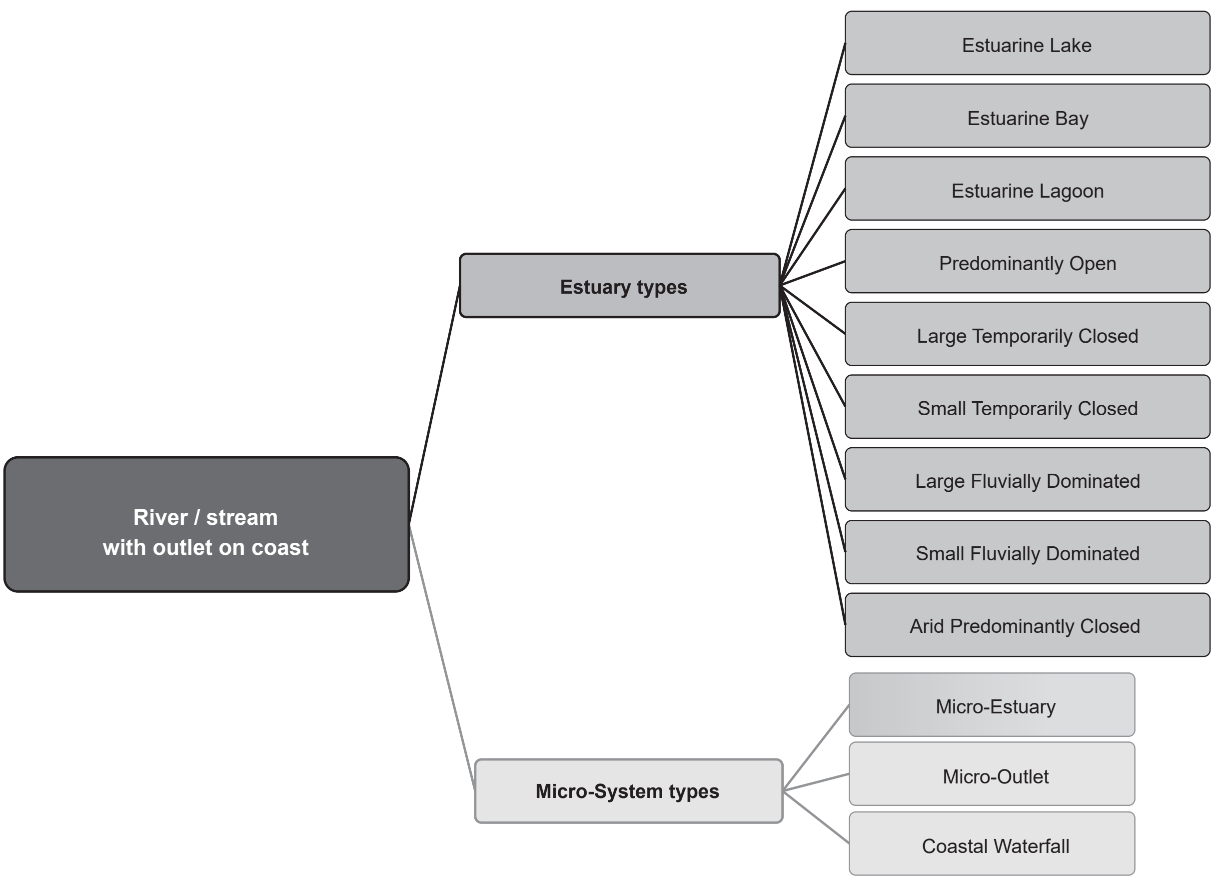

Figure 2: The extended South African estuarine typology into nine estuary types and three micro-system types

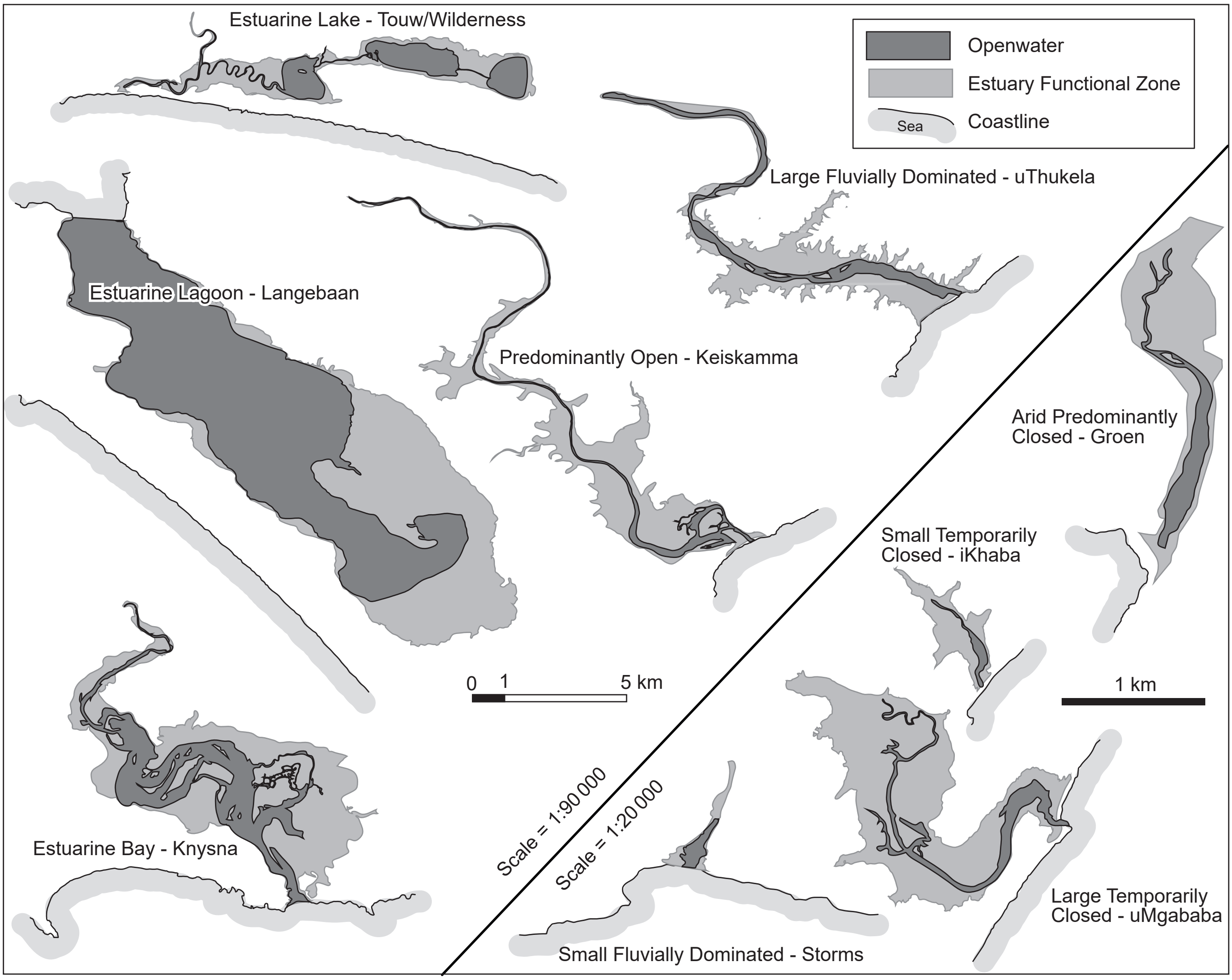

Figure 3: Maps showing examples of South African estuary types, with larger types represented at 1:90 000 scale and smaller types at 1:20 000 scale

large surface areas. Average tidal amplitudes are negligible (15–20 cm) when connected to the sea, primarily as a result of restricted mouth conditions (Department of Water and Sanitation tidal recorders G4T004, G4T003, K3T006, W3T002, W7T003). Sediment processes tend to be stable, with infilling occurring over long time scales and system resetting confined to larger flood events.

Estuarine Bays

Estuarine Bays (also known as coastal or estuarine embayments) are permanently linked to the sea by unrestricted, deep mouths and are dominated by tidal processes, with tidal amplitude close to that of the sea (Figure 3, Table 3) (Department of Water and Sanitation tidal recorder K5T001). These are large systems (>1 200 ha), with generally round basins, where only the upper reaches experience a degree of constriction to tidal flows. a result of relatively low river inputs they have a predominantly euhaline salinity regime in the lower and mid reaches, with freshwater mixing processes being mostly confined to the more restricted upper areas. Sediments are typically marine in origin and grain size distributions are stable over time. There are two natural occurrences of Estuarine Bays in South Africa (namely Knysna and Durban Bay; Figures 3 and 4).

Estuarine Lagoons

Langebaan Lagoon (Figure 3) has many of the characteristics of an estuary (Whitfield 2005), including calm waters that are protected from marine wave action and biota that reflect many of the species usually found in estuaries (Figure 4, Table 3). However, despite groundwater seeps into some areas, it lacks riverine inflow and a normal estuarine salinity gradient (Table 2). Langebaan Lagoon represents a unique coastal ecosystem type (Table 4). It is recognised as an estuary, because its ecological functioning includes both freshwater and marine inputs into a semi-enclosed embayment. Estuarine Lagoons, as defined here, are permanently connected to the sea and are therefore marine dominated. Tidal action is the dominant mixing process and sedimentary processes are therefore generally stable. Tidal amplitude and water levels are close to those of the sea.

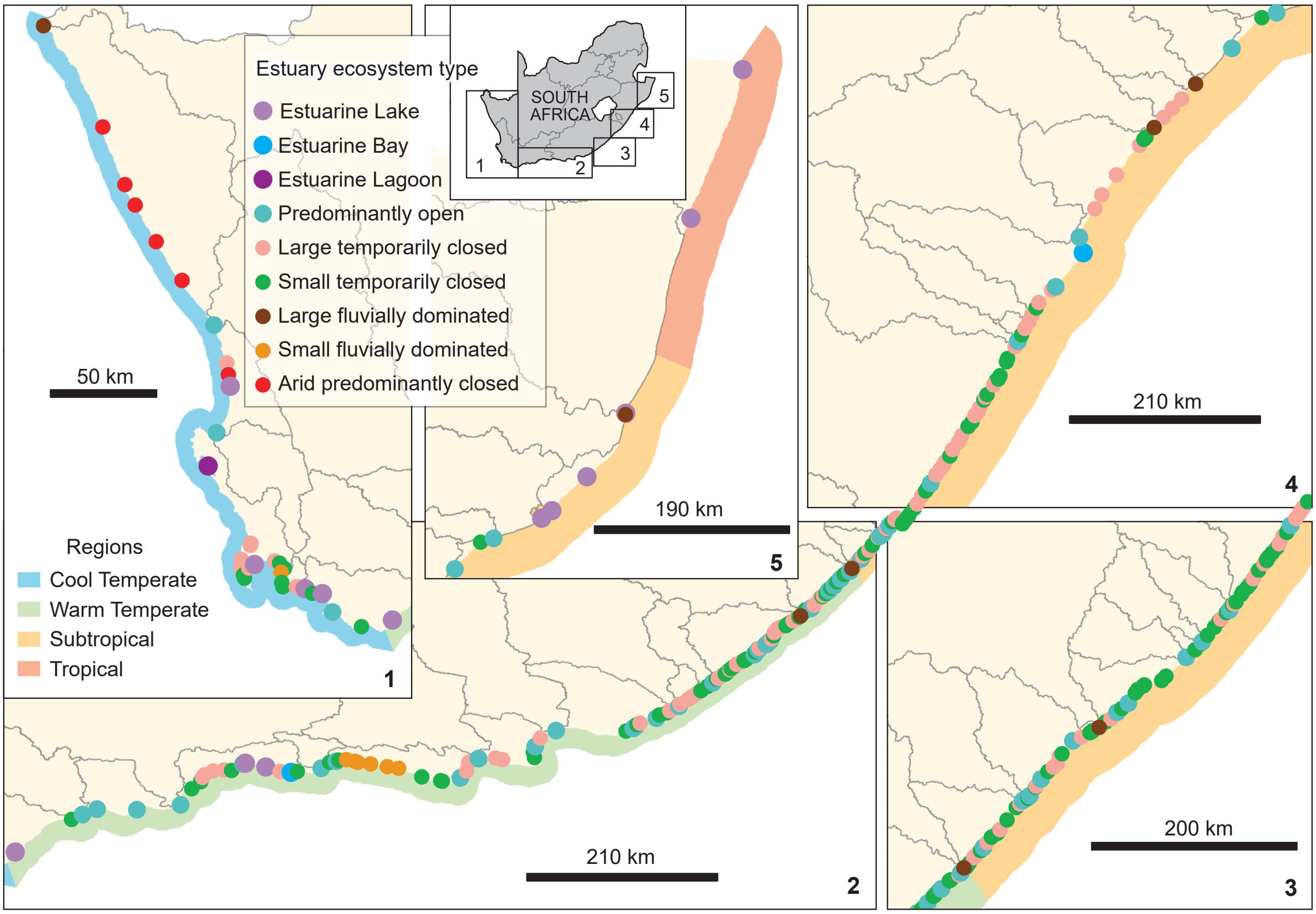

Figure 4: Estuary distribution across four biogeographical regions in accordance with the Estuarine Classification System shown in maps 1 to 5. Cool Temperate region depicted in light blue (1), Warm Temperate region depicted in light green (2), Subtropical region depicted in orange (3 and 4), Tropical region depicted in red (5)

Predominantly Open Estuaries

Predominantly Open Estuaries (also known as tidal river lagoons) are open to the sea for more than 90% of the time (similar to the Permanently Open Estuary type of Whitfield 1992). Some are permanently open owing to perennial river flow or the presence of a large tidal prism (Figure 3, Table 3). Tidal amplitude ranges from 0.75 to 1.5 m (Department of Water and Sanitation tidal recorders E2T014, G1T074). Predominantly Open Estuaries are linear systems where mixing processes are dominated by both fluvial inputs and tidal action creating vertical and horizontal salinity gradients. Under low river flows and high summer evaporation, hypersalinity can develop in the upper reaches. The degree to which the mouth is restricted depends on the rate and volume of freshwater inflow. Some systems become severely constricted during low flow periods, decreasing the tidal amplitude and increasing the duration of the ebb tidal cycle. Regular flooding results in relatively mobile sediments. These estuaries usually support wetlands, salt marshes, macrophyte beds and marine and estuarine fauna (Whitfield 1992). Surprisingly, their size varies considerably ranging from 10 to 7 500 ha, with smaller systems afforded a degree of protection against direct wave action by rocky headlands or subtidal reefs, which assists in maintaining an open mouth.

Table 2: Revision of Whitfield's 1992 estuarine classification system

1992 Classification	2018 Classification
Estuarine Lake	Estuarine Lake
Estuarine Bay	Estuarine Bay
	Estuarine Lagoon
Permanently open	Predominantly Open
Temporarily open / closed	Large Temporarily Closed
	Small Temporarily Closed
River mouth	Large Fluvially Dominated
	Small Fluvially Dominated
	Arid Predominantly Closed

Large and Small Temporarily Closed Estuaries

The sizeable temporarily open/closed category of Whitfield (1992) (also called blind estuaries, barrier enclosed lagoons or intermittently open/closed estuaries) was divided into Small and Large Temporarily Closed Estuaries (Figures 3 and 4) using a total habitat area of 15 ha (associated with ~10 ha

Table 3: Revised South African estuary types, key features and dominant physical processes

Estuarine type	Estuarine area (ha)	% time open to the sea	Geomorphology	Average tidal range (m)#	Maximum water level determined by:	Typical salinity range	Mixing process	Sediment stability	Mean annul runoff (× 10^6 m^3)
Estuarine Lake	>800	Variable	Circular, with constricted inlet channel	0.1– 0.15	Mouth state	0–35	Wind/ riverine	Stable	20–650*
Estuarine Bay	> 1 000	100	Circular, with unrestricted inlet	1.5–2.0	Tides	30–35 Average: 35	Tidal	Stable	40–80
Estuarine Lagoon	> 1 000	100	Circular, with unrestricted inlet	1.5–2.0	Tides	35–36 Average: 35	Tidal	Stable	0*
Predominantly Open	10–7 500	90–100	Linear, with restricted inlet	0.75–1.5	Tides/ Mouth state	0–40	Tidal/riverine	Mobile (reset by large floods)	10–1 790
Large Temporarily Closed	>15	>50	Linear /funnel, with highly restricted inlet	0.25–0.5	Mouth state	0–60	Tidal/ riverine/ wind/seepage	Mobile (breaching and floods)	1–280
Small Temporarily Closed	<15	<50	Linear/funnel, with highly unrestricted inlet	0.15–0.3	Mouth state	0–30	Riverine/ wind/ seepage	Mobile (breaching and floods)	0.1–70
Large Fluvially Dominated	100–3 700	>90	Linear, with highly restricted inlet	0.5–1.0	Mouth State	0–10	Riverine	Highly mobile (reset annually)	370–10 830
Small Fluvially Dominated	< 15	100	Linear, with highly restricted inlet	0.5–1.5	Mouth state	0–5	Riverine	Highly mobile (reset annually)	20–50
Arid Predominantly Closed	10–500	<5	Linear/funnel, with highly restricted inlet	0 (overwash and breaching)	Mouth state	0–200 Average: Hypersaline	Evaporation/ seepage/wind	Stable, but reset on decadal-scales during floods	0.2–10

*Langebaan (Estuarine Lagoon), uMgobezeleni and Kosi (Estuarine Lakes) are groundwater dependent systems.
#Tidal ranges are indicative of what is normally experienced, but some deviations are expected, e.g. after breaching or floods.

Table 4: Number of estuaries in each type across four biogeographical regions and classified into 22 estuary ecosystem types, based on natural condition

Estuary type	Cool Temperate	Warm Temperate	Subtropical	Tropical	Number of estuaries in type	Number of estuaries in ecosystem types
Estuarine Lake	4	3	3	2	12*	4
Estuarine Bay		1	1		2	2
Estuarine Lagoon	1				1	1
Predominantly Open	3	25	17		45	3
Large Temporarily Closed	9	40	44		93	3
Small Temporarily Closed	8	48	60		116	3
Large Fluvially Dominated	1	1	5		7	3
Small Fluvially Dominated	1	6			7	2
Arid Predominantly Closed	6				6	1
Total	33	124	130	2	289 (*290 at present)	22

* Richards Bay Harbour subdivided uMhlathuze Estuarine Lake into two systems in the 1970s

of open water area) as the dividing threshold (Tables 2 and 3). The division was based on differences in recorded biophysical processes and patterns (Teske and Wooldridge 2001; Vorwerk et al. 2003; James and Harrison 2017). Small systems are likely to experience rapid increases and decreases freshwater runoff over a few hours making them strongly event driven. There will be little scouring following berm breaching, and a semi-closed mouth condition can easily develop owing to a small, perched, outflow channel that restricts tidal amplitude to 10 to 15 cm (Department of Water and Sanitation tidal recorder T7T004). There is minimal water column area during the open state. Habitat diversity is likely to be low (and without intertidal salt marshes) and species diversity and abundance reduced. Significant differences have been noted between invertebrate and fish assemblages of Small and Large Temporarily Closed Estuaries along the southeast coast (e.g. Teske and Wooldridge 2001; Vorwerk et al. 2003; James and Harrison 2016).

Both large and small systems tend to be linear or funnel shaped, with highly restricted inlets. Smaller systems especially tend to be "perched" above normal tidal levels, resulting in little to no open water area during the open mouth low tide state. Water levels are dominated by the state of the mouth, with highest levels of 1 m to 2 m above mean sea level during the closed phase. Tidal ranges are very restricted, varying from 25 to 50 cm in Large Temporarily Closed Estuaries (Department of Water and Sanitation tidal recorders K2T004, K4H100, P4T002) to 15 to 30 cm in Small Temporarily Closed Estuaries (Department of Water and Sanitation tidal recorders U7T001, K8T004; unpublished field observations). Open phase mixing processes are dominated by fluvial input and partially by tides. When closed, wind and seepage losses through the berm play a key role. Sediment composition is largely stable, resetting mainly during floods. Salinity regimes range from almost fresh to hypersaline, which in large systems can develop during times of low flow or droughts. Small Temporarily Closed Estuaries tend to be fresher in character, because they have less connectivity with the sea.

Small and Large Fluvially Dominated Estuaries

Estuaries characterised as river mouths by Whitfield (1992) (also known as river-dominated and tidal river mouths) were divided into two categories, Small and Large Fluvially Dominated systems to distinguish between small (<15 ha), black-water dominated, rocky, temperate southern coast estuaries, and large, shallow, sediment rich, freshwater dominated systems of the east and west coasts (Figure 2, Tables 2 and 3). The larger systems have very high sediment turnover, often develop ebb-tidal deltas, are turbid and can close during periods of low flow, e.g. uThukela and Orange Estuaries (Figure 3). Large Fluvially Dominated Estuaries tend to be constricted and can even periodically close during low flows (Department of Water and Sanitation tidal recorders S7T008, T3T018, V5T003). Small, sediment-starved, fluvially dominated systems have unrestricted mouths, because they usually occur along rocky shores and receive clear humic-stained water from Table Mountain Sandstone catchments. Fluvial processes are dominant and salinities are mostly fresh throughout the estuary for more than half the time. During peak flood conditions, outflows can influence salinities for a considerable distance offshore.

Arid Predominantly Closed Estuaries

This type comprises six small estuaries, namely the Buffels, Swartlintjies, Spoeg, Groen, Sout (Noord) and Wadrift Estuaries, located in the Namaqua west coast region (Figures 3 and 4, Supplementary table). They are linear or funnel shaped and closed on annual to decadal time scales. Salinities tend to be euhaline to hypersaline, as a result of low fluvial input and high evaporation rates (Table 3). Accordingly, mixing processes tend to occur over long time periods and they are dominated by the effects of evaporation, winds and seepage through the berm at the mouth. Occasional breaching and overwash during high sea conditions provide for marine input and connectivity. Sediment processes are generally stable on decadal time scales and are reset by large intermittent flash floods. Water levels are determined by the interplay between sand berm level, evaporation rates and seepage losses. Groundwater and inflows from local fountains replenish these losses and influence the salinity regimes of these estuaries.

Arid conditions promote the growth of unique vegetation, such as salt tolerant, succulent *Sarcocornia* spp. and *Salicornia* spp. that can occur kilometres inland, making it difficult to distinguish between arid estuarine salt marsh vegetation and upstream Namaqualand riverine vegetation. These vegetated areas can be stable despite open water salinities reaching >200 (Wooldridge et al. 2016). Fish diversity, abundance and community structure relies on "suicidal" recruitment that is largely a function of connectivity with the sea and the degree of overwash during high seas. Fish survival depends mostly on groundwater inflow maintaining a suitable salinity gradient, with at least some areas having a salinity not exceeding 50. Safe return of fish to the sea can occur during river flood events and depends on a quick breach and fish not suffocating in sediment-laden water backing up against the berm. Invertebrate diversity, abundance and community structure are related to changing salinity gradients, including long cycles of hypersalinity. The Swartlintjies, Sout and Groen Estuaries are hypersaline, with a high biomass of brine shrimp *Artemia* sp. that hatch at salinities >40 and encyst, sinking to the bottom when salinities exceed 150. Cycles of *Artemia* abundance follow salinity regimes that in turn affect the diversity, abundance and occurrence of flamingos and other birds that feed on them.

Micro-system types

The approximately 400 river and stream outlets along the coast were categorised into two broad categories: fully functional estuaries (described in Section 3.1.2) and micro-systems (Figure 5), with micro-systems generally being permanent or non-permanent coastal waterbodies <2 ha in area or >200 m in length (Supplementary table). Historical datasets contain information on some outlets not deemed to be functional estuaries (Harrison et al. 2000). Nine small systems previously classified as estuaries were reclassified as micro-systems under the new classification (Table 2), because of clear indications that they do not support typical estuarine functionality, e.g. some systems have limited estuarine biota (Magoro et al. 2020), with no fish fauna recorded in micro-outlets over a number of visits (Magoro 2018). Micro-systems were classified into three categories based on spatial features (e.g. size and length) and field biotic observations:

Micro-estuaries

These are defined as small, permanent coastal waterbodies where mixing of salt- and freshwater can periodically occur owing to overwash from the sea or tidal exchange following breaching of the mouth. These small systems are likely to support low densities of a limited number of estuarine and marine species (Bate et al. 2017; Dalu et al. 2018; Human et al. 2018; Magoro et al. 2020).

Micro-outlets

These are very small waterbodies (<1 ha in area or <50 m in length) that are ephemeral in nature (i.e. they can dry out during periods of low flow) or are elevated above mean sea level, with a perched outflow channel that does not facilitate tidal mixing of salt- and freshwater (Dalu et al. 2018; Human et al. 2018). It can, however, act as a limited conduit between the land and the sea during periods of elevated stream outflow or exceptionally high storm sea events.

Coastal waterfalls

This outlet type is represented by waterbodies elevated more than 10 m above mean sea level that have no direct channel connection with the sea. Because of their elevation, they do not serve as conduits between the land and the sea. These systems occur along rocky shorelines where the presence of bedrock does not allow for channel erosion to mean sea level. However, the continuous outflow of freshwater into rocky coastal habitats could support unique marine biotic assemblages along the coast. The localities of designated micro-estuaries, coastal outlets/seeps and coastal waterfalls are shown in Figure 5, including distributions across the revised biogeographical regions. Listing and designation of all systems is provided in the supplementary material (Supplementary table).

Developing an ecosystem-level classification scheme

The final step in the ecosystem classification of South Africa's 290 estuaries is to intersect the four biogeographical zones, namely the Cool Temperate (Orange to Ratel), Warm Temperate (Heuningnes to Mendwana), Subtropical (Mbashe to St Lucia) and Tropical (uMgobezeleni to Kosi) zones with the nine primary estuary types. This resulted in 22 estuary ecosystem categories for South Africa (Table 4) and represents a high diversity of estuary ecosystem types, which is not unexpected considering the country's diverse climatic, oceanographic and geological drivers. Overall the Tropical biogeographical region has the least number of estuaries, whereas the Subtropical (130) and Warm Temperate (124) regions incorporate the highest number of estuaries.

Estuarine Lagoons are the rarest South African estuary type, with only one member in the Cool Temperate region, followed by Estuarine Bays, with two in the Subtropical and one in the Warm Temperate region, and Arid Predominantly Closed Estuaries, with six systems confined to the Cool Temperate region. The Large and Small Fluvially Dominated primary type have seven systems each, occurring in three and two biogeographical regions, respectively. The most numerically dominant types are the Small Temporarily Closed (116), Large Temporarily Closed (93), and Predominantly Open (45) Estuaries that occur across the Cool Temperate, Warm Temperate and Subtropical biogeographical regions. Estuarine Lakes occur in all four biogeographical zones and, although not numerically common, represent the largest surface area of all estuarine types, with Lake St Lucia representing more than half of South Africa's estuarine surface area.

From an ecosystem type perspective Cool Temperate Estuarine Lagoons, Cool Temperate Large and Small Fluvially Dominated Estuaries, Warm Temperate Estuarine Bays, Warm Temperate Large Fluvially Dominated Estuaries, and Subtropical Bays are the rarest types, because they each have only one member. Overall, the Subtropical and Warm Temperate Small Temporarily Closed Estuary types dominate numerically with 60 and 48 members, respectively.

An additional 202 micro-systems were recorded around the coast, albeit with a very low confidence, because of lack of data (Table 5). Of these, a total of 42 micro-estuaries were tentatively identified, with five systems located the

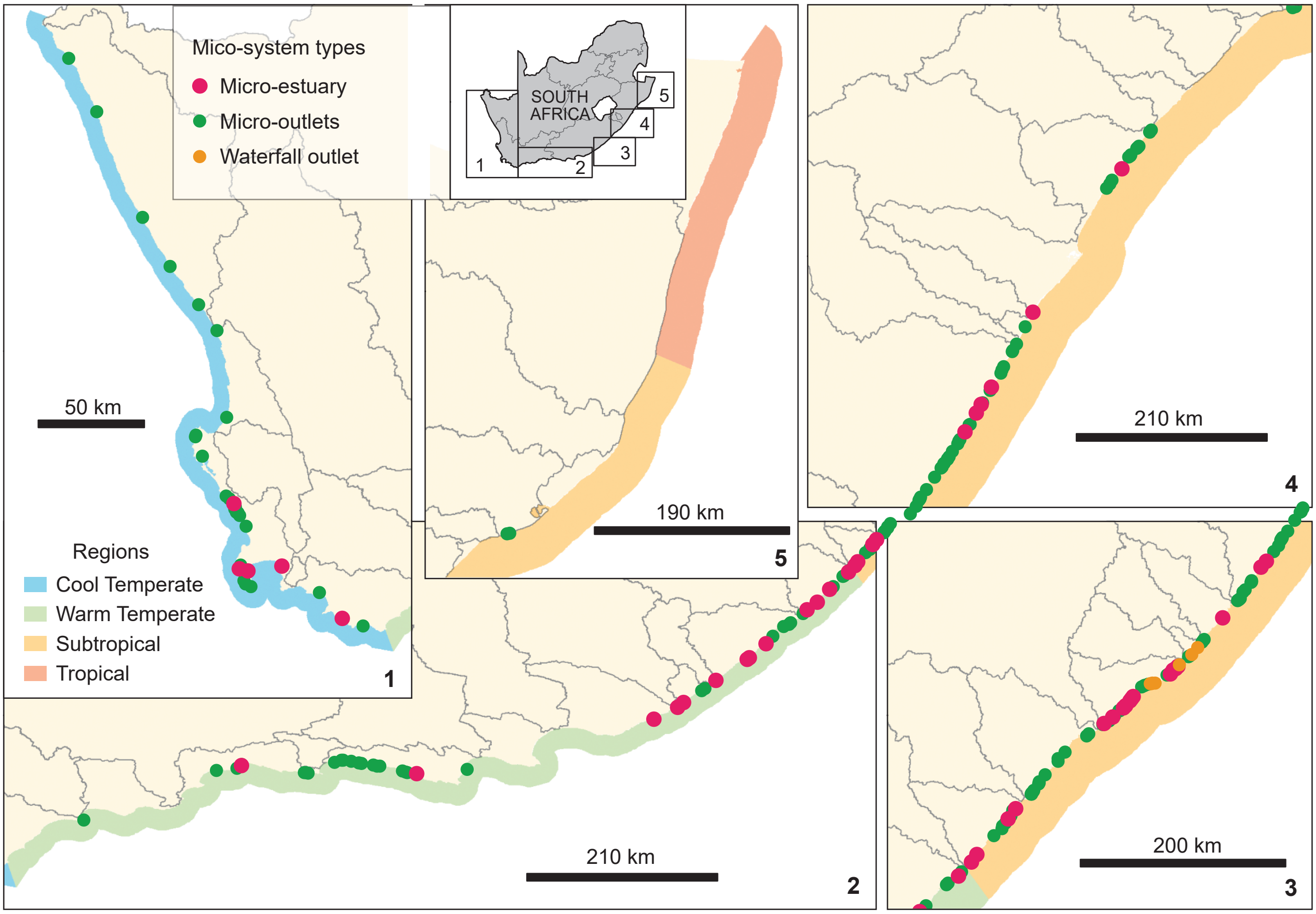

Figure 5: Map of the location and biogeographical distribution of micro-systems (<2 ha or <200 m) in length) depicted in maps 1 to 5. Cool Temperate (1), Warm Temperate (2), Subtropical (3 and 4), Tropical (5)

Cool Temperate zone, 13 in the Warm Temperate zone and 24 in the Subtropical biogeographical region. Micro-outlets and waterfalls were only identified in as much as that act as a potential conduit for land-sea interactions and should not be targeted for coastal and water resource development to preserve estuarine ecosystem services.

Estuaries subjected to functional type shifts and causative factors

Estuaries and coastal ecosystems are facing increasing anthropogenic pressures affecting their productivity and ability to provide ecosystem services (Borja et al. 2016). The main pressures on South African estuaries include flow modification, catchment degradation, coastal development, pollution, exploitation of living and non-living resources, and mouth (inlet) manipulation (van Niekerk et al. 2013). These have altered key defining features or processes (i.e. mouth behaviour, water level fluctuations, mixing processes) in some estuaries to the extent that they no longer function in accordance with their natural type (see Table 6 for summary of estuaries that were subjected to functional shifts). Type shifts should not be confused with degraded estuaries that still function in a similar way to natural, e.g. iSiphingo Estuary is severely degraded (i.e. has undergone a condition shift), as a result of pollution and habitat loss, but it still maintains its function as a Predominantly Open Estuary through a concrete pipe constructed in the sand berm at the mouth.

Estuarine lakes

The Zeekoei, Heuninges, uMhlathuze (Richards Bay) and iNhlabane systems were once Estuarine Lakes that have all been irreversibly altered through mouth manipulation and development (Table 6). The Zeekoei lake system naturally closed for long periods until the 1940s when the connection between the lakes and main estuary channel was severed by weirs and levees that were constructed to prevent flooding of surrounding urbanised areas, while maintaining high water levels in the main waterbodies. A concrete canal currently connects the lake system to the sea. Although there is no tidal exchange, the system is essentially permanently open, but no longer functions as an Estuarine Lake.

Development and agriculture on the Heuningnes Estuary floodplain have contributed to the system function changing from an Estuarine Lake that used to close periodically, into a Permanently Open Estuary. More than a century ago, drains were excavated throughout the floodplain and adjacent wetlands to “reclaim” land for grazing and dry-land agriculture. Since the 1940s, sand dunes at the mouth have

Table 5: Number of estuaries in each micro-system type across four biogeographical regions and classified into nine micro-system ecosystem types

Micro-system type	Cool Temperate	Warm Temperate	Subtropical	Tropical	Number of estuaries in type	Number of ecosystem types
Micro-estuary	5	13	24		42	3
Micro-outlet	26	31	96		153	3
Waterfall outlet			7		7	3
Total	31	44	127		202	9

been manipulated to prevent mouth closure and natural inundation of the estuarine floodplain, much of which is now under farmland. Subsequently, the mouth has closed on only a few occasions. Artificial breaching is then practised to ensure an open mouth. The topography suggests that in its natural state the estuary would have supported a large open water area that would develop over several years under closed mouth conditions, followed by natural breaching after river flooding and significant sediment scour in the lower reaches and subsequent tidal exchange with the estuarine lake before the mouth closed again.

In its pristine state, the uMhlathuze Estuary was an Estuarine Lake that once connected a network of coastal marine lakes to the sea (Weerts et al. 2014). The development of a deep-water harbour at Richards Bay in the 1970s and the construction of a 4 km long berm wall divided the lake into a northern harbour section and a southern estuarine sanctuary. The uMhlathuze River to the west was canalised and diverted into the sanctuary and a new marine outlet created by dredging through the coastal berm 5 km south of the natural outlet (Weerts and Cyrus 2002). The new intertidal habitat and delta of the sanctuary was rapidly colonised by the white mangrove *Avicennia marina* and currently constitutes the largest mangrove habitat in South Africa (Bedin 2001; Adams et al. 2016). Invertebrate estuarine communities have become species rich from increased marine exposure, but have lost endemic species, such as the burrowing ocypodid crab, *Paratylodiplax blephariskios* (MacKay and Cyrus 1998). Currently both Richards Bay and uMhlathuze function as an Estuarine Bay and a Predominantly Open system, respectively (Supplementary material).

Similarly, a concrete barrage was constructed in 1978 across the estuarine connection for Lake iNhlabane to increase water storage for mining purposes. Prior to 1978, iNhlabane consisted of two interconnected lakes that had a direct connection to the sea through the iNhlabane Estuary. Raising of the water level resulted in the merging of the two lakes into a single lobed freshwater lake and the loss of typical estuarine fish and invertebrate communities (Cyrus and Wepener 1997). The downstream section of this system now functions as a Small Temporarily Closed Estuary.

Predominantly Open Estuaries

Excessive flow modifications have fundamentally changed the type and function of these systems. Freshwater abstraction and the presence of dams upstream can cause permanently open estuaries to close, as portrayed by the Uilkraals Estuary, which was once predominantly open. In 2008, it closed (seemingly permanently) for the first time and is currently experiencing successive artificial breaches and closures. In its natural state, the mouth might have closed briefly (days to weeks) during drought conditions, but current mouth closures endure for months, changing the system from functioning as a Predominantly Open Estuary to that of a Large Temporarily Closed Estuary (Table 6).

Increased mouth closure has led to abnormal brackish to fresh conditions in the Uilkraals caused by inundation levels well above the average high tide, or hypersaline conditions that result from low freshwater inputs and high evaporation. Tidal flushing has been reduced and this affects the estuary's capacity to exchange nutrients, remove accumulated salts and maintain the diversity and zonation of species-rich salt marshes (Mucina et al. 2003; Adams et al. 2010). Maintaining the system's biodiversity is important, because it falls in a biogeographic and phylogeographic transition zone between the Cool Temperate and Warm Temperate regions, with several aquatic macrophytes having phylogeographic breaks and distinct lineages within this zone (Harrison 2002; Teske et al. 2011). Closed conditions are also inhibiting for fish recruitment and estuarine nursery function.

Large Temporarily Closed Estuaries

Excessive regulated inflow can also permanently change an estuary type. Historically, the Eerste Estuary was temporarily closed and seawater intrusion created estuarine conditions up to 2.5 km from the mouth (Brown and Magoba 2009). Currently, inflow from five municipal wastewater treatment works causes the mouth to remain permanently open (Table 6). There is limited tidal influence, because seawater penetrates only 500 m into the estuary under specific mouth and river flow conditions (CSIR 2001). Fish surveys conducted before the municipal inflows commenced recorded 3–11 endemic marine and estuarine species (Clark et al. 1994). Subsequent surveys have yielded almost mono-specific catches, reduced catch rates, and the size distributions are indicative of a severe deterioration in suitable habitat for indigenous estuary-associated fish species. The invasive freshwater sharptooth catfish *Clarias gariepinus* is currently caught in high numbers in this once important estuarine system.

The placement of development infrastructure, such as housing, canals, railway embankments and bridges has affected the natural hydrology of numerous estuaries. Silvermine Estuary in Cape Town was once a series of large, shallow, seasonal pans and marshes that formed periodically behind a low barrier dune above the high-water mark (Brown and Magoba 2009). It would have functioned as a Large Temporarily Closed system, but in the 1990s, to alleviate flooding of surrounding properties, the estuary's floodplain was engineered using gabions and earth berms reducing its size, therefore changing its character to that of a Small Temporarily Closed Estuary (Table 6), with limited marine connectivity.

One of the earliest maps of Table Bay, drawn by Barbier in 1786, show that the Sout-Diep system shared a common mouth. The map indicates that the Sout (Wes) Estuary was in the same location as currently, with the exception of the lower section, which used to join up with the Diep, Liesbeek and Black Rivers along the alignment of the present-day Zoarvlei, before flowing out to sea. The system is now artificially separated from the Diep, with the Diep Estuary mouth being located some three kilometres north of its historical position. Between 1930 and 2000, a series of projects were undertaken that resulted in the Sout (Wes) Estuary being diverted to the Black River and canalised in its current configuration. Extensive urbanisation of the area surrounding the Sout-Diep Estuary has largely resulted in a complete loss of estuarine function and habitat within this system.

Small Temporarily Closed Estuaries

Farther to the east, records indicate that in the early 1800s, the Small Temporarily Closed Baakens Estuary in Port Elizabeth formed a deep inlet that could be used by small sailing vessels and it was also an important recreational area. The establishment of wool-washing operations and laundries on the banks led to the water becoming polluted and unusable for recreational activities (thecasualobserver.co.za/port-elizabeth). Later, more industries were developed nearby and construction rubble was dumped into the estuary during the 1800s. This led to it becoming predominantly open and canalised along much of its length (Table 6). Over many years, almost all the estuarine natural vegetation had been removed, with only small patches of reeds remaining. Although it currently supports about nine estuary-associated fish species, the prevalence of small size classes, dominance of marine species, and lack of habitat diversity suggests that the fish fauna is severely constrained. This contrasts with the rich diversity of estuary-associated fish (30 species) found in the large permanently open Swartkops Estuary to the north (James and Harrison 2010).

The development of freeways and an industrial area close to the banks of the Small Temporarily Closed Papenkuils Estuary in Algoa Bay led to the canalisation of its lower reaches and the construction of a concrete bed (Table 6). The estuary receives industrial and domestic effluent that pollutes its water (James and Harrison 2010). It was even known historically as Smelly Creek in the 1800s. The system currently functions as a stormwater and industrial effluent canal. Prior to these developments, typical salt marsh plants, such as *Sarcocornia* sp. occurred in the lower reaches, with bird life being prolific and 57 water bird species (especially flamingos) frequenting its banks (Taylor 1964). An estuary transformed into polluted stormwater canal, such as the Papenkuils Estuary, is unlikely to provide any suitable habitat for endemic estuary-associated biota (James and Harrison 2010).

Table 6: Estuaries where functional type shifts have occurred

Estuary name	Natural type	Functional type	Driver of change	Compromised estuarine processes that defined natural estuary type					
				Mouth closure	High water levels	Tidal regime	Salinity gradient	Mixing process	Connectivity (i.e. Floodplain, lakes, catchment)
Zeekoei	Estuarine Lake	Predominantly Open (Canalise)	Mouth manipulation, development	•	•	•	•	•	•
Heuningnes		Predominantly Open	Mouth manipulation, development	•	•		•	•	•
uMhlathuze / Richards Bay		Estuarine Bay / Predominantly Open	Mouth manipulation, development			•	•	•	•
iNhlabane		Small Temporarily Closed	Development, impoundment	•	•	•	•	•	•
Uilkraals	Predominantly Open	Large Temporarily Closed	Flow modification (–)			•	•	•	•
Eerste	Large Temporarily Closed	Predominantly Open	Flow modification (+)	•	•	•	•	•	•
Silvermine		Small Temporarily Closed	Mouth manipulation, development		•	•	•	•	•
Sout (Wes)	Small Temporarily Closed	Predominantly Open (canalise)	Mouth manipulation, development	•	•	•	•	•	•
Baakens		Predominantly Open (canalise)	Development	•	•	•	•	•	•
Papenkuils		Predominantly Open (canalise)	Development	•	•	•	•	•	•

Mitigating for functional shifts in estuaries

Overall, where feasible, estuary management plans should ensure that natural estuarine processes in degraded estuaries are restored to ensure the overall resilience of estuarine ecosystems in South Africa. In extreme cases, some estuaries have been so extensively modified that they have completely lost functionality. Science-based management and intervention is needed to improve functionality of these modified estuaries.

Each estuary has its own issues that require remediation. The Zeekoei Estuary requires an improved stormwater infrastructure, in order to enhance its water quality. The mouth of the Heuningnes Estuary should be allowed to close, so that breaching at naturally high water levels can scour accumulated sediment.

The Uilkraals Estuary requires restoration of its baseflows to ensure the mouth remains permanently open. Recently accumulated sediment in this system might have to be removed to restore tidal flows to 2010 conditions and ensure a permanent connection to the sea. The Eerste Estuary would benefit from the establishment of an artificial wetland and decreased wastewater input to reduce excessive nutrient loading. Artificial manipulation of the Silvermine Estuary mouth and/or meandering outflow channel, by the local authorities and illegal bridge squatters, should be discontinued, because the backwater area that forms under closed mouth or meandering channel conditions is the only remaining functional estuarine area in the system. Hydrocarbons and other pollutants enter the uMhlathuze Sanctuary via the obsolete Richards Bay Harbour tidal gates should be closed off to prevent ongoing contamination of the Sanctuary area. Illegal gillnetting that is negating the uMhlathuze regionally important nursery function should also be addressed through increased compliance. The partial link between Nhlabane Lake and estuary must be established. This in turn requires continuous operation of the fishway, lowering of the barrage level, and rehabilitation of riparian areas around the lake. There are few options to improve the functioning of the canalised Sout (Wes), Baakens and Papenkuils Estuaries, apart from ensuring that pollution levels are controlled and that the water column of these systems remains oxygenated.

Conclusions

Estuary ecosystem types can serve as surrogates for ecosystem processes and enable predictions of biophysical characteristics. Understanding ecological processes and patterns associated with an estuary type facilitates an assessment of its resilience to anthropogenic pressures. This allows for extrapolation in data-limited environments.

For nearly three decades, the characterisation scheme of Whitfield (1992) served as the reference framework to type South African estuaries. This paper revises the characterisation scheme through the development of an ecosystem classification scheme that explicitly incorporates biogeographical zonation, introduces new estuary types and redefines existing types based on size. The revised classification also introduces three micro-system types previously omitted from coastal outlets on the subcontinent.

The classification scheme divided the biogeographical regions that characterise the South African coast into four major zones; the Cool Temperate (Orange to Ratel), the Warm Temperate (Heuningnes to Mendwana), the Subtropical (Mbhashe to St Lucia) and the Tropical (uMgobezeleni to Kosi), the latter being a new addition to the estuarine biogeographical provinces.

All rivers or streams with outlets to the sea were categorised broadly as estuaries and micro-systems. For estuaries, Estuarine Lakes, Estuarine Bays and Predominantly Open Estuaries were largely retained. New types, previously omitted, are Estuarine Lagoons (e.g. the groundwater-fed Langebaan system) and the Arid Predominantly Closed Estuaries that occur on the west coast (e.g. Groen and Spoeg Estauries). The numerically dominant temporarily open/closed category was subdivided into Small and Large Temporarily Closed Estuaries based on size, with a total habitat area of 15 ha serving as the threshold that separates small from large types. River mouths were renamed Fluvially Dominated Estuaries and divided into large and small size categories to reflect dissimilar catchment influences, with a total habitat area of 15 ha serving as the threshold separating types. Micro-systems were additionally divided into micro-estuaries, micro-outlets, and coastal waterfalls based on spatial features and biotic observations in the field.

Overall, South Africa's 290 estuaries were classified into 22 estuarine ecosystem categories arising from the interplay between four biogeographical zones, with nine estuary types. In addition, 202 micro-systems were also classified into nine ecosystem types, of which only the micro-estuaries (42 systems) share some functionality with estuaries. This represents a high diversity of estuary types. This is not unexpected, considering the country's diverse climatic, oceanographic and geological characteristics.

The variety of estuarine types collectively form an interconnected network of estuarine systems providing resilience to climate fluctuations and the impacts of climate change predicted for the future. Large-scale human activities, especially urbanisation and industrialisation, change ecological processes in estuaries that can permanently alter the functioning of these systems. Impacts are shown in morphological changes that affect estuary hydrodynamics and marine connectivity, chemical characteristics, such as salinity, and ultimately large-scale biodiversity loss and susceptibility to invasion by non-native species.

South African Estuarine Lakes are large and rare estuarine systems on the subcontinent. However, they are in crisis, with the majority being subjected to alterations in key ecological processes. This group of estuaries has undergone extensive infrastructure development to their functional zones, substantial flow reduction, nutrient pollution, overfishing (especially gillnetting) and manipulation of mouth areas. These combined impacts have reduced their ability to provide key ecological services, such as flood regulation, nutrient cycling and nursery habitat provision, and have compromised their value as recreation and tourism venues. To ensure their resilience to future climate-change stressors, a strategic programme is needed to restore habitat, improve water quantity and quality, reduce pressure on natural resources, and increase protection levels.

The revised classification scheme is useful because its ecosystem-level approach provides a holistic and detailed framework that integrates biogeographical factors and the extensive range of biophysical parameters evident in South African estuaries. The classification scheme forms the "blue print" for South Africa's IUCN red listing of estuarine ecosystem types, which allows for the identification of threatened ecosystem types, i.e. Critically Endangered, Endangered, or Vulnerable (Van Niekerk et al. 2019d), thus highlighting ecosystem types with an urgent necessity of management intervention and protection. Determining the condition of estuarine ecosystem types have the added advantage that it can also be used for reporting on United Nations Sustainable Development Goal 14 (Conserve and sustainably use the oceans, seas and marine resources) that specifically highlights coastal ecosystems, such as estuaries.

Ecosystem types, together with species and habitat targets, are used in setting conservation planning targets to ensure that all life supporting abiotic and biotic processes are captured in a representative protected areas network (Turpie et al. 2012). Given that the identified estuary types characterise physical and biotic processes, they can also be used as proxies for predicting sensitivity to anthropogenic pressures, such as flow reduction and increased nutrient loading, in environmental flow assessment in data-poor environments. Aquatic ecosystem typing is one of the fundamental datasets for extrapolating freshwater flow requirements across a region in low confidence assessments (van Niekerk et al. 2015).

Although this study focused on developing a data-driven ecosystem classification system, key datasets were found to be lacking that could facilitate a more detailed assessment. Critical parameters that would have allowed for a more nested or hierarchal classification include information on seasonal salinity regimes, mouth states, water clarity, estuary topography and bathymetry, and sediment structure. Accurate records/observations of the duration of the closed mouth condition are especially critical for future classification updates. In addition, very little information was available on the invertebrate community for most of South Africa estuaries. Overall, data on biological responses are more than 30 years old (e.g. national bird counts date from the 1980s and national fish surveys date from the 1990s). While new data are being collected on some of the larger systems, very little information is currently being gathered on the numerous smaller estuaries, especially those in remote areas along the coast. Without a major investment in baseline information from numerous poorly studied South African estuaries, it will be difficult to refine and possibly expand this new classification system in the future.

The classification of estuaries is not an exact science, because some systems demonstrate biophysical features that fit criteria of more than one type. The uMthavuna is a Predominantly Open Estuary (mouth open >90% of the time); however, on most recent satellite imagery the mouth is highly constricted and more representative of a Large Temporarily Closed system in a semi-closed or closed condition. Similarly, some Subtropical Predominantly Open Estuaries are fed by sediment-rich catchments and they therefore meet some of the criteria of a Large Fluvially Dominated type, e.g. the uMzimkhulu and uMkhomazi Estuaries. Classification schemes should therefore not be divorced from the context within which they are applied, e.g. an evaluation of important systems contributing to coastal sediment supply cannot only focus on Large Fluvially Dominated systems, but should also include sediment-rich Predominantly Open Estuaries. Although classification schemes strive to provide structure and guidance on estuarine biophysical processes and features, estuary classification anomalies are to be expected along such a geological and climatic diverse coastline.

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References

Adams JB, Veldkornet D, Tabot P. 2016. Distribution of macrophyte species and habitats in South African estuaries. *South African Journal of Botany* 107: 5–11.

Adams JB, Snow GC, Veldkornet DA. 2010. Updated estuary habitat and plant species data. National Spatial Biodiversity Assessment. 2010: Estuares Component. Report submitted to CSIR. 14 p. Kirstenbosch, South Africa: South African National Biodiversity Institute (SANBI).

Allee RJ, Dethier M, Brown D, Deegan L, Ford RG, Hourigan TF, et al. 2000. Marine and Estuarine Ecosystem and habitat Classification. Mary Yoklavich US Department of Commerce, National Oceanic and Atmospheric Administration, National Marine Fisheries Service, NOAA Technical Memorandum NMFS-F/SPO-43, July, 2000. Silver Spring, MD: NOAA/National Marine Fisheries Service. 43 pp.

Bate GC, Nunes M, Escott B, Mnikathi A, Craigie J. 2017. Micro-estuary – a new estuary type recognised for South African conditions. *Transactions of the Royal Society of South Africa* 72(1): 85–92.

Bedin T. 2001. The progression of a mangrove forest over a newly formed delta in the Umhlatuze Estuary, South Africa. *South African Journal of Botany* 67: 433–438.

Begg GW. 1978. The estuaries of Natal. Report No. 41. (657 p). Pietermaritzburg, South Africa: Natal Town and Regional Planning Commission

Bennett BA. 1989. A comparison of the fish communities in nearby permanently open, seasonally open and normally closed estuaries in the south-western Cape, South Africa. *South African Journal of Marine Science* 8: 43–55.

Blaber SJM, Cyrus DP. 1981. A revised checklist and further notes on the fishes of the Kosi system. *Lammergeyer* 31: 5–14.

Bland LM, Keith DA, Miller RM, Rodríguez JP, Murray NJ. 2017a. *Guidelines for the application of IUCN Red List of Ecosystems Categories and Criteria, Version 1.1*. Switzerland, Gland: IUCN.

Bland LM, Regan TJ, Dinh MN, Ferrari R, Keith DA, Lester R, Mouillot D, Murray N J., Nguyen HA, Nicholson E. 2017b. Using multiple lines of evidence to assess the risk of ecosystem collapse. *Proceedings of the Royal Society B: Biological Sciences* 284: 20170660.

Bland, LM, Rowland JA, Regan TJ, Keith DA, Murray NJ, Lester RE, Linn M, Rodríguez JP, Nicholson E. 2018. Developing a standardized definition of ecosystem collapse for risk assessment. *Frontiers in Ecology and the Environment* 16: 29–36.

Bolton JJ, Leliaert F, Clerck O, Anderson RJ, Stegenga H, Engledow HE, Coppejans E. 2004. Where is the western limit of the tropical Indian Ocean seaweed flora? An analysis of intertidal seaweed biogeography on the east coast of South Africa. *Marine Biology* 144: 51–59.

Borja A, Elliott M, Snelgrove P, Austen M, Berg T, Cochrane S, et al. 2016. Bridging the gap between policy and science in assessing the health status of marine ecosystems. *Frontiers in Marine Science* 3: 175.

Boyd R, Dalrymple R, Zaitlin BA. 1992. Classification of clastic coastal depositional environments. *Sedimentary Geology* 80: 139–150.

Brown C and Magoba R. 2009. Rivers and wetlands of Cape Town. Caring for our rich aquatic heritage. Water Research Commission. No TT 376/08. Pretoria, South Africa: Water Research Commission.

Cameron WM, Pritchard DW. 1963. Estuaries. p 306–324. In: Hill MN (Ed.). *The Sea*. Vol 2. New York, United States: Wiley-Interscience.

Clark BM, Bennett BA, Lamberth SJ. 1994. A comparison of the ichthyofauna of two estuaries and their adjacent surf-zones, with an assessment of the effects of beach-seining on the nursery function of estuaries for fish. *South African Journal of Marine Science* 14: 121–131.

Council for Scientific and Industrial Research (CSIR). 1992. Building the Foundation for Sustainable Development in South Africa. National Report to the United Nations Conference on Environment and Development (UNCED) held in Rio de Janeiro. Pretoria, South Africa:.Department of Environmental Affairs.

Council for Scientific and Industrial Research (CSIR). 2001. The Effects of water abstraction on the estuaries of the Eerste and Lourens rivers. Ninham Shand Consulting Engineers. CSIR Report ENV-S-C. 2001–007. Stellenbosch, South Africa: Council for Scientific and Industrial Research (CSIR).

Cyrus DP,Wepener V. 1997. Dune mining and the Nhlabane system: can biodiversity and the nursery function be maintained? *Southern African Journal of Aquatic Sciences* 23: 103–113.

Dalu T, Magoro ML, Tonkin JD, Human LRD, Perissinotto R, Deyzel SHP, Adams JB, Whitfield AK. 2018. sessing phytoplankton composition and structure within micro-estuaries and micro-outlets: a community analysis approach. *Hydrobiologia* 818: 177–191.

Davies JL. 1964. A morphogenetic approach to world shorelines. *Zeitschrift fur Geomorphologie* 8: 127–142.

Day JH. 1980. What is an estuary? *South African Journal of Science* 76: 198.

Day JH (Ed.). 1981. *Estuarine ecology*. Cape Town, South Africa: AA Balkema.

Day JH, Gridley JR. 1981. The management of estuaries. p 373–397. In: Day JH (Ed.). *Estuarine ecology with particular reference to southern Africa*. Cape Town, South Africa: AA Balkema.

Department of Water and Sanitation (DWS). 2016. Resource Directed Measures: Reserve determination study of selected surface water and groundwater resources in the Usutu/ Mhlathuze Water Management Area. Kosi Estuary Rapid Environmental Water Requirements Determination. Report produced by CSIR on behalf of Tlou Consulting (Pty) Ltd. Report no: RDM/WMA6/CON/COMP/2613. Pretoria, South Africa: Department of Water and Sanitation.

Dyer KR. 1997. *Estuaries: a physical introduction*. 2nd ed. Chichester, United Kingdom: John Wiley and Sons.

Department of Water and Sanitation, South Africa (DWS). 2014. Resource Directed Measures: Reserve determination study of selected surface water and groundwater resources in the Usutu/ Mhlathuze Water Management Area. Summary of relevant EWR information for Mhlatuze and Nhlabane estuaries. Report produced by Tlou Consulting (Pty) Ltd. Report no: RDM/WMA6/ CON/COMP/1713. Pretoria, South Africa: Department of Water and Sanitation.

Elliott M, McLusky DS. 2002. The need for definitions in understanding estuaries. *Estuarine, Coastal and Shelf Science* 55: 815–827.

Emanuel BP, Bustamante RH, Branch GM, Eekhout S, Odendaal FJ. 1992. A zoogeographic and functional approach to the selection of marine reserves on the west coast of South Africa. *South African Journal of Marine Science* 12: 341–354.

Fischer HB. 1972. Mass transport mechanisms in partially stratified estuaries. *Journal of Fluid Mechanics* 53: 671–687.

Gillson J. 2011. Freshwater flow and fisheries production in estuarine and coastal systems: where a drop of rain is not lost. *Reviews in Fisheries Science* 19: 168–186.

Hansen DV, Rattray M. 1966. New dimensions in estuary classification. *Limnology and Oceanography* 11: 319–326.

Harris L, Bessinger M, Dayaram A, Holness S, Kirkman S, Livingstone T-C, et al. 2019. Advancing land-sea integration for ecologically meaningful coastal conservation and management. *Biological Conservation* 237: 81–89.

Harris PT, Heap AD, Bryce SM, Porter-Smith R, Ryan DA, Heggie DT. 2002. Classification of Australian clastic coastal depositional environments based on a quantitative analysis of wave, tide and river power. *Journal of Sedimentary Research* 72(6): 858–870.

Harrison AD. 1962. Hydrobiological studies on alkaline and acid still waters in the Western Cape Province. *Transactions of the Royal Society of South Africa* 36: 4 213–244.

Harrison TD, Cooper JAG, Ramm AEL. 2000. State of South African estuaries: geomorphology, ichthyofauna, water quality and aesthetics. State of the Environment Series, Report No. 2. Department of Environmental Affairs and Tourism. 127 p. Pretoria, South Africa: Department of Environmental Affairs and Tourism.

Harrison TD. 2002. Preliminary assessment of the biogeography of fishes in South African estuaries. *Marine and Freshwater Research* 53: 479–490.

Heggie DT, Skyring GW, Berelson WE, Longmore AR, Nicholson GJ. 1999a. Sediment-water interaction in Australian coastal environments: implications for water and sediment quality. *AGSO Journal of Australian Geology & Geophysics*17(5/6): 159–173.

Heggie DT, Skyring GW. 1999b. Flushing of Australian estuaries, coastal lakes and embayments: an overview with biochemical commentary. *AGSO Journal of Australian Geology & Geophysics* 17: 211–225.

Heydorn AEF. 1989. The conservation status of southern African estuaries. (pp. 290-297). In: Huntley BJ (Ed.). *Biotic Diversity in Southern Africa: Concepts and Conservation*. Oxford, United Kingdom: Oxford University Press.

Human LRD, Magoro M, Dalu T, Perissinotto R, Whitfield AK, Adams JB, Deyzel SHP, Rishworth GM. 2018. Natural nutrient enrichment and algal responses in near pristine micro-estuaries and micro-outlets. *The Science of the Total Environment* 624: 945–954.

Jacobs D, Stein ED, Longcore T. 2010. Classification of California estuaries based on natural closure patterns: templates for restoration and management. *Southern California Coastal Waters Research.* Costa Mesa, United States: SCCWRP.

James NC, Harrison TD. 2016. A preliminary survey of the estuaries on the southeast coast of South Africa, Cape Padrone – Great Fish River, with particular reference to the fish fauna. *Transactions of the Royal Society of South Africa* 65: 3 149–164.

James NC, Harrison TD. 2016. A preliminary fish survey of the estuaries on the southeast coast of South Africa, Kayser's Beach – Kei Mouth: a comparative study. *Water SA* 42: 82–101.

Keith DA, Rodríguez JP, Brooks TM, et al. 2015. The IUCN Red List of Ecosystems: Motivations, Challenges, and Applications. *Conservation Letters* 8: 214–226.

Keith DA, Rodríguez JP, Rodríguez-Clark KM, Nicholson E, Aapala K, Alonso A, Asmussen M, Bachman S, Basset A, Barrow EG, et al. 2013. Scientific foundations for an IUCN Red List of Ecosystems. *PLoS One* 8(5): e62111.

Kench, PS. 1999. Geomorphology of Australian estuaries: Review and prospect. *Australian Journal of Ecology* 24: 367–380.

Kennish MJ. 1986. *Estuarine ecology.* Boca Raton, Florida, United States: CRC Press.

Ketchum BH (Ed.). 1983. *Ecosystems of the World*. Vol. 26. *Estuaries and Enclosed Seas*. Amsterdam, Netherlands: Elsevier.

MacKay CF, Cyrus DP, Russell K-L. 2010. Macrobenthic invertebrate responses to prolonged drought in South Africa's largest estuarine lake complex. *Estuarine, Coastal and Shelf Science* 86: 553–567.

Mackay CF, Cyrus, DP. 1998. A review of the macrobenthic fauna of the Mhlathuze Estuary: setting the ecological reserve. *Southern African Journal of Aquatic Sciences* 24(1/2): 111–129.

Magoro ML. 2018. Characterization and ecology of selected micro-estuaries and micro-outlets in the Eastern Cape Province, South Africa. PhD thesis, Nelson Mandela University, Port Elizabeth, South Africa.

Magoro M, Dalu T, Human LRD, Perissinotto R, Deyzel SHP, Wooldridge TH, Adams JB, Whitfield AK. 2020. Characterization of micro-estuaries and micro-outlets in South Africa using algal, zooplanktonic and macrozoobenthic assemblages. *African Journal of Aquatic Science* 45: This Special Issue.

McSweeney SL, Kennedy DM, Rutherfurd ID. 2017. A geomorphic classification of intermittently open/closed estuaries (IOCE) derived from estuaries in Victoria, Australia. *Progress in Physical Geography* (41): 421–449.

Mucina L, Janssen JA, O'Callaghan M. 2003. Syntaxonomy and zonation patterns in the coastal salt marshes of the Uilkraals Estuary, Western Cape (South Africa). *Phytocoenologia* 33: 309–334.

Mumby PJ, Edwards AJ, Arias-Gonzales JE, Lindeman KC, Blackwell PG, Gall A, Gorczynska MI, Harborne AR, Pescod CL, Renken H, et al. 2004. Mangroves enhance the biomass of coral reef fish communities in the Caribbean. *Nature* 427: 533–536.

Nagelkerken I, Roberts CM, Van der Velde G, Dorenbosch M, Van Riel MC, De La Moriniere EC, Nienhuis PH. 2002. How important are mangroves and seagrass beds for coral-reef fish? The nursery hypothesis tested on an island scale. *Marine Ecology Progress Series* 244: 299–305.

Nagelkerken I, Van der Velde G, Gorissen MW, Meijer GJ, Van't HoF T, Den Hartog C. 2000. Importance of mangroves, seagrass beds and the shallow coral reef as a nursery for important coral reef fishes, using a visual census technique. *Estuarine, Coastal and Shelf Science* 51: 31–44.

Nichols, MM, Biggs, RB. 1985. Estuaries. p 77–186. In: *Coastal Sedimentary Environments*, 2nd edn. Davis RA. (Ed.) New York, United States: Springer-Verlag.

Nicholson E, Keith DA, Wilcove DS. 2009. Assessing the threat status of ecological communities. *Conservation Biology* 23: 259–274.

Perissinotto R, Stretch DD, Taylor RH. 2013. *Ecology and Conservation of Estuarine Ecosystems: Lake St Lucia as a Global Model*. Cambridge, United Kingdom: Cambridge University Press.

Potter IC, Chuwen BM, Hoeksema SD, Elliott M. 2010. The concept of an estuary. A definition that incorporates systems, which can become closed to the ocean and hypersaline. *Estuarine, Coastal and Shelf Science* 87: 497–500.

Pritchard DW. 1952. Salinity distribution and circulation in the Chesapeake Bay estuarine system. *Journal of Marine Research* 11: 106–123.

Pritchard DW. 1955. Estuarine circulation patterns. *Proceedings American Society Civil Engineers* 81 No. 717: 1–11.

Pritchard, DW. 1967. Observations of circulation in coastal plain estuaries. p 37–44. In: *Estuaries*. Lauff GH. (Ed.). *American Association for the Advancement of Science*, Vol. 83. Washington, DC, United States: American Association for the Advancement of Science Science.

Rodríguez JP, Rodríguez-Clark KM, Baillie JEM, Ash N, Benson J, Boucher T, Brown C, Burgess N, Collen B, Jennings M, et al. 2011. Establishing IUCN Red List Criteria for Threatened Ecosystems. *Conservation Biology* 25: 21–29.

Schleyer MH, Kruger A, Celliers L. 2008. Long-term community changes on a high-latitude coral reef in the Greater St Lucia Wetland Park, South Africa. *Marine Pollution Bulletin* 56, 493–502.

Simpson JH, Brown J, Matthews J, Allen G. 1990. Tidal straining, density currents, and stirring in the control of estuarine stratification. *Estuaries* 13: 125–132.

Sink,KJ, Branch GM, Harris JM. 2005. Biogeographic patterns in rocky intertidal communities in South Africa. *African Journal of Marine Science* 27(1): 81–96.

Sink KJ, Van der Bank MG, Majiedt PA, Harris L, Atkinson L, Kirkman S, Karenyi N (Eds). 2019. *South African National Biodiversity Assessment. 2018 Technical Report Volume 4: Marine Realm*. Pretoria, South Africa: South African National Biodiversity Institute

Stephens E. 1929. The botanical features of the south Western Cape Province. Wynberg, Cape Town, South Africa: Speciality Press.

Teske PR, Von der Heyden S, McQuaid CD, Barker NP. 2011. A review of marine phylogeography in southern Africa. *South African Journal of Science* 107(5/6): 43–53.

Teske PR, Wooldridge TH. 2001. A comparison of the macrobenthic faunas of permanently open and temporarily open/closed South African estuaries. *Hydrobiologia* 464: 227–243.

Thandar AS. 2015. Biodiversity and distribution of the southern African sea cucumbers (Echinodermata: Holothuroidea). *Zootaxa* 4058: 341–361.

Turpie JK, Wilson G, Van Niekerk L. 2012. National Biodiversity sessment. 2011: National Estuary Biodiversity Plan for South Africa. Report produced for the Council for Scientific and Industrial Research and the South African National Biodiversity Institute. Cape Town, South Africa: Anchor Environmental Consulting.

Turpie JK, Clark BM. 2007. The health status, conservation importance, and economic value of temperate South African estuaries and development of a regional conservation plan. Report to CapeNature. Stellenbosch, South Africa: CapeNature.

Turpie,J, Beckley LE, Katua SM. 2000. Biogeography and the selection of priority areas for conservation of South African coastal fishes. *Biological Conservation* 92: 59–72.

Van Niekerk L, Adams JB, Bate GC, Forbes N, Forbes A, Huizinga P, et al. 2013. Country-wide assessment of estuary health: An approach for integrating pressures and ecosystem response in a data limited environment. *Estuarine, Coastal and Shelf Science* 130: 239–251.

Van Niekerk L, Taljaard S, Adams JB, Fundisi D, Huizinga P, Lamberth SJ, et al. 2015. Desktop provisional eclassification of the temperate estuaries of South Africa.Water Research Commission Report No. 2187/1/15. Pretoria, South Africa: Water Research Commission.

Van Niekerk L, Taljaard S, Adams JB, Lamberth DJ, Huizinga P, Turpie JK, Wooldridge TH. 2019a. An environmental flow determination method for integrating multiple-scale ecohydrological and complex ecosystem processes in estuaries. *The Science of the Total Environment* 656: 482–494.

Van Niekerk L, Adams JB, Allan D, Taljaard S, Weerts S, Louw D, Talanda, C, Van Rooyen P. 2019b. sessing and planning future estuarine resource use: A scenario-based regional scale freshwater allocation approach. *The Science of the Total Environment* 657: 1000–1013.

Van Niekerk L, Adams J, Fernandez M, Harris L, Lamberth SJ, MacKay F, et al. 2019c. 'Chapter 4: Extending the estuary functional zone to include key habitats and processes' in South African National Biodiversity sessment. 2018: Technical Report. Volume 3: Estuarine Realm. CSIR report number SIR/SPLA/EM/EXP/2019/0062/A. South African National Biodiversity Institute, Pretoria. Report Number: http: //hdl.handle.net/20.500.12143/6373. Pretoria, South Africa: South African National Biodiversity Institute.

Van Niekerk L, Adams JB, Lamberth SJ, MacKay F, Taljaard S, Turpie JK, Weerts S, Raimondo DC (Eds). 2019d. South African National Biodiversity sessment. 2018: Technical Report. Volume 3: Estuarine Realm. CSIR report number CSIR/SPLA/EM/EXP/2019/0062/A. South African National Biodiversity Institute Report Number: http: //hdl.handle.net/20.500.12143/6373.Pretoria, South Africa. South African National Biodiversity Institute.

Van Niekerk L, Turpie JK (Ed.). 2012. South African National Biodiversity sessment. 2011: Technical Report. Volume 3: Estuary Component. CSIR Report Number CSIR/NRE/ECOS/ER/2011/0045/B. Stellenbosch, South Africa: CSIR.

Vorwerk PD, Whitfield AK, Cowley PD, Paterson AW. 2003. The influence of selected environmental variables on fish assemblage structure in a range of southeast African estuaries. *Environmental Biology of Fishes* 66 237–247.

Weerts SP, Cyrus DP. 2002. Occurrence of young and small-sized fishes in different habitats within a Subtropical South African estuary and adjacent harbour. *Marine and Freshwater Research 53*(2): 447–456.

Weerts SP, MacKay CF, Cyrus DP. 2014. The potential for a fish ladder to mitigate against the loss of marine–estuarine–freshwater connectivity in a Subtropical coastal lake. *Water SA* 40(1): 27–38.

Whitfield AK. 1992. A characterization of southern African estuarine systems. *Southern African Journal of Aquatic Sciences* 18: 89–103.

Whitfield, AK. 2005. Langebaan – A new type of estuary? *African Journal of Aquatic Science* 30: 207–209.

Whitfield AK, Baliwe NG. 2013. A century of science in South African estuaries: Bibliography and review of research trends. SANCOR Occasional Report No. 7: 289 p. Grahamstown, South Africa: South African Institute for Aquatic Biodiversity.

Whitfield AK, Elliott M. 2011. Ecosystem and biotic classifications of estuaries and coasts. p 99–124. In: *Treatise on Estuarine and Coastal Science*. Vol 1. Wolanski E, McLusky DS. (Eds). Waltham Academic Press. Waltham, United States: Academic Press.

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