Characteristics and landcover of estuarine boundaries: implications for the delineation of the South African estuarine functional zone

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Introduction

One of the fundamental issues associated with the management of estuaries is defining the spatial boundary (i.e. the smallest management unit) of an estuary (van Niekerk and Taljaard 2003). Authors such as Cameron and Pritchard (1963) define an estuary as a semi-enclosed body of water that has a free connection with the ocean and within which there is a measurable dilution of seawater by fresh water derived from the land. This classic definition was expanded to include explicitly the large number of small, temporarily closed estuaries along the South African coast (van Niekerk et al. 2013). The National Water Act (RSA 1998, Chapter 1) provides a reliable, legal definition of a South African estuary. The Act states: “estuary” means a partially or fully enclosed body of water – (a) which is open to the sea permanently or periodically; and (b) within which the seawater can be diluted, to an extent that is measurable, with fresh water drained from land” (p 15). The National Environmental Management: Integrated Coastal Management Act (ICM Act; RSA 2009) proposes a similar definition, but is less clear about the boundaries of estuaries that close from time to time. Estuaries that are closed to the sea have higher water levels during the closed phase and require an extended management boundary to include back-flooding areas. For this reason the 5 m topographical contour (national estuaries layer) is currently used to demarcate the South African estuarine functional zone (EFZ) (van Niekerk and Turpie 2012).

A functional zone is defined as a geographic entity where there are common structural and functional characteristics that can be defined and quantified by measurement (Dennison and Abal 1999; Pantus and Dennison 2005). The EFZ encapsulates not only the estuary waterbody but also the physical and biological processes and habitats necessary for estuarine function and health (DWA 2010; van Niekerk et al. 2013). This extended definition has formed the basis for most spatial planning frameworks or assessments since 2010 (van Niekerk and Turpie 2012). The EFZ was listed as Notice 3 (GN R 546) under the National Environmental Management Act (NEMA), Environmental Impact Assessment (EIA) Regulations (RSA 2010). The ICM Act also requires the setting of coastal and estuary set-back lines.

Internationally there are various methods to determine the lateral boundaries or set-back lines of estuaries. Some of these methods use the extent of permanently or mean-maximum flooded and waterlogged areas (e.g. Junk et al. [2013] for Brazilian estuaries and wetlands). The outer borders of estuaries can also be indicated by the absence of hydromorphic soils and/or hydrophytes and/or specific woody species (e.g. Adam [1992] for Australian estuaries).
For the Sado Estuary, Portugal, Caeiro et al. (2003) used three attributes: fine-fraction particle size (FF; %), redox potential (Eh), and total organic matter (OM; %), in association with discriminant analysis of kriging spatial analysis to delineate the estuarine lateral boundary. The latter method would provide a good demarcation in the case of a very stable estuary environment, not subjected to significant shifts in water level and habitat distribution over long timescales, but would not be suitable for highly dynamic systems that can shift configuration between episodic events, which is typical of small KwaZulu-Natal (KZN) estuaries, for example.

South African estuaries have undergone significant changes in terms of land use (van Niekerk and Turpie 2012; van Niekerk et al. 2013). Changes in landcover are expected to complicate the identification of boundaries (Masefield et al. 2014). Landcover (LC) and land use (LU) changes show the loss of natural habitat due to urban sprawl and cultivation. Spatial LC/LU patterns often form a reference for applications such as monitoring, planning, biodiversity and climate change assessments. Most of these applications and projects were used in the National Land Cover project of 2000 [NLCC 2000] that was updated in 2009 (SANBI 2009). Masefield et al. (2014) used this dataset to quantify landcover classes present within the EFZ of the East Kleinemonde Estuary on the Eastern Cape coast. Their results found that this estuary remains in a natural state (‘natural’ = 89.4% of the total EFZ of this estuary) with only 10.6% transformed by urban encroachment (i.e. ‘urban built-up’).

Within the EFZ, i.e. defined by the 5 m contour or national estuaries layer, development may have limited the efficacy of indicators to delimit the actual boundaries of an estuary. For example, the limited estuarine vegetation occurring within KZN estuaries, combined with the extent of sugarcane cultivation and invasion of alien plant species, renders it unlikely that a distinct boundary between estuarine and terrestrial vegetation will be evident. Ecotones between saltmarshes and terrestrial vegetation are important areas of ecosystem functionality (Wasson and Wolfolk 2011). Such areas need to be in a healthy state to prevent invasion by alien plants and to ensure landward migration of saltmarsh vegetation under different scenarios of climate change, including sea-level rise (Wasson et al. 2013).

The South African coastline spans three biogeographical regions (or climatic zones), namely, cool-temperate, warm-temperate and subtropical (Harrison 2004). Rainfall patterns vary greatly between the different regions due to high variability in climate (Harrison 2004). Based on this and other biophysical characteristics, all estuaries between the Orange and Rietvlei/Diep estuaries can be recognised as cool-temperate, those to the south and east of this point as far as the Mbashe Estuary, which lies between the Ku-Mpenjati and Mendwana estuaries, are warm-temperate, and those between the Mbashe Estuary and Kosi Bay are subtropical (Figure 1). Estuaries are significantly different in structure and function across biogeographical regions because coastal temperature and salinity vary (van Niekerk and Turpie 2012; van Niekerk et al. 2013).

The aims of this study were to: (i) determine the extent to which the current estuarine delineation is effective in including all estuarine habitats; (ii) measure the extent of landcover changes (from the pristine state) in the South African estuarine functional zone (EFZ); and (iii) investigate the delineation of the estuarine lateral boundary using sediment and groundwater characteristics and plant species.

Separate indicators of estuarine boundaries were investigated for cool-temperate and warm-temperate estuaries from a vegetation perspective. Only the cool- and warm-temperate estuaries were sampled in this aspect of the study as the focus was on the saltmarsh vegetation.

Material and methods

Inclusion of estuarine habitats in the estuarine functional zone

A georeferenced spatial layer of the National Estuaries Shapefile was added to Google™ Earth (van Niekerk and Petersen 2011, available on BGIS website [http://bgis.sanbi.org] as 'National Estuaries'). Converting the ESRI (Environmental Systems Research Institute) file to a KMZ (zipped Keyhole Markup Language) format in Google Earth allowed for both the viewing of the outline of the EFZ as well as the estuarine habitats. This allowed for a visual assessment (changes in colour from the terrestrial to estuarine vegetation) of the estuarine area that either lay within or outside the EFZ. Estuarine vegetation was identified by a dark-red colour that signified saltmarsh vegetation or grey colour that signified reeds and sedges. Mangrove and swamp forests were identified as fringing dark-green strips along estuaries. Only recent Google Earth imagery (2010–2014) was used in this assessment. Assessments were done at an eye-altitude of 100 m or less. In total, 304 estuaries were assessed.

The current EFZ boundary was ground-truthed at 31 estuaries: Orange (Gariep), Olifants, Verlorenvlei, Groot Berg, Langebaan, Hout Bay, Palmiet, Uilkraals, Goukou, Gourits, Hartenbos, Klein Brak, Groot Brak, Keurbooms, Groot (Oos), Kabeljous, Swartkop, Naahoon, Kandandhlovu, Mpenjati, Kaba, Bilanhlolo, Mhlangeni, Fafa, Mdesingane, Mzimayi, Rocky Bay, Happy Wanderers, Umgababa, Little Manzimitoli and St Lucia estuaries. In all, 38 transects were sampled across the lateral boundary of the EFZ or saltmarsh terrestrial ecotone for cool- and warm-temperate estuaries. Alternatively, for estuaries that were not ground-truthed, geographical information systems (GIS) software ArcMap 10.1 was used to record vegetation in the following habitat types: intertidal saltmarsh, reeds and sedges, supratidal saltmarsh, open water area, sand banks and the vegetation that extended past landward of the EFZ.

The National Vegetation Map (as a Shapefile) (Mucina and Rutherford 2006, available on BGIS [http://bgis.sanbi.org/vegmap/map2006.asp]) was also converted to KMZ and viewed in Google Earth to determine whether it identified estuarine vegetation outside the EFZ. The map includes 440 zonal and azonal vegetation types mapped at a scale of 1:250 000 (Mucina and Rutherford 2006). For the azonal vegetation (the biome that includes estuarine vegetation), generally a minimum size of 10 ha of habitat area was used for inclusion in the final map. Using this scale, estuaries were mapped by referring to Landsat 5 images from 2005. When an estuary did not...
have any area mapped (based on the National Vegetation Map) as either arid estuarine saltmarshes, Cape estuarine saltmarshes, Cape coastal lagoons, subtropical estuarine saltmarshes, subtropical coastal lagoons, mangrove or swamp forest (Mucina et al. 2006), then it was classified as ‘no estuarine vegetation’. Swamp forests were included in this study although they are not exclusively estuarine. They are important components of estuaries in the subtropical region (Adams et al. 2012). All data were added to an Excel sheet and, dependent upon whether an estuary had habitat area outside the EFZ, it was assigned a ‘yes’ or a ‘no’. If an estuary was assigned ‘yes’, additional

Figure 1: Map of South Africa showing the location and names of the estuaries investigated for the assessment
The extent of landcover changes in South African estuaries

The impact of development on saltmarsh–terrestrial boundaries was measured using a method similar to that of Silliman and Bertness (2004). The South African national landcover [NLC 2009] layer (SANBI 2009) was used to determine landcover within the EFZ. Estuarine habitat below the EFZ was divided into the following landcover classes: natural (including ‘waterbodies’ as estuarine water), cultivation, urban built-up, degraded, plantation, and mines, using the landcover types from the South African national landcover layer. Habitats within each estuary were given a landcover class.

Delineation of the estuary lateral boundary based on sediment and groundwater characteristics and plant species

Species sampling

Macrophyte composition and environmental variables at the ecotone between estuarine and terrestrial vegetation were studied in eight estuaries. The Verlorenvlei and Kabeljous estuaries are temporarily open/closed. The Gouritz Estuary is permanently open and has a large supratidal saltmarsh but limited intertidal habitat. The Uilkraals Estuary is a modified system where there has been significant flow reduction that has resulted in the closure of the previously permanently open mouth and loss of intertidal habitats. The Olifants, Berg, Goukou and Keurbooms estuaries are permanently open and have large intertidal saltmarshes that are inundated diurnally. Six transects at each estuary were chosen where there was a transition from saltmarsh to terrestrial vegetation. The ecotone was chosen subjectively as the area where the saltmarsh ended or where there was an overlap of saltmarsh and terrestrial species. An ecotone can be recognised as the plant assemblages at the edge of the terrestrial vegetation (an example is given of the Keurbooms Estuary in Supplementary Figure S1 [available online]). Representative sites were limited due to the high degree of transformation that has already occurred in most systems. Along each transect, species cover and changes in species composition were measured using replicate quadrats (1 m²) located every 5 m. Vegetation classification followed Mucina and Rutherford (2006). The sampling did not include subtropical estuaries due to extensive transformation of the natural estuary boundaries.

Environmental sampling

Two replicate surface-sediment samples were collected along transects at each site within the ecotone. Samples were sealed and transported to the laboratory for analyses of sediment moisture content, redox potential, pH (Black 1965), organic content (Briggs 1977), and sediment electrical conductivity (Barnard 1990). At each site, the depth to groundwater was determined for each zone by augering. Groundwater analyses followed Bornman et al. (2002). The groundwater was allowed to stabilise, after which depth to the water table was determined using a graduated pole. Groundwater electrical conductivity was measured using a YSI 30M/10FT hand-held conductivity meter. Abiotic variables for cool-temperate and warm-temperate biogeographical regions were summarised and presented as boxplots to depict the full range of variation for each parameter. Biogeographical classification followed Harrison (2004). To determine significant differences in physicochemical variables, the Student’s t-test was used for parametric data and the Mann–Whitney U-test was used for non-parametric data. All analyses were conducted using R (R Core Team 2013).

Results

Inclusion of estuarine habitats in the 5 m boundary

According to van Niekerk and Peterson (2011), the previously defined EFZ covers an area of 173 930 ha distributed across 304 estuaries/outlet systems nationally (Figure 1). The distribution of the EFZ by region is as follows: cool-temperate 24 221 ha; warm-temperate 47 218 ha; and subtropical 99 710 ha. In total, 82 of the 304 estuaries under study had estuarine habitat occurring outside of the present demarcation of the EFZ (Table 1). The area of habitat outside the EFZ was 12 957 ha (6.9%), hence making the total area of the new revised EFZ 186 887 ha. In the cool-temperate region, 10 estuaries had habitat area that was not represented within the previously defined EFZ. The reason for this was because Mucina et al. (2006) identified saltmarsh or estuarine area outside the previously defined EFZ (Supplementary Figure S2A – the top figure shows the estuarine habitat not represented within the previously defined EFZ and the bottom figure shows the entire previously defined EFZ of the Bushmans Estuary). Furthermore there were two small systems that had estuarine habitat that was located above the EFZ and was not assessed as part of the National Biodiversity Assessment (van Niekerk and Turpie 2012). These cool-temperate systems were labelled NBA1 and NBA2 (see Table 1).

In the warm-temperate region, 38 estuaries had estuarine habitat outside the previously defined EFZ. In 21 estuaries, habitat was not represented in the vicinity of the mouth. In subtropical estuaries such as the Mtata, Mzimpuzi, Mkweni, Zolwane, Mpenjati, Richards Bay, Nhlabane, Mgobezeleni and Kosi, Mucina et al. (2006) recognised swamp forest as being outside the EFZ.

In total, 165 estuaries (approximately 50% of the total) were not recognised as having estuarine vegetation based on the National Vegetation Map classification. This represented 6 417 ha of the previously defined EFZ (an example of the estuarine habitats in the East and West Kleinemonde estuaries is given in Supplementary Figure S3A). The warm-temperate region had the highest number (84) of estuaries with estuarine vegetation that was not represented, and the largest area of unrepresented
vegetation (2 938 ha) (Table 2). In the subtropical region, there were 76 estuaries with a total of 2 300 ha that was not represented and in the cool-temperate region only five estuaries with a total of 1 178 ha that was not represented.

The extent of landcover changes in South African estuaries

Landcover classification showed that most South African estuaries were transformed (Table 3; Supplementary Figure S4). At a national scale, only 81 (28% of the total) estuaries remain in a completely natural state; they cover 7 883 ha of the national estuarine area. However, the total natural estuarine area (including waterbodies) is 130 769 ha. ‘Urban built-up’ was associated with 275 estuaries (6 630 ha), and 168 estuaries (26 855 ha) were identified as having been subject to some cultivation.

Delineation of the estuary lateral boundary based on sediment and groundwater characteristics and plant species

In all, 55 plant taxa were found within the ecotone habitats (Table 4). These plants indicate the boundary between saltmarsh and terrestrial habitats for estuaries in the cool- and warm-temperate regions. Ecotone sediment variables

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**Table 1:** Estuaries in different biogeographical regions that had habitat area not represented in the estuarine functional zone (EFZ). Degree of confidence: H = high, M = medium, L = low

| Reason | Region       | Estuary                        | Degree of confidence |
|--------|--------------|--------------------------------|----------------------|
| Entire estuarine area not represented (habitat above the EFZ) | Subtropical | Lubanzi Beach | M |
| Some estuarine habitat not represented in the EFZ (based on field and visual assessments) | Cool-temperate | Rietvlei/Diep | H |
|          | Warm-temperate | Zeekoei, Tweekuilien, Seekoei, Kabeljous, Boknes, Bushmans, Kariega, Kowie, West Kleinemonde, Riet, Klein Palmiet, Great Fish, Old Womans, Gqutywa, Ngqinisa, Kiwane, Tyolommqa, Ross’ Creek, Hlaze, Cefane, Nyara, Haga Haga, Kobonqaba, Ngadla, Shxini, Mendwana | |
| Subtropical | Ku-Mpenzu, Nilonyane, Sundwana, Xora, Mncwasa, Tshani, Sinangwana, Gxwaleni, Bulolo, Mtambane, Nkodusweni, Mzintlava, Kaba, Bilanhlolo, Mbango, Mlungwa, Mfazazana, Mdloti, Mialazi, Nhlabane | |
| Impossible to assess due to landcover change | Cool-temperate | Hout Bay | L |
| Warm-temperate | Coega (Ngcura), Swartkops | |
| Subtropical | Kongweni, Zotsha, Mzumbe | |
| Map overlay did not align with estuarine area due to satellite image edge effects in Google Earth or lateral movement in estuary shape | Subtropical | Nqakanqa, Unnamed2, Msikaba, Zolwane, Tongazi, Kandandhlovu, Mzinto | L |
| Estuarine habitat not represented in the EFZ based on the National Vegetation Map (Mucina and Rutherford 2006) | Cool-temperate | Buffels, Swartlintjies, Spoeg, Groen, Sout, Jakkals | M |
| Warm-temperate | Sundays, Keiskamma, Kwenxura | |
| Subtropical | Mtata, Mzimpunzi, Mkweni, Mpenjati, Richards Bay, Mgoabezeleni, Kosi | |
| Not clear from Google Earth and needs to be ground-truthed | Warm-temperate | Wilderness, Swartvlei, Knysna | M |
| Estuarine vegetation present but estuary excluded from previous National Biodiversity Assessment (NBA) on the grounds of small size/functionality | Cool-temperate | NBA1 (17.730103° E, 31.098398° S), NBA2 (17.442387° E, 30.596479° S)2 | H |

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**Table 2:** The number of estuaries and area not recognised as having estuarine vegetation (based on Mucina and Rutherford 2006); the total number of those estuaries that had natural landcover; and estuaries with natural landcover that had habitat that fell outside the previously defined EFZ

| Biogeographical region | Number of estuaries | Area (ha) | Natural EFZ | Outside EFZ |
|------------------------|---------------------|-----------|-------------|-------------|
| Cool-temperate         | 5                   | 1 178     | 146         | 37          |
| Warm-temperate         | 84                  | 2 938.10  |             |             |
| Subtropical            | 76                  | 2 300.50  |             |             |
| Total                  | 165                 | 6 417     |             |             |
| Natural                |                     | 4 873     |             | 603         |
| Outside EFZ            |                     |           |             |             |

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1 This is an estuary that does not have a known name
2 Estuaries not assessed as part of the National Biodiversity Assessment
that can be used to delineate the lateral boundaries of estuaries were moisture content, organic content, electrical conductivity, pH and redox potential, whereas groundwater characteristics were salinity, conductivity and depth (Figure 2). Mean moisture content was significantly lower in the cool-temperate region (5%) compared to the warm-temperate region (11%) \( (U = 100, p < 0.05) \). Similarly, mean organic content was lower in the cool-temperate region (2%) compared to the warm-temperate region (5%) \( (U = 50, p < 0.001) \). There was no difference between pH in the cool-temperate and warm-temperate systems \( (t = -1.089, p > 0.05) \). Mean redox potential was similar in the cool- \( (7.3 \text{ mV}, SE 12.95) \) and warm-temperate regions \( (12.5 \text{ mV}, SE 7.08) \) \( (t = 0.349, p > 0.05) \). In contrast, electrical conductivity was higher and showed greater variability in the cool-temperate region \( (\text{mean} = 16.4 \text{ mS cm}^{-1}, SE 4.55) \) than in the warm-temperate region \( (\text{mean} = 88 \text{ cm}, SE 10.63, t = 1.987, p = 0.05) \). Groundwater electrical conductivity was higher in the cool-temperate region \( (25.3 \text{ mS cm}^{-1}, SE 5.67) \) than in the warm-temperate region \( (10.9 \text{ mS cm}^{-1}, SE 1.79) \) \( (U = 193, p < 0.05) \).

### Discussion

**Inclusion of estuary habitat in the estuarine functional zone**

The purpose of the EFZ was to spatially define and delineate South African estuarine habitat for use in biodiversity assessments, estuary health assessments and conservation planning, and in the development of estuarine management strategies.

### Table 3: Distribution of landcover classes (after SANBI 2009) within the estuarine functional zone, according to biogeographical region

| Landcover class     | Area covered (ha)       |
|---------------------|-------------------------|
|                     | Cool-temperate | Warm-temperate | Subtropical | National |
| Natural             | 16 831         | 30 903        | 83 035      | 130 769  |
| Cultivation         | 2 330          | 15 120        | 9 405       | 26 855   |
| Degraded            | 234            | 207           | 387         | 828      |
| Urban built-up      | 1 086          | 4 729         | 814         | 6 630    |
| Plantation          | 0              | 332           | 333         | 665      |
| Mines               | 201            | 86            | 0           | 286      |

### Table 4: Species found at the fringe of saltmarshes in the different South African biomes: S = saltmarsh, E = ecotone, T = terrestrial

| Species                                      | Habitat          |
|----------------------------------------------|------------------|
| All ecotones (found in all biomes)           |                  |
| Galenia secunda (L.f.) Sond.                 | S,E,T            |
| Lycium spp.                                 | E,T              |
| Oxalis pes-caprae L.                         | E,T              |
| Panicum maximum Jacq.                       | S,E,T            |
| Pennisetum clandestinum Hochst. ex Chiov.   | S,E,T            |
| Searsia spp.                                | E,T              |
| Sideroxylon inerme L. subsp. inerme          | E,T              |
| Spergularia media (L.) C.Presl ex Griseb.    | E,T              |
| Azonal (found only in saltmarshes)           |                  |
| Aizoza rigidum L.f.                          | S,E              |
| Conyza scabrida DC.                          | E                |
| Cotula filifolia Thunb.                      | S,E,T            |
| Cynodon dactylon (L.) Pers.                  | S,E,T            |
| Disphyma crassifolium (L.) L.Bolus          | S,E              |
| Ehrharta villosa J.H.Schult. var. villosa    | E                |
| Ficinia nodosa (Rottb.) Goelgh., Muasya & D.A.Simpson | S,E  |
| Ficinia ramosissima Kunth                    | E,T              |
| Ficinia repens (Nees) Kunth                  | S,E              |
| Juncus acutus L. subsp. leopoldii (Parl.) Snogerup | S,E  |
| Juncus kraussii Hochst. subsp. kraussii      | S,E              |
| Osteospernum moniliferum (Chrysanthemoides monilfera) (L.) | E,T  |
| Phragmites australis (Cav.) Steud.           | S,E              |
| Salsola aphylla L.f.                         | S,E              |
| Solanum porosus (L.f.) Thunb.                | S,E              |
| Sarcocornia pillansii (Moss) A.J.Scott      | S,E              |
| Senecio thunbergii Harv.                     | E                |
| Spergularia media (L.) C.Presl ex Griseb.    | S,E,T            |
| Tetragonia fruticosa L.                      | E,T              |

| Species                                      | Habitat          |
|----------------------------------------------|------------------|
| Fynbos                                       |                  |
| Carpodotus muini (L.Bolus) L.Bolus           | E                |
| Chronia baccifera L.                         | E,T              |
| Elegia macrocarpa (Kunth) Moline & H.P.Linder| E,T              |
| Helichrysum teretifolium (L.) D.Don          | E,T              |
| Metalasia densa (Lam.) P.O.Karis             | E,T              |
| Passerina rigida Wikstr.                     | E,T              |
| Succulent Karoo                              |                  |
| Atriplex cineara Poir.                       | E,T              |
| Atriplex semibaccata R.Br.                   | E                |
| Cleretum bellidiforme (Burm.f.) G.D.Rowley   | E                |
| Exomis microphylla (Thumb.) Aellen var. axyiroides | E               |
| (Fenzl) Aellen                               |                   |
| Mesembryanthemum crystallinum L.             | S,E,T            |
| Subtropical thicket                          |                  |
| Althanasia filiformis L.f.                   | E,T              |
| Maytenus procumbens (L.f.) Loes              | E,T              |
| Pentzia incana (Thumb.) Kunz.                | E                |
| Psilocaulon dinteri (Engl.) Schwantes        | E,T              |
| Subtropical thicket, forest                  |                  |
| Maytenus procumbens (L.f.) Loes              | E,T              |
| Subtropical thicket, fynbos                  |                  |
| Euclia racemosa Murray subsp. racemosa       | E,T              |
| Subtropical thicket, succulent Karoo         |                  |
| Atriplex vestitla (Thumb.) Aellen var. appendiculata Aellen | E |
| Disturbed                                    |                  |
| Acacia cyclops A.Cunn. ex G.Don              | E,T              |
| Acacia longifolia (Andr.) Wild.              | E,T              |
| Acacia mearnsii De Wild.                     | E,T              |
| Lantana camara L.                            | E,T              |
| Opuntia fiscus-indica (L.) Mill.             | E,T              |
| Ricinus communis L.                          | E,T              |
| Solarium americanum Mill.                    | E,T              |
plans (van Niekerk and Taljaard 2003; van Niekerk and Turpie 2012). This study showed that the current demarcation of the EFZ did not include all estuarine vegetation. At Richards Bay, Mgobezeleni and Kosi estuaries, Mucina et al. (2006) recognised swamp forest far outside the EFZ, with northern coastal forest and Maputaland coastal vegetation at its boundaries. Adams et al. (2012) reported that swamp forests may be associated with estuaries in KZN, with common species being *Syzygium cordatum*, *Barringtonia racemosa* and *Ficus trichopoda*. The mangrove *B. racemosa* is often difficult to distinguish from coastal forest in aerial photographs (DAV pers. obs.). It can therefore be expected that, in these estuaries, critical habitats may be under threat of development due to inaccurate delineation of the EFZ.

**Figure 2:** Box-and-whisker plots of the physico-chemical variables that can be used to delineate the lateral boundaries of estuaries in the cool- and warm-temperate regions. For each variable the bottom and top of the box represent the first and third quartiles, respectively, and the band inside the box the second quartile (median). Black dot represents the mean. Outliers are plotted as individual points.
The need to include all swamp forest habitat (that which occurs within the EFZ) explicitly in the next round of the EFZ delineation was also highlighted by the spatial layers being developed by Ezemvelo KZN Wildlife, which included swamp forest habitats in the EFZ (Scott-Shaw and Escott 2011).

Estuarine habitats were often not represented in the EFZ as an artefact of the mapping process rather than the inability to use vegetation as an indicator of the lateral boundary. Affected subtropical estuaries included the Nhakanqa, Kandandhlovu and Zolwane estuaries (Figure 1; Supplementary Figure S2B). Van Niekerk and Turpie (2012) explained that some narrow, deeply incised estuaries (e.g. Mzimkulw Estuary) may be above the 5 m contour that demarcates the EFZ. The authors recommended that, in such cases, a detailed topographical survey should be conducted and the floodlines – e.g. 1:100 year – estimated using engineering principles. Estuaries that have estuarine habitats outside the current demarcated boundaries need to be remapped and clearly demarcated in an attempt to clarify uncertainties over ownership and implementation of legislation.

The area of non-estuarine vegetation within the EFZ was not determined in this study. In many cases, the EFZ includes coastal dunefields and forests (e.g. Namaqualand seashore vegetation in the Berg Estuary, Overberg dune strandveld in the Hueningnes Estuary and northern coastal forest in the Mhlanga Estuary). Van Niekerk and Turpie (2012) suggested that vegetation adjacent to estuaries should be incorporated in the EFZ in site-specific cases. This will provide these vegetation types with added protection.

As a result of the coarse scale of the National Vegetation Map, estuarine habitats were not mapped accurately in 50% of South African estuaries and hence any quantitative information (such as conservation status) derived from this dataset must be viewed with caution. For example, ‘Cape estuarine saltmarshes’ are found in association with warm-temperate estuaries in the Eastern and Western Cape provinces and have been classified as Least Threatened, with a conservation target of 24% with only 14% transformed. This vegetation type has been estimated to cover 10 214 ha, but in fact it covers 47 218 ha based on the area below the EFZ in warm-temperate estuaries. This underestimates the size and overstates the conservation priority of this vegetation type. It is recommended that conservation targets be used as suggested by Turpie et al. (2012). Habitat mapping is a fundamental tool used by ecologists and environmental managers and forms the basis of site management plans (Cherrill and McClean 1999). The National Vegetation Map should not be used as the only source for determining the extent of estuarine vegetation because that may result in an estuary being placed under severe threat by development. This would be the case for relatively small estuaries such as the Riet, Gwaing, West Kleinemonde, Lubanzi Beach, Zolwane and Zotscha. These and other small estuaries may be important in providing refuge for threatened species and maintaining genetic connectivity between different populations along the coastline (Kadereit et al. 2005; Weising and Freitag 2007; Teske et al. 2011).

The extent of landcover changes in South African estuaries

South African estuaries have been subjected to a range of land-use changes (mapped as landcover) that have removed estuarine habitat. Only 81 out of 304 estuaries investigated remain in a natural state, with most estuaries having at least one class of transformed landcover associated with them. Landcover differed between biogeographical regions and this reflects the major economic activities within each region. Many estuaries (169, or 56% of the total) have been transformed by cultivation (in the form of sugarcane plantations) within the EFZ. Van Niekerk et al. (2013) listed habitat destruction as one of the key pressures on South African estuaries. The authors noted that landcover change due to development can lead to changes in structural habitat of an estuary, which could lead to local extinctions of species (King et al. 2007; Noe et al. 2014). Many of these changes are irreversible, leading to a loss of ecosystem services. This is particularly the case for estuaries such as the Baakens Estuary, Port Elizabeth, the entire estuarine habitat of which has been lost (Supplementary Figure S4A).

‘Urban built-up’ is also a dominant landcover class, particularly in warm-temperate and subtropical estuaries in South Africa that are in the vicinity of major coastal towns. Noe et al. (2014) found that coastal development within the EFZ removes existing ecotonal vegetation and increases impervious surfaces. This might then lead to changes in both sediment and freshwater input into estuarine habitats. Corbett et al. (1999) and Byrd and Kelly (2006) described increased freshwater runoff that decreased soil salinity and altered saltmarsh plant assemblages. In a study of the False Bay estuaries in the Western Cape, O’Callaghan (1990) showed that alien vegetation encroachment was a major factor causing changes in estuarine vegetation. This occurred in response to disturbance, particularly when there was a restriction in tidal exchange and a decrease in salinity. Changes in land use have been shown to affect the boundary structure between estuarine and terrestrial vegetation (Silliman and Bertness 2004). Estuaries with transformed landcover can be expected to show a local loss of native, terrestrial vegetation along the boundary and changes in biological and physical interactions (Pennings et al. 2005). In the current study, landcover changes made identification of the estuarine lateral boundary difficult.

The datasets evaluated in this study have some limitations than can be attributed to data capture resolution. According to SANBI (2009), the resolution of the National Landcover Map is 30 m × 30 m. This means that estuarine habitats smaller than this have incorrect landcover classes. For the ‘urban built-up’ landcover class, the ‘building count’ dataset, which includes all the building structures, was used. Urban built-up is therefore more accurately mapped compared to other landcover classes. It is most important to determine the suitability of the National Landcover Map in the estuarine health-determination process. In estuarine management the health condition of an estuary is determined based on the extent to which it differs from its reference or natural condition. As part of the macrophyte component of the Ecological Water Requirement Studies (National Water Act; RSA 1998), the change in natural landcover is perhaps more important than other criteria.
It is suggested that the National Landcover Map be used in desktop assessments for large estuaries (estuaries or estuarine habitats >0.09 ha) where resolution is sufficient to include landcover types. This is especially the case for estuaries in which the landcover change is related to urban development or formal agricultural use, which includes estuaries such as the Orange, Olifants, Berg, Riet/Diep, Bot/Kleinmond, Klein, Breede, Wilderness, Knsyna, Keurbooms, Gamtoos, Swartkops, Keiskamma and Durban Bay. It is also recommended that estuarine maps that are being produced for reserve determination studies should include the extent of landcover changes. Regardless of the limitations of the National Landcover Map, it has proven to be a valuable tool to assess the extent of landcover change on a national scale in this study.

**Delineation of the estuary lateral boundary based on sediment and groundwater characteristics and plant species**

Our results have shown that there are estuaries that have associated habitats outside the present delimited EFZ. These estuaries and habitats are vulnerable to development. The ecotone vegetation includes critical biodiversity elements that may be more susceptible to encroaching development than intertidal and supratidal saltmarshes (Rehfeldt et al. 2012; Malavasi et al. 2013). It has therefore become imperative to provide protection for estuarine habitats and their ecotone vegetation. Sediment characteristics such as redox potential, moisture content and electrical conductivity are useful in delineating the lateral boundaries of estuaries, because the magnitude of these variables becomes severely reduced at the edges of saltmarshes (Caeiro et al. 2003; Junk et al. 2013; Veldkornet et al. 2015). There were also geographical differences in sediment characteristics contributing to the recognition of estuarine boundaries, because estuaries along the West Coast (cool-temperate) are cooler than those along the South Coast (warm-temperate). Cool-temperate estuaries are characterised by high salinities and low turbidity as a result of low rainfall and runoff, high seawater input (high sediment and groundwater electrical conductivity) and evaporation loss (relatively lower sediment moisture content) (Harrison 2004). The best indicators are ultimately those that show the least variability; for example, mean sediment moisture content was lower in the cool-temperate region (5%) compared to the warm-temperate region (11%).

It can also be expected that sediment in the fringe and the terrestrial habitats would have considerably lower salt content because non-halophytes occupy these niches (Veldkornet et al. 2015). There is a gradient of sediment and groundwater characteristics from the saltmarsh (within the EFZ) to the adjacent vegetation. However, this tendency was not displayed in the current study. The edge of a saltmarsh was identified where sediment electrical conductivity was ≤0.4 mS cm\(^{-1}\) in the warm-temperate region and ≤0.9 mS cm\(^{-1}\) in the cool-temperate region. Sediment electrical conductivity is therefore a good indicator of the landward margin in estuaries.

Groundwater characteristics also proved to be good indicators. The depth to the groundwater table has frequently been used in freshwater wetland delineation (Kotze and Marneweck 1999). In this study, maximum depth was found to be 175 cm in the ecotone. Groundwater salinity and electrical conductivity were also good indicators as they reflect the extent of tidal intrusion (Veldkornet et al. 2015). In order to obtain a holistic characterisation, a combination of sediment and groundwater characteristics should be used to delineate the estuarine lateral boundary.

It was possible to identify ecotone species associated with different biomes. Species that occurred in the azonal biome (referred to here as coastal vegetation and saltmarshes) were considered to be the best indicators because generally they will be found at most saltmarsh boundaries. With regard to specific biomes, the best indicators are species that occur only within the ecotone in that biome; for example, *Carpopròtus muiri* only occurs in the fringe of fynbos vegetation and *Atriplex vestita* only occurs in the fringe of succulent Karoo and subtropical thicket vegetation. Annuals such as *Senécio thunbergii* and other *Senécio* spp. were frequently found at the boundaries of thicket, forest and fynbos vegetation (Supplementary Figure S1). Human disturbances have led to changes in the lateral boundary of estuarine vegetation, making them susceptible to invasion by alien plant species. It is suggested that a list of alien invasive and encroaching species could be used as indicators for disturbed boundaries in the cool- and warm-temperate estuaries.

Environmental variables and selected species can be used to delineate those estuaries where the vegetation was not included in the EFZ. The recent National Biodiversity Assessment excluded 81 coastal inlets, 20 in the cool-temperate, 33 in the warm-temperate and 28 in the subtropical region (van Niekerk et al. 2012). Van Niekerk et al. (2012) recommended that a separate study be undertaken to demarcate these smaller and/or more ephemeral outlets and integrate them into current planning frameworks. Our proposed method for delineating lateral boundaries could be used to demarcate these systems, thereby ensuring that they are included in national management plans. However, one disadvantage of this approach is that it is time-consuming and requires skilled and experienced scientists to perform the necessary field and laboratory analyses. The seasonal variability of environmental characteristics would also need to be considered, given that Bornman et al. (2002) recorded lower sediment electrical conductivity, groundwater electrical conductivity and depth to groundwater during the high rainfall season (winter) in the Olifants Estuary saltmarsh on the West Coast. Furthermore, the boundary is not fixed in time as saltmarshes are anticipated to shift either landward or seaward, depending on future climate change scenarios (Veldkornet et al. 2015). However this method can be used in regions with similar climates, such as those with Mediterranean climates (Wasson et al. 2013). This allows for a global comparison of factors forming the boundaries between vegetation types, within a particular climate type. It also facilitates the monitoring of subtle changes in species composition and environmental variables in response to climate change for both estuarine and terrestrial vegetation.

In conclusion, the current method of estuary delineation (using the 5 m contour) does not include all estuarine habitats. Improving on this would require delineation based
on field mapping of vegetation and measurements of environmental variables, which is not possible on a national scale in the short to medium term. A pragmatic approach to the delineation of the South African EFZ is proposed in which the following are considered collectively to define the lateral boundary: (1) 5 m contour; (2) 1:100 year floodline; (3) estuarine vegetation types; and (4) detailed mapping of ecotone features. As the EFZ is ultimately a management boundary, this delineation needs to balance the requirement for stable/consistent demarcation, inclusive of all estuarine physical and biological processes, and cost-effectiveness.

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