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Using Historic Land Cover Data to Predict Estuarine Macrobenthos Characteristics in South Africa

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ABSTRACT

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Human socioeconomic activities affect natural environments worldwide. Coastal environments like estuaries are especially threatened by the disproportional population growth and development taking place within the coastal zone. Within semiarid South Africa, and especially within the KwaZulu-Natal (KZN) Province, estuaries face human development pressures from a growing coastal population ranging in socioeconomics and types of natural resource use, and many systems are degraded. Although estuary management is well legislated, it is slow to be implemented. Unlike biophysical data, land cover data (historical–present) for KZN's coastal zone is readily available. Of interest was whether land cover is related to estuary ecological condition. If so, there is potential to use land cover characteristics around estuaries in future development of a tool for short-term interim management that addresses common management challenges including a paucity of historical ecological information, money, and expertise. In a novel approach for this region, land cover and biophysical (water physicochemical, sediment, and estuary macrobenthic invertebrates) data sets for seven of the province's estuaries for three points within a 30-year period (1980–2010) were examined. Land cover around these estuaries ranged from seminatural, agriculturally dominated to highly urbanized systems. Macrobenthos communities within the systems showed a similar distinction in terms of taxonomic dominance, although species richness and abundances were variable. Land cover within the 20-m contour line was found to be a very strong predictor of estuary macrobenthos characteristics, with a subset of 8 land cover types and five invertebrate species identified in this study for use as potential future indicators.

ADDITIONAL INDEX WORDS: *Coastal zone, land use, estuary functional zone, ecological indicator, KwaZulu-Natal, management tool.*

INTRODUCTION

Human socioeconomic activities have affected almost every natural environment worldwide (Martínez *et al.*, 2006; Pinto, de Jonge, and Marques, 2014; Sale *et al.*, 2008). Water systems in particular are affected by human presence, not only because freshwater is essential to human life, but also because river systems accumulate human-use impacts along their length (Elliott and Whitfield, 2011; Spalding *et al.*, 2014). At the receiving end of river drainage systems, estuaries are particularly sensitive to human-derived impacts (Kennish, 2002, 2003; McLusky and Elliott, 2004; Morant and Quinn, 1999). Estuaries are further at risk from development within the coastal zone. Coastal areas worldwide experience disproportional population and development growth, due to the benefits associated with living at the coast (McGranahan, Balk, and Anderson, 2007; NOAA, 2013; Palmer *et al.*, 2011; Pinto, de Jonge, and Marques, 2014; Seto *et al.*, 2011). In semiarid areas such as southern Africa where water resources are already limited, this situation is exacerbated (Clark, 1999).

Estuaries in South Africa

In South Africa, an estuary includes all land area up to the 5-m above-mean-sea-level (amsl) contour line that constitutes the estuarine functional zone (EFZ) (Integrated Coastal Management [ICM] Act 24 of 2008). Five estuary geomorphological types have been described for the country, of which 77% are intermittently open estuaries (IOEs) (Whitfield, 1992). These are typically small systems periodically separated from the sea by a sand berm at the mouth (Van Niekerk and Turpie, 2012).

The physical environment in South African estuaries is complex and changing, influencing estuary functioning as it is driven by natural and human-induced effects that are cumulative, interact in a nonlinear fashion, and have emergent properties (Cilliers *et al.*, 2013; Pinto, de Jonge, and Marques, 2014). Estuarine fauna must be able to tolerate such changeable conditions. The macrozoobenthic invertebrates (greater than 0.5 mm in size) numerically dominate estuarine aquatic fauna in South African estuaries (De Villiers, Hodgson, and Forbes, 1999). They are sensitive to changes in water and sediment quality (Borja and Dauer, 2008; Diaz, Solan, and Valente, 2004; Neto *et al.*, 2010), and community metrics including species richness and diversity are used within several established environmental indices.

The topography and rainfall patterns in South Africa have resulted in most of the country's estuaries being situated on its east coast. Within these coastal provinces, the northeastern coastal province of KwaZulu-Natal (KZN) has a disproportionately high number of the country's estuarine systems, and 68% of the country's total estuary area (Van Niekerk and Turpie, 2012). The KZN coastal area is the most densely populated

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Table 1. *Physical characteristics of the study estuaries. Estuary types included are intermittently open estuaries (IOEs) and permanently open systems (PO). Ecological categories are as per the methods for the determination of the ecological reserve (DWA, 2010).*

Estuary	Location		Length (km)[†]	Area within 5 m (km^2)	Area within 20 m (km^2)	Catchment Area (km^2)[†]	Estuary Type[‡]	Estuarine Health Index[§¶]	Ecological Category[‖]
North Coast									
Zinkwazi (Zin)	29°16′ S,	31°26′ E	7.5	2.0788	5.4674	73	IOE	23.2	C (moderately modified)
Nonoti (Non)	29°19′ S,	31°24′ E	1.9	0.7144	2.7368	251	IOE	19.0	B (largely natural)
Durban									
Mgeni (Mge)	29°48′ S,	31°02′ E	2.5	2.4186	3.4930	4872	PO	15.4	D (largely modified)
South Coast									
Amanzimtoti (Tot)	30°03′ S,	30°53′ E	2.0	0.2654	1.2347	39	IOE	10.2	D (largely modified)
Little Amanzimtoti (LTot)	30°04′ S,	30°52′ E	0.8	0.1485	0.4848	18	IOE	10.3	D (largely modified)
Mhlabatshane (Mhl)	30°35′ S,	30°34′ E	1.0	0.2189	0.5759	47	IOE	19.4	B (largely natural)
Intshambili (Int)	30°38′ S,	30°32′ E	0.6	0.2083	0.4677	33	IOE	19.8	B (largely natural)

Data sourced form published literature: [†]*Begg (1978),* [‡]*Whitfield (1992),* [§]*Cooper et al.* (1993), [‖]*Van Niekerk and Turpie (2012).*
[¶]*Estuarine health index is a composite score of 30 comprising Aesthetic (/10), Biological (/10), and Water Quality (/10) values.*

coastline in all of Africa at a current density of 118 individuals km^{-2} (DEAT, 1999; Statistics South Africa, 2015), and its coastal population is highly disparate in terms of income, education, and resource dependence levels.

Management and protection levels of the country's estuaries are also not well distributed. Although the country's environmental legislation is very good and estuaries are afforded protection under five different acts including the National Environmental Management: ICM Act (NEMA, Act 24 of 2008), implementation and enforcement of management plans have been slow. To date, 83% of the country's estuaries have no form of official management, most of which are situated in KZN (Van Niekerk and Turpie, 2012). This low level of environmental protection can be attributed to several reasons, including the devolution of management responsibility under the NEMA from national to local (municipal) government (Palmer *et al.*, 2011). Coastal municipalities have widely varying numbers of estuaries within their borders, and also differ in their institutional capacity for management. Despite the lack of environmental protection, development continues along the KZN coastline. The opportunity to evaluate and conserve critical estuarine environments is rapidly being lost and there is an urgent need for an approach that addresses the challenges (time, money, expertise) facing municipalities mandated with management responsibilities, and acts to protect the natural environment while at the same time promoting economic and social development within the coastal zone.

Estuaries and Land Use

Human patterns of land use and resultant land cover affect estuaries through indirect and cumulative processes. Because it incorporates human use activities and associated loss of a natural state, land cover has been studied in relation to change within natural systems, including aquatic systems (*e.g.,* Dauer, Weisberg, and Ranasinghe, 2000; Jetz, Wilcove, and Dobson, 2007; Knysh, Giberson, and van den Heuvel, 2016; Wu *et al.*, 2012).

Much estuary biophysical work has been conducted in South Africa (see Whitfield and Baliwe, 2013), but little relates to land use within the surrounding coastal zone or lower catchment, or else is limited to studies of single systems with limited potential for wider application (*e.g.,* Masefield, McGregor, and Whitfield, 2014). Unlike biophysical data, land cover data (current and historical) for KZN's coastline are readily available, and it was of interest to investigate whether land cover can be used as a proxy to support estuary condition status, which is derived from a different biophysical analysis process (*e.g.,* Van Niekerk and Turpie, 2012). If successful, this work could assist in the future development of a management tool to address some of the challenges facing estuary management in this province.

Using several of KZN's estuaries across a range of surrounding land cover types (highly urban to agricultural), this study assessed if land cover around an estuary reflects estuary ecological condition. To test this, land cover characteristics and temporal change around seven of KZN's estuaries over a period of 30 years was examined together with abiotic (water physicochemical and sediment characteristics) and macrozoobenthos data collected from these same estuaries in two discrete periods a decade apart.

Study Estuaries

Study estuaries were chosen within KZN, South Africa's northeastern coastal province (Figure 1). The seven test estuaries fall within a range of land uses, two on the North Coast (NC; north of Durban), which is dominated by agriculture, and five urbanised estuaries, three of which fall within the eThekwini (Durban) municipal boundaries and are highly urbanised.

The Zinkwazi and Nonoti estuaries north of Durban (NC) are on a coastline characterised by extensive sugarcane farming. Isolated pockets of formal development are near and around the estuary mouths, with additional large-scale, long-term development being on the cards as coastal populations increase (Goble and van der Elst, 2012).

The Mgeni, Amanzimtoti, and Little Amanzimtoti estuaries fall within the boundaries of the eThekwini Municipality; the Mgeni Estuary within Durban city and the Amanzimtoti and Little Amanzimtoti on its South Coast (SC). Development along the SC began as early as the 1930s, and continued to the extent that at present this section of coastline is characterised by so-called "ribbon development," with coastal towns overlapping to form an almost unbroken strip (Goble and van der Elst, 2012). These estuaries are heavily affected "urban" estuaries (Forbes and Demetriades, 2008, Table 1), although to a certain extent the mangrove stands that line the northern bank of the Mgeni contribute to a better-than-expected ecological state (Begg, 1978, 1984; Cooper *et al.*, 1993; Forbes and Demetriades, 2008).

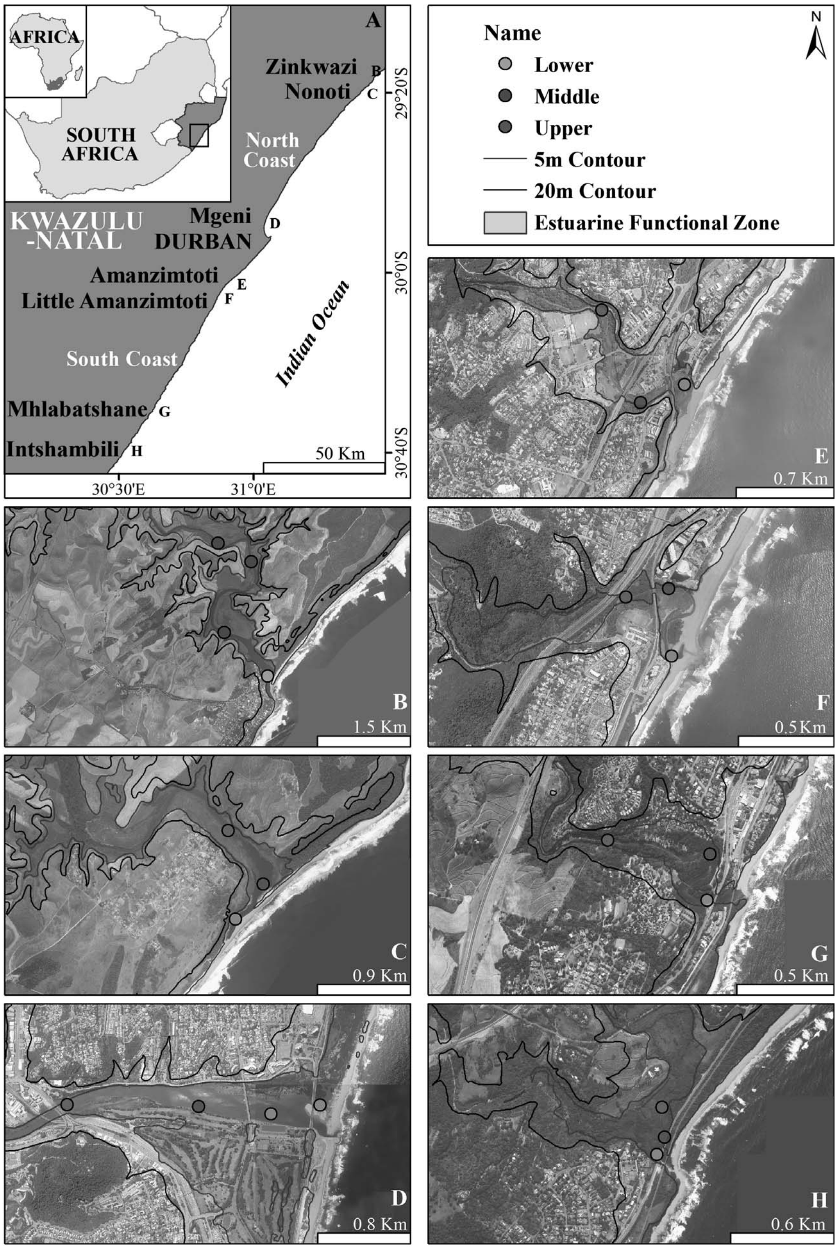

Figure 1. Location of study estuaries along the KwaZulu-Natal coastline (A), position of biophysical sampling sites and the 5-m and 20-m contour lines within which land cover was recorded, and estuary functional zone. From north to south the estuaries are: Zinkwazi (B) and Nonoti (C) (North Coast estuaries); Mgeni (D) (Durban estuary); and Amanzimtoti (E), Little Amanzimtoti (F), Mhlabatshane (G), and Intshambili (H) (South Coast estuaries).

In contrast, the Mhlabatshane and Intshambili estuaries, located on the far SC away from the intensive land uses associated with Durban city, are considered to be in a far more natural state (Cooper *et al.*, 1993; Van Niekerk and Turpie, 2012) (Table 1).

All estuaries are classified as IOEs. Although the Mgeni Estuary has a groyne holding its mouth permanently open to the sea, low freshwater inflow has in recent times resulted in periods of closure. Of these systems, the Zinkwazi is the longest (length 7.5 km, catchment 73 km^2, Begg, 1978) and the Little Amanzimtoti is the smallest (0.8 km length, catchment area 18 km^2, Begg, 1978) (Table 1).

Estuary health and ecological condition have been estimated for the study estuaries by various practitioners (Table 1). The estuarine health index (EHI) is a composite score based on estuary aesthetic, biological, and water-quality variables (Cooper *et al.*, 1993), whereas estimation of an estuary's ecological category is a requirement of the National Water Act's (1998) resource directed measures (RDM; DWA, 2010). The RDM is primarily focused on the calculation of the quantity,

Table 2. *Definitions of the eight land cover (LC) higher-order categories including descriptions with examples pertinent to the study estuaries, and typical state*.

LC Higher Category	Description† and Example LC	Typical LC State
Natural bare areas	Less than 4% vegetative cover (*e.g.,* beach)	Natural
Natural water bodies	Areas naturally covered by water (*e.g.,* Estuary water surface area)	Natural
Aquatic vegetated areas	Vegetation that is significantly influenced by water/flooding (*e.g.,* reed/grass swamps, mangroves)	Natural/disturbed
Vegetated areas	Riparian or terrestrial vegetation not associated with water (*e.g.,* coastal forest)	Natural/disturbed
Managed vegetated areas	Planted vegetated areas for urban or recreational use (*e.g.,* recreational open spaces including golf courses)	Transformed
Cultivated vegetated areas	Food crops or forestry (*e.g.,* formal agriculture)	Transformed
Artificial nonvegetated areas	Human-derived artificial cover (*e.g.,* transport infrastructure)	Transformed
Artificial water-related areas	Artificial standing or flowing water bodies (*e.g.,* dams, canals)	Transformed

†*Land cover higher categories' descriptions are based on Lück et al*. (2010).

quality, and timing of freshwater requirements (the Reserve) of a river's natural habitats, including estuaries. In both cases, the study estuaries have been weighted in a similar manner. The urban estuaries (Mgeni, Amanzimtoti, and Little Amanzimtoti that fall within eThekwini's municipal boundaries) are all in the poorest state. The Mgeni Estuary was, however, given a higher EHI score because of the presence of a large mangrove stand on its northern shoreline (Cooper *et al*., 1993). The estuaries determined to be in the best state are those farthest from human use and with less intense development pressure, and include the Nonoti Estuary on the NC and the two farthest to the south (Mhlabatshane and Intshambili estuaries on the SC). The Zinkwazi Estuary on the NC was assigned the highest score in the EHI but was determined to be in a moderately modified (category C) state in the later RDM (Table 1).

METHODS

To explore the relationship between surrounding estuarine land cover and estuary ecological state, land cover and estuary instream biophysical data sets were collected and compared (physicochemical, sediment distribution, and macrobenthos community). Where possible, comparable time periods a decade apart and spanning a total of 30 years were compared (period 1 1980s, period 2 late 1990s, period 3 late 2000s). The exception was macrobenthos data, which were available for two periods only (periods 2 and 3).

Land Cover

Land cover was captured from aerial photographs sourced from a national repository (South African Chief Directorate: Surveys and Mapping). Images were obtained for the three time points that corresponded most closely to the dates of collection of the biological and physicochemical estuary data, but ultimately depended on availability of the images. Photographs after 2000 were orthorectified, whereas images for the periods before 2000 were monochromatic aerial photographs with no spatial reference, and had to be georeferenced using ArcGIS (V10.2) software. All data were captured according to predetermined ecologically significant boundaries, the 5-m and 20-m amsl contour lines. The land within the 5-m amsl up to the highest inland measurable penetration of seawater, together with all associated estuarine processes, constitutes the estuary (EFZ, Van Niekerk *et al*., 2012), and the land around an estuary up to 20 m is a conservative but proposed long-term management boundary goal including proposed ecological buffers, development set-backs, and protection zones. The EFZ includes water area and adjacent environments including floodplains and riparian vegetation that include all natural estuary ecological processes and functioning. It therefore preserves estuary integrity as well as providing a buffer for development.

From each estuary mouth, the northern and southern boundaries of this area were drawn at a uniform distance of approximately 600 m from the most extreme extent of the water's edge, taking into account the dynamics of each individual system (system size and land cover characteristics). The inland boundary was drawn by creating a 100-m buffer around the estuary upper boundary, defined as the point of maximum salinity penetration upstream (ICM Act 24 of 2008). Land within the 5-m contour was further divided into lower, middle, and upper regions of the estuary, the extent of which was determined by expert opinion and making use of available salinity data for each estuary. This was done to allow for more detailed analysis with the biophysical data, considering the ecological processes and natural variability that exists along the salinity gradient in an estuary.

During the heads-up digitising process, land cover was assigned to eight high-order categories, with further division into 73 feature classes based on the Land Cover Classification System developed by the Council for Scientific and Industrial Research (CSIR) Satellite Application Centre, modified slightly for the KZN environment (Lück *et al*., 2010) (refer to Supplementary Table). According to expert opinion, a state was then also assigned to each category on the basis of the degree of perturbation, these being natural (unchanged, original and undisturbed), disturbed (in transition), or Transformed (completely changed from a natural state, artificial) (Table 2). A single operator was responsible for digitising all estuary area to eliminate variability because of subjective interpretation of the images. Data were captured as area (square metres) and totals per category calculated for further analysis.

For clarity, the first instance of an in-text reference to each of the study estuaries per section in the manuscript will be followed by information in parentheses that includes the estuaries' position within the larger study area (NC, Durban or South Coast = SC), the dominant land cover state by area, as defined above (natural, transformed, or disturbed), and a qualitative reference to the overall nature of the land use around each estuary (*e.g.,* agricultural, urban, *etc*.).

Macrobenthos and Physicochemical Sampling

To generate a long-term data set, the estuary biophysical data for this study include those collected by several investigators. The macrobenthos and physicochemical environment of 7 estuaries in KZN were sampled on a once-off basis between October 1998 and March 1999 (Harrison, Cooper, and Ramm, 2000). These estuaries were repeat sampled in 2009–10 using the same site localities and sampling season (austral spring/summer) to build up a data set for comparison (Stow, 2011). Additional historical estuary physicochemical data were available for these estuaries in the early 1980s (Begg, 1978, 1984).

Water physicochemistry (depth, temperature, dissolved oxygen, salinity, pH, turbidity) was measured at the water surface and bottom using a YSI 6600 multiparameter sonde. Estuary sediment and macrobenthic samples were collected along a gradient from the lower to upper reaches of each estuary according to standardised methodology for estuary ecological studies (outlined in MacKay, Cyrus, and Russell, 2010). Replicate sediment samples were selected to characterise the nature of the benthic habitat of the estuary according to sediment grain size distribution (according to a modified Wentworth scale with coarse sand categories collapsed into one and fine sand categories collapsed into one, such that medium–very coarse sand = 0.25–2 mm, fine sand = 0.0625–0.25 mm, and mud $<$ 0.0625 mm; Wentworth, 1922) and total organic content (using the hydrogen peroxide digestion method; Schumacher, 2002). A Zabalocki-type Eckman sediment grab was used to collect macrobenthic invertebrate samples in triplicate from each site. In the laboratory, preserved benthic samples were sorted, enumerated, and species identified to the lowest possible taxonomic level. Mean faunal abundance (density) for each site was expressed as individuals per square metre for analysis of estuary function and benthic community characteristics.

Statistical Analysis

Data were analysed (univariate or multivariate tests as appropriate) using PRIMER-E software (PRIMER V.6.1.13 and PERMANOVA+ V.1.0.3) (Clarke and Warwick, 2001), including trend analysis by estuary, region (where applicable), and period. Environmental data were normalised and if covariates and correlates parameters were present, the most relevant to explain ecological condition (through macrobenthos distribution) was retained. Macrobenthic data were analysed at the individual species level except when exploring overall trends in the data, when they were aggregated to higher taxonomic levels (Class or Order).

Initial data analysis focussed on identifying similarities or differences between estuaries. Discrete communities within the data were identified using the CLUSTER and nMDS techniques within the PRIMER package. The CLUSTER technique groups samples such that samples within a group share more similarities than samples in different groups (Clarke and Warwick, 2001). Data were further analysed by nMDS ordination, which uses rank order to arrange samples such that distance between samples indicates degree of similarity (Clarke and Gorley, 2006). Analysis of similarity (ANOSIM) was then used to test the significance of *a priori* specification of groups according to results of the grouping techniques (CLUSTER and nMDS ordination), whereas SIMPER analysis used similarity percentages within and between groups to identify variables that accounted for Bray–Curtis dissimilarities (biological, land cover data) or Euclidean distances (environmental data) (Clarke and Gorley, 2006). The Bray–Curtis measure was used for land cover data (area per land cover category analysed as a percentage of total area) according to the definition of data types presented by Clarke and Gorley (2006). The subset of variables characterising groups and discriminating between them was identified using the dis/similarity measure over its standard deviation $\delta_i/\mathrm{SD}(\delta_i)$ (Clarke and Warwick, 2001), for use as indicators in the possible future development of a management tool.

To test whether land cover characteristics around an estuary were related to estuary ecological condition, the various macrobenthos, physicochemical, sediment, and land cover data sets were then compared with each other as predictor-response pairs as appropriate using the RELATE and DistLM routines within the PRIMER PERMANOVA+ package. RELATE investigates the relatedness between two independently derived similarity matrices, in this case the biota and environmental (biophysical and land cover) variables, whereas DistLM analyses and models the relationship between a multivariate data set and several predictor variables (*e.g.,* biota and environmental variables) (Clarke and Gorley, 2006).

As a further step, land cover data were linked to macrobenthos data using the BEST routine. This routine makes use of the BIOENV procedure, which uses Spearman's rank correlation to identify the subset of environmental variables that has the maximum correlation with the biotic data (Clarke and Ainsworth, 1993).

RESULTS

To begin with, individual data sets (land cover, estuary physicochemical, and marobenthos) were analysed to explore similarities or differences between estuaries.

Land Cover

There has been no significant change in land cover in the study estuaries over time (PERMANOVA, $p = 0.48$). Overall, 31 different land cover categories were represented within the 20-m contour of the seven study estuaries. Within the 20-m contour, the NC estuaries are dominated by formal agriculture, reed/grass swamps, and coastal forest. Recreational open space and transport infrastructure are common among the urban estuaries. Coastal forest is increasingly prevalent in the far SC systems (Intshambili in particular), whereas the Mgeni Estuary is the only one with the presence of mangroves.

Estuaries separated clearly into three groupings at the 50% level of similarity for land cover (to the 5-m and 20-m contours, R = 0.908 and 0.996 respectively, $p = 0.001$, cluster analysis, Figure 2). These were the Zinkwazi (NC, transformed, agricultural) and Nonoti (NC, transformed, agricultural); the Mgeni (Durban, transformed, urban); and Amanzimtoti (SC, transformed, urban), Little Amanzimtoti (SC, transformed, urban), Mhlabatshane (SC, transformed, semiurban), and

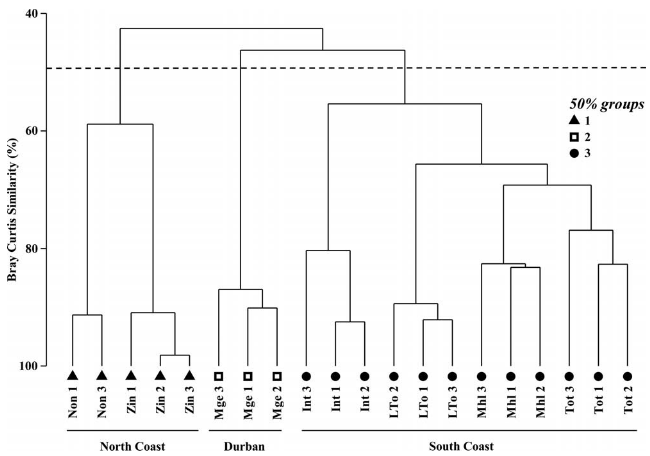

Figure 2. Dendrogram of all land cover within the 20-m contour line for all estuaries over three study periods (1, 2, 3). The 50% level of similarity is indicated, and sample groupings indicated by different symbols. North Coast estuaries Zin = Zinkwazi and Non = Nonoti; Durban estuary Mge = Mgeni; South Coast estuaries Tot Amanzimtoti, LTo = Little Amanzimtoti, Mhl = Mhlabatshane, and Int = Intshambili.

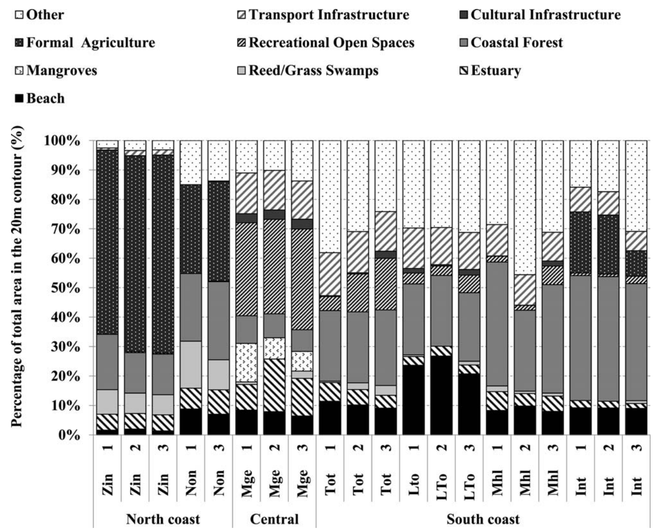

Figure 3. Land cover types as a percentage of total area within the 20-m contour, for all estuaries over three study periods (1, 2, 3). Only land cover categories contributing greater than 10% to total within-group similarity or greater than 8% to total between-group dissimilarity are included (SIMPER analysis). North Coast estuaries Zin = Zinkwazi and Non = Nonoti; Durban estuary Mge = Mgeni; South Coast estuaries Tot = Amanzimtoti, LTo = Little Amanzimtoti, Mhl = Mhlabatshane, and Int = Intshambili.

Intshambili (SC, transformed, semiurban) estuaries. Further analysis of the 5-m land cover by estuary region (lower, middle, and upper reaches) revealed four distinct groupings at the 40% level of similarity: all regions of the Mgeni Estuary, the lower reaches of all other estuaries, and finally the middle and upper reaches of the NC estuaries (Zinwazi and Nonoti) and SC estuaries (Amanzimtoti, Little Amanzimtoti, Mhlabatshane, and Intshambili), respectively ($R = 0.939$, $p = 0.001$).

Within the 20-m contour, the presence of fringing reed beds (*Phragmites australis*) creates similarity between the NC systems (Sim/SD 8.22, percentage contribution to similarity 14.03%), and sugarcane cultivation (formal agriculture) distinguishes this group from the other estuaries. The Mgeni Estuary is especially distinguished by large areas of recreational open spaces (mainly a golf course) (Sim/SD 47.39 and percentage contribution to similarity 19.12%) as well as mangroves (*Avicennia marina*, *Bruguiera gymnorrhiza*, and *Rhizophora mucronata*). The SC estuaries are characterised by coastal forest (largely freshwater mangrove *Barringtonia racemosa*), but also by the presence of transport infrastructure (rail and road) (Sim/SD 6.66 and 5.94 respectively, percentage contribution to similarity 23.57% and 13.34% respectively) (Figure 3).

In the case of the 5-m contour, five land cover types were found to distinguish these groupings from each other (average dissimilarity between groups greater than 60% in all cases). The proportional area of beach and estuary water surface area, as well as the presence of reed stands, were important categories for the NC estuaries. SC systems were characterised by the presence of coastal forest. Being an urban system, the Mgeni Estuary overall was distinguished by the category recreational open spaces, which includes a golf course and other recreational amenities found along the length of this estuary.

Physicochemical and Sediment Characteristics

Unlike land cover. which was fairly stable over time, the physicochemical conditions within each system were far more dynamic (PERMANOVA, $p = 0.02$) and reflected temporal and spatial changes characteristic of the IOE type, even within comparable seasons (Table 3).

Estuary sediment distribution is presented in Table 3. The Zinkwazi Estuary (NC, transformed, agricultural) was the only system consistently dominated by mud. Coarse and medium sands were dominant in most of the SC estuaries, whereas the Mgeni (Durban, transformed, urban) was dominated by a combination of medium to fine sands. With the exception of the Zinkwazi and Intshambili (SC, transformed, semiurban) estuaries, which are on the extremes of the study region, all other estuaries show a high degree of sediment variability between periods 2 and 3, mostly in the extremes of the grain particle sizes (mud–gravel).

Estuary Macrobenthos

A total of 99 macroinvertebrate species was encountered over the study period from the seven estuaries. Ranges in the numbers and abundances of macrobenthic species illustrate the variability that is inherent in these communities (Table 4). Estuarine macrobenthos differed between estuaries as well as within individual systems over time (PERMANOVA, $p = 0.001$). On the basis of species composition and abundance, three groups were found at the 15% level of similarity ($R = 0.831$, $p = 0.001$, Figure 4). The groups relate to ecological variability between the two periods in the Zinkwazi (NC, transformed, agricultural) and Mgeni (Durban, transformed, urban) estuaries, and between regions within the Amanzimtoti (SC, transformed, urban) and Little Amanzimtoti (SC, trans-

Table 3. *Ranges of water-quality variables and sediment characteristics recorded in the test estuaries during the three study periods, where pertinent. Water transparency was measured as Secchi depth in period 1 and turbidity (nephelometric turbidity units [NTU]) in periods 2 and 3. Sand particle size categories medium–very coarse sand = 0.25–2 mm, fine sand = 0.0625–0.25 mm, and mud < 0.0625 mm. Zin = Zinkwazi, Non = Nonoti, Mge = Mgeni, Tot = Amanzimtoti, LTot = Little Amanzimtoti, Mhl = Mhlabatshane, Int = Intshambili.*

Estuary	Period	Depth (cm)	Temperature (°C)	Dissolved Oxygen (mg L^{-1})	Salinity (‰)	pH	(Secchi cm) or Turbidity (NTU)	% Medium–Very Coarse Sand	% Fine Sand	% Mud
North Coast										
Zin	1	60.0–110.0	30.3–31.9	5.8–6.4	22.0–25.0		(35, fair)			
	2	110.0–160.0	26.5–30.30	0.42–4.98	11.40–14.6	7.66–7.92	60.0–80.0	38.2	7.4	54.4
	3	144.2–177.2	26.06–27.54	2.1–5.44	8.22–12.99	6.69–7.66	36.4–79.8	30.7	7.7	61.6
Non	1	75.0–115.0	27.8–30.2	5.2–5.7	2.0–10.0		(30–999, clear)			
	3	162.78–175.17	24.87–27.38	0.46–8.61	0.91–15.11	6.91–8.23	2.80–9.15	66.6	2.5	30.9
Durban										
Mge	1	45.0–170.0	21.7–24.0	5.8–6.7	14.0–26.0		(20–45, fair)			
	2	50.0–210.0	22.5–23.1	2.28–6.32	11.0–28.4	7.53–7.97	13.0–23.0	40.4	36.8	22.8
	3	38.3–71.9	22.28–26.1	2.36–6.33	7.82–30.18	6.84–7.58	7.5–18.2	69.5	26.3	4.2
South Coast										
Tot	1	90.0–180.0	22.8–25.4	5.2–13.8	4.0–9.0		(50–85, very clear)			
	2	95.0–120.0	21.5–22.2	0.49–5.96	1.3–3.7	7.02–7.75	30.0–57.0	75.5	20.2	4.3
	3	87.2–149.4	21.25–23.59	4.92–15.33	0.18–1.49	7.35–8.62	6.0–18.2	59.8	23.6	16.6
LTot	1	75.0–270.0	22.6–24.8	3.8–8.7	8.0–18.0		(60–999, very clear)			
	2	110.0–140.0	20.3–22.0	1.02–2.12	0.2–4.2	7.08–7.5	30.0–73.0	65.2	22.8	12.0
	3	46.1–70.4	22.31–23.32	1.61–2.39	0.39–1.55	7.6–7.62	8.3–10.4	86.7	10.6	2.7
Mhl	1	90.0–120.0	26.0–26.7	5.7–6.1	18.0–22.0		(999, very clear)			
	2	70.0–155.0	26.8–28.2	1.18–5.28	10.3–18.6	7.09–7.41	6.0–38.0	32.6	63.2	4.2
	3	51.4–165.5	20.83–24.17	4.17–4.92	15.17–34.12	7.15–7.69	9.9–17.1	59.7	6.5	33.8
Int	1	115.0–390.0	21.1–21.5	0.0–3.0	0.0–1.0		(90, very clear)			
	2	75.0–150.0	24.5–25.5	3.8–4.45	3.0–3.3	7.22–7.36	7.0–8.0	89.1	10.7	0.2
	3	128.0–195.0	21.93–22.52	0.31–2.2	13.8–17.98	7.01–7.2	9.9–17.8	91.1	6.5	2.4

formed, urban) estuaries. The Nonoti Estuary (NC, transformed, agricultural) is different, presumably because of its very low overall abundances and species richness. The remaining groups include the Mgeni Estuary's period 2 data, and then all of the other systems in both periods. All other estuaries separate further along a geographical gradient at the 30% level of similarity into seven distinct groups constituting the Mgeni (period 3) and Zinkwazi (period 3) estuaries, the Amanzimtoti and Little Amanzimtoti middle and upper regions together with the Zinkwazi (period 2), and last, the Mhlabatshane (SC, transformed, semiurban) and Intshambili (SC, transformed, semiurban) benthic communities together with data from the lower reaches of both Amanzimtoti and Little Amanzimtoti estuaries ($R = 0.759$, $p = 0.001$, Figure 4).

Five invertebrate species were found to be especially important in terms of distinguishing estuary groupings from each other (dissimilarity between groups greater than 79% in all cases, Table 4). The Intshambili, Mhlabatshane, and lower

Table 4. *Characteristics of the macrobenthos community sampled in each study estuary in periods 2 and 3. Shannon diversity was calculated from data averaged over the estuary. Abundance of the five distinguishing species (Oligochaeta Naidinae spp., Polychaeta* Desdemona ornata *and* Prionospio *cf.* multipinnulata*, Amphipoda* Grandidierella *spp., Gastropoda* Tarebia granifera*) is also included. Shading (dark to light) indicates relative abundance (highest to lowest). Zin = Zinkwazi, Non = Nonoti, Mge = Mgeni, Tot = Amanzimtoti, LTot = Little Amanzimtoti, Mhl = Mhlabatshane, Int = Intshambili.*

Estuary		Period	No. sites	No. species	Shannon Diversity H	Total abundance (no. ind.)	Density ($ind.m^{-2}$)	Total abundance (no. ind.) Naidin.	*D. orn.*	*P. mult.*	*Grandid.*	*T. gran.*
North coast	Zin	2	4	14	1.283	2648	9268	399	258	618	0	0
		3	4	16	1.131	2520	8820	611	6	93	0	14
	Non	3	3	5	0.86	172	803	4	0	6	0	33
Durban	Mge	2	4	15	0.6695	920	3220	1	789	0	30	0
		3	4	28	1.533	2256	7896	507	199	162	21	0
South coast	Tot	2	3	16	1.16	4219	19689	144	360	2982	157	0
		3	3	13	0.9303	2182	10183	6	23	921	0	1153
	LTot	2	3	16	1.006	2375	11083	12	24	1665	381	0
		3	2	13	1.335	1157	8099	11	1	459	287	0
	Mhl	2	3	26	1.872	2474	11545	22	60	870	507	0
		3	3	24	1.626	1994	9305	101	33	698	759	1
	Int	2	3	15	1.271	7600	35466	135	7	468	3462	0
		3	3	20	1.604	1671	7798	96	129	296	796	0

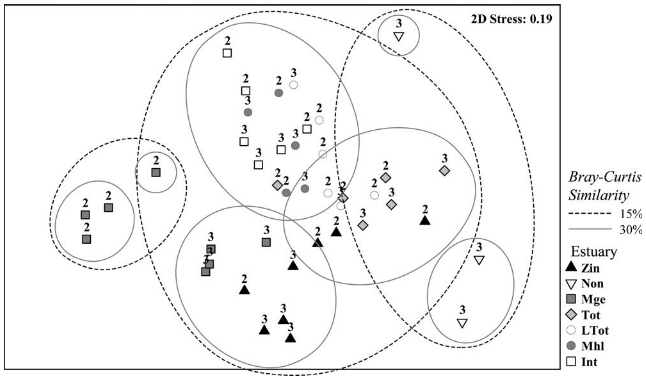

Figure 4. nMDS ordination of macrobenthos counts for all estuaries and replicates for the two periods for which data were available (periods 2 and 3). The 15% and 30% levels of similarity are indicated by the black dotted and grey solid lines respectively. North Coast estuaries Zin = Zinkwazi and Non = Nonoti; Durban estuary Mge = Mgeni; South Coast estuaries Tot = Amanzimtoti, LTot = Little Amanzimtoti, Mhl = Mhlabatshane, and Int = Intshambili.

reaches of the Amanzimtoti and Little Amanzimtoti were distinguished by and separated from all other groupings by the corophiid amphipod *Grandidierella* spp. (alone contributing 38.7% to within-group similarity). Similarly, the Naidinae oligochaetes distinguished the Zinkwazi and Mgeni period 3 grouping (contributing 42.2% to within-group similarity) and the spionid polychaete *Prionospio* cf. *multipinnulata* the Zinkwazi period 2 and Amanzimtoti and Little Amanzimtoti middle and upper reaches (contributing 81% to within-group similarity). The Mgeni period 2 group was characterised by the sabellid polychaete *Desdemona ornata* and the Nonoti Estuary by the invasive thiarid gastropod *Tarebia granifera* (both contributing greater than 95% to similarity within their respective groups). As was previously noted, the Amanzimtoti and Intshambili estuaries were characterised by very high abundances of their respective distinguishing species in period 2, in the lower reaches especially (Table 4).

Mean macrobenthos density (ind. m^{-2}) was mostly comparable between estuaries with some exceptions (Table 4). The Nonoti Estuary had a highly depauperate benthos in density and representative species. Similarly, a relatively low benthic density was recorded in the Mgeni Estuary in period 2. The highest densities overall were in the Amanzimtoti and Intshambili estuaries in period 2. In the case of the Amanzimtoti this can be attributed to a high abundance of the spionid polychaete *P.* cf. *multipinnulata* (average abundance in period 2 of 13,916 ind. m^{-2}), and the corophiid amphipods *Grandidierella* spp. and *Americorophium triaenonyx* for the Intshambili (average abundances in period 2 of 16,156 and 13,202 ind. m^{-2} respectively). The Mgeni, Mhlabatshane, and Intshambili estuaries showed the highest species richness, with the Mgeni being most variable between periods.

A geographical distinction is apparent in the higher taxonomic composition of the macrobenthos within estuaries and between periods. There appears to be a shift in dominance from the Phylum Annelida (polychaetes and oligochaetes) in the northern estuaries to a benthic community that is dominated by Amphipoda in the southern systems. The Mgeni and Amanzimtoti estuaries appear to be in an intermediate zone to this pattern; although Annelida are highly prevalent in both of these estuaries, there is an increased abundance of Amphipoda. The Zinkwazi, Mgeni, and Amanzimtoti estuaries all showed a high degree of variability in community composition between periods 2 and 3. The highly invasive gastropod *T. granifera* was recorded in high abundances in the Nonoti and Amanzimtoti estuaries (Table 4).

Land Cover–Biophysical Predictor-Response Statistical Analyses

Overall, the strongest correlations between land cover and each of the biophysical data sets were found between land cover (20 m and 5 m) and the biological data (RELATE rho = 0.44 and 0.32 respectively, $p > 0.05$, Table 5). Estuary sediment data were least strongly correlated to macrobenthos (RELATE rho = 0.127, $p > 0.05$). The separate physicochemical and sediment data sets were both poorly correlated to the land cover data (RELATE rho = 0.15 and 0.17 respectively, $p > 0.05$). Without exception, the response biophysical data sets (macrobenthos and physicochemical) were more strongly related to land cover in the 20-m than land cover within the 5-m contour in every study estuary.

Further exploratory analysis using the BEST routine showed that patterns in the biology of the study estuaries were most closely linked to four land cover categories within the 20-m contour, these being aquatic vegetation, estuary water surface area, reed/grass swamps, and transport infrastructure (Spearman's rank correlation $\rho = 0.830$). The addition of a fifth category, exposed sandbanks, yielded the same result (Spearman's rank correlation $\rho = 0.830$).

The relationship between macrobenthos and land cover (5 m and 20 m) data sets was further analysed by separating study estuaries into the three groups previously based on land cover (NC, Durban city and SC groups, cluster and ANOSIM, Figure 2.). Land cover within the 20-m and not the 5-m contour was still the better match to macrobenthos in all cases and included types related to the nature of the human activities within each estuary grouping (Table 5). Many of the types within the 5-m contour identified in this exercise for all estuary groupings were related to the estuarine water area (in-stream) or its associated habitats, with the exception of formal agriculture. The best results overall were found in the NC systems up to the 20-m contour (Table 5). The types estuary water surface area and periurban scattered residential were strongly related to variability within the macrobenthos; however, this is likely skewed by the marked differences in the macrobenthic fauna of the Zinkwazi (NC, transformed, agricultural) and Nonoti (NC, transformed, agricultural) (species richness and abundance).

Land cover categories identified as being important explanatory variables in the DistLM routine (Table 5) were overlaid as a proportional representation on a nMDS ordination of estuary macrobenthos data for the two periods for which they were available (Figure 5). The Nonoti Estuary was an outlier because of its depauperate macrobenthos and high proportional representation of aquatic vegetation. The Mgeni Estuary (Durban, transformed, urban) also separated out having land

Table 5. *Results of pattern matching statistical analyses (RELATE and DistLM) between land cover (LC; within 5 m and 20 m) and macrobenthos from the study estuaries. Estuaries were analysed all together (All) and then by group according to land cover characteristics (analysis of similarity): North Coast (Zinkwazi and Nonoti), Durban (Mgeni), and South Coast (Amanzimtoti, Little Amanzimtoti, Mhlabatshane, and Intshambili) systems. Statistically significant resuts (*$p > 0.05$*) for the RELATE test are indicated in bold text.*

Estuaries	RELATE Rho ($p > 0.05$)	DistLM Land Cover Types	DistLM R^2	Total Variation Explained (%)
LC 5 m				
All	**0.321**	Aquatic vegetation, estuary water surface area, formal agriculture, reed/grass swamps	0.340	26.4
North Coast	**0.392**	Estuary water surface area	0.261	26.1
Durban	0.017	Informal paths	0.376	37.6
South Coast	**0.153**	Estuary water surface area	0.165	16.5
LC 20 m				
All	**0.444**	Aquatic vegetation, bare soil, beach, estuary water surface area, reed/grass swamps	0.510	28.3
North Coast	**0.775**	Estuary water surface area, periurban scattered	0.566	56.6
Durban	**0.715**	Formal commercial, urban medium density	0.528	52.8
South Coast	0.255	Pier and reinforcing structures	0.362	36.2

cover types not represented in other systems. All SC systems grouped together, having high proportional representations of the categories beach, periurban scattered, residential, and informal paths.

DISCUSSION

Study estuaries formed distinctive groupings in terms of land cover characteristics that were statistically significantly different from each other. As expected, the NC (Zinkwazi and Nonoti), Durban (Mgeni), and SC (Amanzimtoti, Little Amanzimtoti, Mhlabatshane, and Intshambili) estuaries formed separate groups. No pattern was apparent in terms of sediment and water physicochemistry, reflecting the characteristically highly variable nature of the estuarine physical environment (Elliott and Quintino, 2007; Elliott and Whitfield, 2011).

This pattern becomes a little more complicated when analysing patterns of similarity/difference within the biological data. The groupings suggest variability between periods (change along a temporal gradient) in the larger Zinkwazi (NC, transformed, agricultural) and Mgeni (Durban, transformed, urban) estuaries, and between regions (change along a spatial gradient) within the SC systems. The Nonoti Estuary (NC, transformed, agricultural) is completely distinctive from all other systems, having a highly depauperate benthos.

Overall the Mhlabatshane (SC, transformed, semiurban) and Intshambili (SC, transformed, semiurban) estuaries showed a higher abundance of Amphipoda, especially the corophiid *Grandidierella* spp. These crustaceans are less tolerant of pollution and are commonly used as bioindicators of a good ecological condition (Borja, Franco, and Pérez, 2000), reinforcing the allocation of a "B" (largely natural) ecological category in the RDM process (Table 1, DWA, 2010). The invasive gastropod *T. granifera* was recorded from the Nonoti and Amanzimtoti (SC, transformed, urban) estuaries and indicates a disturbed and degraded condition. A superabundance of *P.* cf *multipinnulata* and the amphipod *Grandidierella* spp. was recorded from the Amanzimtoti and Intshambili estuaries respectively, both in period 2. *Prionospio* cf *multipinnulata* is a deposit feeder that relies on detritus as a food source. Its larvae have been recorded in very high numbers in neritic plankton samples and such an abundant larval supply facilitates high adult abundances when estuary conditions are right (Day, 1967).

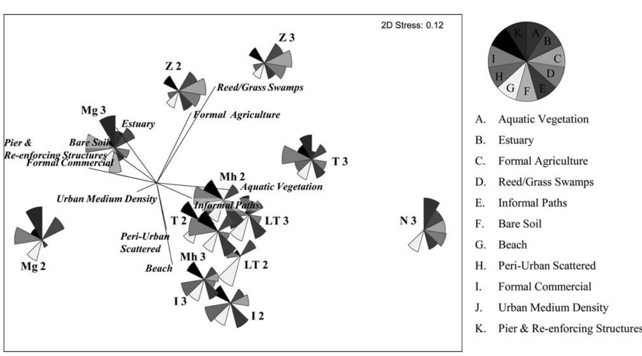

Figure 5. nMDS ordination of the macrobenthos data for each region (L = lower, M = middle, U = upper) within the study estuaries for periods 2 and 3 with the proportional representation of land cover categories identified through DistLM overlaid on it. North Coast estuaries Z = Zinkwazi and N = Nonoti; Durban estuary Mg = Mgeni; South Coast estuaries T = Amanzimtoti, LT = Little Amanzimtoti, Mh = Mhlabatshane, and I = Intshambili.

Relatedness of Data Sets

Human impacts that arise from land use (expressed physically as land cover) on an estuarine condition may be hard to elucidate, as the pathway by which they affect an estuary is indirect and via the modification or disruption of natural processes that already demonstrate naturally high levels of variability (Elliott and Quintino, 2007). Although statistically significant, land cover was poorly related to physicochemical or sediment (benthic habitat) variables in this study. These environmental variables that themselves are critically important in shaping estuarine faunal communities (Borja and Dauer, 2008; Neto *et al.*, 2010) were in the case of this study also poorly related to patterns in the macrobenthos.

Of all the data sets, land cover around the study estuaries was most strongly related to the invertebrate fauna. By its very nature, an estuary's physical environment is highly dynamic, especially over the short term. This was demonstrated by the variability in the physicochemical and sediment data presented in this study. In contrast, land cover showed very little variation over the study's 30-year period. Patterns in the macrobenthos reflect an *in situ* biological response to cumulative changes, effects, and stressors over the long term.

This relationship between land cover and macrobenthos data was especially true of land cover within the 20-m contour, which, although less closely associated with the estuary, reflects catchment effects and changes. The current spatial delineation of South African estuaries by the 5-m contour line (the EFZ) was an attempt to define an estuary management unit that included not only the water surface area but also the fringing estuary-associated habitats, recognising the importance of such habitats in estuary ecological functioning and integrity (Van Niekerk and Taljaard, 2003; Van Niekerk and Turpie, 2012). Recent work, however, has shown that for many of the country's estuaries the EFZ does not contain all estuarine vegetation (Veldkornet, Adams, and Van Niekerk, 2015). For this reason and as supported by the results of this study, land cover beyond the EFZ and perhaps in case-by-case instances to the 20-m contour should be considered for the future development of an estuary management tool.

Regional Patterns of Land Cover and Estuary Ecological Condition

The NC is characterised by sugarcane agriculture and residential settlements, often at the mouths of the coastline's estuaries. In keeping with this pattern, the periurban scattered residential land cover category accounted for most of the variability in the macrobenthos data for the Zinkwazi (NC, transformed, agricultural) and Nonoti (NC, transformed, agricultural) estuaries. In contrast with all other study estuaries, the macrobenthic fauna of the Nonoti Estuary is depauperate and characterised by the invasive gastropod *T. granifera*. In aquatic systems, the negative effects of high-impact disturbances on biodiversity may be persistent, with historical events being the strongest predictor of current-day trends (Foster *et al*., 2003; Harding *et al*., 1998). In the case of the Nonoti Estuary, the macrobenthos likely reflects previous impacts not linked to current physical conditions, with obvious implications for the future interpretation of land cover data.

In comparison, the land cover categories that were most important in the Mgeni Estuary (Durban, transformed, urban) were those characteristic of urbanisation, namely formal commercial and urban medium density residential, which together accounted for over half of the variability in the biotic data. These urban land uses can affect the estuary in several ways that include a loss of natural fringing habitat, a reduction in water quality through the runoff of pollutants and sewage or wastewater generation, as well as increased demand for freshwater.

The Mgeni Estuary showed amongst the highest macrobenthos species richness and abundance of all the systems in period 3, but was variable over time. The rich macrobenthos recorded in period 3 is characteristic of larger estuarine systems, and can be attributed to the large estuary size, semipermanent connection, and greater exchange with the marine environment, as well as the presence of mangroves. The Naidinae oligochaetes and the polychaete *D. ornata* were numerically important in this system. Both feed on detritus and their abundance is closely linked to the availability of food (Rossi, 2002).

Within the SC estuaries, the type "pier and reinforcing structures" was important, although the patterns of variability within the macrobenthos and land cover were not statistically significantly related to each other. The benthic communities in these systems showed a strong spatial trend, with the lower reaches being different from the middle or upper reaches. Extensive road and rail bridges cross these estuaries in the lower reaches. Supporting structures such as pylons have been built on the estuary banks or within the estuaries themselves, causing sedimentation or in some cases (the Amanzimtoti) rerouting of the estuary (Begg, 1978). Moreover, there was variation within the nature of the land cover within these systems: the Amanzimtoti (SC, transformed, urban) and Little Amanzimtoti (SC, transformed, urban) are far more urbanised than the Mhlabatshane (SC, transformed, semiurban) and Intshambili (SC, transformed, semiurban), which retain extensive natural fringing vegetation. Because these estuaries are small and land uses varied, and keeping in mind their long history of human presence, the lack of a statistically significant relationship between land cover and macrobenthos within this group is expected.

Overall, the increased numerical contribution in the southern estuaries by the Amphipoda, especially the corophiid *Grandidierella* spp., is noteworthy, as amphipods are less tolerant of pollution (Borja, Franco, and Pérez, 2000) and characterise well-functioning intermittently open estuaries in the south tropics. These amphipods were more abundant in the Mhlabatshane and Intshambili estuaries than in the Amanzimtoti or Little Amanzimtoti, which are more highly developed. Instead, the polychaete *P.* cf *multipinnulata* was more important in these two systems. A superabundance of *P.* cf *multipinnulata* and the amphipod *Grandidierella* spp. was recorded from the Amanzimtoti and Intshambili estuaries respectively, both in period 2. *Prionospio* cf *multipinnulata* is a deposit feeder that relies on detritus as a food source. Its larvae have been recorded in very high numbers in neritic plankton samples and such an abundant larval supply facilitates high adult abundances when estuary conditions are right (Day, 1967).

Selection of Indicators for KZN's Estuaries

Of the 31 land cover categories present around the study estuaries within the 20-m contour, variability in the data set was largely attributable to a much smaller subset of 11 categories. More than half of these are associated with anthropogenic activities reflecting the largely modified state of the KZN coast. These 11 categories are the most important in the seven study estuaries and could be used as indicators in the future development of a management tool.

Similarly, the 99 benthic invertebrate species recorded during this study can be reduced to a far smaller subset of only five that accounted for most of the variability in the data. These species included the oligochaetes Naidinae spp., polychaetes *D. ornata* and *P.* cf. *multipinnulata*, amphipod *Grandidierella* spp., and the gastropod *T. granifera*. This subset includes a range of species that indicates good ecological condition (*e.g.,* Amphipoda), to opportunistic species able to tolerate fluctuating conditions (*e.g.,* Polychaeta) and invasive pest species that indicate poor ecological condition (*e.g., T. granifera*) (Borja, Franco, and Pérez, 2000).

Effect of Geography

Land cover and macrobenthos data sets were highly correlated and this has great promise for the development of a tool for management. However, the data sets may show similar patterns in response to a common and confounding factor, namely geography. Patterns of topography and climate drive human settlement and resultant land-use patterns. Biology shows variation with geography too because of its effect on temperature and other variables that are important in shaping biological communities, and biogeographical boundaries are apparent in every aspect of ecology.

Analyses on the basis of land cover separated the estuaries into three distinct and unique groups according to a human-geographical history: the two NC agricultural systems (Zinkwazi and Nonoti), the urbanized Durban city Mgeni Estuary, and the four SC estuaries (Amanzimtoti, Little Amanzimtoti, Mhlabatshane, and Intshambili), which have varying degrees of development. These groupings were consistent over the 30-year period of the study, indicating that there has been very little variation in land cover (although possibly not land use) during this time. A geographical trend was also evident in the higher taxonomic composition of the macrobenthos in the estuaries; the phylum Annelida was numerically important in the northern estuaries, whereas the order Amphipoda was far more important in the SC estuaries. The Mgeni and Amanzimtoti estuaries appeared to form a transition zone between the two, with both annelids and amphipods being represented. Of interest, this same pattern has been found in an investigation of offshore benthic communities in KZN's coastal waters (MacKay, Untiedt, and Hein, 2016; Untiedt and MacKay, 2016).

The fact that both patterns of human development within the coastal zone as well as natural processes that drive the species distribution and composition of natural communities are both strongly shaped by geography may confound the correlation that was found between land cover characteristics and estuary macrobenthic communities in this study. The depauperate benthic fauna of the Nonoti Estuary and presence of the invasive *T. granifera* in the Nonoti and Amanzimtoti estuaries are, however, an unnatural state that is a highly disturbed condition. Furthermore, within the SC systems land cover around the estuaries ranged from more highly urbanized to largely undisturbed, and this pattern was mirrored in the varying numerical dominance of the disturbance-tolerant polychaete *P.* cf *multipinnulata* and the *Grandidierella* spp. amphipods that characterise well-functioning IOEs. These factors both suggest some external influence that upsets the natural biogeographic variation of the area.

CONCLUSIONS

This work is an initial effort to tie together different data sets to address some of the most critical challenges hindering protection of KZN's estuaries: a general lack of reliable historical or even current ecological information, and management constraints including poor levels of expertise. This study has shown that land cover is related to patterns of variability within the estuary macrobenthos. Specifically, land cover within the 20-m contour is a much better predictor of benthic fauna than land cover within the 5-m contour, with implications for current legislation and future management. This study has also helped to identify a smaller subset of land cover categories and macrobenthic invertebrate species that could be used as indicators in the future development of a management tool. These species range from indicators of well-functioning systems to opportunistic species able to tolerate changing environments, and highly invasive pest species that indicate a disturbed environment.

Although highly correlated, further work needs to be done to determine causal effect of land cover categories on estuary condition. Further development of the management tool will require the addition of supplementary estuaries and ground-truthing of these results with a much larger data set. Although such a tool would have been unlikely to have accurately predicted the ecological state of the Nonoti Estuary without some understanding of its historical condition, there is great value in the development and application of a tool to facilitate short-term interim management of the province's estuary resources.

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LITERATURE CITED

Begg, G.W., 1978. *Estuaries of Natal*. Durban, South Africa: Natal Town and Regional Planning Commission, *Report 41*, 657p.

Begg, G.W. 1984. *Estuaries of Natal (Part II)*. Durban, South Africa: Natal Town and Regional Planning Commission, *Report 55*, 631p.

Borja, A. and Dauer, D.M., 2008. Assessing the environmental quality status in estuarine and coastal systems: Comparing methodologies and indices. *Ecological Indicators*, 8(4), 331–337.

Borja, A.; Franco, J., and Pérez, V., 2000. A marine biotic index to establish ecology quality of soft bottom benthos within the European estuarine coastal environments. *Marine Pollution Bulletin*, 40(12), 1100–1114.

Cilliers, P.; Biggs, H.C.; Blignaut, S.; Choles, A.G.; Hofmeyr, J.S.; Jewitt, G.P.W., and Roux, D.J., 2013. Complexity, modelling and natural resource management. *Ecology and Society*, 18(3), 1. http://dx.doi.org/10.5751/ES-05382-180301

Clark, B.M., 1999. Possible effects of climate change on South African estuaries. *In:* Clarke, B.M.; Steffani, N.C.; Young, S.; Richardson, A.J., and Lombard, S.T. (eds.), *The Effects of Climate Change on Marine Biodiversity in South Africa*. Cape Town: Anchor Environmental Consultants, pp. 73–117.

Clarke, K.R. and Ainsworth, M., 1993. A method of linking multivariate community structure to environmental variables. *Marine Ecology Progress Series*, 92(3), 205–219.

Clarke, K.R. and Gorley, R.N., 2006. *PRIMER v6: User Manual/Tutorial*. Plymouth, U.K.: PRIMER-E, 190p.

Clarke, K.R. and Warwick, R.M., 2001. *Changes in Marine Communities: An Approach to Statistical Analysis and Interpretation*. Plymouth, U.K.: PRIMER-E Ltd, 172p.

Cooper, J.A.G.; Harrison, T.D.; Ramm, A.E.L., and Singh, R.A., 1993. *Refinement, Enhancement and Application of the Estuarine Health Index to Natal's Estuaries, Tugela–Mtamvuna*. Durban, South Africa: CSIR, *Technical Report*, 120p.

Dauer, D.M.; Weisberg, S.B., and Ranasinghe, J.A., 2000. Relationships between benthic community condition, water quality, sediment quality, nutrient loads, and land use patterns in Chesapeake Bay. *Estuaries*, 23(1), 80–96.

Day, J.H., 1967. *Polychaeta of Southern Africa. Part 2. Sedentaria*. London: Trustees of the British Museum (Natural History), *Publication number 656*, 419p.

DEAT (Department of Environmental Affairs and Tourism), 1999. *Draft White Paper for Sustainable Coastal Development in South Africa*. Pretoria, South Africa: Department of Environmental Affairs and Tourism, 134p.

De Villiers, C.; Hodgson, A., and Forbes, A., 1999. Studies on estuarine macroinvertebrates. *In:* Allanson, B. and Baird, D. (eds.), *Estuaries of South Africa*. Cambridge, U.K.: Cambridge University Press, pp. 167–207.

Diaz, R.J.; Solan, M., and Valente, R.M., 2004. A review of approaches for classifying benthic habitats and evaluating habitat quality. *Journal of Environmental Management*, 73(3), 165–181.

DWA (Department of Water Affairs), 2010. *Resource Directed Measures for Protection of Water Resources: Methods for the Determination of the Ecological Reserve for Estuaries. Water Resource Protection and Assessment Policy Implementation Process. Version 3*. Pretoria, South Africa: Department of Water Affairs, 134p.

Elliott, M. and Quintino, V., 2007. The estuarine quality paradox, environmental homeostasis and the difficulty of detecting anthropogenic stress in naturally stressed areas. *Marine Pollution Bulletin*, 54(6), 640–645.

Elliott, M. and Whitfield, A.K., 2011 Challenging paradigms in estuarine ecology and management. *Estuarine, Coastal and Shelf Science*, 94(4), 306–314.

Forbes, A.T. and Demetriades, N., 2008. *Estuaries of Durban, KwaZulu Natal, South Africa*. Durban, South Africa: eThekwini Municipality, *Report for the Environmental Management Department*, 224p.

Foster, D.; Swanson, F.; Aber, J.; Burke, I.; Brokaw, N.; Tilman, D., and Knapp, A., 2003. The importance of land use legacies to ecology and conservation. *BioScience*, 53(1), 77–88.

Goble, B.J. and van der Elst, R., 2012. Trends in coastal development and change: The case of KwaZulu-Natal, South Africa. *Western Indian Ocean Journal of Marine Science*, 11(2), 193–204.

Harding, J.S.; Benfield, E.F.; Bolstad, P.V.; Helfman, G.S., and Jones, E.B.D., 1998. Stream biodiversity: The ghost of land use past. *Proceedings of the National Academy of Sciences of the United States of America*, 95(25), 14843–14847.

Harrison, T.D.; Cooper, J.A.G., and Ramm, A.E.L., 2000. *State of South African Estuaries. Geomorphology, Ichthyofauna, Water Quality and Aesthetics*. Pretoria: Department of Environmental Affairs and Tourism, 216p.

Jetz, W.; Wilcove, D.S., and Dobson, A.P., 2007. Projected impacts of climate and land use change on the global diversity of birds. *PLoS Biology*, 5(6), e157.

Kennish, M.J., 2002. Environmental threats and environmental future of estuaries. *Environmental Conservation*, 29(1), 78–107.

Kennish, M.J., 2003. *Estuarine Research, Monitoring, and Resource Protection*. Boca Raton, Florida: CRC Press LLC, 297p.

Knysh, K.M.; Giberson, D.J, and van den Heuvel, M.R., 2016. The influence of agricultural land use on plant and macroinvertebrate communities in springs. *Limnology and Oceanography*, 61(2), 518–530.

Lück, W.; Mhangara, P.; Kleyn, L., and Remas, H., 2010. *Land-Cover Field Guide, version 2.0*. Pretoria, South Africa: CSIR Satellite Applications Centre: Earth Observation Service Centre, 179p.

MacKay, F.; Cyrus, D., and Russell, K.-L., 2010. Macrobenthic invertebrate responses to prolonged drought in South Africa's largest estuarine lake complex. *Estuarine, Coastal and Shelf Science*, 86(4), 553–567.

MacKay, C.F.; Untiedt, C.B., and Hein, L., 2016. Local habitat drivers of macrobenthos in the northern, central and southern KwaZulu-Natal Bight, South Africa. *African Journal of Marine Science*, 38(S1), 105–121.

Martínez, M.L.; Intralawan, A.; Vázquez, G.; Pérez-Maqueo, O.; Sutton, P., and Landgrove, R., 2006. The coasts of our world: Ecological, economic and social importance. *Ecological Economics* 63(2–3), 254–272.

Masefield, V.A.; McGregor, G.K., and Whitfield, A.K., 2014. Does estuarine health relate to catchment land cover in the East Kleinemonde system, South Africa? *African Journal of Aquatic Science*, 39(4), 395–402.

McGranahan, G.; Balk, D., and Anderson, B., 2007. The rising tide: Assessing the risks of climate change and human settlements in low elevation coastal zones. *Environment and Urbanization*, 19,(1) 17–37.

McLusky, D.S. and Elliott, M., 2004. *The Estuarine Ecosystem: Ecology, Threats and Management*. Oxford, U.K.: Oxford University Press, 224p.

Morant, P. and Quinn, N., 1999. Influence of man and management of South African estuaries. *In:* Allanson, B.R., and Baird, D. (eds.), *Estuaries of South Africa*. Cambridge, U.K.: Cambridge University Press, pp. 289–321.

Neto, J.; Teixeira, H.; Patrício, J.; Baeta, A.; Veríssimo, H.; Pinto, R., and Marques, J., 2010. The response of estuarine macrobenthic communities to natural- and human-induced changes: Dynamics and ecological quality. *Estuaries and Coasts*, 33(6), 1327–1339.

NOAA (National Oceanic and Atmospheric Administration), 2013. *State of the Coast*. http://stateofthecoast.noaa.gov/.

Palmer, B.J.; Van der Elst, R.; Mackay, F.; Mather, A.A.; Smith, A.M.; Bundy, S.C.; Thackeray, Z.; Leuci, R., and Parak, O., 2011. Preliminary coastal vulnerability assessment for KwaZulu-Natal, South Africa. *Journal of Coastal Research*, 64, 1390–1395.

Pinto, R.; de Jonge, V.N., and Marques, J.C., 2014. Linking biodiversity indicators, ecosystem functioning, provision of services and human well-being in estuarine systems: Application of a conceptual framework. *Ecological Indicators*, 26, 644–655.

Rossi, F., 2002. Dynamics of the polychaetes *Desdemona ornata* and *Perinereis cultrifera* and their resources of food in a Mediterranean mudflat. *Marine Ecology*, 23(4), 285–296.

Sale, P.F.; Butler, M.J.; Hooten, A.J.; Kritzer, J.P.; Lindeman, K.C.; Sadovy de Mitcheson, Y.J.; Steneck, R.S., and van Lavieren, H., 2008. *Stemming Decline of the Coastal Ocean: Rethinking Environmental Management*. Hamilton, Canada: UNU-INWEH, 50p.

Schumacher, B.A., 2002. *Methods for the Determination of Total Organic Carbon (TOC) in Soils and Sediments*. Washington, D.C.: U.S. Environmental Protection Agency, *EPA/600/R-02/069 (NTIS PB2003-100822)*, 23p.

Seto, K.C.; Fragkias, M.; Güneralp, B., and Reilly, M.K., 2011. A meta-analysis of global urban land expansion. *PLoS ONE*, 6(8), 23777.

Spalding, M.D.; Ruffo, S.; Lacambra, C.; Meliane, I.; Hale, L.Z.; Shepard, C.C., and Beck, M.W., 2014. The role of ecosystems in coastal protection: Adapting to climate change and coastal hazards. *Ocean and Coastal Management*, 90, 50–57.

Statistics South Africa (StatsSA), 2015. *Mid-Year Population Estimates, 2015*. https://www.statssa.gov.za/publications/P0302/P03022015.pdf.

Stow, C.A., 2011. Spatial and Temporal Variations in Macrozoobenthic Communities in KwaZulu-Natal Temporarily Open/Closed Estuaries. Durban, South Africa: University of KwaZulu-Natal, Master's thesis, 227p.

Untiedt, C.B. and MacKay, C.F., 2016. Distribution and feeding modes of macrobenthos within three oceanographic feature areas of the KwaZulu-Natal Bight, South Africa. *African Journal of Marine Science*, 38(S1), 91–104.

Van Niekerk, L.; Petersen, C.; April, V.; Daniels, F.; Maherry, A., and Malebu, T., 2012. The estuarine functional zone. *In:* Van Niekerk, L. and Turpie, J.K. (eds.), *South African National Biodiversity Assessment 2011: Technical Report. Volume 3: Estuary Component*. Stellenbosch, South Africa: Council for Scientific and Industrial

Research, *CSIR Report Number CSIR/NRE/ECOS/ER/2011/0045/B*, pp. 28–36.

Van Niekerk, L. and Taljaard, S., 2003. *A Framework for Effective Co-operative Governance of South African Estuaries*. Stellenbosch, South Africa: Council for Scientific and Industrial Research, *Report ENV-S-C 2003-077*.

Van Niekerk, L. and Turpie, J.K., 2012. *South African National Biodiversity Assessment 2011: Technical Report. Volume 3: Estuary Component*. Stellenbosch, South Africa: Council for Scientific and Industrial Research, *CSIR/NRE/ECOS/ER/2011/0045/B*, 225p.

Veldkornet, D.A.; Adams, J.B., and van Niekerk, L., 2015. Characteristics and landcover of estuarine boundaries: Implications for the delineation of the South African estuarine functional zone. *African Journal of Marine Science*, 37(3), 313–323.

Wentworth, C.K., 1922. A scale of grade and class terms for clastic sediments. *Journal of Geology*, 30(5), 377–392.

Whitfield, A.K., 1992. A characterization of southern African estuarine systems. *South African Journal of Aquatic Science*, 18(1–2), 89–103.

Whitfield, A.K. and Baliwe, N.G., 2013. *A Century of Science in South African Estuaries: Bibliography and Review of Research Trends*. South African Network for Coastal and Oceanic Research, *SANCOR Occasional Report No. 7*, 289p.

Wu, S.; Mickley, L.J.; Kaplan, J.O., and Jacob, D.J., 2012. Impacts of changes in land use and on atmospheric chemistry and air quality over the 21st century. *Atmospheric Chemistry and Physics*, 12, 1597–1609.