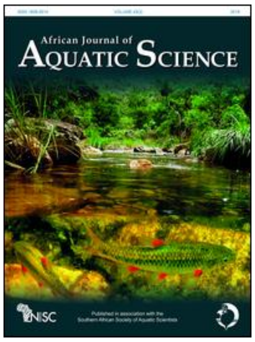

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Review Article

Nutrient enrichment as a threat to the ecological resilience and health of South African microtidal estuaries

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Nutrient pollution in South African estuaries is described using a Driver-Pressure-State-Impact-Response framework. The root cause (‘driver’) of deteriorating water quality is rapid population growth that leads to increasing inputs from wastewater treatment works (WWTWs), stormwater run-off and agricultural return flow (‘pressures’). Nationally, half of the country’s estuaries are affected by nutrient pollution (‘state’). This has elicited marked primary producer and secondary (hypoxia, fish kills, loss of ecosystem services) responses (‘impact’). The Sundays and Swartkops Estuaries are eutrophic with phytoplankton blooms (>20 µg l^{-1}) and bottom-water hypoxia. Similarly, the nationally important Knysna Estuary experiences eutrophic conditions associated with macroalgal blooms, whereas the Wildevoëlvlei and Zeekoe systems have transitioned to alternate stable states characterised by toxic cyanobacteria blooms, as a result of WWTW inputs and increased water residence times. The health of the St Lucia Estuary, a UNESCO World Heritage site, is under threat from agricultural inputs from the uMfolozi system. Nationally, better treatment and recycling of WWTW inputs is required to improve and restore estuary health. Owing to excessive WWTW effluent volumes, treatment to South Africa’s uniform effluent standards no longer prevent eutrophication. Other urgent interventions needed are compliance monitoring, engineering solutions to reduce stormwater and wastewater input, and prudent application of agricultural fertilisers.

Keywords: alien invasive plants, eutrophication, harmful algal blooms, macroalgae, mouth closure, wastewater discharges

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Introduction

Nutrient inputs to coastal waters occur naturally through processes, such as geological weathering and oceanic upwelling, although anthropogenic inputs now often exceed natural sources (Paerl et al. 2014; Cloern et al. 2016). Nitrogen (N) loading globally has increased 10-fold over the past century mainly from municipal wastewater discharges, contaminated stormwater runoff and agricultural return flow. Consequently, eutrophication resulting from nutrient enrichment is recognised as a core threat to the integrity of coastal and estuarine ecosystems worldwide (De Jonge and Elliott 2001; Bricker et al. 2008; Maier et al. 2008; Smith and Schindler 2009; Adams et al. 2016; Lemley and Adams 2019a). Increased diffuse nitrogen and phosphorus inputs have resulted in a new wave of eutrophication described as a wicked problem caused by cumulative actions over large spatial scales (Le Moal et al. 2019).

Eutrophication for this review is defined as ‘*the enrichment of water by nutrients causing an accelerated growth of algae and higher forms of plant life to produce an undesirable disturbance to the balance of organisms present in the water and to the quality of the water concerned*’ (OSPAR 2003). Eutrophication is characterised by a surge in primary production in response to nutrient loading that results in a loss of submerged aquatic vegetation, oxygen depletion, harmful algal blooms, imbalanced food webs, lower biodiversity, altered biogeochemical cycling and fish-kills (Conley et al. 2009; Ferreira et al. 2011; Lemley and Adams 2019a; Van Niekerk et al. 2019a). Depending on the scale of nutrient enrichment and the type of estuary, these impacts can cause the state of an estuary to change from one dominated by macrophytes to another dominated by phytoplankton and/or macroalgae (Dahlgren and Kautsky 2004; Smith and Schindler 2009; Nunes and Adams 2014; Lemley et al. 2018c).

South Africa has a range of estuary types that occur across four biogeographic regions; cool temperate, warm temperate, subtropical and tropical (Whitfield 1992; Van Niekerk et al. 2020). Nutrient enrichment is a serious concern not only in temporarily closed estuaries (e.g. Groot Brak), but also in large permanently open systems

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(e.g. Gamtoos and Sundays) and well-flushed estuarine bays (e.g. Knysna) (Snow et al. 2000; Human et al. 2015b; 2016b; Lemley et al. 2018b).

Strong wave action and high sediment movement along the coastline cause more than 90% of estuaries to have restricted inlets and more than 75% to close for varying periods of time when a sandbar forms across the mouth (Whitfield 1992; Van Niekerk 2019a). These conditions coupled with high land-derived nutrient input promote cultural eutrophication particularly in small microtidal (tidal range <2 m) systems. Consequently, persistent phytoplankton blooms and nuisance macroalgal growth have been recorded in several estuaries (e.g. Kotsedi et al. 2012; Human et al. 2016; Lemley et al. 2017; Adams et al. 2019). Nationally, deteriorating water quality has been linked to an increase in fish kills and the spread of invasive species (e.g. *Tarebia granifera*), parasites, pathogens and diseases (Van Niekerk et al. 2019a, 2019b).

The response of estuaries to nutrient enrichment is governed by their prevailing physical and chemical characteristics (Lemley et al. 2015). Taljaard et al. (2009a, 2009b) showed the extent of fluvial and/or tidal flushing in small South African temperate estuaries to determine water quality conditions. In permanently open estuaries and estuarine bays, tidal mixing processes regulate nutrient status whereas in closed, fluvially dominated and lake systems, mouth state plays a key role. Concomitantly, eutrophication impacts in highly turbid estuaries or those with short flushing times are likely to be less severe than in clear water systems with long residence times (Elliott and Quintino 2007). Continually enriched estuaries develop into ecosystems with a reduced capacity to adjust to increases in water residence times caused by droughts. The assimilation and cycling of nutrients are essential ecosystem services that must be protected for estuaries to retain their inherent resilience.

This review assesses nutrient enrichment and the associated deterioration of water quality in a selection of South African estuaries. It describes responses to nutrient enrichment by primary producers and identifies secondary effects and implications for estuary health and the provision of ecosystem services. Progress and challenges in management interventions are highlighted and recommendations made for future management and research. In South Africa, we could make significant improvements in estuary health by addressing nutrient enrichment.

Materials and methods

This study drew on scientific literature, government documentation and experiential knowledge to generate a critical overview of nutrient pollution in South African estuaries. The Drivers-Pressures-State-Impact-Response (DPSIR) approach was chosen as the conceptual framework within which to present this critical review (OECD 1993). This framework is widely used in coastal and marine ecosystem management as a means to structure and analyse ecosystem information for management and decision-making (Atkins et al. 2011; De Jonge et al. 2012; Patricio et al. 2016; Elliott et al. 2017), including in South Africa (Goble et al. 2017). Although the DPSIR framework has limitations, it has the ability to address the 'wicked problem' of integrating ecosystem assessments with management responses.

We produced a national-scale overview of generic root causes of deteriorating water quality ('drivers') by investigating anthropogenic sources of nutrient enrichment ('pressure') (Figure 1). Because water quality of river runoff is strongly influenced by land cover and land-use in catchments (Dabrowski et al. 2013; Taljaard et al. 2017), land cover datasets were used to identify the major sources of nutrient enrichment of river inflow into estuaries (Van Niekerk et al. 2018). Also incorporated where available were data from the chemical monitoring of river inflows (De Villiers and Thiart 2007; DWS 2019). Wastewater volumes and nutrient loads (N and P) were obtained from available data sources (e.g. Lemley et al. 2014; Van Niekerk et al. 2018; DWS 2019). Using the collected data, estuaries affected by different pollution sources (wastewater treatment works (WWTW), stormwater run-off and agricultural return flow) were compared between biogeographic zones (cool temperate, warm temperate, subtropical, tropical) and volumes and nutrient loads from WWTW discharges to the nine different estuary types (Van Niekerk et al. under review, this special issue volume) were summarised for the country. Characteristics of the estuaries are summarised in Table S1.

Nutrient enrichment is the main cause of deteriorating water quality in South African estuaries (Taljaard et al. 2017). The extent to which it has modified estuarine water quality ('state') was derived either from ecological flow requirement and classification studies (using the Estuarine Health Index (EHI))(Van Niekerk et al. 2018; Van Niekerk et al. 2019c), or by using a water quality screening model specifically designed for data-poor environments (Taljaard et al. 2017; Van Niekerk et al. 2018). Estuarine Health Index water quality scores were used as proxies to determine the extent to which nutrient pollution has modified the state of estuary water quality. The six category (A to F) water quality scoring of the EHI (Turpie et al. 2012) was simplified into four 'state' categories: near natural (A and B), moderately modified (C), heavily modified (D) and severely/critically modified (E and F). Estuaries in categories A and B were considered to be largely unaffected by nutrient pollution and were therefore excluded from the assessment. The ecological consequences of nutrient enrichment ('impact') were explored using a selection of case studies. Key advances and management challenges were reviewed ('response') and, future management and research requirements recommended.

In assessing ecological consequences, estuary response to nutrient enrichment was described for different primary producers (phytoplankton, macroalgae, floating aquatic macrophytes and emergent macrophytes). Secondary impacts were identified and implications for the provision of ecosystem services outlined using published literature and expert knowledge. A DPSIR conceptual framework was generated where 'pressure' represents the dominant nutrient pollution sources, 'state' is the effect on water quality status and 'impact' the ecological consequences. The severity of ecological impact was rated as medium, high or very high. The rating 'very high' indicates that the estuary is eutrophic,

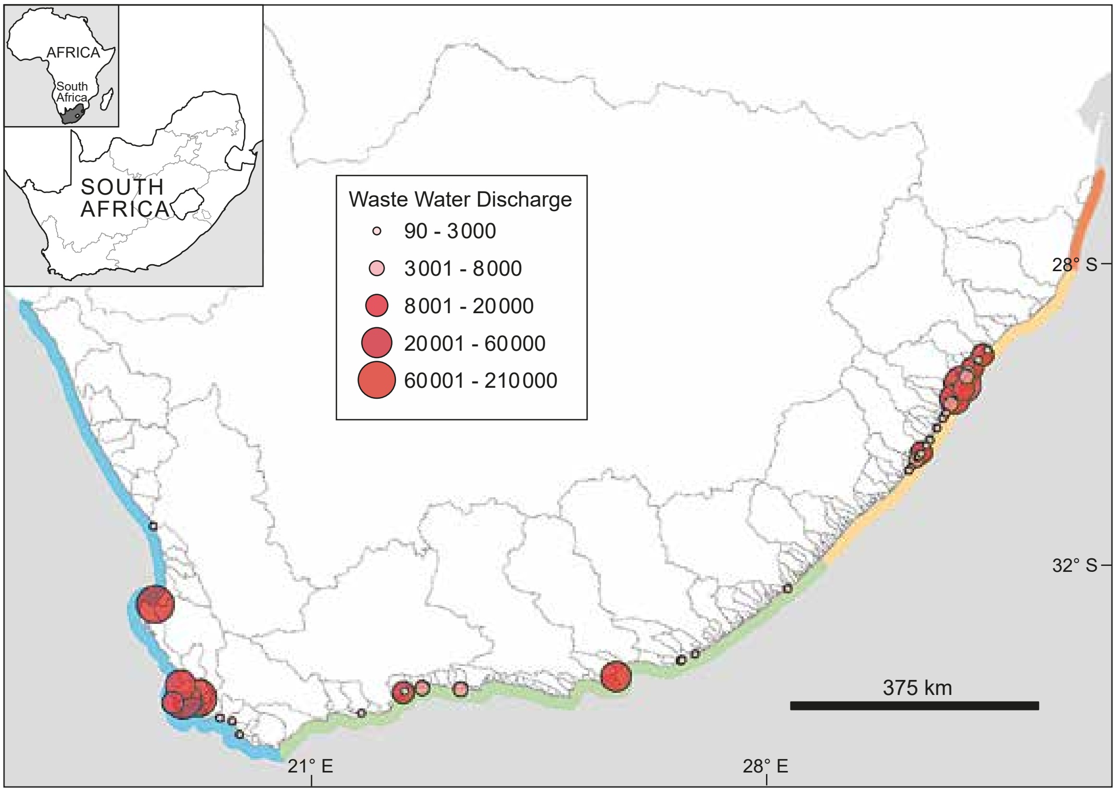

Figure 1: Spatial distribution of WWTW effluent discharges into estuaries, as well as estimated daily volumes (m^3 day^{-1}), including fish factory effluent discharged along the west coast

‘high’ that it can show eutrophic symptoms sometimes in an annual cycle and ‘medium’ that only a section of the estuary shows eutrophic symptoms (e.g. upper reaches). These categories can be related to the moderately modified (C), heavily modified (D) and severely/critically modified (E and F) categories used in South Africa’s Estuarine Health Index (Van Niekerk et al. 2018). The actual health index scores cannot be used as the ecological impacts are not presented separately for biotic health. Biotic health integrates all pressures (e.g. fishing, development, reduced freshwater inflow), including changes in water quality.

Information on the occurrence of floating aquatic macrophytes (invasive plants) was compiled from literature sources that included the Southern African Plant Invaders Atlas (SAPIA) database, CSIR Estuaries of the Cape reports and the Botanical Database of Southern Africa (http: // newposa.sanbi.org/). Data are not available for invasive phytoplankton, macroalgae and emergent macrophytes on a national scale. The extent of invasive aquatic macrophytes in the lower, middle and upper reaches was rated as low, medium and high cover (category 1–3). This represents coverage of the open estuary water surface area where 1 is <5%, 2 is 5%–15% and 3 is >15%.

Root causes of water quality deterioration (‘drivers’)

Understanding the root causes of environmental issues is essential for the effective implementation of policies and sound management strategies (Bowen and Riley 2003). Within the African context, UNEP et al. (2009) found the root causes of coastal water quality deterioration to be rapid population growth and urbanisation, poverty and inequality, inappropriate governance, limited knowledge and awareness, inadequate financial resources, climate change and environmental variability. Although most of these apply to the South African situation, Goble et al. (2017) and Sowman and Malan (2018) added a lack of political support, inadequate institutional capacity, lack of human and financial resources, uncertainty in governmental roles and responsibilities and conflicting policy frameworks to the list. Since the early 1980s, coastal cities, such as Cape Town, Port Elizabeth, Durban and Richards Bay have experienced rapid economic growth and a demand for urban housing (DEA 2013a). Expanded waste management facilities have exceeded the carrying capacities of treatment facilities resulting in a marked deterioration in water quality of receiving water bodies, such as estuaries (Van Niekerk et al. 2019b).

The legal landscape governing estuarine water quality management is complex, with conflicting or overlapping mandates creating confusion over roles and responsibilities (Taljaard et al. 2019). For example, the disposal of land-based wastewater from WWTWs to estuaries is a joint mandate shared between the national environmental department and the national water department, whereas management and control of urban runoff (or stormwater) resides with local municipalities. Water quality issues pertaining to agricultural sources (e.g. return flows) are under the control of national and provincial agriculture departments (Taljaard et al. 2019). This division of jurisdiction has created uncertainty within and between authorities and hampered timeous government responses to escalating pressures.

Lead national, provincial and municipal coastal management agencies are generally under resourced and valuable institutional memory has been lost, because of high staff turnover rates. Insufficient financial resources are allocated to address critical water quality issues, such as developing appropriate wastewater treatment facilities or adequate stormwater management; this applies especially to small coastal municipalities. A compounding factor is a lack of political will and accountability that has resulted in large-scale corruption and mismanagement of public funds earmarked for infrastructure development and the maintenance of public facilities. The result has been large-scale failure of WWTWs with negative consequences for estuaries (Pillay 2004; Sundström 2013). Although national government's incentive-based mechanism, the National Green Drop Certification Programme (Green Drop Programme), has contributed to some improvement in the wastewater sector, numerous challenges still are hampering effective enforcement (Ntombela et al. 2016).

Major sources of nutrient pollution ('pressure')

The disposal of municipal wastewater (through point and diffuse sources), diffuse urban runoff and agricultural return flow are the chief causes of nutrient enrichment in South African estuaries (Taljaard et al. 2017). Rapid population growth in coastal areas generates increasing demand for wastewater treatment facilities and results in higher effluent volumes that require disposal. Resources are often not available for infrastructure maintenance or upgrades, because they are not municipal priorities and some smaller coastal municipalities do not have the requisite skills for operational management of treatment works. Treatment facilities are therefore often overloaded or malfunctioning, causing spillage from pump stations and substandard effluent flow into rivers and estuaries. Many densely populated coastal settlements are not serviced by reticulated sewage systems. This results in untreated sewage entering stormwater runoff into rivers and estuaries, an occurrence that contributes significantly to nutrient and organic loading through diffuse urban runoff (Van Niekerk et al. 2019b). Over fertilisation on crop farms and contaminated runoff from cattle and dairy farms are additional nutrient sources (Pearce and Schumann 2001; Lemley et al. 2017).

The distribution of nutrient pollution sources (WWTW effluent, diffuse urban run-off, agricultural return flow) across estuaries in each of the biogeographical regions is shown in Table 1. Few data are available on the volumes of nutrient enriched waters entering estuaries from these sources, especially diffuse sources, such as urban runoff and agricultural return flow. In the case of WWTWs, legislation mandates operators to monitor the effluent prior to disposal. The volume of wastewater disposed to estuaries (or to river reaches upstream) is estimated at 840 000 m^3 day^{-1} (Van Niekerk et al. 2019a), mostly derived from municipal WWTWs with the exception of the fish factories' wastewater (130 000 m^3 day^{-1}) disposed of along the west coast into the Groot Berg Estuary. The spatial distribution of WWTW effluent volumes released to estuaries (or just upstream of estuaries) along the South African coast is illustrated in Figure 2. As expected, the focal points of WWTW effluent disposal occur in the two major coastal urban centres (and surrounds), namely Cape Town and Durban.

Comparing the distribution of WWTW effluent disposal across various estuarine types (Table 2) shows the largest volumes are discharged to temporarily closed estuaries (Figure 2) followed by permanently open systems, estuarine lakes, estuarine bays and large fluvially dominated systems. Temporarily closed estuaries are especially vulnerable during the closed state when low flushing rates and longer water residence times allow nutrient inputs to accumulate and primary producers to flourish ('primary response' of eutrophication). Data on nutrient loads are limited and not readily available on a national scale. However, minimum standards required by legislation stipulate effluent limits of 21 mg l^{-1} (1 500 μM) and 10 mg l^{-1} (320 μM) for inorganic nitrogen (DIN) and phosphorus (DIP), respectively (DWA 2013a). Municipal effluents are at least treated to these minimum standards and the daily nutrient loads into estuaries are estimated at 14.9 and 7.1 tonnes of DIN and DIP, respectively (Table 2). This study shows that these concentrations are extremely high for estuaries resulting in eutrophication.

Effect on water quality status ('state')

The national EHI water quality scores (Taljaard et al. 2017: Van Niekerk et al. 2019a) provide an indication of the extent to which nutrient pollution has altered estuary water quality (Table 3). Proportionally, it has most affected 70% of cool temperate estuaries with more than half of these already critically modified. Subtropical estuaries follow this where the water quality in almost 60% of these systems is moderately, heavily or severely/critically affected. The water quality status of 38% of warm temperate estuaries was classified as modified although the largest proportion falls within the moderately modified category. Nutrient pollution has had no marked impact on the water quality status of tropical estuaries, primarily as a result of the absence of extensive catchment development although this is rapidly changing.

Agricultural return flow is the highest contributor to the deteriorating water quality status of estuaries followed by diffuse urban runoff (stormwater) and WWTW effluent discharges (Snow et al. 2000; Snow and Taljaard 2007; Lemley et al. 2014; Lemley et al. 2017; Taljaard et al. 2018). However, where agricultural return flow is the dominant source, the deterioration in water quality is moderate, with some systems being heavily to severely/critically modified (Table 4). In estuaries where urban runoff and WWTW effluent discharges are the dominant sources, water quality deterioration mostly falls within the heavily to severely/critically modified categories. Therefore, although agriculture return-flow might be the dominant cause of water quality deterioration in estuaries, those affected most severely receive urban runoff and WWTW effluent discharges. This does not, however, translate into a direct ecological response.

Ecological consequences ('impact')

In this paper, water quality focuses on anthropogenic nutrient loading and subsequent eutrophication responses (primary producers and secondary impacts). Primary

Table 1: Number of estuaries affected by different pollution sources across the four biogeographical regions

Biogeographical region	Number of estuaries affected	Major nutrient pollution source/s (expressed as number of estuaries)		
		WWTW effluent (point sources)	Diffuse urban runoff	Agricultural return flow
Cool temperate	23	7	12	12
Warm temperate	46	5	14	21
Subtropical	75	20	54	48
Tropical	0			

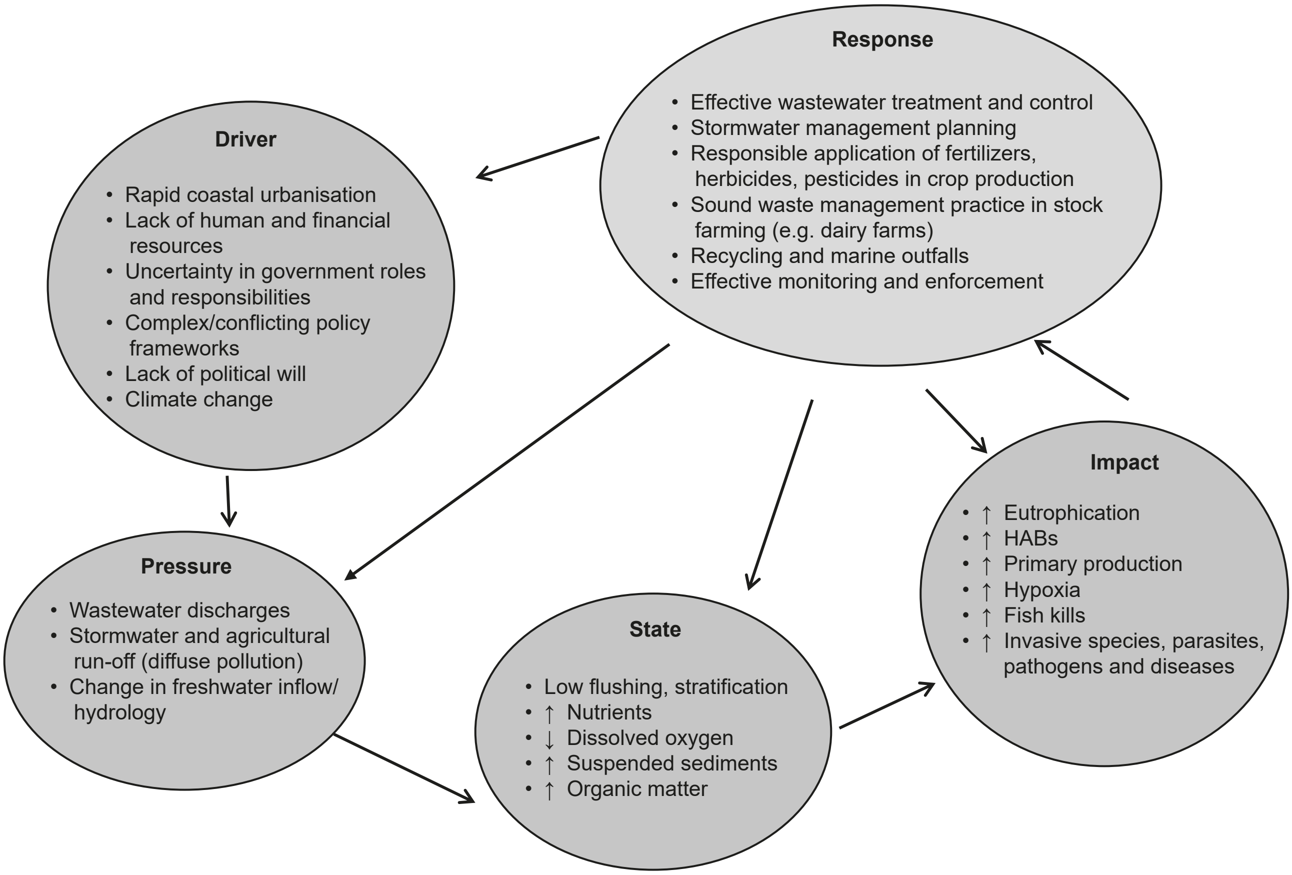

Figure 2: Summary of findings presented as a DPSIR framework

Table 2: Distribution of WWTW effluent disposal across different estuary types, including volumes and estimated nutrient loads

Estuary type	Number of estuaries receiving effluent	WWTW effluent		
		Volume (m^3 day^{-1})	Estimated N load (tonnes day^{-1})	Estimated P load (tonnes day^{-1})
Large temporarily closed	17	346 566	7.28	3.47
Small temporarily closed	9	78 608	1.65	0.79
Predominantly open	8	131 417	2.76	1.31
Estuarine lake	3	118 040	2.48	1.18
Estuarine bay	2	22 380	0.47	0.22
Large fluvially dominated	2	12 826	0.27	0.13
Arid predominantly closed	0			
Small fluvially dominated	0			
Estuarine lagoon	0			
Total	41	709 837	14.9	7.1

Table 3: Effect of nutrient pollution on the water quality status of estuaries across biogeographical regions and various estuary types within each region

Biogeographical/estuary type (number of estuaries)	Number of estuaries affected (percentage of total type in region)	Effect on water quality status (expressed in number of estuaries)		
		Moderately modified	Heavily modified	Critically modified
Cool temperate (33)	23 (70%)	2	7	14
Arid predominantly closed (6)	2 (33%)		1	1
Estuarine lagoon (1)	0			
Estuarine lake (4)	4 (100%)		2	2
Large fluvially dominated (1)	1 (100%)		1	
Large temporarily closed (9)	9 (100%)	1	2	6
Predominantly open (3)	3 (100%)		1	2
Small fluvially dominated (1)	0			
Small temporarily closed (8)	4 (50%)	1		3
Warm temperate (124)	47 (38%)	25	10	12
Estuarine bay (1)	1 (100%)		1	
Estuarine lake (3)	1 (33%)	1		
Large fluvially dominated (1)	0			
Large temporarily closed (40)	12 (30%)	8	3	1
Predominantly open (25)	12 (48%)	6	3	3
Small fluvially dominated (6)	1 (17%)	1		
Small temporarily closed (48)	20 (42%)	9	3	8
Subtropical (131)	75 (57%)	24	28	23
Estuarine bay (1)	1 (100%)	1		
Estuarine lake (4)	4 (100%)	1	2	1
Large fluvially dominated (5)	4 (80%)		3	1
Large temporarily closed (45)	33 (73%)	14	9	10
Predominantly open (16)	4 (25%)	1	1	2
Small temporarily closed (60)	29 (48%)	7	13	9
Tropical (2)	0			
Estuarine lake (2)	0			
Total (290)	145 (50%)	51	45	49

Table 4: Contribution of various nutrient pollution sources to the extent of deterioration in water quality status across South African estuaries

Dominant source/s	Number of affected estuaries	Effect on water quality status		
		Moderately modified	Heavily modified	Critically modified
Agricultural return flow	56	33	13	10
Urban runoff	31	8	9	14
WWTWs	4	1		3
Agricultural return flow and urban runoff	22	6	12	4
WWTWs and urban runoff	18	1	4	13
Agricultural return flow, urban runoff and WWTWs	3		2	1
Agricultural return flow and WWTWs	11	2	5	4
Total	145	51	45	49

producers that proliferate in response to nutrient loading are freshwater microalgae (e.g. *Microcystis aeruginosa*), phytoplankton and harmful bloom-forming algae (e.g. *Heterosigma akashiwo*, *Heterocapsa rotundata*, *Prymnesium parvum*), macroalgae (*Cladophora glomerata, Ulva lactuca*), floating aquatic macrophytes (*Eichhornia crassipes, Pistia stratiotes*) and emergent macrophytes (*Typha capensis*, *Phragmites australis*). Growth of salt marsh and mangroves are likely to occur in response to nutrient enrichment, but there are no studies that report on this. Eutrophication causes the loss of submerged macrophytes (i. e. through shading) although some species, such as pondweed (*Stuckenia pectinata* (L.) *Börner*), have increased in response to nutrient inputs.

The response of primary producers to nutrient loading in the range of South African estuary types is summarised in Table 5. The major sources of nutrient pollution and the extent to which they have modified water quality status are listed. Where agricultural return flow was the main source of nutrient pollution, the water quality status was moderately modified (e.g. Goukamma, Gamtoos, St Lucia/uMfolozi). Where WWTW effluent and urban runoff were the main nutrient pollution sources, the water quality was degraded to a heavily or critically modified state (e.g. Wildevoëlvlei, Zand,

Table 5: Dominant nutrient pollution sources ('pressure'), the effect on water quality status ('state') and resultant ecological consequences ('impact') for the selected estuaries (listed from west to east coast). The severity of the impact is listed as medium, high and very high. Different types of estuaries are indicated by symbols: * = estuarine lakes, $^{!}$ = temporarily closed, $^{\#}$ = estuarine bay, • = predominantly open; $^{\times}$ = fluvially dominated)

Estuary	Dominant sources ('pressure')		Effect on water quality ('state')	Ecological consequence ('impact')		
	Type/s	WWTW in estuary (m^3 day^{-1})		Severity (M, H, VH)	Description	Reference
Wildevoelvlei $^{!}$	WWTW/Urban runoff	9 500	Critically modified	VH	High water retention, toxic blue-green *Microcystis aeruginosa* blooms.	Heinecken 1985; DWS 2017
Zand $^{!}$	Urban runoff	–	Critically modified	H	Increase in nutrients and growth of pondweed, *Stuckenia pectinata* and golden algae *Prymnesium parvum* blooms.	Harding 1994; Quick and Harding 1994; Lemley et al. 2019b
Zeekoe *	WWTW/urban runoff	116 640	Critically modified	VH	Toxic cyanobacteria (*Microcystis* sp.) blooms followed by *S. pectinata* dominance has been problematic since the 1920s	Harrison 1962
Hartenbos $^{!}$	WWTW	10 000	Critically modified	VH	High nitrogen and ammonium, low oxygen, microalgal and macroalgal blooms, fish kills	Lemley et al. 2015
Groot Brak $^{!}$	Urban runoff/ agricultural return flow	–	Heavily modified	H	Flow reduction increasing mouth closure, reduced flushing and build-up of nutrients, macroalgal blooms, dieback of submerged macrophytes and salt marsh.	Nunes and Adams 2014; Human et al. 2015a, 2015b; Lemley et al. 2015; Human et al. 2016a
Gwaing $^{!}$	WWTW/urban runoff	7 931	Critically modified	H	High nitrogen, benthic microalgal biomass high	Lemley et al. 2015
Goukamma $^{!}$	Agricultural return flow	–	Moderately modified	H	Eutrophic conditions in the middle reaches, as a result of water retention and input of organic load from surrounding agriculture and dairy activities.	Kaselowki and Adams 2013; Lemley et al. 2015
Knysna $^{\#}$	WWTW/urban runoff	6 500	Heavily modified	H	Anoxic sediment, ammonium release, SRP, weak flushing, macroalgal growth, dieback of seagrass, *Zostera capensis*	Allanson et al. 2016; Human et al. 2016b
Gamtoos •	Agricultural return flow	–	Moderately modified	M	Localised agricultural activities providing lateral input, high chlorophyll *a*, occasional hypoxia	Lemley et al. 2017
Swartkops •	Urban runoff (including WWTW from catchment)	27 507	Critically modified	VH	High chlorophyll *a*, water hyacinth and other aquatic invasive plants in upper reaches. Permanent eutrophic state.	Pretorius 2015; Adams et al. 2019; Lemley et al. 2019c
Sundays •	Agricultural return flow	–	Critically modified	VH	Fish kills, hypoxia, HABs, high Chl *a*, aquatic invasive plants upstream e.g. *Azolla filiculoides.* Permanent eutrophic state.	Lemley et al. 2017, 2018a, 2018b
uMngeni •	WWTW/urban runoff	121 999	Critically modified	VH	Flow reduction causing increased retention, storm water runoff, water hyacinth, low oxygen, epiphytic and bacteria growth on mangrove aerial roots.	DWA 2013
uMhlanga $^{!}$	WWTW/urban runoff	4 983	Critically modified	H	Eutrophic conditions, high nutrient concentrations and high phytoplankton biomass.	DWA 2013; Thomas et al. 2005
uMdloti $^{!}$	WWTW/urban runoff	7 529	Critically modified	H	Eutrophic conditions, frequent mouth breaching, decline in estuary health, fish kills	Thomas et al. 2005; Van Niekerk et al. 2019b
uMvoti $^{\times}$	WWTW/urban runoff	12 156	Heavily modified	VH	Eutrophic, anoxic conditions, floating grasses, riparian alien plant growth causing loss of bird habitat	Van Niekerk et al. 2019b
St Lucia/uMfolozi *	Agricultural. return flow	–	Moderately modified	M	Increase DIN, DIP from sugarcane run-off in Mfolozi, increase cyanophytes and dinoflagellates, HAB species	Nunes et al. 2018

Table 6: Estuaries reported to have aquatic invasive plants (1 low cover, 2 medium cover, 3 high cover). Different types of estuaries are indicated by symbols: * = estuarine lakes, ! = temporarily closed, ◊ = river mouth, • = predominantly open, × = fluvially dominated

Estuary	Aquatic invasive plants in estuary reaches			*Azolla filiculoides*	*Ceratophyllum demersum*	*Eichhornia crassipes*	*Lemna gibba*	*Myriophyllum aquaticum*	*Pistia stratiotes*	*Salvinia molesta*
	Lower	Middle	Upper							
Orange ×	3	3	3	x						
Olifants •			2	x						
Groot Berg •	2	2	2			x				
Rietvlei/Diep !	2	2	2	x		x				
Wildevoëlvlei !	2	2	2				x			
Zand !	2	2	2	x	x	x	x	x		x
Zeekoe *		2	2			x				
Eerste !			3			x		x		
Lourens !	2	2	3	x						x
Onrus !	2	2	2	x						
Breede •			3			x				
Blinde !	2	2	2	x		x				
Hartenbos !	2	2	2	x		x				
Wilderness *	2	2	2	x						x
Swartvlei *	2	2	2	x						x
Gamtoos •			1	x						
Swartkops •			3	x	x	x				x
Sundays •			3	x						
Nahoon •			2			x				
Umhlangankulu !	3	2	2	x						
Little aManzanamtoti !	2		1			x			x	
aManzanamtoti !	2	2	2	x		x			x	
iZimbokodo !	2	2	2			x			x	
Sipingo !	1		1			x			x	
uMngeni •	2	2	2	x		x			x	
uMdloti !	2	2	2	x		x			x	
uThongathi !	2	2	2			x			x	x
uMvoti ×	1					x				
iNonoti !	1					x				
uThukela ×	2	2	2			x				
Matikulu/Nyoni !	1				x					
Siyaya !		1		x	x					
Richard's Bay •			1		x				x	x
Nhlabane *		1							x	
St Lucia *		2		x						
Kosi *			1		x					

Zeekoe, Hartenbos, Gwaing, Knysna, Swartkops, uMngeni, uMdloti and uMvoti). Water quality changes and the loss of estuary ecosystem services are summarised in Table 7.

In this study, the response of primary producers to nutrient inputs and the severity of the impact were ranked as medium, high and very high (Table 5). In some cases, the effect of anthropogenic activities on water quality was ranked as severely/critically modified, but the ecological impact was only high, because the response depends on the duration of the impact and physical dynamics of the estuary. For example, active mouth management keeps the Zand Estuary well flushed, accordingly decreasing residence time (Lemley et al. 2019b). Similarly, the uMdloti Estuary was severely/critically modified, but the severity of impact was high, because of short water residence times and frequent mouth breaching events stemming from large volumes of WWTW discharges (Thomas et al. 2005). Similarly, the ecological impacts in uMvoti Estuary were very high, but water quality was heavily modified, because the expansion of invasive aquatic grasses covers extensive areas of the estuary impacting available habitat for birds (Fernandes and Adams 2016). The water quality has also had a negative impact on the fish community (O'Brien et al. 2009). Active management to reduce nutrient inputs is needed to ensure that estuaries with a high to medium ecological impact are not on a negative trajectory of change in terms of deteriorating water quality.

Nutrient assimilation and cycling are important ecosystem services that require protection if resilience is to be maintained. Wildevoëlvlei and Zeekoe estuarine lakes are currently in an alternate stable state characterised by toxic cyanobacteria blooms caused by WWTW inputs and increased water residence times (Table 5). The blooms are evidence of a loss of ecological resilience that require drastic and costly interventions, such as water level drawdown and dredging, to restore. These estuaries function as nutrient sinks, because flushing of polluted sediment is unlikely, as a result of large water surface areas, low freshwater inputs

Table 7: Loss of ecosystem services in response to eutrophication by different primary producers

Primary producer	Secondary effect	Impact on ecosystem service
Microalgal blooms		
HABs and toxin production	Toxins influence all trophic levels Bioaccumulation, fish and shellfish poisoning	Loss of fisheries and food production, subsistence use Loss of shellfish e.g. mussels Loss of biodiversity and trophic structure No contact recreational activities Decline in public health Loss of recreation and tourism
HABs and mucilage production	Mechanical interference and suffocation of fish and invertebrates	Loss of fisheries and food production Loss of estuary nursery habitat for fishes
Smells	Aesthetic degradation	Loss of recreation and tourism
Macroalgal blooms		
Clogging of waterways, smells	Aesthetic degradation	Loss of real estate value Decrease in business opportunities and livelihoods Loss of recreation and tourism
Increased cover and loss of intertidal habitat	Loss of biodiversity, intertidal salt marsh, invertebrates and wading birds	Decrease in bank stabilisation by salt marsh Decrease in bait resources Loss of tourist appeal, bird watching
Collapse of seagrass, microalgal and grazer communities	Smothering of seagrass Change in invertebrate communities that influence fish and birds	Loss of trophic structure and biodiversity Extinction of benthic fauna and flora Loss of sheltered nursery areas
Oxygen fluctuations	Fish and invertebrate kills, change in habitat structure and biodiversity	Loss of fisheries and food production Loss of estuary nursery habitat for fishes
Floating aquatic macrophytes / Invasive aquatic plants		
Floating aquatic macrophytes	Loss of native species Aquatic food webs and nutrient cycles disrupted	Local extinctions Loss of biodiversity
Floating aquatic macrophytes	Decrease in water transparency Loss of submerged aquatic vegetation, such as seagrass	Loss of fisheries, economic value, subsistence use Loss of waste assimilative capacity
Floating aquatic macrophytes, clogging of waterways	Aesthetic degradation Decrease in flow and water movement Loss of connectivity estuary and river	Reduced movement of boats (navigability) Loss of recreation and tourism, boating, fishing and swimming become difficult Loss of biodiversity and nursery habitat
Emergent macrophytes (reeds and sedges)		
Reeds and sedges expansion	Loss of open water surface area	Reduced movement of boats (navigability) Loss of recreation and tourism, boating, fishing and swimming become difficult
Reeds and sedges expansion	Dense monospecific stands Die back and high organic load, anoxia and smells	Loss of biodiversity Loss of tourist appeal, bird watching

and alteration of hydrodynamic processes. Wastewater nutrients (N and P) can remain in estuarine lakes as 'legacy nutrients' even after the input has ceased. In Tallow Creek, a closed system on the east coast of Australia, wastewater N remained in plants, animals and sediments for up to eight years after cessation of the source (Smith et al. 2016). Most highly impacted estuaries (Table 5) can recover if the nutrient source is halted and large floods remove anoxic sediments. This applies to permanently open (Swartkops, Sundays, uMgeni), temporarily closed (Hartenbos) and river mouth/fluvially dominated (uMvoti) estuary types.

Phytoplankton and harmful algal blooms

Water residence influences the type of primary producer that grows in response to nutrient enrichment. In open estuaries, particularly long narrow systems with high retention zones, phytoplankton is dominant and often form blooms in the middle to upper reaches (the river-estuary interface zone or REI) (Snow et al. 2000; Bate et al. 2002). The Sundays and Swartkops estuaries have become eutrophic over the past decade (Lemley et al. 2017; Lemley et al. 2018a, 2018b; Adams et al. 2019; Table 5). Bottom-water oxygen depletion is regularly recorded and phytoplankton biomass is seldom lower than 20 µg Chl *a* l^{-1}. At the forefront of eutrophic symptoms in the Sundays Estuary are recurrent and seasonal high biomass (>100 µg Chl *a* l^{-1}), harmful algal bloom (HAB) events of *Heterosigma akashiwo* (Y. Hada) Y. Hada ex Y. Hara and M. Chihara (Raphidophyceae) and *Heterocapsa rotundata* (Lohmann) G. Hansen (Dinophyceae) in spring/summer and winter, respectively. Research is currently underway to investigate the influence of these HABs on the fishes in the estuary as mucilage and toxin production (directly or indirectly) by HAB taxa can cause the loss of fauna (Branco et al. 2014; Basti et al. 2016).

In estuarine lakes, phytoplankton and HABs occur in the basin section where there is greater water residence, because of limited tidal flushing and extended closed mouth conditions. In the estuarine lake Wildevoëlvlei, the inflow of wastewater combined with long water residence times has resulted in the outbreak of toxic *Microcystis aeruginosa* (Kützing) Kützing cyanobacterial blooms (DWS 2017). The mouth of the lake is an important bird breeding area and the blooms pose a threat to bird populations through their consumption of bio-accumulated toxins in mussel prey (Figure 3). These bivalves are also eaten by subsistence harvesters and pose a threat to human health. In freshwater lakes there are reports of decaying *Microcystis aeruginosa* blooms releasing microcystins into the air and affecting human health up to 10 km from the source (May et al. 2017). The eutrophic Zeekoe Estuary has cycled between periods of extensive submerged pondweed (*S. pectinata*) beds and widespread toxic cyanobacteria blooms (*Microcystis* sp.) since the 1920s (Harrison 1962). N-fixing *Microcystis* species reach a spring maximum and following their collapse N-fixing filamentous *Anabaena* bloom. An increase in non-nitrogen-fixing *Aphanocapsa* occurs during summer. These species all produce toxins and form surface scums (Harding 1992).

Phytoplankton blooms in response to wastewater input also occur in temporarily closed estuaries. In 2012 in the heavily urbanised Zand Estuary in Cape Town, *Prymnesium parvum* N. Carter (Prymnesiophyceae) formed an extensive, almost monospecific HAB (peaking at 530 µg Chl *a* l^{-1}) over a month-long period that culminated in anoxic conditions and fish kills (Lemley et al. 2019b). The mouth was artificially breached to increase salinity, decrease nutrients and halt the occurrence of HABs. The responsible municipality adopted an adaptive management approach that included scheduled mouth breaching and removal of obstructions to water flows. Mouth breaching to maintain water quality takes place in similar estuaries globally. For example the Vasse-Wonnerup Estuary in south west Australia is artificially breached to prevent fish kills and toxic algal blooms (Warwick et al. 2018).

Additionally, the temporarily open Goukamma Estuary was considered to be in a good condition until the water column was sampled. Regular sampling indicated the eutrophic and anoxic conditions in highly stratified bottom waters, as a result of inputs from the surrounding dairy farms (Kaselowski and Adams 2013). Input of sewage effluent from WWTWs is a large problem on the developed KwaZulu-Natal coast, where frequently this is the only flow into small estuaries during the low flow season (Van Niekerk et al. 2019b). High nutrient inputs from WWTWs (Table 5) have resulted in eutrophic conditions in both the Mhlanga and uMdloti estuaries (Thomas et al. 2005). Dissolved inorganic nitrogen (DIN) concentrations in the estuaries have attained peaks of approximately 200 µM at the uMdloti and 400 µM at the uMhlanga (Thomas et al. 2005). Similarly, DIP concentrations have escalated to maxima of approximately 15 µM in the uMdloti and 80 µM in the uMhlanga. This high nutrient availability has culminated in high chlorophyll *a* levels in these estuaries (100–300 µg Chl *a* l^{-1}), especially during closed mouth conditions (Thomas et al. 2005).

Recent research has reported on the presence of HAB species in the Narrows of St Lucia, a UNESCO World Heritage site. Conditions are fresh, silty and nutrient rich, as a result of agricultural inputs from the iMfolozi system and a prolonged closed mouth state (Nunes et al. 2018; Nunes et al. 2019). The presence of HABs alter the functioning of closed estuaries, because entire foodwebs might become dysfunctional or impaired in a relatively short period of time (Table 5). Their presence or persistence affects the provision of ecosystem services by destroying essential nursery habitats, directing toxicity to higher trophic levels, altering natural biogeochemical cycling and drastically shifting foodweb structures. These impacts reduce the socio-economic benefits enjoyed from estuarine ecosystems.

Macroalgal blooms

Macroalgae form extensive mats in closed estuaries (Figure 4). Filamentous green algae grow rapidly in response to nutrient input and can cover large areas. *Enteromorpha, Ulva* and *Cladophora* often form accumulations known as 'green tides', because of their filamentous nature and high nutrient uptake rates (Sfriso et al. 1992; Karez et al. 2004). Although nutrient input from WWTWs, stormwater run-off

Figure 3: Blue-green algal blooms at the mouth of the Wildevöelvlei Estuary in January 2017

and agricultural lands cause these blooms, internal fluxes from tissue decomposition and sediment recycling of N and P are also important nutrient sources (Lemley et al. 2018c; Gladyshev and Gubelit 2019).

Macroalgae occur in all types of estuaries, but are most prevalent in those with increased water residence times, such as estuarine lakes and temporarily closed systems. In the Zeekoe Estuary, they thrive in the sheltered, nutrient rich waters where excessive growth and thick floating mats prevent light penetration. Upon decomposition, oxygen is removed from the water, creating anoxic conditions rich in hydrogen sulphide. In the Groot Brak Estuary, regeneration of N and P from anoxic sediments ensures a tight cycle of nutrients between the sediment and primary producers (Human et al. 2015b). Despite low *in situ* nutrient concentrations, macroalgal blooms, such as *Cladophora glomerata* (Linnaeus) Kützing, indicate a deterioration in water quality. During closed mouth conditions, these blooms cover the submerged macrophytes and salt marsh causing dieback (Nunes and Adams 2014). Eutrophication in a California estuary reduced salt marsh resilience through the proliferation of algal mats, reducing salt marsh cover and increasing salt marsh edge erosion (Wasson et al. 2017).

Areas in permanently open estuaries that experience poor tidal flushing are also susceptible to macroalgal blooms. In the shallow Ashmead Channel of the Knysna estuarine bay, WWTW inputs and urban runoff caused the proliferation of *Ulva lactuca* Linnaeus. Although an oligotrophic estuary, macroalgal blooms occur more frequently in areas with higher water residence. The green tide event of 2015 caused the dieback of seagrass *Zostera capensis* Setch. (Allanson et al. 2016; Human et al. 2016b) and changed the diversity of intertidal macrofauna (Barnes 2019). Polychaete numbers increased, but small malocostracan crustaceans and microgastropods diminished to insignificant levels. These changes altered the availability of food for adult and juvenile fish and reduced the estuary's value as a nursery and feeding ground (Barnes 2019). The deterioration of water quality in the Knysna Estuary is cause for concern, because it has been ranked most important in the country for ecosystem services and biodiversity conservation (Turpie et al. 2002; Turpie and Joubert 2005).

Macroalgal mats limit the provision of estuary ecosystem services, because they create foul smells, choke waterways, limit light penetration to deeper waters, reduce benthic fauna and flora and pollute recreational facilities (Table 7). Blooms can cover the intertidal zone (Figure 4) and impact feeding of invertebrates and intertidal wading birds. Decaying mats of filamentous algae adversely affect the social acceptability of water in the Groot Brak and Kleinmond estuaries and are often the reason for artificially breaching the mouth (Adams et al. 1999). Decomposing mats promote anoxia and anaerobic bacterial activity that produces hydrogen sulphide in the sediment and atmosphere (Flindt et al. 1999; Berglund et al. 2003). Eutrophication can change the structure of an estuarine ecosystem from a grazing and/or nutrient controlled, stable system to an unstable detritus/mineralisation one where the turnover of oxygen and nutrients is dynamic and oscillations between aerobic and anaerobic states occur frequently (Flindt et al. 1999). Opportunist macroalgae can out-compete other seaweeds, seagrasses and sometimes phytoplankton by taking advantage of nutrient influxes (Scanlan et al. 2007; Lemley et al. 2018c).

Figure 4: Macroalgal blooms in the Hartenbos Estuary in February 2019

Extreme fluctuations in oxygen production and consumption can result in fish kills. In the Klein estuarine lake, extensive macroalgal blooms and low oxygen at night caused a six-week long fish kill in 2010/2011 (SJ Lamberth, DEFF, pers. comm.; Clark et al. 2015). Photosynthetic oxygen production during daylight and consumption through respiration at night causes diurnal variations in dissolved oxygen (Trancoso et al. 2005). The Groot Brak Estuary experienced a diurnal variation of dissolved oxygen, which ranged from a daytime high of 9 mg l^{-1} to a night-time low of 3.2 mg l^{-1} (DWA 2009). Low oxygen conditions can disrupt normal functioning, which results in massive fish kills.

Floating aquatic macrophytes

Floating aquatic macrophytes generally occur in fresh and oligohaline (<5) sections of estuaries where there is quiet water (Adams et al. 1999). Many are exotic and classified as aquatic invasives. Low flow and high nutrient conditions promote the growth of *Eichhornia crassipes* (Mart.) Solms (water hyacinth) and invasives, such as *Azolla filiculoides* Lam. (water fern), *Ceratophyllum demersum* L. (hornwort), *Echinochloa pyramidalis* (Lam.) Hitchc. and Chase (antelope grass), *Lemna gibba* L. (duckweed), *Nymphaea nouchali* var. *caerulea* (Sav.) Verdc. (Egyptian water lilies), *Myriophyllum aquaticum* (Vell.) Verdc. (parrots feather), *Pistia stratiotes* L. (water cabbage) and *Salvinia molesta* D. S. Mitch. (Kariba weed).

Reports of aquatic invasive macrophytes are summarised in Table 6; although these are likely to have a more widespread distribution than reported in the literature. For example, there are no records for large parts of the Eastern Cape coastline. Nutrient loading and increasing global temperatures are facilitating biological invasions (Nguyen et al. 2015). Invasive species are characterised by rapid growth rates, higher tolerance to environmental stress and enhanced phenotypic plasticity that enables the competitive displacement of native pioneer species (Legualt et al. 2018). Research is needed to document and understand their spread in South African estuaries.

Invasive aquatic plants occur in all types of estuaries (Table 6). In permanently open systems, they are found in the upper reaches and in closed systems throughout the estuary. Although floods and high flow conditions shift plants to the middle and lower reaches, they do not persist when the salinity increases. In the Swartkops Estuary, eutrophication might have caused large areas of water hyacinth to displace the seagrass (*Zostera capensis*) in the middle to upper reaches (Figure 5). In the Groot Berg Estuary, dense deposits of water hyacinth debris from the upper reaches along the spring high tide line at Die Plaat in the lower reaches has resulted in the destruction of salt marsh vegetation and subsequent bank erosion (Boucher and Jones 2007).

Water hyacinth also occurs in the freshwater upper reaches of open estuaries and in several temporarily closed systems particularly in KwaZulu-Natal (Glennie 2001; DWA 2013b; Pillay 2013; DWS 2015) where conditions are fresh during closed mouth phases. Despite implementation of a biological control programme, water hyacinth remains the most problematic aquatic weed in South Africa (Coetzee and Hill 2012). When it invades water surfaces, evaporation rates increase, stream flow decreases, waterways are obstructed and nutrient cycles become altered (Kasulo 2000; Charmier et al. 2012). Impenetrable mats limit phytoplankton growth by rapidly depleting water column nutrients and preventing light penetration to deeper waters, which in turn impacts zooplankton growth. Disruptions to food webs potentially culminate in the loss of commercially important fish species (Villamagna and Murphy 2010; Nguyen et al. 2015). Integrated control programmes use a range of eradication methods, such as biocontrol agents and manual, mechanical or herbicide control. Successful control, however, ultimately depends on the implementation of effective nutrient management strategies.

Proliferation of invasive alien plants (IAPs) results in a loss of ecosystem services similar to that of the other primary producers. Moreover, IAPs impact ecosystem functioning through a loss of native species diversity, creating a homogenous habitat and disrupting aquatic food webs and nutrient cycles (Charmier et al. 2012; Gallardo et al. 2016). The decrease in water transparency, because the often-dense surface cover of IAPs causes the loss of rooted submerged aquatic vegetation with knock on effects, such as a loss of fisheries. Aquatic invasive plants also impact recreational activities (e.g. boating and sailing) and property values (Table 7).

Submerged macrophytes

Submerged macrophytes are dominant in some eutrophic estuaries. The pondweed *Stuckenia pectinata* forms extensive beds in the upper reaches of permanently open eutrophic estuaries, such as the Olifants, Berg and Sundays. It is also prolific in closed systems with oligohaline conditions (salinity <5). In the Zand (Zandvlei) Estuary, it grows rapidly in response to nutrient enrichment from the urbanised catchment. Hardening of the catchment has increased runoff and anthropogenic nutrient loading from stormwater and sewage inputs. For many years, pondweed was mechanically removed, because its dense mats restricted boating, exacerbated flooding and caused unpleasant odours upon decomposition. Its reduced population resulted in microalgal blooms and showed that the beds and associated filter-feeding polychaetes were essential for the maintenance of good water quality (Davies et al. 1989; Harding 1994; Quick and Harding 1994). Today, there is active management of stormwater and river inflows (e.g. detention ponds, improved infrastructure, litter removal), harvesting of *S. pectinata* to maintain ecosystem service provision (e.g. nursery habitat, nutrient uptake, oxygenation) and artificial opening and closing of the estuary mouth (Quick and Harding 1994; DWS 2017; Lemley et al. 2019b). Regular WWTW pump station failure, however, has resulted in serial sewage spills in the high residence upper reaches, which often negates the positive impact of artificial mouth manipulation.

Figure 5: *Eichhornia crassipes* (water hyacinth), *Lemna gibba* (water fern), *Salvinia molesta* (Kariba weed) and *Ceratophyllum demersum* (hornwort) in the upper reaches of the Swartkops Estuary at Perseverance (April 2019)

Emergent macrophytes: reeds and sedges

Reeds and sedges form an important interface between fresh and brackish habitats and aquatic and terrestrial environments. They are natural biological filters, stabilise banks, because of their effectiveness in trapping sediments and contribute to aquatic diversity particularly avifauna (Coetzee et al. 1997). In many estuaries, they play an important role in taking up nutrients from septic tanks and stormwater input (Human and Adams 2011). Reeds are abundant in numerous South African estuaries at sites of stormwater run-off, freshwater seepage and adjacent to fertilised lawns.

These emergent macrophytes grow rapidly in response to nutrient enrichment and can become invasive. The common reed *Phragmites australis* invaded sedge marsh and other riparian vegetation in the Groot Berg Estuary after a fire (DWS 2017). Genetic studies show native populations to be expanding in their range and abundance in southern Africa. This is attributed to anthropogenic activities and in the case of *P. australis* is labelled expansive and not invasive (Canavan et al. 2018). Catchment disturbance and dam development also promote reed and sedge expansion through reducing floods that results in channel siltation.

Stimulated by high nutrient availability, reeds and hygrophilous grasses can also replace open water surface area. At uMvoti Estuary, reduced freshwater inflow and input of wastewater resulted in reeds expanding to 50% greater cover than natural and grasses growing into open water areas (Fernandes and Adams 2016). Reeds have also expanded considerably in the Wilderness Lakes system (Russell 2003; Russell and Kraaij 2008) and Siyayi Estuary (Weisser and Parsons 1981). These dense monospecific stands reduce biodiversity that negatively affects ecosystem functioning and interfere with boating and recreational activities. In addition, their high biomass creates considerable detrital loading that causes sediment anoxia and smells (Table 7). Without controlling nutrient input, reeds will continue to grow and expand. Despite dredging to remove accumulated sediment and reeds in the Onrus Estuary, it remains heavily encroached. This has been a problem since the 1940s, following sedimentation caused by erosion from catchment activities combined with reduced freshwater inflow, which prevented scouring and breaching of the mouth (Massie and Clark 2016).

Management interventions: progress and challenges (‘response’)

Improved coastal and estuarine legislation and policy represent significant progress in providing the framework needed to address complex issues that confront environmental managers (Table 8). The National Estuarine Management Protocol, a requirement under the Integrated Coastal Management (ICM) Act of 2008, came into force in 2013 (DEA 2013b) stipulating minimum requirements for the management and control of estuarine ecosystems, including water quality. Under the protocol, estuarine management plans must be developed and implemented for all estuaries. The Department of Environmental Affairs (DEA) responded by publishing national guidelines to help authorities prepare these plans (DEA 2015) and additional guidelines to control the disposal of land-derived effluent to estuaries (DEA 2014). Most recently, it published Coastal Water Discharge Permit Regulations stipulating that effluent discharge from a land source into coastal waters requires authorisation at ministerial level (DEA 2019). Under these regulations, a permit to discharge to estuaries can only be granted in exceptional circumstances. This disposal, however, also requires a permit under a separate Act (Section 21 of the National Water Act) resulting in duplication of licensing processes. This remains a source of confusion requiring intervention.

Effluent discharges from WWTW or industrial plants are also listed activities under the NEMA Environmental Impact Assessment (EIA) regulations. Any new development or upgrading of more than 5 Ml effluent day^{-1} is subject to an EIA. On approval, operations may commence only after general authorisation or a coastal waters discharge permit is granted. Challenges with implementing new policies and regulations relating to estuaries remain a problem, because most still operate under historical legislation (DWA 2013) and comply to outdated uniform effluent standards (Van Niekerk et al. 2019a). EIA regulations allow for ‘serial’ upgrades of existing WWTWs with volumes below 5 Ml day^{-1}. Such upgrades do not require full impact assessments and hence do not consider long-term cumulative ecological impacts. With rapid urbanisation and demand for WWTW facilities, effluent volumes have grown beyond handling capacities and minimum standards (e.g. DWA 2013a) are no longer effective in preventing eutrophication. Lemley et al. (2019c) attributed these factors as likely agents of eutrophication in estuaries and coastal waters of Algoa Bay. Existing technologies promoted under special standards (DWA 2013a) focus mainly on reducing the P component of effluent. Estuaries, however, are more sensitive to N and benefit little from cleaner technologies developed for freshwater aquatic systems.

Although both the ICM Act and National Water Act intend to address diffuse land-based wastewater sources in future (e.g. urban stormwater), the current permitting and licensing processes only deal with point source discharges mainly from municipal WWTW and some industrial plants. Management and control of urban stormwater primarily still resides with local municipalities where the prevention of contamination of stormwater quality is addressed in by-laws.

Recommendations and research requirements (‘future outlook’)

In this study, the DPSIR approach was successfully used to frame the complex environmental issues pertaining to nutrient pollution in estuaries. The integration of ecosystem assessment (from source-to-impact) with management responses provided important insights to inform future restoration planning and research requirements. Nationally, upgraded treatment or recycling of WWTW and industrial inputs is required to improve estuary health. Owing to excessive WWTW effluent volumes, current uniform treatment standards are no longer sufficient to combat eutrophication. The receiving water quality objective approach should be adopted where the volume and constituent composition of wastewater inputs are determined by an estuary’s assimilative capacity and its Resource Quality Objectives (as set by the National Water Act as part of Classification).

Nutrient reduction strategies for WWTWs aimed at combatting eutrophication must consider both N and P. Implementation of a dual-nutrient reduction strategy should occur along the land-ocean aquatic continuum, because shifts in the magnitude and stoichiometric proportions of N and P facilitate shifts in phytoplankton growth and composition (Glibert 2017; Lemley et al. 2019c). With *in situ* nutrient concentrations alone not an obligatory reliable indicator of eutrophication, frameworks and methodologies should adopt a multimetric and adaptive approach that incorporates both pressure and response variables to obtain robust assessments of eutrophic conditions in coastal environments (Lemley et al. 2015).

There is ample evidence that nutrient pollution increases the growth of invasive plants, the spread of reeds and occurrence of HABs. Little, however, is known regarding the effect excessive plant growth has on ecosystem processes at higher trophic levels (e.g. fish nursery function) and therefore the impact on ecosystem services. Consequently, the relationship between different nutrient species and microalgal and macrophyte production should be

Table 8: Key legislative instruments for addressing estuary water quality management in South Africa (adapted from Taljaard et al. 2019)

Act	Supporting instrument
National Environmental Management: Integrated Coastal Management Act (No. 24 of 2008)	National Estuarine Management Protocol (Government Gazette, 10 May 2013) Guidelines for Development and Implementation of Estuarine Management Plans in terms of National Estuarine Management Protocol (March 2015) South African water quality guidelines for coastal marine waters. Volume 2: Recreational use (March 2012) National Guideline for the Discharge of Effluent From Land-based Sources into the Coastal Environment (2014) South African water quality guidelines for coastal marine waters: Natural Environment and Mariculture (1995, under revision) Coastal Waters Discharge Permit Regulations (Government Gazette, 15 March 2019)
National Water Act (No. 36 of 1998)	Revision of general authorisation in terms of section 39 of the National Water Act (Government Gazette, 6 September 2013) (including estuaries)
National Environmental Management Act (No 107 of 1998)	Environmental Impact Assessment Regulations (Government Gazette, 4 December 2014) (e.g. Assessments required for WWTW or industrial plants where effluent > 5 Ml day−1)
Conservation of Agricultural Resources Act (No. 43 of 1983)	Conservation of agricultural resources Regulations (Government Gazette, 25 May 1984, as amended) (potential mechanism to address pollution from agriculture)
Local Government: Municipal Systems Act (Act 32 of 2000)	Potential legislative mechanism to address municipal stormwater pollution (e.g. through by-laws)

investigated so that plant responses to nutrient thresholds can be predicted. Organic loading (e.g. dissolved organic carbon and particulate organic carbon) and its processing within estuaries also needs a better understanding. This will require dedicated research on eutrophic systems to inform decision making, especially because restoration comes at significant infrastructure cost (Van Niekerk et al. 2019b). Currently sampling effort is heavily biased towards measuring physico-chemical parameters (e.g. dissolved oxygen and pH) during the day. However, studies elsewhere has shown that these variables can show marked diurnal fluctuation during periods of eutrophication (e.g. Wallace et al. 2014), also warranting additional investigation.

Research should focus on ways to reduce and improve diffuse wastewater inputs into estuaries. These could include engineering solutions to stormwater management (e.g. Sustainable Urban Drainage requirements, based on biomimicry principles), improved agricultural practices through prudent application of agricultural fertilisers and pesticides and re-establishment of riparian buffer zones. The use of natural infrastructure and artificial wetlands/algal mats for water quality treatment also requires investigation.

This study focused on nutrient pollution using existing data and information that provided sufficient evidence of trajectories and endpoints within the South African context. Comparable sources are, however, not available for toxic pollutants, such as metals, herbicides, pesticides and pharmaceuticals. These contaminants are a particular concern in the light of global climate change, where expected changes in temperature, pH and oxygen could alter their chemical behaviour and remobilisation (e.g. Schiedek et al. 2007). This presents an essential area for future research. The impact of plastics, especially microplastics, on estuarine ecosystems in South Africa is largely unknown. Alarming international discoveries about plastic pollution and its effect on coastal and marine systems warrant urgent local attention, not only in terms of gaining understanding on its ecological footprint in estuaries, but also in exploring innovative interventions and policies to eradicate such pollution.

Research should investigate the role of salt marshes in maintaining water quality and delivering ecosystem services (e.g. water purification). Studies have begun at Swartkops Estuary on heavy metal bioavailability and uptake. The magnitude, frequency and type of HABs are increasing in South Africa and an understanding is needed on their autecology, seasonal dynamics and mechanisms facilitating their persistence. Transdisciplinary approaches to aquatic ecosystem restoration are important, i. e. a socio-ecological systems approach to restoration through action research should be adopted. There are opportunities to implement a circular regenerative economic approach to restoring estuary health with a focus on water quality management. Globally, there is a call to action as the UN has announced a decade of restoration (2021–2030) that includes wetlands. Reducing nutrient inputs as a restoration activity would significantly improve estuary health in South Africa.

Finally, greater effort is necessary to implement ameliorative actions and ensure that compliance monitoring is taking place. Poor legal compliance and lack of enforcement contributes significantly to deteriorating water quality in estuaries. Cooperation and collaboration between government departments and stakeholders through sharing of resources must address this growing pressure that threatens the ecological resilience and health of South Africa's estuaries. Healthy functional estuaries support the commercial, recreational and subsistence activities upon which we depend.

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References

Adams J, Cowie M, Van Niekerk L. 2016. Assessment of completed ecological water requirement studies for South African estuaries and responses to changes in freshwater inflow. Water Research Commission. WRC Report No. KV 352/15. pp 64. Pretoria, South Africa: Water Research Commission.

Adams JB, Bate GC, O'Callaghan M. 1999. Estuarine primary producers. pp 91–118. In: Allanson BR, Baird D (Eds). *Estuaries of South Africa*, Cambridge, United Kingdom: Cambridge University Press.

Adams JB, Pretorius L, Snow GC. 2019. Deterioration in the water quality of an urbanised estuary with recommendations for improvement. *Water SA* 45: 86–96.

Allanson BR, Human LRD, Claassens L. 2016. Observations on the distribution and abundance of a green tide along an intertidal shore, Knysna Estuary. *South African Journal of Botany* 107: 49–54.

Atkins JP, Burdon D, Elliott M, Gregory AJ. 2011. Management of the marine environment: integrating ecosystem services and societal benefits with the DPSIR framework in a systems approach. *Marine Pollution Bulletin* 62: 215–226.

Basti L, Nagai K, Go J, Okano S, Oda T, Tanaka Y, Nagai S. 2016. Lethal effects of ichtyotoxic raphidophytes, *Chattonella marina*, *C. antiqua* and *Heterosigma akashiwo*, on post-embryonic stages of the Japanese pearl oyster, *Pinctada fucata martensi*. *Harmful Algae* 59: 112–122.

Barnes RSK. 2019. Context dependency in the effect of *Ulva*-induced loss of seagrass cover on estuarine microbenthic abundance and biodiversity. *Aquatic Conservation: Marine and Freshwater Ecosystems* 29: 163–174.

Bate GC, Whitfield AK, Adams JB, Huizinga P, Wooldridge TH. 2002. The importance of the river-estuary interface zone in estuaries. *Water SA* 28: 271–279.

Berglund J, Mattila J, Ronnberg O, Heikkila J, Bonsdorff E. 2003. Seasonal and inter-annual variation in occurrence and biomass of rooted macrophytes and drift algae in shallow bays. *Estuarine, Coastal and Shelf Science 56*: 1167–1175.

Boucher C, Jones L. 2007. Chapter 6: Estuarine and floodplain vegetation. In: Clark BM. (Ed.) Berg River Baseline Monitoring Programme Final Report - Volume 3: Berg River Estuary. Anchor Environmental Consultants CC and Freshwater Consulting Group for the Department of Water Affairs. Cape Town, South Africa: Anchor Environmental Consultants.

Bowen RE, Riley C. 2003. Socio-economic indicators and integrated coastal management. *Ocean and Coastal Management* 46: 299–312.

Branco S, Menezes M, Alves-de-Souza C, Domingos P, Schramm MA, Proença LAO. 2014. Recurrent blooms of *Heterosigma akashiwo* (Raphidophyceae) in the Piraquê Channel, Rodrigo de Freitas, southeast Brazil. *Brazilian Journal of Biology* 74: 529–537.

Bricker SB, Longstaff B, Dennison W, Jones A, Boicourt K, Wicks C, Woerner J. 2008. Effects of nutrient enrichment in the nation's estuaries: A decade of change. *Harmful Algae* 8: 21–32.

Canavan K, Paterson ID, Lambertini C, Hill MP. 2018. Expansive reed populations—alien invasion or disturbed wetlands? *AoB Plants* 10: 1–11.

Chamier J, Schachtschneider K, Le Maitre DC, Ashton PJ, Van Wilgen BW. 2012. Impacts of invasive alien plants on water quality, with particular emphasis on South Africa. *Water SA* 38: 345–365.

Clark BM, Van Niekerk L, Turpie J, Taljaard S, Adams JB, Cowie M, Biccard A, Lamberth S. 2015. Determination of the Ecological Reserve for the Klein Estuary. Report prepared for the Breede-Gouritz Catchment Management Agency. pp 197. Cape Town, South Africa: Anchor Environmental Consultants

Cloern JE, Abreu PC, Carstensen J, Chauvaud L, Elmgren R, Grall J, et al. 2016. Human activities and climate variability drive fast-paced change across the world's estuarine–coastal ecosystems. *Global Change Biology* 22: 513–529.

Coetzee JA, Hill MP. 2012. The role of eutrophication in the biological control of water hyacinth, *Eichhornia crassipes*, in South Africa. *BioControl* 57: 247–261.

Coetzee JC, Adams JB, Bate GC. 1997. A botanical importance rating of selected Cape estuaries. *Water SA* 23: 81–93.

Conley DJ, Paerl H, Howarth RW, Boesch DF, Seitzinger S, Havens KE, Lancelot C, Likens GE. 2009. Controlling Eutrophication: Nitrogen and Phosphorus. *Science* 323: 1014–1015.

Costanza R, d'Arge R, De Groot R, Farber S, Grasso M, Hannon B, et al. 1997. The value of the world's ecosystem services and natural capital. *Nature* 387: 253–260.

Dabrowski J, Bruton S, Dent M, Graham M, Hill T, Murray K, Rivers-Moore N, Van Deventer H. 2013. Linking land use to water quality for effective water resource and ecosystem management. WRC Report No. 1984/1/13. Pretoria, South Africa: Water Research Commission.

Dahlgren S, Kautsky L. 2004. Can different vegetative states in shallow coastal bays of the Baltic Sea be linked to internal nutrient levels and external nutrient load? *Hydrobiologia* 514: 249–258.

Davies BR, Stuart V, de Villiers M. 1989. The filtration activity of a serpulid polychaete population [*Ficopomatus enigmaticus* (Fauvel)] and its effects on water quality in a coastal marina. *Estuarine, Coastal and Shelf Science* 29: 613–620.

De Jonge VN, Elliott M. 2001. Eutrophication. (P 852–870). In: Steele J, Thorpe S, Turekian K. (Eds). *Encyclopedia of Marine Sciences*. London, UK: Academic Press.

De Jonge VN, Pinto R, Turner RK. 2012. Integrating ecological, economic and social aspects to generate useful management information under the EU Directives' 'ecosystem approach'. *Oceans and Coastal Management* 68: 169–188.

De Villiers S, Thiart C. 2007. The nutrient status of South African rivers: concentrations, trends and fluxes from the 1970s to 2005. *South African Journal of Science* 103: 343–349.

Department of Environmental Affairs (DEA) 2013a. The National Coastal Management Programme of South Africa. Pretoria, South Africa: Department of Environmental Affairs.

Department of Environmental Affairs (DEA) 2013b. National Estuarine Management Protocol. Government Gazette No. 36432, Notice No. 341. Pretoria, South Africa: Department of Environmental Affairs.

Department of Environmental Affairs (DEA) 2014. National guidelines for the discharge of effluent from land-based sources into the coastal environment. RP101/2014. Pretoria, South Africa: Department of Environmental Affairs.

Department of Environmental Affairs (DEA) 2015. Guidelines for the development and implementation of estuarine management plans in terms of the National Estuarine Management Protocol. Pretoria, South Africa: Department of Environmental Affairs.

Department of Environmental Affairs (DEA). 2019. Coastal Water Discharge Permit Regulations. Government Gazette No. 42304, Notice No. 382. Pretoria, South Africa: Department of Environmental Affairs.

Department of Water Affairs (DWA). 2009. Reserve Determination studies for selected surface water, groundwater, estuaries and wetlands in the Outeniqua (Groot Brak and other water resources, excluding wetlands) catchment: Ecological Water Requirements Study – Estuarine RDM Report: Groot Brak Assessment. Report No. RDM/K10 – K30, K40E/00/CON/0307. Pretoria, South Africa: Department of Water Affairs.

Department of Water Affairs (DWA) 2013a. Revision of general authorisation in terms of Section 39 of the National Water Act (Act No. 36 of 1998). Notice 665 of 2013. Government Gazette No. 36820, 6 September 2013. Pretoria, South Africa: Department of Water Affairs.

Department of Water Affairs (DWA), South Africa. 2013b. Classification of Water Resources and Determination of the Comprehensive Reserve and Resource Quality Objectives in the Mvoti to Mzimkhulu Water Management Area: Desktop Estuary EcoClassification and EWR. Prepared by: CSIR. Pretoria, South Africa: Department of Water Affairs.

Department of Water and Sanitation, South Africa, September 2015. Classification of Water Resources and Determination of the Comprehensive Reserve and Resource Quality Objectives in the Mvoti to Umzimkulu Water Management Area: Volume 4: Estuary Resource Quality Objectives. Prepared by: Van Niekerk, Adams, Taljaard, Weerts DWS. Report: RDM/WMA11/00/CON/CLA/0615. Pretoria, South Africa: Department of Water and Sanitation.

Department of Water and Sanitation (DWS), South Africa. 2017. Determination of Water Resources Classes and Associated Resource Quality Objectives in the Berg Catchment: Status Quo Report. Project Number WP10987. DWS Report No: RDM/WMA9/00/CON/CLA/0516. Pretoria, South Africa: Department of Water and Sanitation.

Department of Water and Sanitation (DWS) 2019. Resource quality information services (www. dwa.gov.za/iwqs/wms/data/000key.asp. [accessed on 23 January 2019]. Pretoria, South Africa: Department of Water and Sanitation.

Elliott M, Burdon D, Atkins JP, Borja A, Cormier R, de Jonge VN, Turner RK. 2017. 'And DPSIR begat DAPSI(W)R(M)! '- A unifying framework for marine environmental management. *Marine Pollution Bulletin* 118: 27–40.

Elliott M, Quintino V. 2007. The Estuarine Quality Paradox, Environmental Homeostasis and the difficulty of detecting anthropogenic stress in naturally stressed areas. *Marine Pollution Bulletin* 54: 640–645.

Fernandes M, Adams J. 2016. Quantifying the loss of and changes in estuary habitats in the uMkhomazi and Mvoti estuaries, South Africa. *South African Journal of Botany*: 107: 179–187.

Ferreira JG, Andersen JH, Borja A, Bricker SB, Camp J, Silva MC, et al. 2011. Overview of eutrophication indicators to assess environmental status within the European Marine Strategy Framework Directive. *Estuarine, Coastal and Shelf Science* 93: 117–131.

Flindt MR, Pardal MÂ, Lillebø AI, Martins I, Marques JC. 1999. Nutrient cycling and plant dynamics in estuaries: A brief review. *Acta Oecologica* 20: 237–248.

Gallardo B, Clavero M, Sánchez MI, Montserrat V. 2016. Global ecological impacts and invasive species in aquatic ecosystems. *Global Change Biology* 22: 151–163.

Gladyshev MI, Gubelit YI. 2019. Green Tides: New consequences of the eutrophication of natural waters. *Contemporary Problems of Ecology* 12: 109–125.

Glennie L. 2001. An environmental history of the Mgeni River Estuary: A study of human and natural impacts over time. MSc thesis. University of Kwazulu-Natal, South Africa.

Glibert PM. 2017. Eutrophication, harmful algae and biodiversity-challenging paradigms in a world of complex nutrient changes. *Marine Pollution Bulletin* 124: 591–606.

Goble BR, Hill TR, Phillips MR. 2017. An assessment of integrated coastal management governance and implementation using the DPSIR framework: KwaZulu-Natal, South Africa. *Coastal Management* 45: 107–124.

Harding WR. 1992. Zeekoevlei-water chemistry and phytoplankton periodicity. *Water SA* 18: 237–246.

Harding WR. 1994. Water, quality trends and the influence of salinity in a highly regulated estuary near Cape Town. South Africa. *South African Journal of Science* 90: 240–246.

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

Heinecken TJE. 1985. Report No. 27: Wildevoelvlei/Noordhoek (CW 28). In: (Heydorn AEF, Grindley JR (Eds). *Estuaries of the Cape: Part II: Synopses of Available Information on Individual Systems*. CSIR Research Report No. 426. pp 1–58. Pretoria, South Africa: CSIR.

Human, LRD, Adams JB. 2011. Reeds as indicators of nutrient enrichment in a small temporarily open/closed South African estuary. *African Journal of Aquatic Science* 36: 167–179.

Human LRD, Snow GC, Adams JB, Bate GC, Yang SC. 2015a. The role of submerged macrophytes and macroalgae in nutrient cycling in the Great Brak Estuary South Africa: A Budget Approach. *Estuarine, Coastal and Shelf Science* 154: 169–178.

Human LRD, Snow GC, Adams JB, Bate GC. 2015b. The benthic regeneration of N and P from the benthos of the Great Brak Estuary. *Water SA* 41: 594–605.

Human LRD, Snow GC, Adams JB. 2016a. Responses in a temporarily open/closed estuary to natural and artificial mouth breaching. *South African Journal of Botany* 107: 39–48.

Human LRD, Adams JB, Allanson BR. 2016b. Insights into the cause of an *Ulva lactuca* Linnaeus bloom in the Knysna Estuary. *South African Journal of Botany* 107: 55–62.

Karez R, Engelbert S, Kraufvelin P, Pedersen M, Sommer U. 2004. Biomass response and changes in composition of ephemeral macroalgal assemblages along an experimental gradient of nutrient enrichment. *Aquatic Botany* 78: 103–117.

Kaselowski T, Adams JB. 2013. Not so pristine - characterizing the physico-chemical conditions of an undescribed temporarily open/closed estuary. *Water SA* 39: 627–635.

Kasulo V. 2000. The impact of invasive species in African lakes. (p 262–297). In: Perrings C (Ed.). *The Economics of Biological Invasions*. Cheltenham, United Kingdom: Edward Elgar Publishing Limited.

Kotsedi D, Adams JB, Snow GC. 2012. The response of microalgal biomass and community composition to environmental factors in the Sundays Estuary. *Water SA 38:* 177–190.

Le Moal M, Gascuel-Odoux C, Ménesguen A, Souchon Y, Étrillard C, Levain A, Moatar F, Pannard A, Souchu P, Lefebvre A, Pinay G. 2019. Eutrophication: A new wine in an old bottle? *The Science of the Total Environment* 651: 1–11.

Legualt RII, Zogg GP, Travis SE. 2018. Competitive interactions between native *Spartina alterniflora* and non-native *Phragmites australis* depend on nutrient loading and temperature. *PLoS One* 13(2): e0192234.

Lemley DA, Taljaard S, Adams JB, Strydom N. 2014. Nutrient characterisation of river inflow into the estuaries of the Gouritz Water Management Area, South Africa. *Water SA* 40: 687–698.

Lemley DA, Adams JB, Taljaard, S. Strydom N. 2015. Towards the classification of eutrophic conditions in estuaries. *Estuarine Coastal Shelf Science* 164: 221–232.

Lemley D, Adams JB, Bate GC. 2016. Microalgae as indicators in South African estuaries. *South African Journal of Botany* 107: 12–20.

Lemley DA, Adams JB, Taljaard S. 2017. Comparative assessment of two agriculturally influenced estuaries: Similar pressure, different response. *Marine Pollution Bulletin* 117: 136–147.

Lemley DA, Adams JB, Rishworth GM. 2018a. Unwinding a tangled web: a fine-scale approach towards understanding the drivers of harmful algal bloom species in a eutrophic South African estuary. *Estuaries and Coasts* 41: 1356–1369.

Lemley DA, Adams JB, Strydom NA. 2018b. Triggers of phytoplankton bloom dynamics in permanently eutrophic waters of a South African estuary. *African Journal of Aquatic Science* 43: 229–240.

Lemley DA, Nunes M, Adams JB. 2018c. Estuarine algal responses to increasing nitrate concentrations during closed mouth conditions of oligotrophic systems: A laboratory microcosm experiment. *Botanica Marina,* 61: 559–572.

Lemley DA, Adams JB. 2019a. Eutrophication. In: Faith B (Ed.) *Encyclopedia of Ecology*, Second edition. Oxford, UK: Elsevier Science and Technology.

Lemley DA, Adams JB, Rishworth GM, Bouland C. 2019b. Phytoplankton responses to adaptive management interventions in eutrophic urban estuaries. *Science of the Total Environment* 693: 133601. 10.1016/j.scitotenv.2019.133601.

Lemley DA, Adams JB, Bornman TG, Campbell EE, Deyzel SHP. 2019c. Land-derived inorganic nutrient loading to the coastal waters of a warm temperate embayment: Potential implications for nearshore plankton dynamics. *Continental Shelf Research* 174: 1–11.

Maier G, Nimmo-Smith RJ, Glegg GA, Tappin AD, Worsfold PJ. 2009. Estuarine eutrophication in the UK: current incidence and future trends. *Aquatic Conservation* 19: 43–56.

Massie V, Clark BM. 2016. Onrus Estuarine Management Plan, Situation Assessment Report. Report prepared for the Overstrand Municipality and the Lagoon Preservation Trust by Anchor Environmental Consultants (Pty) Ltd. 107 pp. Cape Town, South Africa: Anchor Environmental Consultants.

Nathaniel W. May, Olson NE, Panas MG, Axson JL, Tirella PS, Kirpes RM, Craig RL, Gunsch MJ, China S, et al. 2017. Aerosol emissions from Great Lakes harmful algal blooms. *Environmental Science & Technology* 52: 397–405.

Nguyen THT, Boets P, Lock K, Ambarita MND, Forio MAE, Sasha P, et al. 2015. Habitat suitability of the invasive water hyacinth and its relation to water quality and macroinvertebrate diversity in a tropical reservoir. *Limnologica* 52: 67–74.

Ntombela C, Funke N, Meissner R, Steyn M, Masangane W. 2016. A critical look at South Africa's Green Drop Programme. Water SA 42: 703–709.

Nunes M, Adams JB. 2014. Responses of primary producers to mouth closure in the temporarily open/closed Great Brak Estuary in the warm temperate region of South Africa *African Journal of Aquatic Science* 39: 387–394.

Nunes M, Adams JB, Rishworth GM. 2018. Shifts in phytoplankton community structure in response to hydrological changes in the shallow St Lucia Estuary. *Marine Pollution Bulletin* 128: 275–286.

Nunes M, Adams JB, Bate, GC. 2019. The use of epilithic diatoms grown on artificial substrata to indicate water quality changes in the lower reaches of the St Lucia Estuary, South Africa. *Water SA* 45: 149–159.

O'Brien, G, Swemmer R, Wepener V. 2009. Ecological integrity assessment of the fish assemblages of the Matigulu/Nyoni and Umvoti estuaries, KwaZulu-Natal, South Africa. *African Journal of Aquatic Science* 34: 293–302.

OECD. 1993. Core set of indictors for environmental performance reviews. A synthesis report by the Group on the State of the Environment. Environment Monographs No. 83. Paris, France: Organisation for Economic Co-operation and Development.

OSPAR. 2003. Strategies of the OSPAR commission for the protection of the marine environment of the north-east Atlantic (reference number: 2003e21). In: OSPAR Convention for the Protection of the Marine Environment of the Northeast Atlantic: Ministerial Meeting of the OSPAR Commission, Bremen, 25 June 2003, Vol. Annex 31 (Ref. B-4.2). London, United Kingdom: OSPAR Commission.

Patricio J, Elliott M, Mazik K, Papadopoulou K-N, Smith CJ. 2016. DPSIR- two decades of trying to develop a unifying framework for marine environmental management? *Frontiers in Marine Science* 3: 1–14.

Paerl HW, Hall NS, Peierls BL, Rossignol KL. 2014. Evolving paradigms and challenges in estuarine and coastal eutrophication Dynamics in a Culturally and Climatically Stressed World. *Estuaries and Coasts* 37: 243–258.

Pearce MW, Schumann EH. 2001. The impact of irrigation return flow on aspects of the water quality of the upper Gamtoos Estuary, South Africa. *Water SA* 27: 367–372.

Pillay S. 2004. Corruption – the challenge to good governance: a South African perspective. *International Journal of Public Sector Management* 17: 586–605.

Pillay RK. 2013. An integrated study of the Isipingo River and Estuary: Water and sediment quality, estuary-nearshore material fluxes, anthropogenic impacts and management. MSc thesis. University of KwaZulu-Natal, South Africa. pp 226.

Pretorius L. 2015. Spatial and temporal variability in water quality characteristics of the Swartkops Estuary. MSc thesis. Nelson Mandela Metropolitan University, South Africa.

Quick AJR, Harding WR. 1994. Management of a shallow estuarine lake for recreation and a fish nursery: Zandvlei, Cape Town, South Africa. *Water SA* 20: 289–297.

Russell IA. 2003. Changes in the distribution of emergent aquatic plants in a brackish South African estuarine-lake system. *African Journal of Aquatic Science* 28: 103–122.

Russell IA, Kraaij T. 2008. Effects of cutting *Phragmites australis* along an inundation gradient, with implications for managing reed encroachment in a South African estuarine lake system. *Wetlands Ecology and Management* 16: 383–393.

Scanlan CM, Foden J, Wells E, Best MA. 2007. The monitoring of opportunistic macroalgal blooms for the water framework directive. *Marine Pollution Bulletin* 55: 162–171.

Schiedek D, Sundelin B, Readman JW, Macdonald RW. 2007. Interactions between climate change and contaminants. *Marine Pollution Bulletin* 54: 1845–1856.

Sfriso A, Pavoni B, Marcomini A, Orio AA. 1992. Macroalgae, Nutrient Cycles, and Pollutants in the Lagoon of Venice. *Estuaries and Coasts* 15: 517–528.

Smith VH, Schindler DW. 2009. Eutrophication science: where do we go from here? *Trends in Ecology and Evolution* 24: 201–207.

Smith VH, Wood SA, McBride CG, Atalah JH, Hamilton D, Jonathan M. 2016. Phosphorus and nitrogen loading restraints are essential for successful eutrophication control of Lake Rotorua, New Zealand. *Inland Waters* 6: 273–283.

Snow GC, Adams JB, Bate GC. 2000. Effect of river flow on estuarine microalgal biomass and distribution. *Estuarine, Coastal and Shelf Science* 51: 255–266.

Snow GC, Taljaard S. 2007. Water quality in South African temporarily open/closed estuaries: A conceptual model. *African Journal of Aquatic Science* 32: 99–111.

South African National Biodiversity Institute (SANBI) 2014. Updating national land cover. Pretoria: South African National Biodiversity Institute. http://bgis. sanbi. org/DEA_Landcover/project.asp. [Accessed 23 May 2019].

Sowman M, Malan N. 2018. Review of progress with integrated coastal management in South Africa since the advent of democracy. *African Journal of Marine Science* 40: 121–136.

Sundström A. 2013. Corruption in the commons: why bribery hampers enforcement of environmental regulations in South African fisheries. *International Journal of the Commons* 7: 454–472.

Taljaard S, Van Niekerk L, Joubert W. 2009a. Extension of a qualitative model on nutrient cycling and transformation to include microtidal estuaries on wave-dominated coasts: Southern hemisphere perspective. *Estuarine, Coastal and Shelf Science* 85: 407–421.

Taljaard S, Snow GC, Gama P, Van Niekerk L. 2009b. Verification of a conceptual model of water quality for small temporarily open/closed estuaries: East Kleinemonde Estuary, South Africa. *Marine and Freshwater Research* 60: 234–245.

Taljaard S, Slinger JH, Van Niekerk L. 2017. A screening model for assessing water quality in small, dynamic estuaries. *Ocean & Coastal Management* 146: 1–14.

Taljaard S, Van Niekerk L, Lemley DA. 2018. A glimpse into the littoral nutrient dynamics of a lake system connected to the sea. *Water SA* 44: 65–74.

Taljaard S, Van Niekerk L, Weerts SP. 2019. The legal landscape governing South Africa's coastal marine environment - helping with the 'horrendogram'. *Ocean & Coastal Management* 178, 1 August 2019, 104801.

Thomas C. Perissinotto R, Kibirige I. 2005. Phytoplankton biomass and size structure in two South African eutrophic, temporarily open/closed estuaries. *Estuarine, Coastal and Shelf Science* 65: 223–238.

Trancoso R, Saraiva S, Fernandes L, Pina P, Leitão P, Neves R. 2005. Modelling macroalgae using a 3D Hydrodynamic-Ecological model in a shallow, temperate estuary. *Ecological Modelling* 187: 232–246.

Turpie JK, Adams JB, Joubert A, Harrison TD, Colloty BM, Maree RC, et al. 2002. Assessment of the conservation priority status of South African estuaries for use in management and water allocation. *Water SA* 28: 191–206.

Turpie JK, Joubert AR. 2005. The recreational use value of the Knysna Estuary and implications of future development. In: Turpie JK, Hosking SG (Eds). Proceedings of a national workshop on Resource Economics as a tool for the management and conservation of estuaries in South Africa. Rivierra Hotel, Veldrif, 10-11 March 2005. Cape Town, South Africa: Anchor Environmental Consultants.

Turpie JK, Taljaard S, Van Niekerk L, Adams J, Wooldridge T, Cyrus D, Clark B, Forbes N. 2012. The Estuary Health Index: a standardised metric for use in estuary management and the determination of ecological water requirements. WRC Report No. 1930/1/12. Pretoria, South Africa: Water Research Commission.

UNEP/Nairobi Convention Secretariat. 2009. Transboundary Diagnostic Analysis of Land-based Sources and Activities affecting the Western Indian Ocean Coastal and Marine Environment. Nairobi, Kenya: UNEP Nairobi.

Van Niekerk L, Adams JB, Bate GC, Forbes N, Forbes A, Huizinga P, Lamberth SJ, MacKay F, Petersen C, Taljaard S, Weerts S, Whitfield AK, Woolridge TH. 2013. Country-wide assessment of estuary health: An approach for integrating pressures and ecosystem response in a data limited environment. *Estuarine, Coastal and Shelf Science* 130: 239–251.

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

Van Niekerk L, Taljaard S, Ramjukadh C-L, Adams, JB, Lamberth SJ, Weerts S, et al. 2018. A multi-sectoral resource planning platform for South Africa's estuaries. Water Research Commission Report No. TT 748/18. Pretoria, South Africa: Water Research Commission.

Van Niekerk L, Adams JB, Lamberth SJ, MacKay F, Taljaard S, Turpie JK, Weerts S. 2019a. South African National Biodiversity Assessment 2019a: Technical Report. Volume 3: Estuarine Environment. Report Number: SANBI/NAT/NBA2018/2019/Vol3/A. Pretoria, South Africa: South African National Biodiversity Institute.

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

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

Van Niekerk, L, Adams JB, James, N, Lamberth S, Mackay F, Rajkaran A, Turpie J, Weerts S, Whitfield AK. 2020 An Estuary Ecosystem Classification that encompasses biogeography and a high diversity of types in support of protection and management. *African Journal of Aquatic Science* 45(1): This special issue.

Villamagna AM, Murphy BR. 2010. Ecological and socio-economic impacts of invasive water hyacinth (*Eichhornia crassipes*): a review. *Freshwater Biology* 55: 282–298.

Wallace RB, Baumann H, Grear JS, Aller RC, Gobler CJ. 2014. Coastal ocean acidification: The other eutrophication problem. *Estuarine Coastal and Shelf Science* 148: 1–13.

Wasson K, Jeppesen R, Endris C, Perry DC, Woolfolk A, Beheshti K, et al. 2017. Eutrophication decreases salt marsh resilience through proliferation of algal mats. *Biological Conservation* 212: 1–11.

Warwick RM, Tweedley JR, Potter IC. 2018. Microtidal estuaries warrant special management measures that recognise their critical vulnerability to pollution and climate change. *Marine Pollution Bulletin* 135: 41–46.

Weisser PJ, Parsons RJ. 1981. Monitoring *Phragmites australis* increases from 1937 to 1976 in the Siyai Lagoon (Natal, South Africa) by means of air photo interpretation. *Bothalia* 13: 553–556.

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

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