Approaches to detecting and assessing patterns, processes and responses to change in South African estuaries

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In accordance with Rule G4.6.3, I hereby declare that the above-mentioned thesis is my own work and that it has not previously been submitted for assessment to another University or for another qualification.

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SUMMARY

The objective of this thesis was to develop and apply approaches for detecting patterns, processes and responses to change in South African estuaries to key Global Change pressures. This required the development, and application, of a change detection method in complex estuarine ecosystems with a focus on integrating multiple-scale hydrological and ecosystem processes. The method enables the coupling between freshwater inflow and the downstream chemical and biological ecosystem processes following ecohydrology and ecosystem-based approaches. A unique feature of the method is the identification of physical states and the evaluation of their distribution and associated biotic responses. This couples inflow and ecosystem processes in a predictive manner using concepts such as zoning and physical states.

The above approach was then scaled-up to a country-wide assessment of the health of the nearly 300 South African estuaries. The assessment examined both key pressures (freshwater inflow modification, pollution, habitat modification, exploitation of living resources, artificial breaching) and health state. The approach allowed for the assessment of the pressures and the ecological health status of a large number of estuaries in a data limited environment. The results showed that estuaries in the Warm Temperate region are healthier than those in the Cool Temperate and Subtropical regions, largely reflecting the country's demographics and developmental pressures. While a large number of estuaries are still in an excellent to good condition, they tend to represent very small systems in rural areas with few pressures. Larger systems, which are of higher economic and ecological importance, are in a fair to poor condition.

A scenario-based regional-scale estuarine resource allocation process was designed, and applied, to assess potential changes to key drivers, namely freshwater flow and water quality. The approach dictates a progression of steps that share commonalities with international best practise, but are unique in the way they have been aligned in this application. The case study included 64 estuaries for which estuarine health, importance and resilience to anthropogenic pressures were evaluated against future dam development and wastewater discharge scenarios as a means of optimising

freshwater allocations. Each estuary was screened to assess its expected condition under the various scenarios. The approach highlighted that the small estuaries had very little resilience to changes in freshwater quantity and quality, particularly where there were discharges from wastewater treatment works. In contrast, larger systems – generally targeted for dam development - only showed sensitivity during low-flow periods when flow reduction caused mouth closure and increased sensitivity to nutrient cycling.

The final challenge was to review and synthesise how vulnerable South African estuaries are to Climate Change. The regional-scale assessment was based on the physical characteristics of South African estuaries and predicted/measured change in the drivers of estuary health. Key stressors evaluated were change in: climatic and hydrological processes; ocean circulation; increase in sea storms; sea level rise; and ocean acidification. Abiotic responses included changes in salinity regimes; mouth closure; biochemical inputs (e.g. nutrients); sediment dynamics and the behaviour of contaminants. The analysis showed that change in ocean circulation processes seem to be driving shifts in the coastal temperature regimes of the transitional zones, with related biological responses, e.g. range extensions/contractions. However, the largest structural and functional changes are expected along the Cool Temperate and Subtropical regions, with shifts in mouth closure and salinity regimes, which in turn will affect critical estuary ecosystem services such as nursery function.

The study showed that although data may be a limiting factor in the assessment of change in the processes and patterns of South African estuaries; sufficient information is available to accurately determine their responses and future trajectories to Global Change pressures. The methods developed, and applied here, are robust enough to accommodate both data rich and data poor parameters/estuaries and use a range of statistical or numerical methods.

ACKNOWLEDGEMENTS

First and foremost my sincere gratitude to my colleagues Piet Huizinga and Susan Taljaard who contributed significantly to my love and knowledge of estuaries over the years. Gratitude is also owed to Pat Morant for his fine editing skills and insights into estuarine management in South Africa. Carla- Louise Ramjukadh is thanked for her assistance with maps. While Steve Lamberth is appreciated for his input on structure and teaching me how a fish sees an estuary.

The approaches promoted in this thesis is the culmination of months of deliberation and debating and years of application. This would not have been possible without a range of collaborators across a spectrum of abiotic and biotic research interests that has strengthened my understanding of how estuaries work on an ecosystem level.

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To Janine that believed in my work and used every opportunity to show case it. From the bottom of my heart I thank you for the mix of patience and pressure that gave birth to this painful thesis.

DEDICATION

To the chaotic factors in my life – the love of my life, my son and my family (especially my parents) – may you subject me to change every day…

PUBLICATIONS

The following scientific articles originated from this thesis:

Van Niekerk L, Adams JB, Bate GC, Forbes AT, Forbes NT, Huizinga P, Lamberth SJ, MacKay CF, Petersen C, Taljaard S, Weerts SP, Whitfield AK and Wooldridge 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.

Inputs were made to the follow publications and details from these studies informed my thesis:

James NC, Van Niekerk L, Whitfield AK, Potts WM, Götz A, Paterson AW. (2013). Effects of Climate Change on South African estuaries and associated fish species. *Climate Research* 57: 233–248.

Department of Environmental Affairs. (2013). Long-Term Adaptation Scenarios Flagship Research Programme (LTAS) for South Africa. Climate Change Implications for Marine Fisheries in South Africa. Pretoria, South Africa.

Data and details relating to specific estuaries were collated in the following product that can be viewed specifically for geographic details of estuaries referred to in this thesis:

South African Estuary Spatial Planning Platform:

https://csir.maps.arcgis.com/apps/MapSeries/index.html?appid=a58ab2075a954549b9b1f8b5e063380e

Van Niekerk L, Taljaard S, Ramjukadh C-L Adams JB, Lamberth SJ, Weerts SP, Petersen C, Audouin M, Maherry A. 2017. A multi-sector Resource Planning Platform for South Africa's estuaries. Water Research Commission Report No K5/2464. South Africa.

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ACRONYMS

AR5	Assessment Report Five
CORDEX	Coordinated Regional Downscaling Experiment
CWAC	Co-ordinated Waterbird Counts
DEA	Department of Environmental Affairs
DWS	Department of Water and Sanitation
EFR	Ecological Flow Requirement
EHI	Estuarine Health Index
GHG	Green House Gasses
IPCC	Intergovernmental Panel on Climate Change
IWRM	Integrated Water Resource Management
MPA	Marine Protected Area
NWA	National Water Act (No. 36 of 1998)
PES	Present Ecological State
REC	Recommended Ecological Category
RQO	Resource Quality Objectives
SANBI	South African National Biodiversity Institute
TEC	Target Ecological Category
TOCEs	Temporarily open/closed estuaries
WMA	Water Management Area
WSAM	Water Situation Assessment Model
WWTW	Wastewater treatment works

CHAPTER 1

INTRODUCTION

1.1 ESTUARINE HEALTH AS A MEASURE OF CHANGE

South African estuaries differ considerably in terms of their physicochemical and biotic characteristics (Colloty et al., 2002; Vorwerk et al., 2008). Despite their differences, proactive planning and effective management of estuaries requires an understanding of changing estuarine patterns, processes and responses to global change pressures (i.e. anthropogenic and Climate Change). As human population pressures escalate, the need for country-wide strategic management becomes increasingly evident (Boehm et al., 2017; Borja et al., 2017). Reactively protecting these ecosystems on an estuary-by-estuary basis is costly, time consuming and not feasible. Proactive management requires a strategic assessment of change at a range of scales to ensure optimum resource use (e.g. freshwater extraction, exploitation of living resources). This thesis investigated the detection of change in South African estuaries at different temporal and spatial scales using estuarine health as a measure.

Sherman (2000) describes ecosystem health on the basis of diversity, productivity, biomass yield, resilience and stability. Costanza (1992) and Costanza and Mageau (1999) define health based on ecosystem organisation (structure), vigour (productivity) and resilience to stress. Cairns and Niederlehner (1992) emphasise that system scale assessments of health need to include the maintenance of heterogeneity, the spatial and temporal interactions across heterogeneous landscapes, and the influences of heterogeneity on biotic and abiotic processes. While more recently Borja et al. (2013, 2017), Strong et al. (2015), O'Brien et al. (2016), and Clare et al. (2016) call for increasing scientific knowledge on ecosystem abiotic and biotic interactions and functioning in order to improve assessments of estuarine health. In the context of this thesis, estuarine health was defined as the maintenance of ecosystem structure and function, including natural variability and resilience, on a landscape scale. An advantage of focusing on health-related terms is that they provide a focus for maintaining (or restoring) the beneficial uses of estuarine ecosystems (Jordan and Smith, 2005). The term 'health' also attracts public attention and elicits little disagreement (value conflict) about whether environmental health or ecosystem health is an essential consideration. In this thesis pattern and process changes are evaluated in the context of change in health across the various types of estuaries.

Assessing the status of estuarine ecosystems also means assessing anthropogenic pressures against a background of inherent variability and natural change (Gray and Elliott, 2009; Elliott, 2011). Society and environmental managers need to know not only the current status of an estuary, but also the degree to which it has been altered, the cause of that alteration, its significance, and what can be done to reverse that change (Borja et al., 2017). In addition this requires an understanding of estuarine health, connectivity and coastal interaction on a regional scale, to ensure resilience to natural and anthropogenic resetting events and ensure recruitment processes. This requires an understanding of how pressures (including the assessment of cumulative pressures) result in a change in the natural system and the implications for resource use (Korpinen and Andersen, 2016). Pressures may be termed “endogenic” if causes and consequences occur within a managed region and “exogenic” if emanating from outside a managed system (Elliott, 2011; Elliott et al., 2014). For example, global Climate Change represents a major exogenic challenge as environmental managers cannot control the causes but must respond to the consequences. Climate Change adds to internal pressures in an area and can shift baselines, complicating the evaluation of change associated with internal activities in a region (Elliott et al., 2015). Thus, mechanisms for determining change should also be able to forecast change within the context of present responses to anthropogenic pressures.

Since the 1970s concern has been raised about the health of South African estuaries (Heydorn, 1972, 1973; Begg, 1978; Morant and Quinn, 1999). Particularly in KwaZulu-Natal where ongoing siltation due to intensive sugarcane cultivation in highly erodible catchments and flow reduction were affecting a high number of systems. Heydorn and Tinley (1980) reviewed the condition of the estuaries of the former Cape Province (i.e. focused on the Cool and Warm Temperate regions (Figure 1.1)), followed by a national health assessment of all South African estuaries in response to concerns over freshwater supplies to estuaries (Heydorn, 1986; Morant and Quinn, 1999). Ramm (1988, 1990) evaluated KwaZulu-Natal estuaries (± 70 subtropical estuaries) using fish as an index of community degradation and also concluded that that KwaZulu-Natal estuaries were highly degraded. None of the earlier assessments included the near pristine estuaries of the rural areas of the former Ciskei and Transkei coasts, which comprises the transition zone between the Warm Temperate and Subtropical estuaries. Using measured data but only a limited choice of parameters, Harrison et al. (2000) assessed the health of all South African estuaries in terms of ichthyofaunal diversity, water quality and aesthetics, while Coetzee et al. (1997) and Colloty (2000) have classified selected estuaries in terms of their botanical integrity.

Whitfield (2000) conducted a country-wide estuarine health assessment, classifying estuaries as: excellent (estuary in near pristine condition with negligible human impact), good (no major negative anthropogenic influences on either the estuary or catchment), fair (noticeable degree of ecological degradation in the catchment and/or estuary), and poor (major ecological degradation arising from a combination of anthropogenic influences). Whitfield (2000) reported that 62% of estuaries were in good or excellent condition. This apparently high proportion of estuaries in good condition was mainly due to the inclusion of the Transkei region, where a large proportion of estuaries are in good/excellent condition. Whitfield found about 26% of KwaZulu-Natal estuaries are in good condition, similar to Heydorn's (1986) assessment.

Turpie (2004) reviewed the Whitfield (2000) assessment and reported that the overall health of South African estuaries was relatively good. A total of 28% of estuaries, were considered to be in excellent condition, and another 31% in good condition. About 25% were deemed to be in a fair condition, and 15% in poor condition. The overall picture was largely a reflection of the state of the 194 temporarily open/closed estuaries as this group contained the most estuaries in an excellent state (31%), and poor state (19%). None of the estuarine bays or lakes remained in an excellent state. The Turpie (2004) catchment level analysis showed that estuaries fed by larger catchments tend to be in poorer health than the estuaries in adjacent smaller catchments, especially along the eastern half of the country (Figure 1.2). Turpie (2004) concluded that the larger estuaries attract more coastal development, and the catchments are more pressured in terms of water abstraction.

Discrepancies in the results of these studies show how change detection depends strongly on input data and assessment parameters, with wide discrepancies reported if a limited set of indicators (e.g. fish or vegetation) were used to evaluate health.

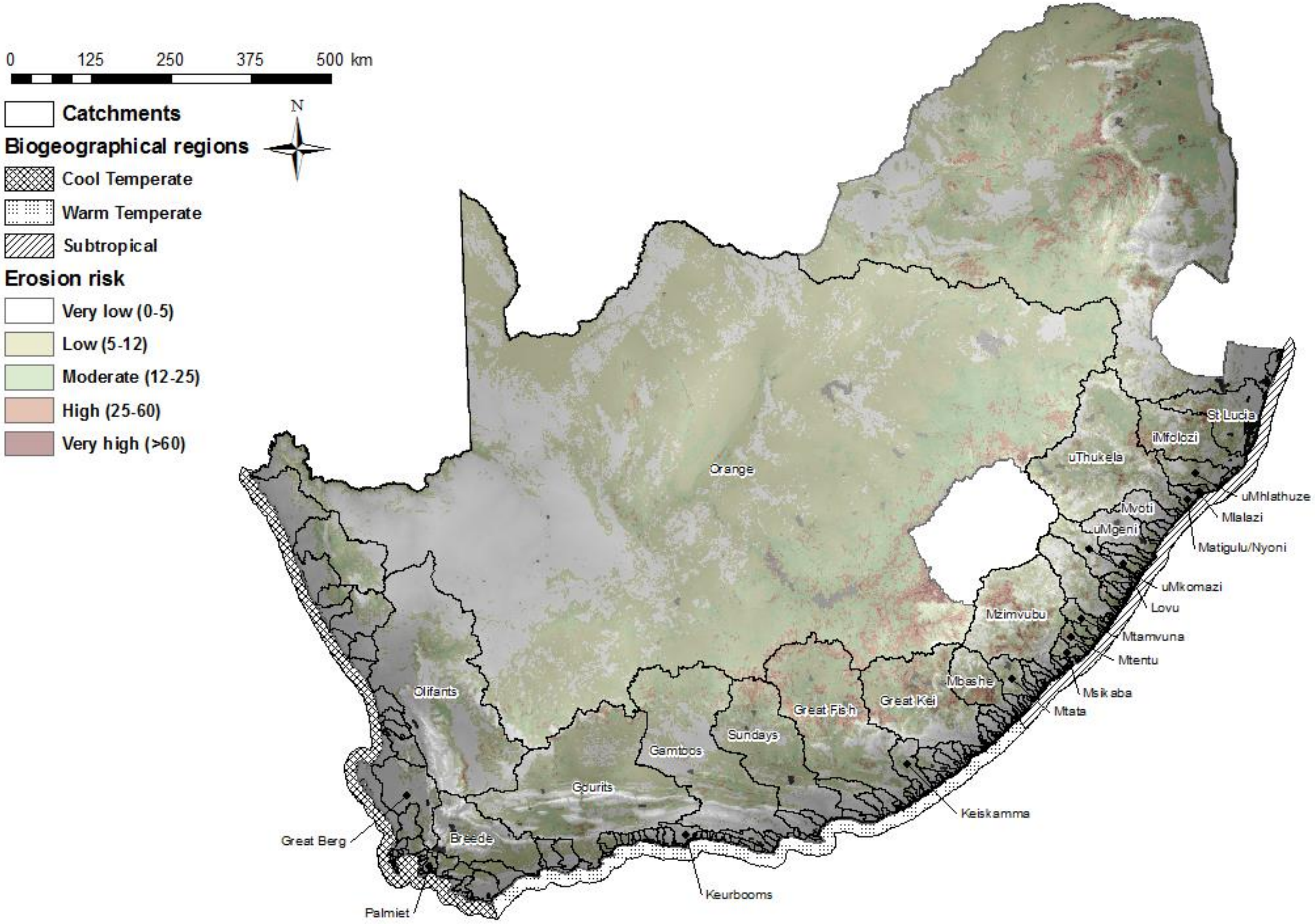


Figure 1.1: Map showing the soil erosion-risk, relative catchment size, and the 30 catchments with the highest runoff in South Africa (Van Niekerk et al. (2015) based on Le Roux et al. (2008)).

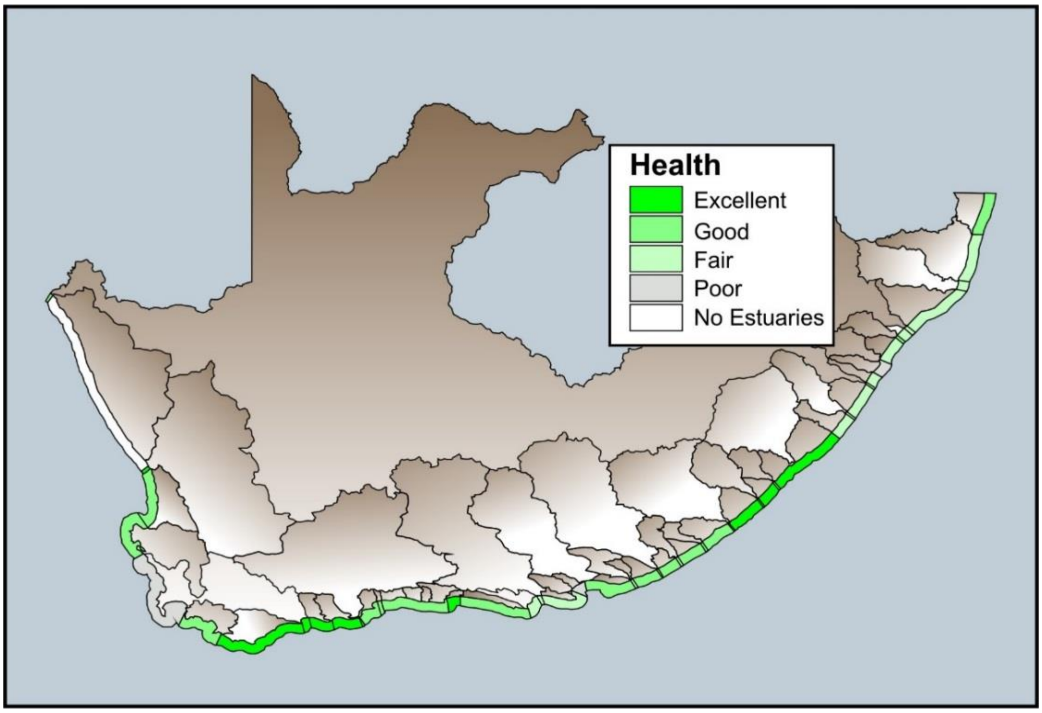


Figure 1.2: Average state of health of estuaries per quaternary catchment (Source: Turpie, 2004).

Ratings were generally done by a single/small number of individual(s), which can result in regional bias or were done using a limited number of parameters. While catchment condition was an important factor in the Heydorn (1986) and Whitfield (2000) assessments, little true quantification was done on the degree to which catchments were transformed and how this changed freshwater inflows, water quality and sediment processes. Harrison et al. (2000) provided information on the extent and type of land cover transformation and tried to couple this to measured *in situ* data, but the study examined only 62 catchments (large catchments of >500 km^2) in South Africa.

One of the objectives of this thesis is thus to address the above inadequacies through the development and application of systematic change detection methods, i.e. change in estuarine health state, on a regional and country-wide scale. The approaches will incorporate standardised models, model outputs (e.g. catchment hydrology) and/or expert opinion from a wide range of sources to remove regional biases and scale results, with a focus on change detection in the abiotic processes (e.g. change in hydrology, hydrodynamics, water quality and sediment processes) as key drivers of all estuarine responses.

1.2 WHAT CONSTITUTES AN ESTUARY IN SOUTH AFRICA?

While the classical definition of an estuary is a "semi-enclosed coastal body of water which has a free connection with the open sea and within which sea water is measurably diluted with freshwater derived from land" (Cameron & Pritchard, 1963; Pritchard, 1967; Elliott and McLusky, 2002), definitions for South African estuaries recognise that local estuaries may not necessarily have a 'free connection with the sea' but are 'either permanently or periodically open to the sea' (Day, 1980; CSIR,1992; Whitfield and Elliott, 2011). Whilst Fairbridge (1980) proposed setting the tidal limit as the upstream extent of an estuary, there are examples in South Africa, e.g. the Bot and Klein estuarine lakes, where salinity penetration can be detected further upstream than the tidal action (unpublished data). In this type of system, tidal variation can be barely discernible (< 5 cm) and easily masked by wind action, while more subtle hydrodynamic processes, such as diffusion drive salinity penetration further upstream. In such cases, the inland limit of salinity penetration represents the upstream boundary. Back-flooding under closed mouth conditions also increases upstream penetration of salinity beyond that of the open (tidal) state (Van Niekerk and Turpie, 2012).

In this thesis I define an estuary as: ''a partially enclosed permanent water body, either continuously or periodically open to the sea on decadal time scales, extending as far as the upper limit of tidal action, back-flooding or salinity penetration'. During floods an estuary can become a river mouth with no seawater entering the formerly estuarine area, and when there is little or no fluvial input, an estuary can be isolated from the sea by a sandbar and become a lagoon or lake which may become fresh or hypersaline" (modified from CSIR, 1992).

Natural resources are features or phenomena of natural systems that exist independently of humankind. They include the atmosphere, water, land and a naturally associated plant and animal life (Statistics South Africa, 2017). Natural resources may be further classified on their basis of origin into two types: biotic resources which are obtained from the biosphere (living and organic material), such as plants and animals; and abiotic resources that originate from non-living, non-organic material including fresh water, air, sand and minerals. Resource allocation is therefore the assignment of available resources to various uses, for example, the allocation of fresh water resources (non-living) or the allocation of fishing rights or permits (living resources). Resource allocation and use, in turn, act as pressures on estuary health often reducing future availability of estuary resources. “Estuarine resources” in this thesis, refer to the collective of living and non-living resources. However, I place an emphasis on freshwater allocation as freshwater inflow forms the basis of estuarine productivity and health, i.e. influences the potential production of living resources such as invertebrates and fish and the benefits society derive from estuaries.

1.3 STUDY APPROACH AND KEY RESEARCH QUESTIONS

South Africa has a wide diversity of estuary types, driven by a range of climatic and oceanic conditions that provide for different ecosystem responses to key anthropogenic pressures such as freshwater inflow modification, pollution, habitat modification, exploitation of living resources and artificial breaching of temporarily open/closed systems (Van Niekerk and Turpie, 2012). Planning requires an understanding of how estuaries may respond to change over a range of temporal scales, i.e. both escalating current pressures and the effects of Climate Change over the coming decades.

However, a significant constraint to change detection in estuaries is the lack of long-term measured data on South African estuaries. An analysis of available data showed that:

- < 15% have continuous water level recoding data (http://www.dwa.gov.za/ Hydrology/);
- < 10% of coastal catchments are well gauged for freshwater inflow but with a bias towards large river systems, i.e. little to no information on small catchments (http://www.dwa.gov.za/Hydrology/);
- water quality monitoring stations in inflowing rivers and long-term data on estuaries are scarce;
- there is a lack of information on the bathymetry (estuary size and shape); and
- there is a lack of reliable national-scale long-term biological data sets (e.g. national bird counts date from the 1980s, e.g. Underhill and Cooper 1984) and national fish surveys date from the 1990s (e.g. Council for Scientific and Industrial Research (CSIR), unpublished data; Harrison, 2000, 2005).

Thus, any national or regional-scale assessments needs to be robust enough to accommodate the lack of information on a large number of estuaries, while remaining scientifically rigorous.

The research reported in this thesis is embedded in the existing South African situation, in that it draws from local methods and approaches as far as possible; it is constrained by a lack of long-term environmental data and can therefore not address change dynamics in detail for individual estuaries. Rather this study strives to understand regional-scale responses and trajectories; it endeavours to address South African legislative and policy needs as stipulated in the National Water Act (Act No. 36 of 1998), National Environmental Management: Biodiversity Act (No. 10 of 2004), Marine Living Resources Act (Act No. 18 of 1998) and National Environmental Management: Integrated Coastal Management Act (Act No. 24 of 2008). Policy needs are further articulated in oversight committees such as the National Estuary Management Task Group of Mintech Working Group 8 (deals with the Implementation of the National Estuarine Management Protocol) and Western Cape Estuaries Task Team (chaired by the Western Cape Government and CapeNature).

This research is based on my knowledge, experience and insight gained through 20 years of collaborative research on estuarine flow requirement (ecological water requirements) studies on more than 50 estuaries, development of mouth management plans and the development of Estuary Management Plans. In addition I serve on the National Estuary Management Task Group and the Western Cape Estuaries Task Team; and led the 2011 National Biodiversity Assessment: Estuaries Component (Van Niekerk and Turpie, 2012). My contribution has been the development of an understanding of how physical processes in estuaries respond to global change pressures, how to translate that understanding into measures that can guide evaluation of biotic responses, and how to integrate these into a holistic outcome reflecting the range of pattern and process responses in estuaries to this ever-increasing change. My original research presented in this thesis focuses on an understanding of the changes in abiotic processes. The detailed biotic information represents collaborative input from other estuarine ecologists that I have interpreted and incorporated in the various approaches, and included here to show the range of responses to the predicted abiotic change. The collective abiotic and biotic outputs, in turn, was analysed by me to provide a holistic overview of changing patterns, processes and responses under ever-increasing pressures with the intent of guiding future resource allocation and use.

The research has incorporated elements of design science in that it follows a practical learning-by-doing approach for solving real-world problems. Methods/approaches were developed, adopted from international best practise, and/or refined as required (Bots, 2007). These in turn, were applied in case studies and evaluated, in terms of both outcomes and possible future refinements. Where detailed datasets were lacking, proxy data sets were found or derived. This approach allows for incremental learning and acknowledges that the availability of detailed data sets (e.g. dynamic models or measured data) would increase the confidence levels of the outcomes. It thus, also assists with the focussing of future research needs.

The aim of this study was to develop, and apply, approaches to detect change in pattern, processes and responses at varying temporal and spatial scales in South African estuaries. Therefore key research questions were:

1. How can the response of estuaries to key pressures be quantified, with a focus on freshwater inflow modification? (Chapter 2)
2. What is the condition of South African estuaries in response to current anthropogenic pressures? (Chapter 3)
3. Can the response of estuaries to escalating future pressures, related to flow and water quality, be quantified on a regional-scale so that they can guide regional-scale planning and estuary resource allocation? (Chapter 4)
4. How vulnerable are South African estuaries to Climate Change pressures? (Chapter 5)

Figure 1.3 provides an overview of the focus and approaches followed in addressing the key research questions. Each chapter presents a novel approach, or a novel application of existing methods. Where possible international best practice was seen as the “blue print”, but adapted for South African constraints, e.g. estuarine types, data limitations, resolution of standardised hydrology model outputs and legislative requirements. The thesis does not have a separate literature review as this was integrated in each chapter.

Figure 1.3: A diagram showing the main themes and study approaches applied in each chapter to address the key research questions.

I set out to evaluate change dynamics in estuary processes and patterns at escalating spatial and temporal scales (Figure 1.4). Starting with the development of a method for change detection in a single estuary (Chapter 2), before spatially scaling it up for a country-wide (Chapter 3), regional (Chapter 4) or bioregional (Chapter 5) applications.

Temporally the thesis evaluates both response to present pressures (Chapter 2 and 3) and to near-future projected resource use over the next 5 to 20 years (Chapter 4) and Climate Change related stressors in the near- to mid future over the next 30 to 50 years (Chapter 5). Change in process and patterns are bench marked against a reference condition (> 150 years ago), with the exception of the Climate Change analysis that reflects change against the present.

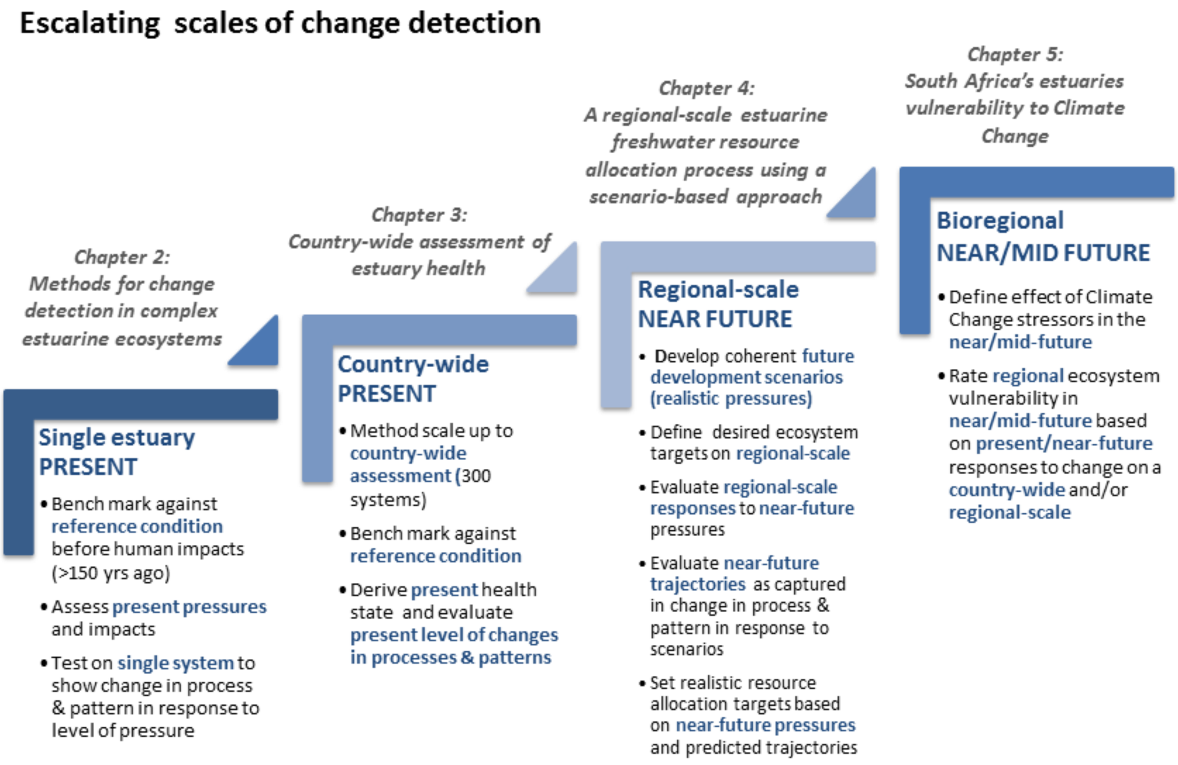


Figure 1.4: A diagram showing the escalating spatial and temporal scales at which change in process and patterns are evaluated in this thesis.

CHAPTER 2

CHANGE DETECTION IN COMPLEX ESTUARINE SYSTEMS: AN ENVIRONMENTAL FLOW DETERMINATION METHOD FOR INTEGRATING MULTIPLE-SCALE HYDROLOGICAL AND ECOSYSTEM PROCESSES

2.1 INTRODUCTION

Freshwater inflow, in all its variability from major floods to low flows, is one of the key factors determining the character of an estuary (Fohrer and Chicharo, 2011; Acreman et al., 2014a). As a result, modification in freshwater inflow can markedly alter the functioning of an estuary, and ultimately the ecosystem services it provides to society (Costanza et al., 1997; Adams et al., 2002; Estevez, 2002; Gillanders and Kingsford, 2002; Lamberth and Turpie, 2003; Lamberth et al., 2008; Whitfield et al., 2008; Acreman et al., 2014a; Costanza et al., 2014). Recognition of estuaries' freshwater requirements led to the development of methods to determine such flows – termed environmental flows. Arthington et al. (2006) define environmental flow requirements as the water regime of a river, wetland, estuary or coastal area necessary to maintain the biophysical and ecological processes, ecosystem health and the associated ecosystem services. Environmental flow methods are increasingly being incorporated into water resource strategies, management frameworks, risk assessments, and even tools for the protection and restoration of inland and coastal aquatic ecosystems (Dyson et al., 2003; King et al., 2003; Naiman et al., 2006; Olsen et al., 2006, Acreman et al., 2014a; Tickner et al., 2017).

Environmental flow methodology for estuaries is a relatively new field of study (Hirji and Panella, 2003, Acreman et al., 2014a and 2014b). It is largely underpinned by the emerging discipline of ecohydrology, straddling a range of engineering and scientific disciplines and borrowing from approaches and technologies developed for rivers, estuaries and the marine environment (Wolanski et al., 2004). Ecohydrology explicitly recognises the need to understand hydrological–ecological interactions at the process level (driver-response relationships in contrast to simple functional (statistical) links at various spatial and temporal scales (Hannah et al., 2004; Naiman et al., 2006).

Most international methods focus on permanently open estuaries with unrestricted inlets, but are less accommodating of shallow, highly dynamic microtidal estuaries situated along wave-dominated coasts such as those found in South Africa, Australia and the Americas (Whitfield and Elliott, 2011). These types of estuaries naturally receive relatively little freshwater inflow from the catchment and often have restricted inlets that can close from time to time, temporarily isolating the estuaries from the sea by the formation of a sand bar across the mouth (Whitfield, 1992; Taljaard et al., 2009a; Whitfield and Elliott, 2011). This chapter describes a method that accommodates a large variety of estuarine types (Whitfield, 1992; Taljaard et al., 2009b).

The method enables coupling between river flow (hydrology) and the downstream chemical and biological ecosystem processes in the estuary embracing both the ecohydrological and ecosystem-based approaches. A particular challenge was linking hydrological-hydrodynamic-biogeochemical processes (typically occurring within shorter temporal cycles – e.g. days to weeks) with biotic responses (typically occurring within longer temporal cycles – e.g. seasonal to annual). These different temporal cycles complicate linkages among these ecosystem components. Furthermore, high specificity in the response of an estuary to freshwater inflow limits extrapolation of results from one estuary to another. This challenge was overcome by simplifying and aggregating these complex abiotic processes to the appropriate temporal and spatial scales more suitable for interpretation of biotic responses, through concepts such as estuary zoning and representative physical states.

Specifically, the chapter expands on the hydrological-hydrodynamic-biogeochemical components of the method, how such knowledge is used to interpret biotic responses and present condition and, ultimately, inform the environmental flow allocation. In this section, the increasing complexity of environmental flow methods globally, is first briefly discussed. Thereafter, the development process that preceded this method is described to provide context and to illustrate the learning-by-doing approach that was adopted. This is followed by a discussion of the various steps in the method using a case study. For illustrative purposes, the steps of the method are combined with the outcomes of its application. Finally, the chapter concludes with an evaluation of the method.

2.2 INCREASING COMPLEXITY OF ENVIRONMENTAL FLOW METHODS FOR ESTUARIES

I define a method here as an approach to determine the environmental flow requirements of a water resource (e.g. an estuary), which encapsulates the identification and quantifying of the hydrological-hydrodynamic-biogeochemical processes and related biological responses to the final recommendation of the environmental flow to the water resource (e.g. King and Louw, 1998; Peirson et al., 2002; Sun et al., 2012a; Acreman et al., 2014a; Kendy et al., 2017; Gu et al., 2017). Environmental flow requirements methods are usually nested within an integrated water resources management framework (discussed in more detail in Chapter 4), which consolidates ecological, economic and social benefits in a coordinated approach to the development and management of water and land resources (Dyson et al., 2003; Overton et al., 2014; Kendy et al., 2017; Bunn, 2016). In turn, environmental flow requirement methods use a range of scientific tools (not the focus of this study), such as: standard statistical analysis, 1 to 3 dimensional numerical modelling of the response of water quality parameters to flow changes, fuzzy logic inference, indices, and ecosystems or resource modelling (Olden and Poff, 2003; Liu et al., 2005; Sun et al., 2012b; Sun et al., 2015).

The complexity of environmental flow methods has increased significantly over the years. Initially, relatively simple hydrology-hydrodynamic relationships provided proxies for assessing ecosystem change (e.g. Alber and Sheldon, 1999; Flannery et al., 2002; Sun and Yang, 2004; Tavassoli et al., 2014; Thompson et al., 2014; Acreman, 2014b). A key assumption is that all ecosystem change is linear and that only flows drive health. This type of approach does not allow for the synergistic (or antagonistic) effects of multiple pressures to be evaluated, e.g. a decline in flow and an increase in fishing pressure due to expanding development. In addition, percentage flow or statistical approaches tend to disregard drought and floods as they are of relatively low incidence. Unfortunately, in the case of estuaries, droughts and floods are the very forces that determine the envelope in which these systems operate and, in not addressing these as part of the flow assessment, key ecosystem processes may be overlooked.

The above hydrology-hydrodynamic relationship methods were followed by more intricate ones including the resource-based approach, where a desired condition is defined in terms of specific living or non-living resources or ecosystem services, for which inflows are determined to achieve the desired condition (e.g. Alber, 2002; Doering et al., 2002; Mattson, 2002; Halliday et al., 2003; Robins et al., 2005; Halliday and Robins, 2007; Lamberth et al., 2009; Sun et al., 2012a, 2015). Resource-based approaches in which the condition of a species or resource serves as a proxy for acceptable change may show some sensitivity to nonlinear responses, but habitat and pollution pressures are often disregarded in this type of study. Generally only one or two of a suite of ecosystem services are evaluated to estimate the possible degree of change an ecosystem may experience and health is reported in this context. These types of approaches also have a very limited ability to project future trajectories of change, especially if feedback loops are through non-linear processes, such as sediment movement that is often event scale and not continuous.

Other, more complex methods, include ecosystem-based approaches where a selection of ecological and socio-economic components are evaluated in order to establish the degree of acceptable change - and associated freshwater inflow - for an estuary (e.g. Peirson et al., 2001, 2002; Adams et al., 2002; Hardie et al., 2006; Richter et al., 2006; Lloyd et al., 2008; Gippel et al., 2009; Adams, 2013; Acreman et al., 2014a, 2014b). Ecosystem-based approaches refer to methods where the focus is on abiotic and biotic system interactions and functioning in response to change in freshwater inflow. These approaches are generally replicable and transferable from one system to another, in contrast to hydrology-hydrodynamic relationships or resource-based approaches that are mainly spatially-based and estuary-specific (Dyson et al., 2003). The inherent complexity of these approaches holds many challenges, ranging from the appropriate integration of diverse data sets to achieving consensus among a wide range of specialists representing various disciplines (e.g. physical, biogeochemical and biological disciplines) that contribute to these studies. Expert opinion and scientific-panel workshop discussions also form a key part of the integration process in ecosystem-based approaches (Hardie et al., 2006).

A number of these methods advocate modelling of hydrological effects on estuarine hydrodynamics, morphology and water quality. These include numerical modelling (e.g. National River Health Program, Peirson et al., 2002)) and statistical modelling techniques (e.g. X2 approach, Alber, 2002). The use of decision matrices and elements of risk assessment are also a recurring theme (Gippel, 2009). Expert opinion and scientific-panel workshop discussions also form a key part of the integration process in ecosystem-based approaches (Hardie et al., 2006).

The selection of biophysical variables used in an ecosystem-based approach, and the temporal scales at which these are resolved, vary greatly. Notwithstanding, hydrology forms the basis of all environmental flow assessments. Most hydrological assessments are done on monthly timescales derived from long-term data sets (e.g. 50 years or longer), either measured or simulated (Peirson et al., 2002; Gippel et al., 2009). Gippel et al. (2009) highlight three key hydrological indices; the low-flow component, the high-flow component and the frequency of mouth opening and subsequent flushing of an estuary. Salinity-distribution is a key thread linking all these approaches (e.g. Doering et al., 2002; Peirson et al., 2002; Powell et al., 2002; Sun et al., 2009, 2015). Other biogeochemical variables that are used or mentioned in an ecosystem-based approach include temperature, pH, dissolved oxygen, inorganic nutrients, particulates (inorganic and organic material) and toxic substances (e.g. heavy metals, pesticides and synthetic compounds). Microbial variables that may be relevant include bacteria and viruses (Peirson et al., 2002; Gippel et al., 2009). Most ecosystem-based methods view biotic variables as condition indicators essential for the quantification of change in an aquatic habitat. Submerged aquatic vegetation is one of the primary variables because of its susceptibility to shifts in salinity and its consequent influence on the nursery function in the estuary for fish and crustaceans. A range of other important biological indicators have also been advocated; and include phytoplankton, seagrass, marsh plants, zooplankton, benthic organisms, crustaceans, molluscs, as well as larval and adult fish (Peirson et al., 2002; Gippel et al., 2009). Some studies also emphasised key ecosystem processes and services such as salinity being an effective control for undesirable or alien invasive species, the transportation of eggs or larvae, the provision of lateral connectivity to other water -bodies adjacent to the estuary, the export of nutrients and sediments to the adjacent marine nearshore environment and the related response in primary production and fisheries production (Peirson et al., 2002; Gippel et al., 2009; Lamberth et al., 2009).

The majority of ecosystem-based methods are data-hungry, emphasizing the need for long-term monitoring to better understand the impacts of altered freshwater inflow. The degree of certainty required largely dictates the data intensity and sophistication of assessment technologies. For example, where water resource development requires a high degree of certainty to inform the decision making process, detailed modelling and monitoring exercises are needed.

2.3 THE SOUTH AFRICAN METHOD DEVELOPMENT PROCESS

The South African environmental-flow method is based on international best practice and intrinsic contextual knowledge, garnered by more than 20 years experience on over 50 estuary flow requirement studies funded mainly by the Department of Water Affairs (DWAF, 1992, 1997, Flyvbjerg, 2001; DWA, 2010; Van Niekerk and Turpie, 2012). As with the development of most environmental flow methods the developmental process for this method followed a learning-by-doing approach, encapsulating the principle of adaptive management (Hennessey, 1994; Rogers, 1998).

The method described here has its roots in the first national scale environmental flow assessments conducted in South Africa in 1983 (Jezewski et al., 1984; Jezewski and Roberts, 1986). In these earlier studies, the allocation of river inflows to estuaries was based on simplified engineering principles with very limited consideration of wider ecological consequences. Flow allocations considered only two components: flood requirements and evaporative requirements (Jezewski and Roberts, 1986). Flood requirements referred to the volume of water necessary to control the opening of an estuary mouth, the flushing of accumulated sediments and the flooding of fringing wetlands – defined as the 2-year return period flood. The evaporative requirement was considered as the amount of water needed to compensate for evaporative losses and to prevent hypersalinity (i.e. salinity above 35).

These initial estimates ignored ecohydrological relationships within estuaries and did not provide detail on either seasonal or monthly flow distributions. Estimates were based on simplistic models and the quantitative results were presented as first-order attempts to indicate the probable freshwater demand of estuaries in water resource planning processes. These first estimates were developed in terms of physico-chemical environmental water requirements and were not intended to provide information on the water requirements to drive ecological processes.

In the 1990s South Africa reaffirmed its commitment to establishing the water requirements of estuaries and commissioned a number of scientific studies to determine environmental flows – referred to as Estuary Freshwater Requirement (EFR) studies. During this period a study conducted on the Great Brak Estuary – linked to the construction of a large dam in the catchment - was a landmark that set the standard for future studies (CSIR, 1990). For the first time a selection of abiotic and biotic components were included in the assessment process, in this instance hydrodynamics, sediment processes, biogeochemical parameters (e.g. nutrients, oxygen and turbidity), as well as two biological components, namely estuarine vegetation and invertebrates. Monthly river inflow scenarios (over a 64-year period) were simulated for natural, pre-dam, and post-dam development using a hydrological model. For the first time a "scenario-based approach" was used to evaluate the implication of such changes in freshwater inflow using the selected abiotic and biotic components. The inclusion of fish and birds as essential ecological components of the EFR were first included in the later Swartkops, Olifants and Berg estuary studies (CSIR, 1998; DWAF, 1994, 1997, 1999). The EFR study on the Palmiet Estuary developed the concept of different "physical states" where distinct hydrodynamic and biogeochemical characteristics were linked to typical river inflow ranges (DWAF, 1992; CSIR, 2000). The value of water level data and mouth state, allowing for the correlation between mouth state and specific flow ranges emerged from the Palmiet and Nhlabane Estuary EFR studies (CSIR, 2000, 2001). Participatory workshops, involving interested parties and various estuarine specialists, had already formed a key part of the integration process in these earlier EFR studies (Morant and Quinn, 1999). Criteria for setting the desired condition typically included: (i) maintenance of a specific mouth state; (ii) regular flushing (defined in terms of resetting the salinity profile) of the estuary by higher flows; (iii) maintenance of nursery function by ensuring delivery of recruitment cues and open mouth condition; and (iv) socio-economic considerations such as prevention of nuisance algal blooms, and open mouth state during summer for recreational purposes. Environmental flows were estimated as annual volumes with specified confidence levels. Monitoring programmes were identified to facilitate future refinement of these estimates. While EFR studies were a significant improvement on the original simplified engineering assessments, they were relatively crude, required limited data and remained largely consensus-based, representing an intuitive expert assessment rather than a scientific defensible method (Morant and Quinn, 1999). The absence of data also hampered the “confirmation” of initial estimates and the refinement of specialist understanding. Further, they only estimated total annual flow allocations, with limited detail on seasonal and monthly distribution patterns.

A paradigm shift in the development process of South African environmental flow methods came with the proclamation of the National Water Act in 1998 (RSA, 1998). This act gave aquatic ecosystems (including estuaries) a right to freshwater so as to maintain aquatic ecosystem functioning. The setting of environmental flows was legislated, necessitating the establishment of an official, scientific defendable and repeatable method. The government appointed experienced estuarine scientists - through the Consortium for Estuarine Research and Management - to consolidate existing place-based learning and international best practice into a legally defensible method. A national workshop was convened whereby scientists and other role players defined nine components (each including a suite of variables) that effectively described relevant response of ecosystem function to flow modification. These included four abiotic components (hydrology, hydrodynamics, sediment dynamics and biogeochemistry) and five biotic components (microalgae, macrophytes, invertebrates (zooplankton and the macrozoobenthos), fish and birds). South Africa’s first official method was adopted in 1999 (DWAF, 1999).

2.4 METHOD DESIGN

The method described here drew on the earlier studies and aimed to develop an approach for integrating multiple-scale hydrological and ecosystem processes to assess the environmental flow requirements of South African estuaries. The stages in this research approach represent a design science research method (Bots, 2007), including the development and testing in practice (empirical validation) of a prototype method to a real-world case study. The method developed included both the ecohydrological and ecosystem-based approaches in that it strived to be holistic in its assessment. Key to the method was the integration and simplification of complex hydrological-hydrodynamic-biogeochemical processes at appropriate temporal and spatial scales so that it was suitable for the interpretation of biotic responses. The proposed method expands on the 1999 method (DWAF, 1999), incorporating incremental learning gained in the application to nearly 50 studies conducted over the last decade – embracing the learning-by-doing approach (Van Niekerk and Turpie, 2012). The method comprises seven basic steps (illustrated in Figure 2.1), namely: 1) Simulation and interrogation of hydrological data; 2) Zonation of the estuary into a number of representative areas; 3) Identification of physical states; 4) Evaluation of annual/seasonal distribution in physical states; 5) Prediction of biotic responses; 6) Definition of present and desired condition; and 7) Allocation of environmental flow requirement. In the results each of these steps is described citing relevant background information that influenced the development of the approach.

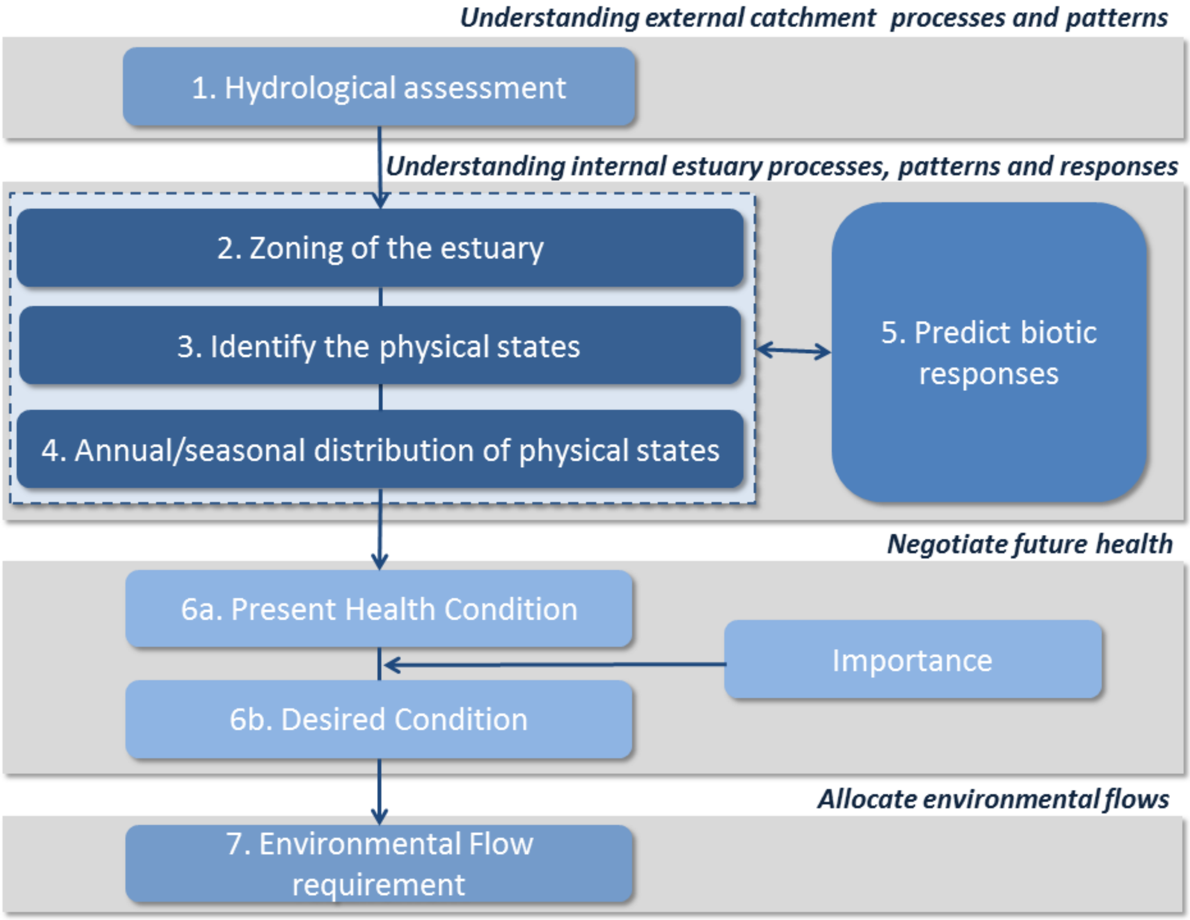


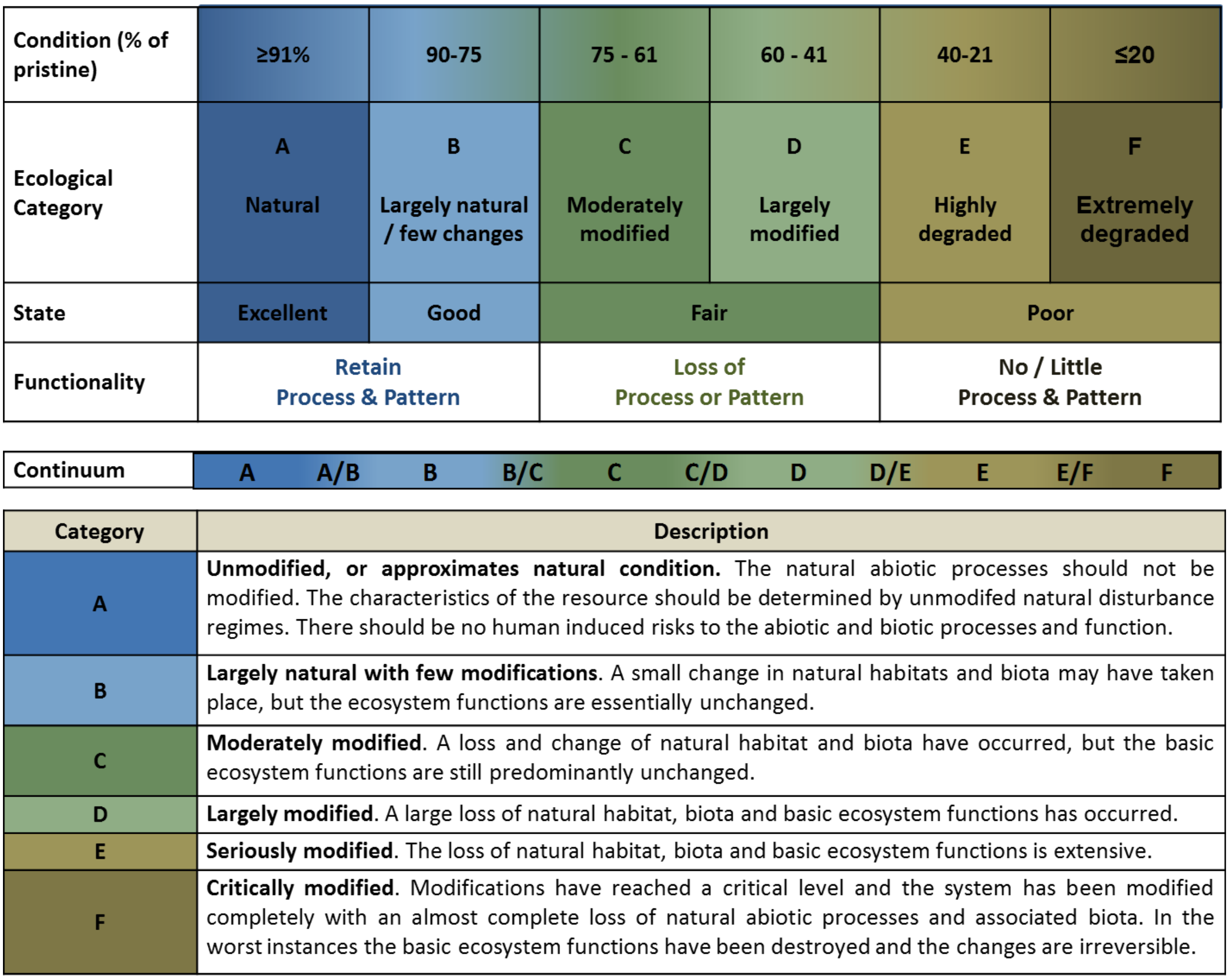
Figure 2.1: Schematic illustration of South African EFR method with the dark blue steps indicating the unique aspects of the approach (modified from DWAF, 1999)

The various steps in the method are illustrated using the temporarily open/closed Palmiet Estuary as a case study (Largier, 1986; Taljaard et al., 1986; Largier and Taljaard, 1991; Largier et al., 1992). See Figure 1.1 for location of Palmiet catchment. The Palmiet Estuary, 75 km south-east of Cape Town, is a small system - 1.67 km long and 300 m at its widest point. The head of the estuary is marked by a series of rocky sills. From 700 m upstream of the mouth, the channel borders the west bank and there are broad, shallow tidal flats on the eastern side. It is estimated that the mean annual run-off has been reduced by 36%, from 256.3 x 10^6 m^3/a under natural conditions to 163.7 x 10^6 m^3/a in 2009 (DWA, 2010).

The method is not prescriptive in the analytical software (e.g. Excel, Primer), spatial analysis tools (e.g. Google Earth, ArcGIS), or numerical modelling platform (e.g. Mike11, Delf3D) that can be used in the analysis of ecosystem processes and prediction of responses (Delft Hydraulics, 1995 and 1996; DHI, 1995; Clarke and Warwick, 2001; Clarke and Gorley, 2006; StatSoft, 2005; ESRI, 2014). It is however prescriptive in that the steps need to be followed sequentially, i.e. abiotic response is determined by the predicted hydrological regime and biotic responses must be based on predicted abiotic conditions. Data richness, ecosystem complexity, and the level of assessment mostly determines the correct analytical approach within the steps of the method.

Various methods or indices can be used to determine change in estuarine processes and pattern using the estuarine health as the measure (See Chapter 3 for a review of estuary health assessments and indexes). For example, in South Africa, an estuary is assigned a condition score based on the similarity to natural for the various abiotic and biotic components described earlier using an estuarine health index (Adams et al., 2002; Adams, 2013; Turpie et al., 2012a). The degree of similarity reflects six broad categories of estuarine condition, ranging from natural to extremely degraded (Table 2.1). These categories in turn relate to decreasing levels of ecosystem function. The loss of function occurs on a continuum, with estuaries retaining more than 90% of their natural function rated as “excellent” and estuaries degraded to less than 40% of natural function as “poor”. It must be emphasised that the A to F scale represents a continuum, and that the boundaries between categories are conceptual points along the continuum. There may therefore be cases where there is uncertainty as to which category a particular estuary belongs, potentially having components that have membership in two categories. To reflect this, straddling categories (±3 from the category scoring range) were therefore introduced in this study, denoted by A/B, B/C,

Table 2.1: The relationship between loss of ecosystem condition and functionality (Van Niekerk et al., 2013a)



Condition (% of pristine)	≥91%	90-75	75 - 61	60 - 41	40-21	≤20
Ecological Category	A Natural	B Largely natural / few changes	C Moderately modified	D Largely modified	E Highly degraded	F Extremely degraded
State	Excellent	Good	Fair		Poor	
Functionality	Retain Process & Pattern		Loss of Process or Pattern		No / Little Process & Pattern	

Continuum										
A	A/B	B	B/C	C	C/D	D	D/E	E	E/F	F

Category	Description
A	**Unmodified, or approximates natural condition.** The natural abiotic processes should not be modified. The characteristics of the resource should be determined by unmodifed natural disturbance regimes. There should be no human induced risks to the abiotic and biotic processes and function.
B	**Largely natural with few modifications**. A small change in natural habitats and biota may have taken place, but the ecosystem functions are essentially unchanged.
C	**Moderately modified**. A loss and change of natural habitat and biota have occurred, but the basic ecosystem functions are still predominantly unchanged.
D	**Largely modified**. A large loss of natural habitat, biota and basic ecosystem functions has occurred.
E	**Seriously modified**. The loss of natural habitat, biota and basic ecosystem functions is extensive.
F	**Critically modified**. Modifications have reached a critical level and the system has been modified completely with an almost complete loss of natural abiotic processes and associated biota. In the worst instances the basic ecosystem functions have been destroyed and the changes are irreversible.

C/D, and so on. The B/C boundary category, for example, is indicated as the light blue to dark green area in Table 2.1. Smaller, more sensitive estuaries tend to degrade rapidly to the lower health Categories (C to F), while the larger, permanently open estuaries demonstrate a degree of resilience and can generally maintain a boundary category as long as pressures are not increased.

2.5 RESULTS AND DISCUSSION

The seven steps are described and applied to the Palmiet Estuary.

2.5.1 Step 1: Simulation and interrogation of hydrological data

Estuaries are complex ecosystems that respond to flow variations at different spatial and temporal scales. Similar to the “Ecological Limits of Hydrologic Alteration” (ELOHA) (Poff et al., 2010), the method described here follows a “top down” approach and defines different levels of change from the perspective of the natural flow regime using a scenario-based approach. To achieve this, rainfall-runoff models are used to simulate catchment inflow. While hydrological data are critical to environmental flow studies, measured inflow data into estuaries, especially smaller systems, would be ideal but is uncommon due to sparse observation networks. Modelling techniques are therefore applied as surrogates to address this shortcoming. Modelling also allows for the forecasting of future flow regimes, which is critical to determine responses to future change in freshwater inflow. The simulated hydrological sequence needs to be as long as possible (> 50 years) to capture variability in inflow. The greater the natural variability in flow in a region, the longer the simulated record needs to be (Poff and Ward, 1989; Poff et al., 1997). This is especially important in dry, temperate regions or monsoon type systems where there is significant variability within (seasonal changes) and between years (Lynch, 2004). In bimodal or equatorial rainfall areas, where runoff is less variable, it might be less important to simulate such long periods since the coefficient off variability is less. As estuaries respond to inflow in all its variability, all components of flow need to be included, from floods to seasonal base flows. In addition, all operational rules for impoundments, abstractions and discharges need to be aggregated into the flow sequence to provide the long term picture of variability.

While the method is not prescriptive with regards to the type of hydrological model that should be applied, it has been shown that hydrological models that can simulate the yield from a catchment based on present or planned water resource use, provide the best results as they provide realistic indication of the impact of water resource development on inflow (e.g. South African Water Resource Yield Model (WRYM) (DWS 2014a). Moreover, from an environmental flow perspective, resolving base flows using these models is critical as these flows significantly influence salinity penetration and estuary mouth condition, especially during low-flow periods (Smakhtin, 2001). Stochastic model outputs are generally presented as simulated monthly or daily flow time-series generated from measured rainfall data in the catchment (or from a representative adjacent catchment). Ideally, the selected temporal resolution should be determined by the expected variability in river flow and the consequent influence on salinity distributions and inlet conditions of an estuary. Monthly data are appropriate for larger catchments, where seasonal base-flow responds on monthly time-frames and floods mostly occur at weekly scales and especially where such peaks in inflow discharge in to a large estuary. In these larger systems signals from flood pulses remain in the system for weeks to months at a time. Daily inflow data may be more appropriate in the case of smaller catchments, where high flows and flood peaks occur at shorter time scales (hours to days), especially where inflow occurs into small estuaries with little retention capacity and little memory response to higher inflows. Small to medium catchments with very erratic flow patterns may well function at a scale of days to weeks, but if they flow into larger estuaries, that tend to have some retention, assessments might need to be done at weekly or monthly time steps. Hydrological data for long time periods (e.g. 70-80 year simulation period), which are generally more representative of South African variable runoff patterns, are normally only available for monthly flow data (Midgley et al., 1994).

Scenarios need to be generated for the natural state (representative of the catchment in an undeveloped state), the present condition, as well as a range of future scenarios (e.g. based on future water resource development options such as forestry or construction of major impoundments). These additional scenarios should ideally include a wide range of realistic operational flow sequences to test the sensitivity of a specific estuary to changes in freshwater inflow. In the absence of operational scenarios, water resources development can also be evaluated as incremental modification from either the natural or present inflow (e.g. 80 %, 60% and 40% of natural flow regime). These scenarios (hereafter referred to as future scenarios) reflect the scenario-based approach adopted in this method and form a critical element in the environmental flow allocation process as discussed in Steps 4 and 7.

The simulated flow scenarios are interrogated to provide an indication - descriptive or statistically - of change in the flow regime focusing on: a) The magnitude of flow events (low and high flows); b) The frequency of flow events (low and high flows); c) The duration of flow events; d) The timing of flow events (seasonality); and e) The rate of change. These analyses can be done on either monthly or daily flow sequences. The simulated inflow scenarios are also used to identify typical flow ranges encountered in a particular system and how they change with water resource development (Figure 2.2), considering both the natural, present and future scenarios. These flow ranges form the basis for the description of the various physical states that are dominant in a specific estuary. For example, in the Palmiet Estuary case study there was a strong focus on how freshwater inflow decreased under the median and drought flow conditions, with specific concerns around the decrease in flow from more than 1.0 m^3/s to about 0.5 m^3/s in the summer months between December and March (i.e. only 30 to 50 % of flow remaining). Similarly, drought flows had been severely reduced to the estuary under present and future scenarios (e.g. only 30 to 40 % of drought flows remaining). This analysis highlighted the importance of understanding mouth state responses to such low flow ranges and the focus of the following steps.

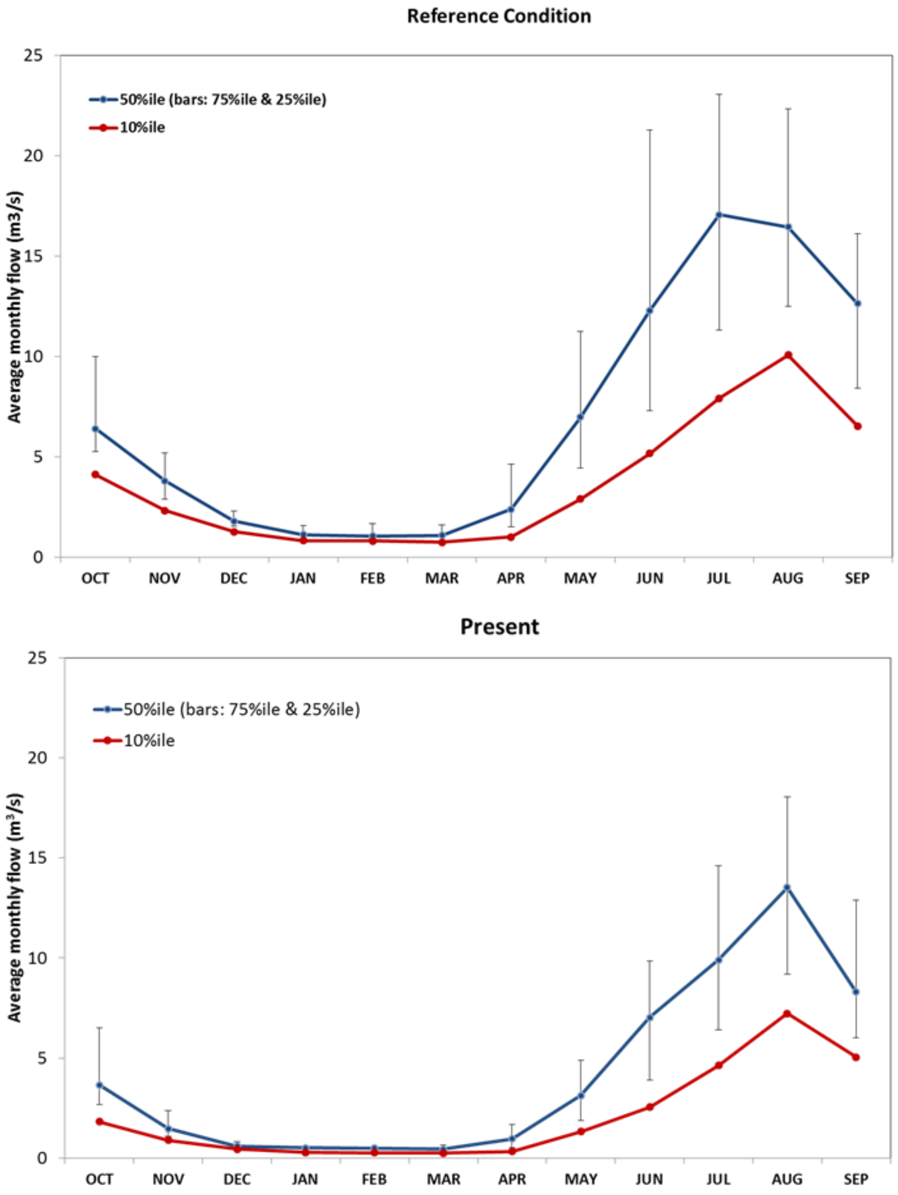


Figure 2.2: Schematic illustration of typical flow ranges occurring in the Palmiet Estuary under reference condition and present state (Blue=median flows, Red=drought) conditions, error bars provide indication of flow variation between 25 and 75 percentile flows)

2.5.2 Step 2: Zonation of the estuary

In order to present complex abiotic processes in a simplified, easily accessible manner for interpretation by biotic specialists, the estuary is zoned into a number of homogenous representative areas. While zonation should firstly be done based on system-specific abiotic and biotic criteria, it can also reflect zones that are sensitive to direct and indirect drivers of change or major conflicts (e.g. critical habitats for species dispersal in fragmented areas; hypoxia zones, low-lying areas prone to major flooding) to allow for the linking of results with socio-economic studies (Pallero et al., 2017; Zhang et al.; 2017). A key criterion in the identification of the zones is bathymetry, as the size and shape of an estuary plays a determining role in its response to flow. Another criterion is the degree of stratification that provides an indication of dominant mixing processes in a system. Using this information a conceptual model is developed, dividing the estuary into homogenous zones of high and low retention. Zones of high retention include, for example, deeper sections that tend to stratify, and areas near narrow bridges and causeways that can hinder tidal or fluvial flushing. Low retention zones are generally represented by shallow areas at the head of the estuary (easily flushed by river inflow) or the lower mouth regions (regularly flushed by tidal action).

The Palmiet Estuary was sub-divided into four zones largely based on measured bathymetry and salinity distribution (Figure 2.3) (Largier, 1986; Taljaard et al., 1986; Largier and Taljaard, 1991; Largier et al., 1992). The Palmiet Estuary is shallower near the mouth with a deeper section towards the head. The system also stratifies with freshwater from the river overlying more saline marine waters. The zones therefore included the "lower" (0-800 m) and the "upper" (800 – 1 800 m) estuary (moving upstream from the mouth left to right) each comprising a "surface" (water depth < 1.5 m) and "bottom" (water depth > 1.5 m) zone.

2.5.3 Step 3: Identification of physical states

In Step 1 hydrological scenarios are used to identify typical flow ranges that occur in a specific estuary. In Step 3, these flow ranges form the basis for the description of dominant physical states in the system. Generically these states may range from a series of freshwater-dominated states to more marine-dominated states. In the case of temporarily open estuaries, closed mouth states also become relevant (Taljaard et al., 2009a).

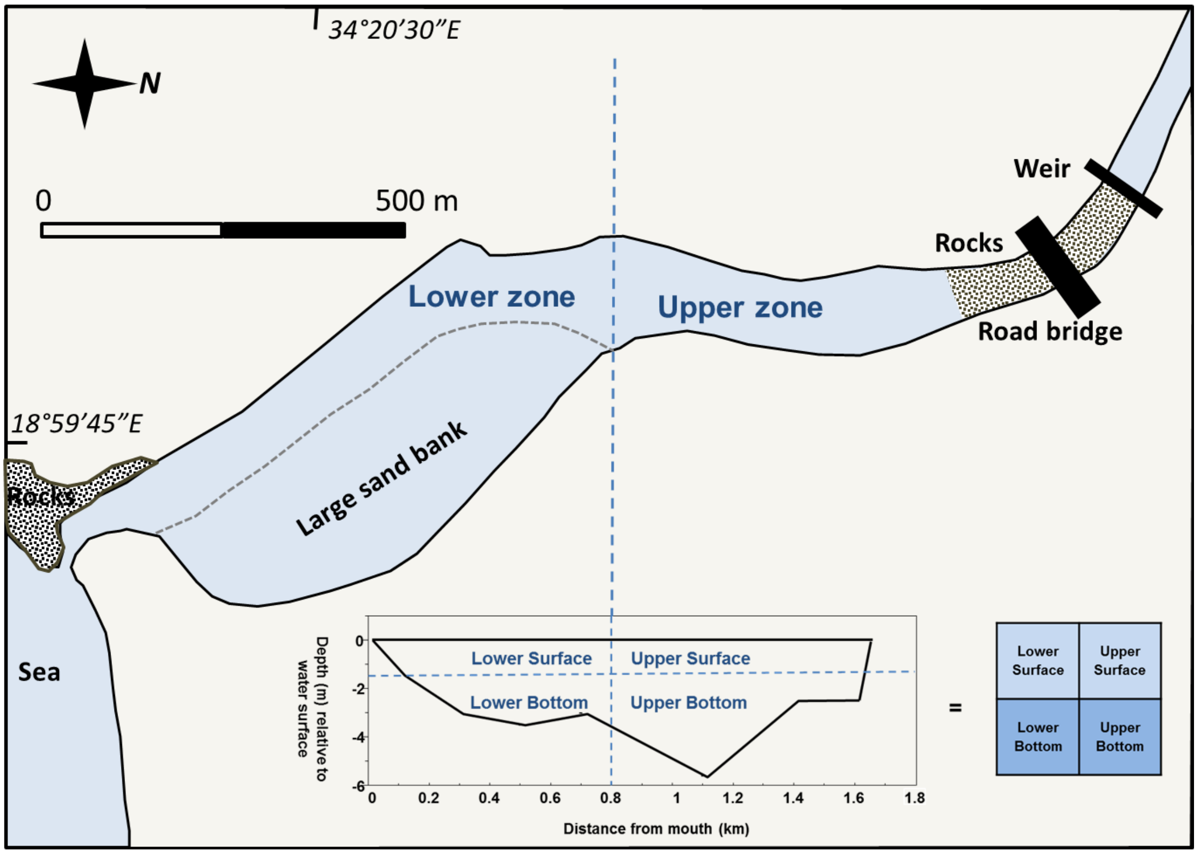


Figure 2.3: Example of zoning of homogenous regions in the Palmiet Estuary.

Depending on the severity of flow modification predicted in future hydrological scenarios, it may be possible that flow ranges emerge not detected in a system before. In such instances "hypothetical" physical states may need to be introduced. For example, permanently open estuaries may close off from the sea in a future scenario due to high freshwater abstraction or hypersalinity may start to occur under some future scenarios. Hydrodynamic and biogeochemical processes are, in most instances, the ecosystem components where modification in flow is first manifested. For example, reduced freshwater inflow first changes water circulation and salinity distribution patterns, which then impacts distribution of various biota. Nutrient loading through river inflow may also change the nutrient chemistry of an estuary which then effects the growth of aquatic plants.

Physical states, associated with each of the flow ranges, are defined in terms of a number of hydrodynamic and biogeochemical characteristics (Table 2.2) using various forms of knowledge ranging from expert judgment, analytical/empirical models based on measured data, to water balance models and sophisticated numerical or GIS models (Duvail and Hamerlynk, 2003; Ben-Hamadou et al., 2011; Acreman et al., 2014a). Hydrodynamic variables can include: a) state of the mouth, b) floodplain inundation patterns, c) amplitude of tidal variation (indicative of exposure of intertidal areas during low tide); d) retention times of water masses, e) total volume and/or estimated volume of different salinity ranges including stratification; and f) estimated (maximum) tidal velocities along the estuary. In addition to the above, physical state descriptions also include typical physico-chemical characteristics of which the most important is salinity distribution. Relevant biogeochemical variables can include: temperature, pH, suspended solids, turbidity and dissolved oxygen and nutrients. Here the pre-defined zones are used as a means of simplifying representation of these processes. For example, Taljaard et al. (2009b) provide a generic qualitative model to describe nutrient distribution patterns for a range of physical states encountered in smaller microtidal estuaries. To define the biogeochemical characteristics of the various physical states it is also important to have knowledge on the biogeochemical composition of inflowing river water and seawater.

Short-term sedimentary processes, generally influenced by seasonal runoff and inter-annual events, are integrated into the descriptions of the physical states, e.g. defining the mouth state and tidal amplitude range associated with a flow range. On the other hand, long-term sedimentation and erosion processes, influenced by major and infrequent inflow events (e.g. 1: 20 years flood events and above), are defined per flow scenario (natural, present and future scenarios) to provide an integrated picture of bathymetric features such as channel depth and size of intertidal areas, as well as sediment composition. An understanding of coastal sedimentary processes is integral to defining estuarine responses to river inflow, but deemed an unchanging factor in the proposed approach unless coastal infrastructure development is identified as a future development scenario.

By applying concepts such as representative physical states and zoning, the information on complex abiotic processes can be sufficiently simplified and aggregated into temporal and spatial patterns that are appropriate for analysis of biotic responses as discussed in the following step. This simplification allows for the development of predictive capabilities in both the hydrological-hydrodynamic-biogeochemical and biotic components based on simulated hydrological data.

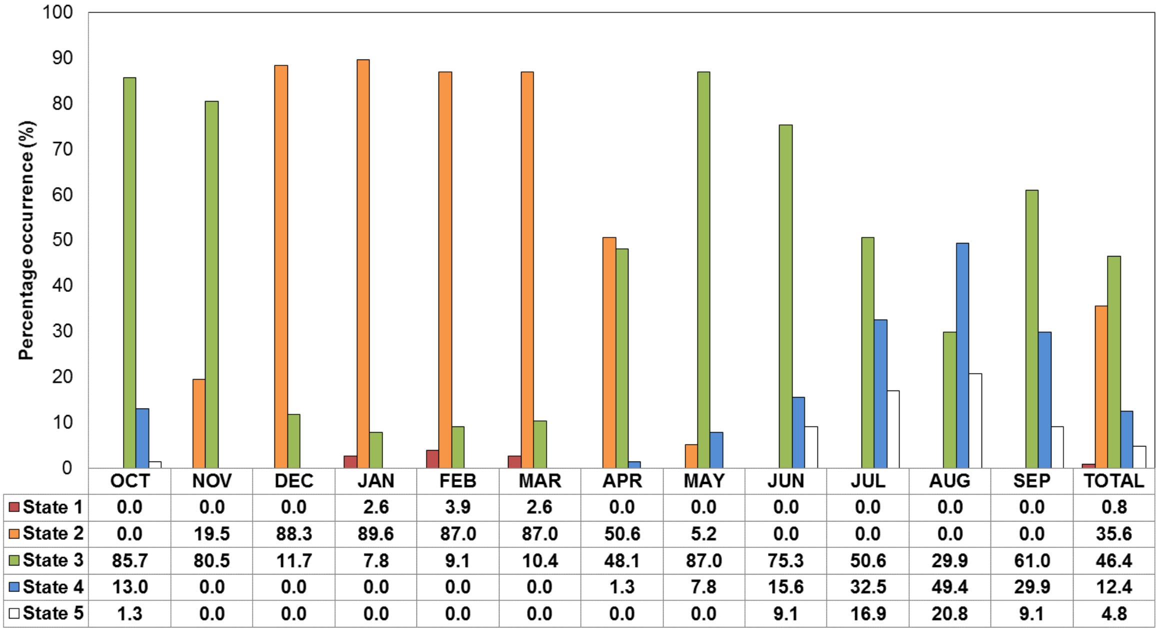
Based on available data, five characteristic 'states', related to tidal exchange, salinity distribution and water quality, were identified for the Palmiet Estuary. These are primarily determined by freshwater inflow patterns. The different states vary from "closed mouth" to "freshwater dominated" and are listed in Table 2.2.

Table 2.2: A summary of typical physical states and associated hydrodynamic and biogeochemical characteristics in the Palmiet Estuary. For the purposes of summarising typical abiotic processes, the system was sub-divided into 4 sections representing the lower (0 - 800 m) and upper (800 – 1 800 m) estuary (moving upstream from the mouth left to right) and into surface (water depth < 1.5 m) and bottom (water depth > 1.5 m) waters (top, left also represents the intertidal area – sand flats).

Variable	State 1	State 2	State 3	State 4	State 5
River flow (m^3/s)	< 0.05	0.05 - 1	1 - 10	10 - 20	> 20
Mouth condition	Closed	Semi-closed	Open (with extensive sea water intrusion)	Open (with limited seawater intrusion)	Open (with no seawater intrusion)
Water level variation	None	None	0.3 m	0.3 m	Backing up effect
Inundation	Limited inundated	Intertidal area inundated	None	None	Intertidal and floodplain during floods
Salinity	5 5 5 10	< 1 month 15 15 20 25 or > 1 month 5 5 5 15	20 15 35 30	0 0 25 10	0 0 0 0
Dissolved Oxygen ($mg.l^{-1}$)	>6 >6 2-6 <2	Natural >6 >6 2-6 <2 Or Present >6 >6 2-6 2-6	>6 >6 >6 >6	>6 >6 >6 >6	>6 >6 >6 >6
Dissolved Inorganic Nutrients ($\mu g.l^{-1}$)	Reference <50 <50 <50 <50 or <50 50-300 <50 <50 Present	Reference <50 <50 <50 <50 or 50 -300 50-300 <50 <50 Present	Reference 50-300 <50 50-300 50-300 or 50-300 50-300 50-300 50-300 Present	Reference <50 <50 <50 <50 or >300 >300 <50 >300 Present	Reference <50 <50 <50 <50 or >300 >300 >300 >300 Present

2.5.4 Step 4: Evaluation of annual / seasonal distribution in physical states

Once physical states have been identified – linked to specific flow ranges - they are superimposed on the natural, present and future hydrological scenarios. In its most simplified form, changes in the distribution of the physical states can be represented by the difference in the percentage occurrence of the physical states over the modelled period (50 or more years) (e.g. Table 2.3). In larger catchments that show strong variability in seasonal flow, physical states are typically interpreted at monthly intervals (e.g. Table 2.3 and Table 2.4, Figure 2.4). However, in small to medium catchments having high flow variability within months, expected variability of physical states within the month are predicted to occur on the scale of days (e.g. estuary is freshwater dominated for 10 days of the month under this flow range).

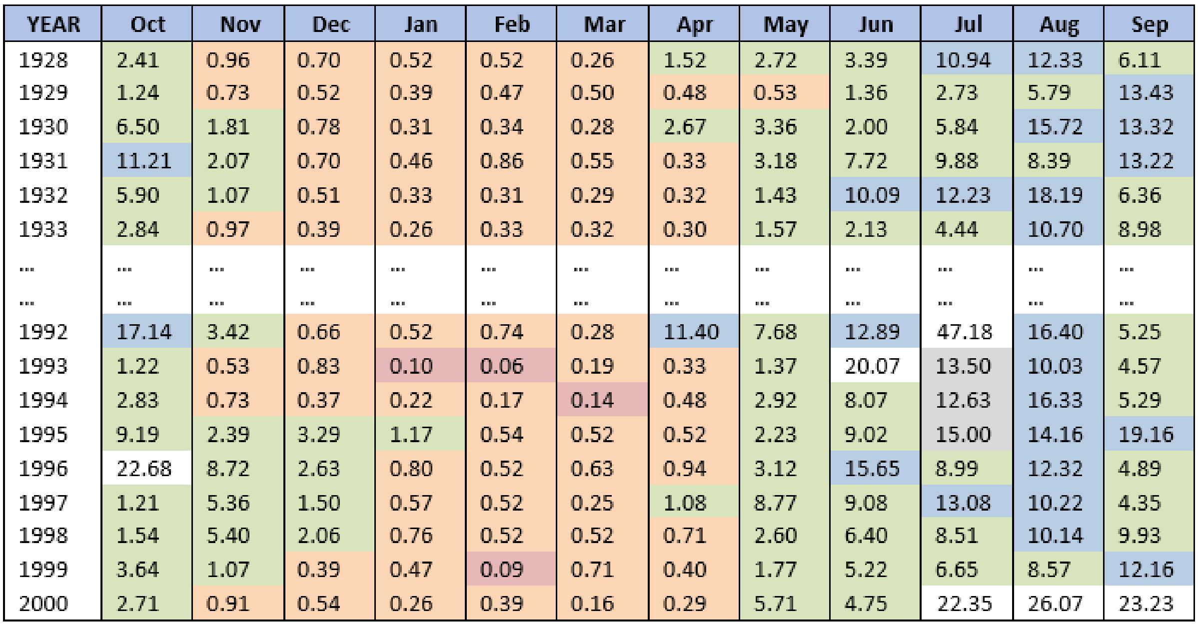


	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	TOTAL
■ State 1	0.0	0.0	0.0	2.6	3.9	2.6	0.0	0.0	0.0	0.0	0.0	0.0	0.8
■ State 2	0.0	19.5	88.3	89.6	87.0	87.0	50.6	5.2	0.0	0.0	0.0	0.0	35.6
■ State 3	85.7	80.5	11.7	7.8	9.1	10.4	48.1	87.0	75.3	50.6	29.9	61.0	46.4
■ State 4	13.0	0.0	0.0	0.0	0.0	0.0	1.3	7.8	15.6	32.5	49.4	29.9	12.4
□ State 5	1.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	9.1	16.9	20.8	9.1	4.8

Figure 2.4: Summary option for seasonal flow distribution (particularly for estuaries where inter-monthly variation is stronger than seasonal variation).

The distribution of the various physical states can be further interrogated for each scenario; for example, by calculating the occurrence of open mouth conditions; average salinity concentration per annum or in a specific season; average water levels (used as proxy for floodplain inundation); and average retention time/exposure time.

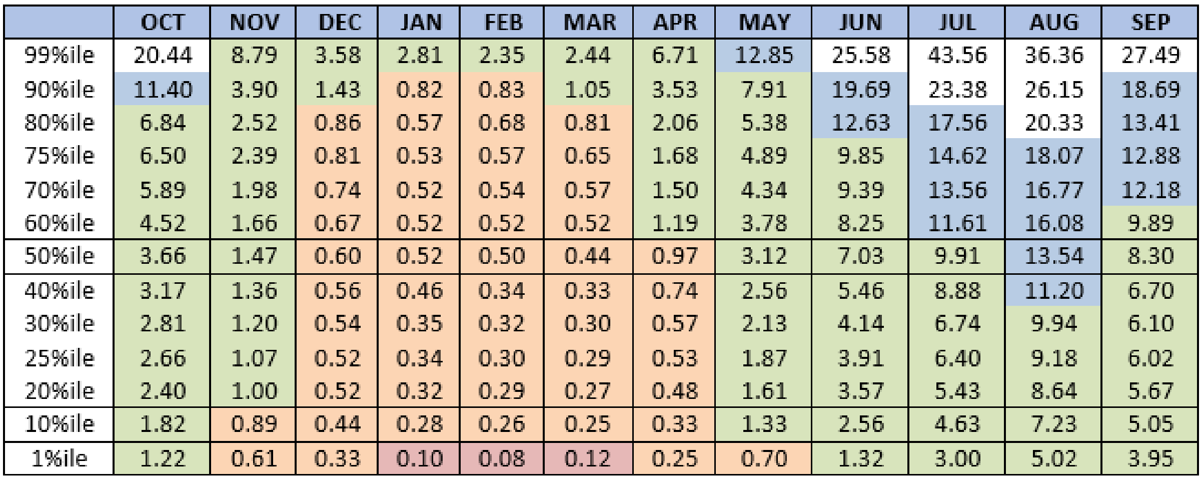
Table 2.3: An example of a time series of simulated monthly freshwater inflow (in m^3/s) to the Palmiet Estuary under the Present State with the different physical states colour coded for visual representation of annual and seasonal distribution of states.



YEAR	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
1928	2.41	0.96	0.70	0.52	0.52	0.26	1.52	2.72	3.39	10.94	12.33	6.11
1929	1.24	0.73	0.52	0.39	0.47	0.50	0.48	0.53	1.36	2.73	5.79	13.43
1930	6.50	1.81	0.78	0.31	0.34	0.28	2.67	3.36	2.00	5.84	15.72	13.32
1931	11.21	2.07	0.70	0.46	0.86	0.55	0.33	3.18	7.72	9.88	8.39	13.22
1932	5.90	1.07	0.51	0.33	0.31	0.29	0.32	1.43	10.09	12.23	18.19	6.36
1933	2.84	0.97	0.39	0.26	0.33	0.32	0.30	1.57	2.13	4.44	10.70	8.98
...	...	...	...	...	...	...	...	...	...	...	...	...
...	...	...	...	...	...	...	...	...	...	...	...	...
1992	17.14	3.42	0.66	0.52	0.74	0.28	11.40	7.68	12.89	47.18	16.40	5.25
1993	1.22	0.53	0.83	0.10	0.06	0.19	0.33	1.37	20.07	13.50	10.03	4.57
1994	2.83	0.73	0.37	0.22	0.17	0.14	0.48	2.92	8.07	12.63	16.33	5.29
1995	9.19	2.39	3.29	1.17	0.54	0.52	0.52	2.23	9.02	15.00	14.16	19.16
1996	22.68	8.72	2.63	0.80	0.52	0.63	0.94	3.12	15.65	8.99	12.32	4.89
1997	1.21	5.36	1.50	0.57	0.52	0.25	1.08	8.77	9.08	13.08	10.22	4.35
1998	1.54	5.40	2.06	0.76	0.52	0.52	0.71	2.60	6.40	8.51	10.14	9.93
1999	3.64	1.07	0.39	0.47	0.09	0.71	0.40	1.77	5.22	6.65	8.57	12.16
2000	2.71	0.91	0.54	0.26	0.39	0.16	0.29	5.71	4.75	22.35	26.07	23.23

State 1 <0.15 **State 2** 0.15-1.0 **State 3** 1-10 **State 4** 10 - 20 **State 5** > 20.0

Table 2.4: A summary of the occurrence of the different physical states for the Palmiet Estuary under the Present State Scenario based Table 2.3. Median flows (represented by 50 percentiles) and drought flows (represented by 10 percentiles) are highlighted.



	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
99%ile	20.44	8.79	3.58	2.81	2.35	2.44	6.71	12.85	25.58	43.56	36.36	27.49
90%ile	11.40	3.90	1.43	0.82	0.83	1.05	3.53	7.91	19.69	23.38	26.15	18.69
80%ile	6.84	2.52	0.86	0.57	0.68	0.81	2.06	5.38	12.63	17.56	20.33	13.41
75%ile	6.50	2.39	0.81	0.53	0.57	0.65	1.68	4.89	9.85	14.62	18.07	12.88
70%ile	5.89	1.98	0.74	0.52	0.54	0.57	1.50	4.34	9.39	13.56	16.77	12.18
60%ile	4.52	1.66	0.67	0.52	0.52	0.52	1.19	3.78	8.25	11.61	16.08	9.89
50%ile	3.66	1.47	0.60	0.52	0.50	0.44	0.97	3.12	7.03	9.91	13.54	8.30
40%ile	3.17	1.36	0.56	0.46	0.34	0.33	0.74	2.56	5.46	8.88	11.20	6.70
30%ile	2.81	1.20	0.54	0.35	0.32	0.30	0.57	2.13	4.14	6.74	9.94	6.10
25%ile	2.66	1.07	0.52	0.34	0.30	0.29	0.53	1.87	3.91	6.40	9.18	6.02
20%ile	2.40	1.00	0.52	0.32	0.29	0.27	0.48	1.61	3.57	5.43	8.64	5.67
10%ile	1.82	0.89	0.44	0.28	0.26	0.25	0.33	1.33	2.56	4.63	7.23	5.05
1%ile	1.22	0.61	0.33	0.10	0.08	0.12	0.25	0.70	1.32	3.00	5.02	3.95

2.5.5 Step 5: Prediction of biotic responses

Based on estimated shifts in the frequency and duration of various physical states (and the associated hydrodynamic and biogeochemical characteristics) biotic responses can now be linked directly to specific abiotic characteristics instead of indirectly through hydrology (or flow).

By simplifying complex abiotic processes - using the concepts of estuary zoning and physical states - information is presented on temporal and spatial scales appropriate for biotic response interpretation. Biotic response assessments – expressed in terms of change in species richness, abundance and community composition in this method - are typically based on site-specific field data, published literature, preference and tolerance ranges or modelled data (Adams et al., 2002; Van Niekerk et al., 2008a; Whitfield at al., 2008; Lamberth et al., 2009). Each biotic component needs to identify key influencing abiotic variables, and together with responses that may be triggered by other biotic components, predict expected responses.

For most biological components, mouth state and salinity are often key abiotic variables (or driver) of responses, although other variables such as sediment characteristics (e.g. particle size distribution, organic content), temperature, pH, dissolved oxygen, turbidity and nutrients may also be key drivers. Where “hypothetical” physical states have been defined, “hypothetical” biotic responses have to be derived using available data, published or unpublished, on preference or tolerance ranges.

Various biotic components use different approaches to link the abiotic assessments from Step 4. In larger, permanently open systems, biota are likely to arrange themselves according to preference whilst in smaller temporarily open systems, biological assemblages are more likely distributed according to tolerance as they have little choice but to remain in these systems under closed mouth conditions; intolerant biota becoming absent (Lamberth et al., 2009). For example, if the mouth closes in a relatively small estuary as a result of reduced freshwater inflow key drivers such as salinity develop weak gradients with little spatial variability (Perissinotto et al., 2010). Predicted responses of the different biota are described below for the Palmiet Estuary case study.

Primary production

To evaluate change in primary producers, a vegetation map is produced for the estuary. The map represents the present state of the estuary and the area covered by each macrophyte habitat type is quantified (e.g. salt marsh, macroalgae, submerged macrophytes, reeds & sedges). Microalgae were not considered in the Palmiet Estuary as the estuary has low retention and light penetration. The most important abiotic variables influencing a specific macrophyte component are identified and the key changes in the variable(s) between the states and scenarios are then used to predict the macrophyte response. In the Palmiet Estuary, macrophytes (small salt marsh area) and macroalgae were restricted to the “lower surface” zone. Macroalgae only occurred in the estuary when the mouth closes or becomes semi-closed (States 1 and 2) as high flow flushed them out of the estuary under open mouth conditions. Besides mouth condition and water flow, macroalgae in the Palmiet Estuary would also respond measurably to nutrient concentrations and salinity. These relationships are then used to predict the response of the macrophytes to future scenarios. A decrease in freshwater inflow results in an increase in the frequency and duration of mouth closure causing macroalgae to proliferate. Predictions on macrophyte species composition were based on a combination of known tolerance to salinity, description of the physical state (Table 2.2), and the duration of the different states (Table 2.3 and Table 2.4) in the “lower surface” zone. The present species composition of the salt marsh in the Palmiet Estuary responded to euryhaline conditions (<18). Higher water levels and closed mouth conditions would result in inundation and die-back of the small area of salt marsh. For each scenario the area covered by each macrophyte habitat is provided, thus providing data on abundance and community composition which is used to predict the responses of the other biotic components (Table 2.5).

Invertebrates

A low number of macrobenthic species (28) occur in the estuary, of which most are benthic (>75%) (Branch and Day, 1984). The sandprawn (*Callichirus kraussi*) is the dominant species, followed by amphipods *Grandidierella* sp. and the gastropod *Hydrobia* sp. Both the sandprawn and gastropod were associated with the intertidal sandbank in the “lower surface” zone. The estuary is depauperate from a zooplankton perspective (Branch and Day, 1984).

Table 2.5: Summary of the degree (and direction) of change in critical parameters used as a proxy for change in the macrophytes, invertebrates, fish and bird assemblage of the Palmiet Estuary.

Key Parameters	Present	Future Scenario 1	Future Scenario 2	Future Scenario 3	Future Scenario 4	Key proxies used for evaluating change in biotic components
Abiotic processes						
Reduction in floods	⇧ 10%	⇧ 10%	⇧ 10%	⇧ 10%	⇧ 10%	invertebrates
Drought duration (in years)	⇧2-5	⇧2-5	⇧2-10	⇧2-12	⇧2-19	fish
Change in duration of mouth opening	26%⇩	25%⇩	26%⇩	27%⇩	31%⇩	macrophytes, invertebrates, birds
Salinity	<1%⇩	4%⇩	3%⇩	3%⇩	3%⇩	macrophytes, invertebrates, fish
Subtidal/ intertidal area	<1%⇩	30%⇩	30%⇩	30%⇩	40%⇩	invertebrates, fish, birds
Hypoxia/ anoxia	10%⇧	5%⇧	5%⇧	7%⇧	7%⇧	fish
Nutrients	⇧ 38 %	⇧ 45 %	⇧ 37 %	⇧ 36 %	⇧ 34 %	macroalgae, macrophytes
Biotic responses						
Macroalgae	38%⇧	35%⇧	37%⇧	37%⇧	42%⇧	invertebrates, fish
Zooplankton	10%⇧	10%⇧	10%⇧	10%⇧	10%⇧	fish
Benthic invertebrates	40%⇧	35%⇧	40%⇧	37%⇧	45%⇧	fish, birds
Fish	0%⇩	0%⇩	30%⇩	40%⇩	50%⇩	birds

Predicted responses of macrozoobenthos and zooplankton were based on changes in the state of the estuary (e.g. changes in the duration of mouth closure and salinity distribution) in the relevant zones. For example, because of the reduction in the magnitude and frequency of floods (<50%) and related increase in the stability and extent of the sandy intertidal area in the lower estuary, zooplankton biomass and composition is likely to have become less variable under the present state (Table 2.5). However this was not a major concern as the natural humic acid content of the estuary water body (blackwater system) results in naturally low zooplankton biomass. In contrast macrozoobenthic biomass is predicted to increase by about 30-35%, with a small shift in the relative dominance of species, as a result of the increase in macroalgal cover leading to an associated increase in detritus for benthic consumers. The nature of the sediment (sand vs mud) in the estuary was predicted to remain similar compared to present resulting in little change predicted in the macro-invertebrate community.

Fish

The EFR method can be applied to fish assemblages in both permanently-open and temporarily open/closed estuaries (Lamberth et al., 2008). This whilst bearing in mind that, on the whole, fish distribution or presence in permanently open estuaries is according to preference for, whereas that in temporarily open / closed systems is according to tolerance of, various physico-chemical or habitat variables. The four estuary zones were treated as one as the Palmiet Estuary is small and the fish are highly mobile. Table 2.5 lists some of the proxies for change in the fish assemblage of the Palmiet Estuary. As the abiotic assessment did not indicate significant changes in average salinity for the system, little change in the fish species richness or community composition is expected. Similarly, water clarity remained high enough under both present and future scenarios for visual foraging by selective feeders and those feeding on benthic invertebrates. Predicted increased hypoxia was unlikely to change the fish assemblage as benthic species are excluded from the deeper naturally hypoxic/anoxic parts of the estuary (zones “lower bottom” and “upper bottom”). An increase in the occurrence of macroalgae, the preferred habitat for some fish, would have allowed these species to persist for longer periods in the estuary, depending on the relationship between algal biomass and oxygen levels. In most future scenarios, closed conditions were not persistent or frequent enough to hinder recruitment into the estuary during the peak spring/summer recruitment period of obligate estuary dependent fish as most are long-lived with a high age at maturity of six years or more.

Birds

Changes in the bird community were assessed based on predicted changes in both physical (habitat) and biotic (food) parameters. Birds are grouped based on habitat and food requirements as well as taxonomic groups, and the influence of the different estuary states on the abundance of each group is described. The estuary has relatively few waterbird species relative to other estuaries in the region (total of 474 birds and

24 species). These birds are dominated by gulls, terns, and include a few waders and cormorants. Mouth state, intertidal area, benthic invertebrate abundance and fish abundance are the main factors influencing birds (Table 2.5). The future development scenarios, which involved hydrological and hydrodynamic changes away from the natural condition, would not have measurable impacts on invertebrates and fish, but would make the estuary less attractive to birds as a result of habitat changes.

2.5.6 Step 6: Definition of present and desired conditions

The present condition of an estuary (and the desired future condition) is expressed as the degree of similarity to its natural state (as defined by the natural flow scenario prior to any human impacts) (DWAF, 1999; Adams et al., 2002; Van Niekerk et al., 2008a; Adams, 2013). This approach was adopted to explicitly reflect the absolute shift or modification in condition of an estuary from its natural (or unimpacted) state. This knowledge is especially important where environmental flow assessments inform biodiversity studies and conservation planning processes. Where coastal development pressures have made it near impossible to hindcast to a natural state, a “reference state” may be defined based on present development levels, e.g. as would be the case for highly modified European estuaries.

The desired condition of an estuary is typically a function of its present condition, its importance, protection status and/or other important resources uses (DWAF, 1999; Adams et al., 2002; Turpie et al., 2002; Hardie et al., 2006; Halliday and Robins, 2007; Van Niekerk et al., 2008a; Acreman, 2014b; Elliott et al., 2016; Tickner et al., 2017; Rossberg et al., 2017). Generally the more important a system, the higher the category that should be allocated for a desired condition (or resource protection status), e.g. important estuaries should be in a “good” condition. Protocols may also stipulate a minimum desired condition.

For example, in South Africa a “fair” category is viewed as the minimum desired condition for any estuary, where systems in a worse condition have to be restored to at least meet this category. The method can also be used to define a desired condition for a specific estuary parameter or ecosystem service to facilitate optimum resource use, e.g. enhance nursery function for important fisheries species, define mouth state for recreational use, inundate a floodplain for irrigation or restoration (Borja et al., 2010; De Jong et al., 2012; Acreman, 2014b; Kendy et al., 2017; Pitt and Kendy, 2017; Schlatter et al., 2017; Tickner et al., 2017; Elliott et al., 2016; Rossberg et al., 2017).

In assessing and categorising health, the term “trajectory of change” is used to define a directional change in the condition of abiotic and/or biotic components at the time of the assessment. This is often as a result of a component not yet adapting to the current configuration of influencing factors, e.g. it may still be in a state of flux as a result of a recent water resources development. A trajectory of change can be absent (close to natural or in stable modified state), negative (moving away from reference conditions) or positive (moving back towards natural). Ideally both the direction of change and rate of change need to be highlighted, e.g. short- to medium-term (1-5 years) and long-term (20 years).

The present health of the Palmiet Estuary was estimated at 67% similar to its natural state using the Estuary Health Index (EHI), translating into an ecological condition of a C (see Table 2.6). Major drivers of change in the system were a significant reduction in freshwater inflow (i.e. floods and baseflow), increased mouth closure, reduced sediment scouring and an increased nutrient loading from the catchment. Of special concern were the occurrences of macroalgal blooms in the estuary as a result of elevated nutrient levels coupled with an increase in closed / constricted mouth conditions. Respiration and die-off of these macroalgal blooms results in hypoxic or anoxic conditions in the estuary, which in turn puts the rest of the ecosystem under stress.

The Palmiet EFR study found that whilst the relatively small estuary was only of an average importance, it abuts the Kogelberg Biosphere and was a critical link in a regional conservation plan for the cool and warm temperate estuaries (Turpie et al., 2002; Turpie et al., 2012b). The recommended condition category was therefore an A or B. The study also concluded that the major pressures currently contributing to the degraded health of the Palmiet Estuary were poor water quality and reduction in freshwater inflow in summer and that these impacts can be mitigated with very little effort. Therefore, based on the recommended health status for a protected area and the ease with which this can be achieved for the Palmiet Estuary, the recommended condition category for was a Category B (Table 2.1).

Table 2.6: Summary of estuarine health scores and resultant category for present and hydrological Scenarios 1 to 6.

Variable	Weight	Hydrological scenario						
		Present	**1**	**2**	**3**	**4**	**5**	**6**
Mean Annual Runoff in million m^3 (% of natural)		163.7 (63.9%)	185.2 (72.2 %)	161.3 (62.9%)	148.7 (58.0%)	111.18 (43.4%)	163.7 (63.9%)	161.3 (62.9%)
Hydrology	25	67	72	66	65	57	67	74
Hydrodynamics (proxy mouth state)	25	46	47	43	43	36	46	77
Water quality	25	75	74	75	76	76	81	75
Physical habitat alteration	25	78	78	78	78	69	78	78
Habitat Health Score		**66**	**67**	**65**	**65**	**60**	**68**	**76**
Microalgae	20	74	75	74	73	69	73	72
Macrophytes	20	45	47	45	45	41	45	64
Invertebrates	20	60	70	65	68	55	65	75
Fish	20	80	80	65	60	50	80	80
Birds	20	81	81	79	78	74	80	93
Biotic health score		**68**	**71**	**66**	**65**	**58**	**69**	**77**
Estuary health score		**67**	**69**	**66**	**66**	**59**	**68**	**76**
Category		**C**	**C**	**C**	**C**	**D**	**C**	**B**

2.5.7 Step 7: Allocation of environmental flow

Taking the stance that, as a result of the complex nature of estuaries, scientists can more accurately predict the consequences of incremental flow modification, rather than "build" hydrological sequences, this method applies a "top down" scenario-based approach to setting environmental flows. This is achieved by deriving "hypothetical" conditions for the range of future hydrological scenarios (Step 1) in a similar way to which the present condition was derived (Step 6). The environmental flow for a specific estuary is then chosen as the hydrological scenario resulting in a condition best matching the desired condition (Step 6). If more than one hydrological scenario meets the desired condition, the environmental flow is set as the scenario providing the most water for development (i.e. highest yield). The matching flow scenario can be further refined through an iterative process.

In the Palmiet EFR study six future water resource development scenarios were evaluated, ranging from 72% to 43% of natural mean annual runoff (see Chapter 4, Section 4.3.2 for more detail on the development of hydrological scenarios). The scores for each of the different abiotic and biotic components are summarised in Table

2.6. In evaluating Scenarios 1 to 4, it was assumed that only the freshwater inflow from the Palmiet catchment would be modified and that other related anthropogenic activities (e.g. fishing, bait collection and human disturbance) will remain at present levels. In contrast, the hydrology for Scenario 5 and 6 was similar to Present State and Scenario 2 respectively, but a 66% reduction in nutrient input from the catchment was assumed.

Scenario 6 was recommended as the Environmental Flow Requirement for the Palmiet Estuary as it was the only scenario that elevated the estuary's condition to a B, the desired state for the system. The study also noted that an increase in freshwater inflow in itself (i.e. Scenario 6) would not be sufficient to ensure the recommended level of estuarine functioning. The study therefore also recommended a number of restoration measures to improve the present health of the Palmiet Estuary: improved agricultural practices in the catchment to reduce nutrient input (already being achieved through stricter European Union trading requirements); improve the compliance monitoring of fishing and bait collection activities on the estuary; restrict bait collection in closed phase; install a fish ladder at the gauging weir and an eelway at the dams to facilitate fish migration. The study concluded that any assessment of future water-resource developments should also include an evaluation of the success of the implementation of these non-flow related mitigation measures in restoring the habitat and protecting biota. Lastly, it was recommended that a Palmiet Estuary Management Plan be developed to assist with facilitating co-operative governance between the various authorities mandated with managing the estuary. In more recent studies similar recommendations have been stipulated in the water resource license agreements granted under a flow requirement study.

2.6 CONCLUSIONS

This study made a significant contribution to new knowledge by developing an approach that integrates multiple scale hydrological and complex ecosystem processes in order to detect change at a range of temporal scales. The method comprises seven basic steps (illustrated in Figure 2.1). Steps 1, 2, 5, 6 and 7 share significant commonalities with that of other international approaches, e.g. simulating natural and present river inflows as the basis of an evaluation (1); simplification of estuary into homogenous regions (2); deciding on the desired condition of a water resource (6); allocation of the environmental flows based on the systems importance and resource use (7). However a unique feature of the South African method described here is the identification of physical states (3) and the evaluation of the annual/seasonal distribution in physical states (4) and associated biotic responses (5), which couples the river flow (hydrology) and the downstream chemical and biological ecosystem processes in a predictive manner, embracing both the ecohydrological and ecosystem-based approaches.

Specifically, it addressed the challenge of mismatching temporal and spatial time scales often evident in the linking of abiotic and biotic process assessments (Barbosa and Chícharo, 2011; Vasconcelos et al., 2011). This challenge was overcome by sufficiently simplifying and aggregating the complexities of abiotic processes to appropriate temporal and spatial scales for analysis of biotic responses, using concepts such as physical states and zoning.

By using the natural state as a benchmark for expressing the present and desired condition, the latter conditions reflect the absolute shift or modification in an estuary from its un-impacted state. In addition to being an important requirement for biodiversity and conservation planning processes, this fixed starting point prevents “creeping normality” or “shifting baseline” syndromes and incremental deterioration of ecosystem function, that arise for example from recurring political and other pressures (Pauly, 1995; Diamond, 2005; Humphries and Winemiller, 2009; Borja et al., 2017)

The method is especially flexible in terms of data richness and can use a range of statistical or numerical methods. It can be applied in systems with very limited data using largely expert opinion/judgment to data-rich systems using sophisticated modelling technologies, indicating degree of certainty by confidence ratings (Van Ballegooyen et al., 2004; Ben-Hamadou et al., 2011). For example, the method uses conceptual, analytical/statistical or numerical modelling to provide predictive capabilities. While salinity is most often used as a proxy from change in desktop / rapid assessments, the method does allow for resolution of other physical and biogeochemical parameters in more detailed studies. Monitoring is viewed as an essential component in the overall process to increase confidence over time and assess whether flow allocations are achieving the desired state (i.e. health category) and associated ecological conditions, and ecosystem services, e.g. fish abundance must remain within 10% of present condition. The method’s flexibility in data requirements also lends itself to applications in countries that are either data limited or have large discrepancies in data quality between systems (e.g. South Africa, Australia and Portugal). As a result of its flexibility the method can be applied in a wide range of estuarine types, from large tidal dominated systems (e.g. United States of America) to small, microtidal systems along wave dominated coasts (e.g. South Africa and Australia).

While this chapter focused on the role of environmental flow (or river flow), it is not the only factor that contributes to changes in estuary function. For a specific estuary, it is also important to have a sound understanding of other human impacts. These include pollution (e.g. wastewater discharges), living resource exploitation (e.g. over-fishing) or physical destruction of habitat (e.g. construction of bridges, causeways, jetties and developments in floodplains) (Whitfield et al., 2012; Van Niekerk et al., 2013a). The cumulative or synergistic impact of all influences must be understood in order to set a realistic environmental flow, e.g. the desired condition may not be achieved for a particular system by only adjusting the river flow (Overton et al., 2014).

Driven by legislation and adopting an adaptive management approach, South Africa is continuously refining its environmental flow methodology, both incrementally on a study-to-study basis and in regular official method reviews (King and Harrison, 2011). Currently the method is in a review cycle where the new learning presented here, specifically relating the assessment of hydrological-hydrodynamic-biogeochemical aspects, will be incorporated. In support of environmental flow assessments, the government is also initiating long-term monitoring programmes (e.g. Cilliers and Adams, 2016) to validate the findings of earlier studies and to provide valuable data for future assessments.

CHAPTER 3

COUNTRY-WIDE ASSESSMENT OF ESTUARY HEALTH: AN APPROACH FOR INTEGRATING PRESSURES AND ECOSYSTEM RESPONSE

3.1 INTRODUCTION

Human activities are increasingly putting pressures on estuarine ecosystems and impacting their ability to sustain estuarine productivity and associated ecosystem services (Borja et al., 2016b). Managing, and potentially reducing human impacts on estuarine ecosystems, requires a scientific basis for management interventions and ultimately the need for spatial and temporal predictions of ecosystem health (Andersen et al., 2015). There is a growing need for science to inform policy (Borja et al., 2016b). Scientists should advance their science and provide policy makers with the best valuable information and timely knowledge (Borja et al., 2016b). Thus, in order to ensure optimum estuarine resource use in a changing world, it is critically important to understand the level of anthropogenic pressures on South African estuaries and concomitant health status.

In 2004 the first National Spatial Biodiversity Assessment was conducted by the South African National Biodiversity Institute (SANBI) to provide a high-level summary of the state of biodiversity within South Africa (Driver et al., 2005; Turpie, 2004). From an estuary perspective however, that summary was largely based on the findings of a health assessment conducted in 1995 (Whitfield, 2000), supplemented with information derived from a limited number of ecological flow requirement studies (Turpie, 2004). This was followed by the 2011 National Biodiversity Assessment (NBA) which covered the terrestrial, freshwater, estuarine and marine environments (Driver et al., 2012; Van Niekerk and Turpie, 2012).

This chapter describes the method developed, and applied, by me to assess the type and level of current anthropogenic pressure, as well as the ecological health status of a large number of South African estuaries in a data limited environment. It also provides a summary of the key pressures on, and ecological health of, nearly 300 estuaries on a country-wide scale. This chapter is updated from the article published in Estuarine, Coastal Shelf Science (Van Niekerk et al., 2013a).

3.2 THE NEED FOR INTEGRATIVE ESTUARINE HEALTH STATUS ASSESSMENTS

Ecological status assessments should take into account ecosystem structure, function and processes through the linking of natural physical, chemical, geographic and climatic factors (Borja et al., 2011; Borja et al., 2014; Mulik, et al., 2017). These should be integrated with anthropogenic impacts within the system concerned (Borja et al., 2014; Korpinen and Andersen, 2016; Borja et al., 2016a; Halpern et al., 2008, 2015). There is also a strong argument for the ecological integrity of an estuary to be evaluated using all available information, including as many biological elements as is reasonable in an overall ecosystem-based approach (Borja et al., 2008, 2009a; Chiu et al., 2014). This is often achieved through Integrative model-based assessments of estuary health, however these emerging approaches require significant data inputs and as yet are not widely applied (Chiu et al., 2014). Borja et al. (2011) reviewed a significant number of single-component indices used to quantify the ecological status of estuaries around the globe, focussing on microalgae, macroalgae, angiosperms, macroinvertebrates and fish components. Indices used ranged from subcellular to population level assessments. In most cases, the indices were data hungry and were thus applied over limited temporal and spatial scales.

Díaz et al. (2004) noted that rather than developing integrative methods, a plethora of indices had been developed for particular biological elements with little consensus or convergence on any one approach amongst environmental managers or scientists. Díaz et al. (2004) emphasised the need for a good understanding of the complexities of estuarine system functioning rather than simplifying and scaling down the system into smaller components. Similarly, Borja et al. (2009b) warned that using only biological indicators made it difficult to relate ecological status to a particular pressure responsible for estuarine deterioration. Distinguishing whether degradation results from flow modification, habitat degradation, over-exploitation of living resources, or pollutant stress, is essential to directing appropriate corrective actions (Borja et al., 2011). The need to integrate multivariate data into a single site-specific numeric value that can be interpreted by a non-specialist within a good-versus-bad gradient, often to meet some minimum legal requirement, was identified by Borja et al. (2011) (i.e., the Clean Water Act or the Water Framework Directive of Europe).

However, Borja et al. (2014) stresses that integration across indicators should be done in an ecologically-relevant manner and that assessment results should also reflect associated confidence in assessments. Integrated assessment is only as good as indicator information allows, and missing or omitting information on specific groups (e.g., biological components) can bias the assessment results (Borja et al., 2016b). Borja et al. (2016a) reviewed a range of marine and coastal integrative assessments e.g. Ecosystem Health Assessment Tool; the Marine Strategy Framework Directive in the Bay of Biscay; the Ocean Health Index (OHI); the Marine Biodiversity Assessment Tool, and the Nested Environmental status Assessment Tool. Globally the most widely used of these, the OHI assess the consequences of human impacts by calculating a weighted average for pressure, status and resilience targets (Halpern et al., 2012; Halpern et al., 2015). The OHI uses the relative deviation from a reference state. While the wide use of such assessment methods will ensure that future results are comparable between regions, it should be stressed that these large-scale integrative assessment approaches were developed for a more homogeneous marine environment, where measured response can be extrapolated with relative confidence to similar ecosystems/regions. This is often not the case for estuaries, where there is a high diversity of types and associated ecosystem responses to anthropogenic pressures over small areas.

A good example of an estuarine integrated assessment on a country-wide scale is the United States of America’s National Coastal Condition Report (USEPA, 2005). The assessment combines five primary indicators: water quality, sediment quality, benthic population and communities, coastal habitat loss and fish tissue contaminants, into a rating of the overall condition of the coastal ecosystem. Coastal monitoring data derived from national programmes (e.g. United States Environmental Protection Agency National Coastal Assessment Program) were used to develop these condition indices. A strength of this assessment is that it is supported by a comprehensive monitoring programme and clearly links individual pressures to their related ecosystems responses. However, it excludes a key pressure, namely the exploitation of living resources. More recent endeavours include the “Integrated Assessments for Watersheds Health” programme in which watersheds are scored with indices of “Watershed Health” (landscape condition, habitat condition, hydrologic condition, geomorphic condition, biological condition and water quality) and “Watershed Vulnerability” (risks from land use change, water use and wildfire) across large areas encompassing tens of thousands of watersheds (e.g. USDA, 2011; Esselman et al., 2011; EPA, 2013, 2014, 2015). Assessment scales range from statewide-scale efforts (e.g. California, Alabama and Tennessee) to targeted studies of specific ecological regions (e.g. Taunton River Basin, the Mobile Bay Watershed). Multimetric indices, or other methods, are used to integrate multiple indicators representing different healthy watersheds attributes. Assessments can range from screening-level assessments using GIS data layers to statistical and geospatial modelling of ecological attributes. The various state-wide assessments are then assimilated into a country-wide summary. This type of assessment provides a good, systemic overview of the different pressures on the estuaries from the upper tributaries down to the coast. However, it dilutes estuary-specific responses to these pressures as it reduces complexity, a key estuarine feature, in order to standardise assessment results across such broad spatial scales. Overall, this approach provides a good starting point for focussing management interventions and further detail site-specific monitoring and evaluation initiatives.

Borja et al. (2004, 2009b) undertook an integrated estuarine ecological status assessment in Spain by including physicochemical, hydromorphological and biological (phytoplankton, macroalgae, macroinvertebrates and fishes) elements and integrating these using a decision tree. This enabled the establishment of clear links between pressures and ecosystem responses, with the results expressed in a management friendly output. Whilst robust and scientifically defensible, the method is data hungry and was only applied to three estuary types within Spain. Ondiviela et al. (2015) also evaluated ecological integrity at a biogeographical scale (on nine medium size estuaries) in northern Spain based on a conceptual model which systematically evaluated how human uses and stressors affect ecosystem functioning. The method allows for a sound regional evaluation of the anthropogenic pressures and estuarine health showing that loss of connectivity and degrading abiotic process was the major driver of declining health. The method integrated a number of well-know indexes and is therefore scientifically strong, but again very data hungry.

A country-wide assessment of Australia's catchments, rivers and estuaries was carried out as part of the National Land and Water Resources Audit (NLWRA) in 2002, using a qualitative set of general health criteria evaluated by an expert panel. Elements included land-use, hydrology, tidal regime, floodplain condition, estuary use, estuarine ecology, and the presence of pests and weeds. The audit covered 972 water-bodies and concluded that more than half (482) were near pristine, although estuary health varied greatly between populated and unpopulated Australian states (NLWRA, 2002). The approach was systematic and repeatable. A wide range of estuary types was accommodated and used as a proxy for susceptibility to pressures. The method accommodated data rich and poor estuaries, using a range of available information and data proxies. Unfortunately, higher trophic levels were represented by only a fish index and near pristine estuaries were not included in the quantitative health assessment, thus providing future assessments with little or no benchmark information. On a regional-scale, New South Wales developed an integrative monitoring and reporting approach that focusses on primary production (chlorophyll a, macroalgae and turbidity), habitat (seagrass, mangrove and salt marsh) and fish (OEH, 2013). An integration rule was set that at least one indicator from a minimum of two indicator groups must be populated, for example at least one eutrophication and one habitat or fish indicator.

Over the past decade, the assessment of Estuarine health in South Africa has progressed from a limited integrative index (Harrison et al., 2000) used for a snapshot country-wide survey (based on only geomorphology, icthyofauna, water quality and aesthetics), to the more comprehensive EHI (four abiotic and five biotic elements) used as part of Ecological Flow Requirement studies (previously called Resource Directed Measures (RDM)) (DWAF, 1999; Adams et al., 2002). While the EHI predates the international approaches and indices discussed above, it contains best practice elements such as assessment abiotic and biotic components, allowing for the linking of specific pressures to ecosystem responses; and is suitable for both data-rich and data-limited environments. The EHI forms the basis of the recent South African National Health Assessment discussed in this chapter.

3.3 MATERIALS AND METHODS

3.3.1 Key estuarine features

Any health assessment needs to consider the diversity of different types of estuaries in South Africa. Three biogeographical regions characterise the South African coast; namely the Cool Temperate west coast, the Warm Temperate southern and south-east coast, and the subtropical east coast (Emanuel et al., 1992; Harrison, 2002; Turpie et al., 2000) (Figure 3.1). Rainfall patterns in these regions also vary significantly (Davies and Day, 1998; Lynch, 2004; Schulze and Lynch, 2007; Schulze and Maharaj, 2007). Catchment size varies significantly, ranging from very small (< 1 km^2) to very large (> 10 000 km^2), with those in the Cool Temperate region tending to be larger than those in the Warm Temperate and Subtropical regions (Jezewski et al., 1984; Reddering and Rust, 1990). In all, the annual runoff of South African rivers is highly variable and unpredictable in comparison with larger Northern Hemisphere systems, fluctuating between floods and extremely low to zero freshwater inflow (Poff and Ward, 1989; Dettinger and Diaz, 2000; Jones et al., 2014). (Figure 3.2). The tidal range around the coast is microtidal (< 2 m tidal range) but high wave energy, makes it a wave-dominated coast (Cooper, 2001).

Most estuaries are highly dynamic and shallow (average water depth 1–3 m). South Africa has nearly 300 relatively small estuaries with over 70% being < 50 ha. Strong wave action and high sediment availability results in more than 90% of the estuaries having restricted inlets (or mouths) while more than 75% close for varying periods of time due to sand bar formation across the mouth (Whitfield, 1992; Cooper, 2001; Taljaard et al., 2009a; Whitfield and Elliott, 2011, the findings of this study).

3.3.2 Spatial delineation of South African estuaries

Estuaries exhibit a high spatial heterogeneity, with each system characterised by its own unique geomorphology and physicochemical environment. The full extent of an estuary is often not known (i.e. tidal limit or back-flooding mark) and this makes it difficult to delineate the dynamic spatial area where estuarine processes occur within each system, the so-called “estuary functional zone”.

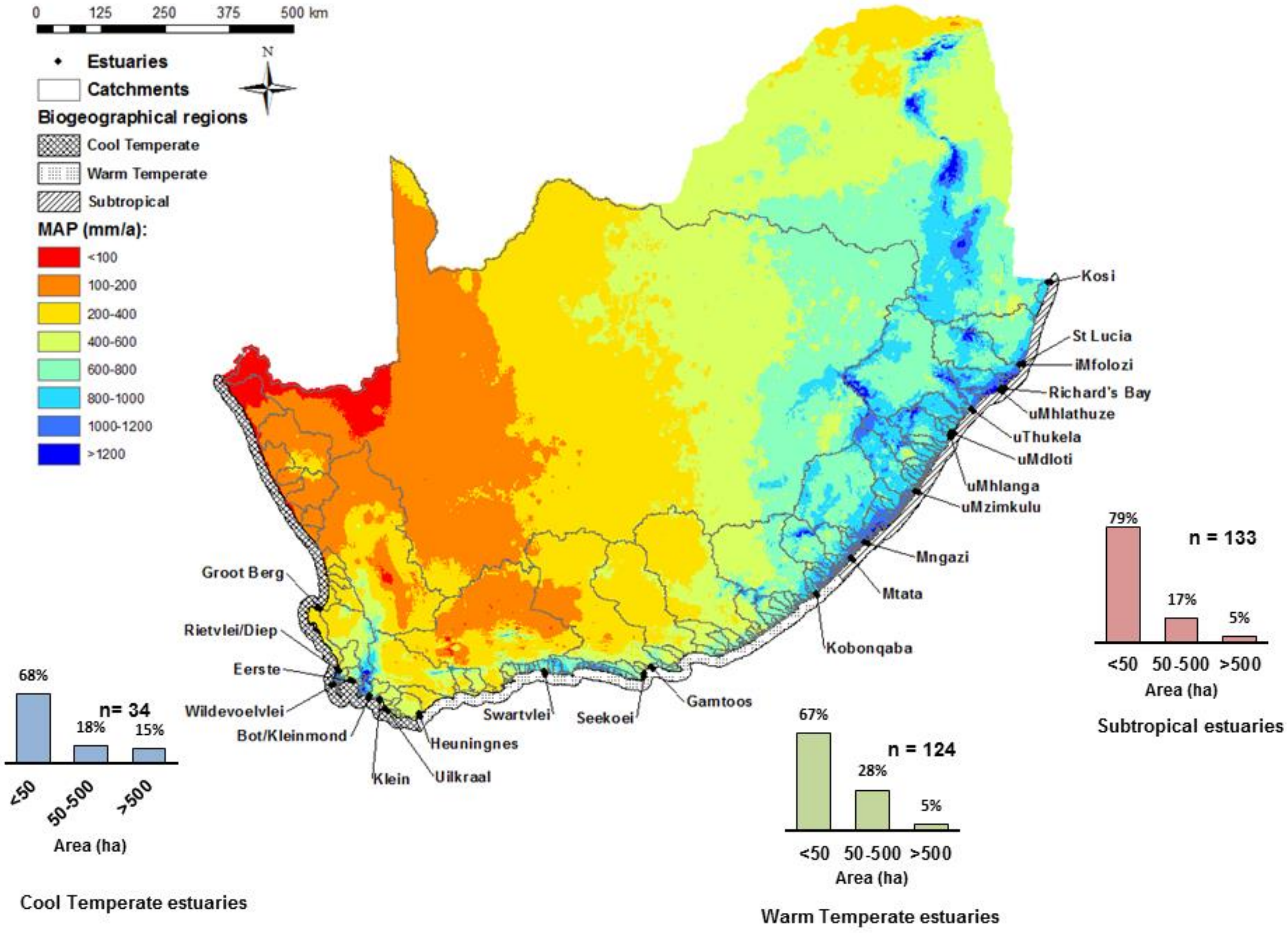


Figure 3.1: Map showing the three biogeographical regions, relative catchment size, mean annual precipitation (MAP) (in mm/a) and estuary size distribution (in ha) for South Africa.

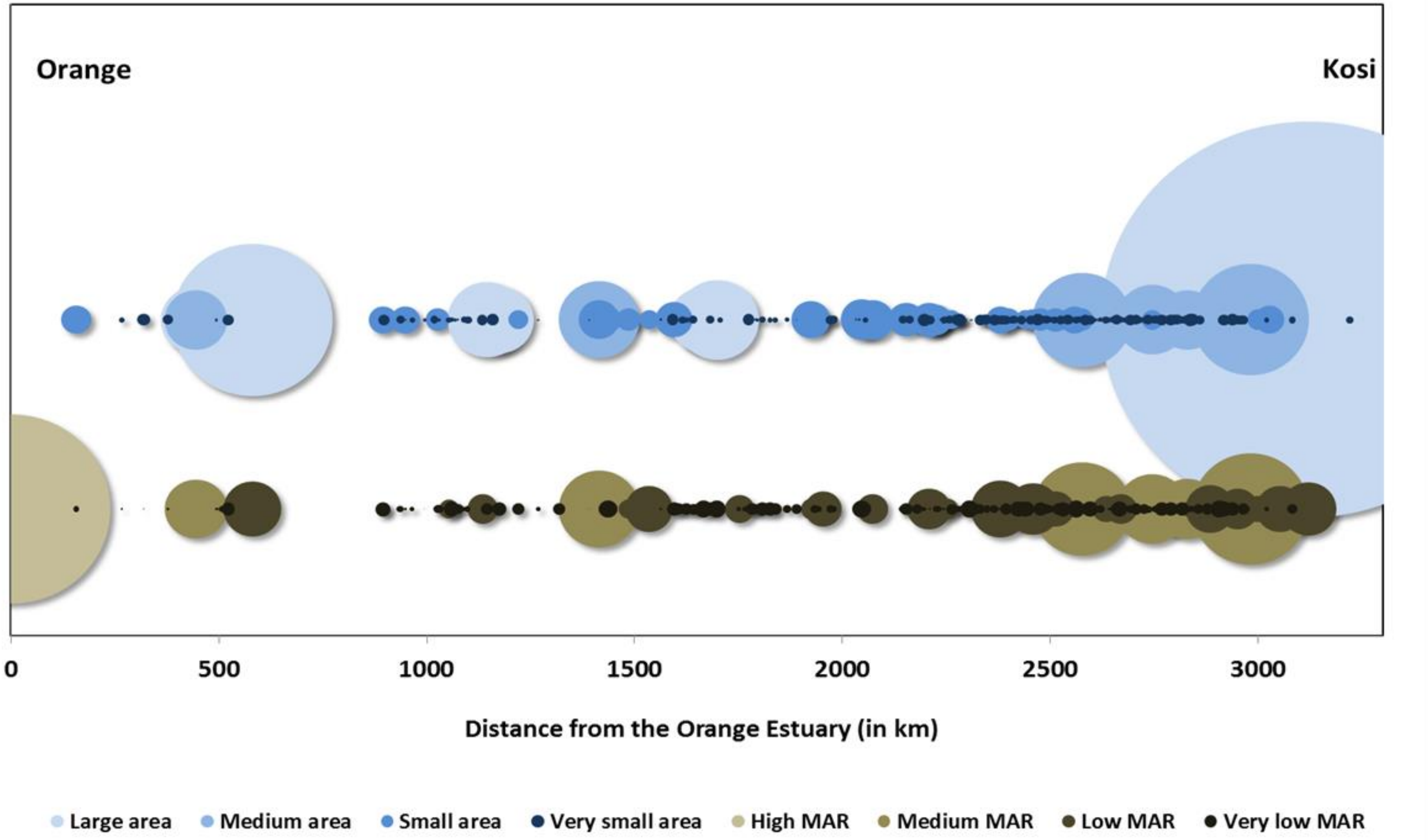


Figure 3.2: A visual illustration of the variability in South African estuary size indicated in blue (top) and mean annual runoff (MAR) indicated in brown (bottom). Estuary size categories: Large area (>1000 ha), Medium area (500-1000 ha), Small area (50-100 ha) and Very small area (<50 ha). Mean annual runoff categories: Large MAR (> 10 000 x 10^6 m^3), Medium MAR (1 000 – 10 000 x 10^6 m^3), Low MAR (100 – 1 000 x 10^6 m^3) and Very low MAR (<100 x 10^6 m^3).

In South Africa the estuary functional zone is defined by the +5 m topographical contour (as indicative of 5 m above mean sea level) and includes all the estuarine open water area; estuarine habitats (sand and mudflats, rock and plant communities) and adjacent floodplain area whether developed or undeveloped. It therefore encompasses not only the estuary water-body but also all the habitats that support physical and biological processes that characterise an estuarine system. All permanent coastal water bodies (i.e. not ephemeral water bodies) sporadically or permanently linked to the sea were regarded as estuarine systems. Using existing estuarine vegetation and fish data sets, published and unpublished literature, as well as anecdotal information, all systems were evaluated by an expert panel and rated as to functionality (Van Niekerk and Turpie, 2012). Very small permanent coastal water bodies (<500 m in length) were excluded from this assessment, with the exception of small systems for which sufficient data indicating that they were biologically important as estuaries existed. Rivers or streams entering the sea as waterfalls were also excluded.

Nearly 300 functional estuarine systems along the South African coastline were mapped. The functional zone and open water areas for each estuary, were digitised using Spot 5 imagery (2008) and Google Earth. For the most part, images were relatively cloud free but where cloudy conditions obscured SPOT 5 images, Google Earth© images were used. The 5 m topographical contour (obtained from the South African Chief Directorate: Surveys and Mapping) was used as the boundary to delineate the estuary functional zone. Where the 5 m contour was not available in digital format, orthophotographs (1:10 000) were scanned, georeferenced and the 5 m contour digitised. Where no orthophotographs were available (13 systems), floodplains were mapped from Spot 5 imagery using changes in topography and vegetation types as indicators. The upstream boundaries of estuaries were determined as the limits of tidal variation or salinity penetration, whichever penetrated furthest. This is in accordance with recent scientific studies and the administrative definition of a South African estuary (DWAF, 1999). Wherever possible the upstream boundaries were derived from the literature, expert judgment or field observations. For most temporarily open/closed estuaries (TOCEs), especially if no data were available, the upper boundaries were taken as the +5 m topographical contour (bearing in mind that the tidal range in South Africa is 2 m and the sand bars of closed estuary mouths can sometimes build up to a height of 4.5 m above mean sea level). The upper boundaries were also screened against other existing spatial delineations, e.g. the KwaZulu-Natal estuaries database (Version 1.00.02) and the delineation developed for Durban estuaries (Forbes and Demetriades, 2010) with preference given to data from the larger scale studies. Spatial files were converted to Google Earth (KMZ formats) and sent for review to the 80 members of the South African Consortium for Estuarine Research and Management (CERM) for comment.

3.3.3 Key pressures assessment

A number of key pressures were identified and broadly ranked (high, medium, low, none) for the estuaries of South Africa based on a review of available data (e.g. hydrological modelling, freshwater-use permits issued), spatial analysis and expert opinion (Table 3.1). Key pressures were also visually examined on Google Earth© to assess extent of anthropogenic alteration (e.g. canalisation, development, infilling or discharges) in the estuary functional zone by a team of regional experts in a workshop environment to confirm the rankings. The visual assessment and ranking were also confirmed with supporting data extracted from the Nelson Mandela Metropolitan University Botanical Database (Colloty, 2000; Colloty et al., 1998; Adams et al., 2004; Adams et al., 2012a), the unpublished fish survey data reports (Council for Scientific and Industrial Research (CSIR), unpublished data; Harrison, 2000, 2005), Lamberth & Turpie (2003) and the 40 CSIR “Green series” Part I and II reports published between 1980 and 1993 (Heydorn, 1986; Heydorn and Bickerton, 1982; Heydorn and Grindley, 1981-1985; Heydorn and Morant, 1986 -1990; Heydorn & Tinley, 1980). In assessing pollution pressure, the 2006 land-cover information was considered as a proxy for the degree of catchment transformation. However, the data were of poor quality and transformed land was often misrepresented as near natural in the analysis. This spatial analysis was therefore also moderated by expert opinion during the workshop using Google Earth images.

Based on the data obtained, five key pressures were identified: freshwater flow modification; pollution; exploitation of living resources; habitat destruction; and manipulation of the tidal inlet. For each of the five key pressures identified in Table 3.1 (column 1), specific data sets, or proxies (Table 3.1, column 2), were used to assess the extent of those threats to individual estuaries within each of the three biogeographical regions.

Table 3.1: Data references for the five key pressures for South African estuaries.

KEY PRESSURE	DATASET	SOURCE
Flow modification	Direct abstraction Dam Development Small farm dams Inter-basin transfer schemes Wastewater treatment works Hardening of catchment	• Historical national assessment (Jezewski et al., 1984; DWA, 1986) • Water Situation Assessment Model (Schultz and Watson, 2002) • Flow requirements studies (RDM)* • Field observations**
Pollution	Municipal Wastewater Industrial Wastewater Stormwater runoff Agricultural runoff	• South African National Programme of Action for Protection of the Marine Environment from Land-based Activities (DEAT, 2008) • 2008 National land-cover layer (South African National Biodiversity Institute) • Flow requirements studies (RDM)*
Exploitation of living resources	Fishing Bait collection	• Lamberth and Turpie, 2003 ** • Subsistence bait collection** • Habitat destruction due to bait collection**
Land-use & development (habitat modification)	Bridges Mining Ports & marinas Dredging Low-lying developments Land reclamation	• Spot 5 images • Google Earth • National data sets (2008 National land-cover layer; Colloty, 2000; Colloty et al., 1998) • Flow requirements studies (RDM)* • Field observations**
Mouth manipulation	Artificial breaching Canalisation Redirecting/diversion of the outlet	• KwaZulu-Natal Estuaries database • Flow requirements studies (RDM)* • Field observations**

* Appendix A list the 24 South African estuaries on which environmental flow studies have been done at the time of the study.

** Based on field observations by estuarine experts / specialists

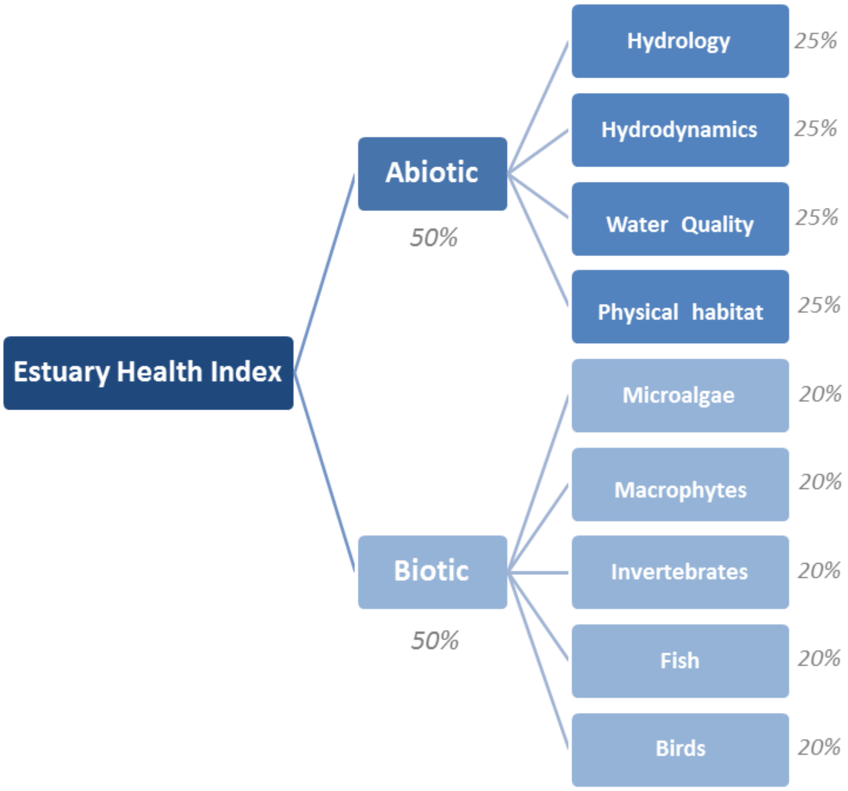


Figure 3.3: Components and weightings of the Estuarine Health Index (DWAF, 1999)

3.3.4 Estuarine Health

Assessment of the health of South African estuaries was based on the EHI developed for South African ecological flow requirement studies (See Section 2.4, DWAF, 1999). The assessment considered both abiotic and biotic components, namely hydrology, hydrodynamics and mouth condition, water chemistry, sediment processes, microalgae, macrophytes, invertebrates, fish and birds (Figure 3.3). Both abiotic and biotic variables are evaluated because the exact relationships between them are often not well understood and because the biotic responses to specific abiotic variables generally occur after a lag period (Whitfield et al., 2008).

The method requires that a multidisciplinary group of estuarine scientists assesses the health of a particular estuary in a workshop setting and is based on their collective understanding of likely impacts affecting that system (DWAF, 1999). Available information and expert knowledge are used to build a “mental picture” of the probable natural state of each estuary and the changes that have occurred under current conditions. For each of the components (abiotic and biotic), the change in health is estimated as a percentage (0 – 100%) of the natural state. Scores are weighted (25% for each abiotic and 20% for each biotic component) and aggregated (50:50) to provide an overall score that reflects the present health of the system as a percentage of that under natural conditions. The EHI score in turn corresponds to an Ecological Management Category (Table 2.1) to describe the health of the estuaries using six categories, ranging from natural (A) to critically modified (F). The formal EHI had only been applied to 24 estuaries in South Africa at the time of the assessment. Consequently, regional expert panels were convened to evaluate each estuary within their region. Individual health assessments were translated into a health category (A to F) or health state (excellent to poor) as shown in Table 2.1. These can, in turn, be further aggregated for homogenous estuarine types or specific management units (e.g. protected areas or Water Management Areas).

In order to develop a clear understanding of the status of estuarine health within South Africa, large complex systems such as the Lake St Lucia system were disaggregated into separate sections, namely Lake St Lucia and the uMfolozi Estuary. Similarly, the uMhlathuze Estuary and Richard’s Bay Harbour were evaluated separately. Consequently, the country-wide health assessment was conducted for a total of 291 estuaries.

3.4 RESULTS AND DISCUSSION

3.4.1 Key pressures assessment

3.4.1.1 Flow modification

The pressure assessment indicated that 4% (11 systems) of South African estuaries are significantly threatened (high) by freshwater inflow modification, with especially the large permanently open estuaries in the Cool Temperate region being affected, e.g. Orange, Great Berg and Olifants (Figure 3.4a). A further 18% of South African estuaries are moderately threatened (medium) of reduced flow modification, with the highest proportion in the Cool Temperate (47%) and Warm Temperate (19%) regions. The majority of estuaries are slightly threatened with respect to flow modification; these being mainly located in the subtropical (83%) region.

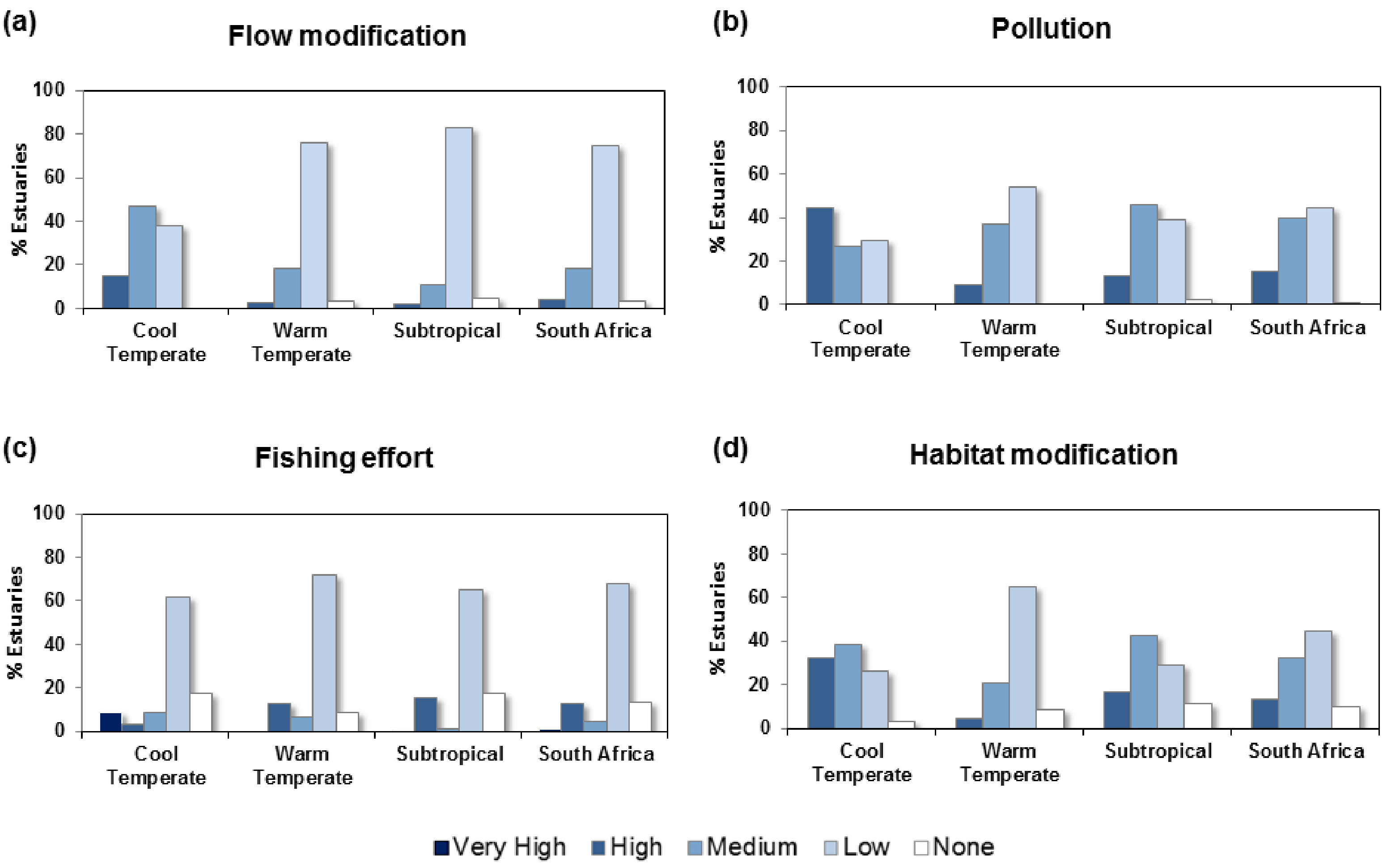


Figure 3.4: Quantification of the level of flow modification (a), pollution (b), fishing (c) and habitat modification (d) pressures for the three biogeographical regions in South Africa

Overall, less than 4% (10 systems) of South African estuaries are not threatened by flow modification – most of these systems are fed by small catchments with limited human development. The increasing human population and a rapidly growing demand for more freshwater constitutes a major threat to estuaries on a global scale (Rosenberg et al., 2000). Run-of-river freshwater abstraction, large impoundments and small farm dams are mainly responsible for the decrease in the overall quantity of freshwater that reaching South African estuaries (Whitfield and Wooldridge, 1994).

On the other hand, inter-basin transfer schemes, waste water treatment works and increased runoff from "hardened" catchments (e.g. road networks) are responsible for increased freshwater inflow to systems that historically received a lower inflow (Nirupama and Simonovic, 2007). Alteration of the freshwater inflow into estuaries impacts directly and indirectly on the ecological functioning of these systems (Whitfield and Bruton, 1989; Adams et al., 1999; Scharler and Baird, 2000). Examples are changes in mouth closure frequency that have been directly linked to decreased freshwater inflow and include the Kobonqaba and Uilkraals estuaries that historically were permanently open systems but closed for the first time in 2010 (unpublished records).

Accurate river flow data from the recent (past 10 years) ecological water requirement studies are available for 24 estuaries. For most of South African estuaries, very little quantitative data are available on seasonal flows, or the degree to which historical seasonal low flows have been altered. Most data dates back to 1986 when the last country-wide study addressing this issue was conducted by the Department of Water Affairs (DWA). Thereafter the Water Situation Assessment Model (WSAM) was developed in 2005 as a macro-scale water resource planning tool for the DWA. The WSAM provided an annual summary on the availability, supply and utilisation of water resources at a national, regional and catchment level for both current and projected future situations (Schultz and Watson, 2002). Unfortunately, small changes in annual flow rates, provided as percentage change in Mean Annual Runoff (MAR), often mask the degree to which seasonal low flows are modified. For example, while the MAR may only be modified by 10%, the seasonal low flows may be altered by as much as 50% due to baseflow abstraction or elevated by 20% as a result of agricultural return flows. Validated against results obtained from detailed EWR studies, the WSAM proved to be accurate within +/- 10% for catchments with small farm dams, direct abstraction and land-use change. However, the WSAM significantly underestimated flow reduction in catchments where large dam development has occurred and, if no alternative information source was available, expert judgment was used to provide the estimated reductions or increases.

3.4.1.2 Pollution

The pressure assessment indicated that 15% of South African estuaries are under severe (high) pollution pressure, with the majority of those under threat being located in the Cool Temperate (44%), followed by the subtropical (13%) and Warm Temperate (9%) regions (Figure 3.4b). Systems moderately (medium) threatened by pollution predominantly occurred in the subtropical (46%) and Warm Temperate regions (37%). Overall, less than 1% (3 systems) of South African estuaries are subject to minimal pollution pressure, with most of these being fed by small catchments located in national or provincial protected areas.

According to DEAT (2008), the four key sources of pollution impacting estuaries are municipal wastewater, industrial wastewater, stormwater runoff and agricultural runoff. Municipal wastewater treatment works generally discharge effluent into estuaries with some of the largest discharges being in the Cool Temperate region, e.g. Eerste (54 494 m^3 per day), Diep (44 126 m^3 per day) and Wildevoëlvlei estuaries (11 577 m^3 per day). In the subtropical region, impacted estuaries include the Mhlanga Estuary (25 000 m^3 per day) (DEAT, 2008). The amount of effluent discharged from municipal wastewater treatment works almost doubled between 1991 and 2004, mainly as a result of the rapid increase in the coastal population growth (DEAT, 2008). The larger urban centres along the coast have reticulation systems for municipal wastewater and most of the discharges to estuaries are subject to treatment (sometimes secondary or even tertiary). However, overloaded and deteriorating infrastructure often malfunctions, causing regular spillage and seepage of untreated wastewater into estuaries. Smaller coastal communities often do not have reticulated sewage systems and alternative wastewater systems such as septic tanks and French drains are typically used for the treatment of sewage. Spillage or seepage from these systems may have detrimental effects on the aquatic ecosystem and human health (DEAT, 2008; Whitfield et al., 2008).

In the case of urban estuaries contaminated commercial and industrial stormwater runoff is a major concern for estuaries located in urban areas. Stormwater runoff contains an array of pollutants ranging from microbial contaminants, excessive nutrients and organic matter (e.g. linked to sewage from informal settlement areas) to high suspended solid loads and toxic chemicals such as trace metals and hydrocarbons (Vermeulen and Wepener, 1999; Binning and Baird, 2001; Mzimela et al., 2003; Jackson et al., 2005; Jackson et al., 2009). Solid waste or litter may also enter estuaries through the stormwater system and this needs to be managed to avoid adverse effects. This is especially relevant in South Africa because of the large informal settlements around cities and towns that are not connected to reticulated sewage systems.

While direct industrial wastewater discharges into South African estuaries are limited, there are concerns with the discharge of such effluents into small and/or less dynamic, and therefore ecologically sensitive estuaries. At present only one estuary in the Cool Temperate region, the Great Berg Estuary, receives industrial effluent. Approximately 130 000 m^3 of fish processing effluent is released daily into the lowermost reaches of the estuary during the fishing season. Although direct industrial effluent discharges into estuaries may be low, upstream inputs may be substantial and have a significant effect on water quality, e.g. uMzimkulu (sugar mill) and Thukela (paper mill) rivers.

Inappropriate agricultural practices also affect the water quality of estuaries, these include the introduction of nutrients originating from over-fertilization (e.g. Gamtoos), increase in suspended sediment loads as a result of poor catchment management (e.g. uMfolozi), and the introduction of toxic chemicals (e.g. herbicides and pesticides) into these systems (Snow et al., 2000; Bate et al., 2002; Snow and Taljaard, 2007). Clearing of floodplains for agricultural purposes also threatens a number of estuaries, especially in the rural regions of the Eastern Cape where there has been significant land transformation (e.g. Mtata and Mngazi estuaries) (Wooldridge and Deyzel, 2012). Sugar cane farming along the KwaZulu-Natal coast has transformed over 200 km of coastline from Durban to Mtubatuba, resulting in significant loss of coastal wetlands and infilling of estuarine habitat. Forestry and its influence on the water table is also becoming a concern along this already highly transformed part of the South African coastline.

3.4.1.3 Exploitation of living resources

An assessment of the fishing pressure on South African estuaries indicates that about 1% (4 systems) of the estuaries are subjected to excessive (very high) fishing pressure (Figure 3.4c). Most of this is confined to the Cool Temperate region where excessive fishing pressure occurs in over 9% (3 systems) of estuaries as opposed to 1% (1 subtropical system) or less in the other biogeographical regions. In addition, 13% of estuaries are under severe (high) fishing pressure, ranging from 13% of those in the Subtropical and Warm Temperate regions to 3% (1 system) in the Cool Temperate region, with 4% (13 systems) of estuaries are subjected to moderate (medium) pressure (Figure 3c). Only 14% of estuaries are not under some (low) fishing pressure as a result of having national, provincial or municipal protection status. Fishing effort, total catch and catch-per-unit-area were also assessed and indicated that although the total catch appeared to be equally distributed among the three biogeographic regions, the Cool Temperate region is severely threatened by overexploitation on a catch-per-unit-area basis (60 kg.ha.yr-1, Figure 3.5).

Estuaries function as nurseries and provide vital habitat for a number of commercially important estuary-associated marine fish species (Lamberth and Turpie, 2003; Pradervand et al., 2003; Meynecke et al., 2008). The over-exploitation of living resources by subsistence, recreational and commercial fisheries can have both direct and indirect consequences for marine and estuarine ecosystems (Barange et al., 2004; Whitfield and Cowley, 2010).

These consequences include changes in population size, biomass, sex-ratios, size/age distributions, community composition and trophic structure (Pauly et al., 1998; Blaber, 2000; Whitfield and Cowley, 2010). In areas where there has been a continuous and systematic overexploitation of target species, recruitment failure has been recorded as juvenile and adult fish are “mined out” of the population, lowering the overall reproductive capacity of the population (Hutchings et al., 2008; James et al., 2008a). The effects of vulnerable life-history characteristics such as estuary-dependence, “natal homing” and predictable aggregations are exacerbated by anthropogenic influences such as fishing and flow modification, ultimately leading to recruitment failure or even extirpation (Lamberth and Joubert, 2000; Griffiths and Lamberth, 2002).

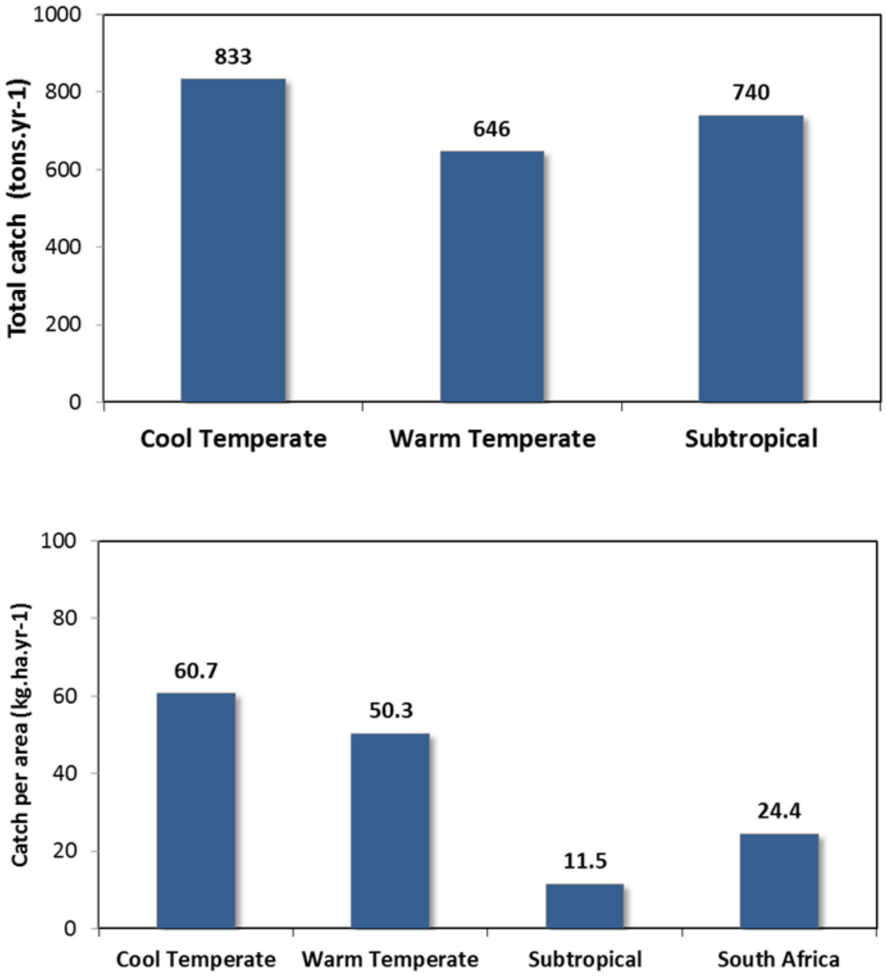


Figure 3.5: Total catch in tonnes (a) and kilograms per hectare (b) of estuarine area in the three biogeographic regions

The larger estuaries have been most affected by the overexploitation of linefish species and this requires urgent management intervention to protect nursery function and ensure that fish stocks do not collapse (Pradervand and Baird, 2002). Both legal and illicit use of gillnets is problematic as these cause immense damage because of high mortalities and selectivity for certain species (Marais, 1985; Hutchings and Lamberth, 2003; Hutchings et al., 2008).

It is estimated that bait collection occurs in 84% of South African estuaries. However, in most of these systems the threat of overexploitation is low due to the high resilience of key species within the invertebrate communities targeted (Wynberg and Branch, 1991; Hanekom and Baird, 1992). However, habitat destruction and the status of non-target species were not included in the current assessment and bait collection could potentially pose a threat, especially to temporarily open closed estuaries (TOCEs) during closed mouth conditions and low water levels (Wynberg and Branch, 1994; Wooldridge, 1999). Exploitation of invertebrates used as bait by recreational and subsistence anglers is a ubiquitous activity in most estuaries around the South African coast. Commonly targeted species include *Upogebia africana* (mud-prawn), *Callianassa kraussii* (sand-prawn), *Solen spp.* (pencil bait), *Arenicola loveni* (bloodworm) and a ribbon worm *Polybrachiorhynchus dayi* (Branch et al., 2002; Branch et al., 2010). Utilization of these living resources and the impact on other organisms and associated habitats may be persistent (e.g. close to urban environments) or more seasonal in nature (e.g. holiday resorts). In some estuaries, the impact of bait collection is considered to be severe (de Villiers and Hodgson, 1999). Bait collection not only removes targeted species, but also results in habitat destruction and a reduction in the biomass of non-target species as a consequence of inappropriate collection methods, e.g. spades and pitchforks (de Villiers and Hodgson, 1999).

3.4.1.4 Land-use and development

Overall, 13% of South African estuaries are subject to severe (high) pressure from habitat modification and development, mostly in the Cool Temperate (32%) and Subtropical (16%) regions. Approximately 5% (6 systems) of estuaries in the Warm Temperate region are under severe pressure (Figure 3.4d). However, an additional 33% of estuaries in South Africa are under a moderate (medium) degree of habitat modification pressure, with estuaries in the subtropical (43%) and the Warm Temperate (38%) regions being the most affected. Less than 10% of all estuaries in South Africa are under no pressure from development; most of these being confined to national, provincial or municipal protected areas.

Land-use changes and development affecting estuaries, including changes in their catchments, have numerous and far-reaching consequences for the health and ecological functioning of these systems. The degree to which estuaries have been modified was assessed visually using Google Earth© and Spot 5 imagery, supported by country-wide data sets, flow requirement studies and field observations. The assessment indicated that the most severe and widely occurring land-use changes and developments affecting South African estuaries are road bridges, mining and port and marina developments, together with their associated dredging activities. Some of the more notable impacts include changes to erosion/depositional cycles, direct habitat loss during construction, changes to flow velocity and circulation patterns, reduced tidal prism, premature mouth closure, smothering of submerged habitats by excessive sedimentation, increased turbidity, reduced primary production, destruction of riparian and instream habitats and biota, contamination and associated poor water quality (Morant and Quinn, 1999; Whitfield et al., 2012).

Within these estuaries the physical changes negatively affect the biota, with cascading effects through the food web. Ultimately changes in the structural habitat of an estuary can result in local extinctions, change in population size or biomass, community composition and structure, ratios of generalist to specialist biota and life-history patterns (Morant and Quinn, 1999; Vorwerk et al., 2003; Levin and Stunz, 2005; Niklitschek and Secor, 2005; Lamberth et al., 2008, 2010). They can also reduce the carrying capacity of an estuary, especially for species at higher trophic levels. Habitat degradation can also render an estuary prone to invasion by more generalist alien species such as the invasive North America cordgrass *Spartina alterniflora* and the Asian mollusc *Tarebia granifera* (Adams et al, 2012b; Appleton et al., 2009; Jones et al., 2017).

3.4.1.5 Estuary mouth manipulation

An assessment of the KwaZulu-Natal estuaries database, together with expert input for the other regions, indicated that 16% of South African estuaries are breached artificially. Most of these systems are clustered around urban centres in the Cool Temperate and subtropical biogeographical regions. Artificially breached systems account for 62% of the total estuarine habitat in South Africa.

As a consequence of inappropriate floodplain development, estuary mouths are manipulated in order to prevent property damage. Mouth manipulation includes artificial breaching (e.g. Bot, Swartvlei, Heuningnes, Mhlanga, uMdloti estuaries), canalisation (e.g. Seekoei, Zandvlei, Great Berg estuaries), and the creation or diversion of an outlet (e.g. uMfolozi mouth). Estuary mouth manipulation may change the type of estuary, e.g. from a temporarily open to a permanently open system. In most cases the need for mouth manipulation is the result of inappropriate development in the estuary functional zone.

Estuary mouth manipulations are often driven by an increase in closed mouth conditions, which in turn are linked to water resource development. Artificial breaching is the most pervasive of these manipulations and occurs when there is back-flooding of adjacent low-lying developments (Whitfield et al., 2012). For example, reduction in freshwater flow can lead to an estuary mouth being closed more frequently and for longer periods, leading to increased sand bar levels and back-flooding of adjacent low-lying developments before breaching. An increase in closed-mouth conditions also causes increased retention and gradual freshening of the estuarine water due to restricted marine inputs and the continuous seepage losses through the sand bar which is offset by limited surface or groundwater freshwater inflow. These more stagnant conditions, especially where there is nutrient enrichment, can cause nuisance algae or macrophyte blooms (e.g. Bot, Zandvlei), which are often intentionally flushed out of the system by artificial breaching of the estuary mouth. However, the artificial breaching of an estuary mouth is often not timed to coincide with natural freshwater inflow events and can have potential cascading effects on the physico-chemistry of the estuary and the biological components.

A change in natural estuary mouth dynamics often results in increased sedimentation. This is often caused by a decrease in flushing potential when premature breaching takes place at low water levels. It can also be due to the ingress of marine sediments when an estuary mouth is kept open artificially for long periods and ultimately leads to premature inlet closure. Changes in salinity, sediment structure, tidal flushing and biogeochemical processes can have severe effects on primary productivity, species composition, recruitment of larval fish and invertebrates (Whitfield et al., 2012). In addition there are changes to the normal migration of marine species back to sea, and genetic exchange between estuaries and the adjacent marine environment.

Mouth manipulation is mainly a result of South African legislation not recognising back-flooding areas as being part of the estuary functional zone, which is not restricted to the area below the high water mark. Consequently, inappropriate low-lying developments (i.e. housing, urban infrastructure, golf courses or agricultural land) within the back-flooding areas (i.e. that inundated under natural breaching levels) are being protected at the cost of the natural estuarine environment. However, the

Integrated Coastal Management Act, promulgated in 2009, now makes provision for back-flooding to be recognised in proposed coastal developments.

3.4.1.6 Emerging pressures on South African estuaries

In addition to the pressures affecting estuaries identified by the more systematic approach, three additional emerging pressures were highlighted as being of significant concern and in need of future investigation: toxic substance and metal pollution in sediments, aquaculture and discharges from desalination plants.

Despite potential ecological and human health risks posed by toxic substances such as trace metals and persistent organic pollutants (e.g. herbicides and pesticides), there is very little research on, and monitoring of, the distribution and accumulation of these compounds in South African estuaries. Expert knowledge was used to identify estuaries where this was considered to be a significant pressure.

Similarly, while the detrimental impacts of marine and freshwater aquaculture are currently not evident in South African estuaries, aquaculture was identified as an activity that can contribute to the destruction of estuarine habitats as well as the pollution of coastal waters (Pauly et al., 2002). If not managed effectively, aquaculture operations can also promote the spread of microbial contaminants, thus introducing disease as well as parasites to wild populations (Goldberg and Naylor, 2005).

South African coastal municipalities are increasingly turning to reverse osmosis (RO) desalination technology to meet bulk water demands. Plant design can be complex, with extensive pre-treatment of the source water required to prevent clogging and biofouling of plant infrastructure and the RO membranes. Any residual chemicals or other additives used in the pre-treatment process are frequently discharged after dilution together with the brine into the receiving environment (usually the sea). Poorly designed or inappropriately situated RO desalination plants may, however, have significant negative impacts on estuaries. Direct or beach-well abstraction of source water from an estuary, and/or brine effluent directly discharged into an estuary (or the adjacent nearshore) from where it may enter the estuary prior to sufficient dilution, can have severe negative impacts on estuarine functioning. Monitoring of the existing three plants situated within estuaries show that RO desalination plants do have impacts of varying significance on estuaries (Bornman and Klages, 2004).

The invasive freshwater snail *Tarebia granifera* (Lamarck, 1822) was first reported in South Africa in 1999 and it has become widespread across the country, with some evidence to suggest that it reduces benthic macroinvertebrate biodiversity (Jones et al., 2017). It has been widely reported in the Subtropical estuaries, but information was lacking on how severe and extensive the infestations was. More recently globally emerging issues such as marine litter (e.g. large volumes of micro-plastics in the Kosi Estuary) and underwater noise pollution (e.g. disrupting fish behaviour in the Breede Estuary) have also been identified as relevant pressures in South African estuaries (personal observations, Borja et al., 2016b).

3.4.2 Estuarine Health Assessment

The assessment determined that 17% of estuaries in South African are considered to be in an excellent state, 41% in a good state, 35% in a fair state and 7% in a poor state. Estuaries in excellent health are mainly located in the Warm Temperate (19%) and Subtropical (17%) regions, while the Cool Temperate region is characterised by estuaries in a fair to poor state (50% and 29%, respectively) (Figure 3.6 and Figure 3.7) (Van Niekerk and Turpie, 2012). That analysis is biased towards the state of the large number of small TOCEs occurring along the South African coast (For more detail on individual estuaries see Appendix A.)

In comparison to the 2004 National Spatial Biodiversity Assessment on 259 estuaries (Turpie, 2004), there is a 10% reduction in the number of estuaries considered to be in an excellent state; however, fewer estuaries were recorded to be in a poor state. The drop in the number of estuaries in an excellent health can be attributed to the increase in human pressures and related degradation, but also to a refinement in the methods used in the 2011 assessment.

When analysed according to “estuarine area” rather than the number of estuaries, the majority (~85%) of estuarine area is in a poor to fair state and only about 1% (17 systems) in an excellent state; the latter are mainly located in the Warm Temperate region (7%) (Figure 3.6).

Part of this result is an artefact of the ‘Lake St Lucia effect’; this Subtropical system accounts for 56% of South African estuarine habitat and is currently classified as being in a very poor state due to the artificial diversion of the uMfolozi River away from the lake and an extended drought in the region (Bate et al., 2011). As many of these pressures are reversible, a programme is now being implemented to have the uMfolozi River reconnected with the St Lucia Estuary, thereby increasing freshwater inflow and improving the status of the system. Over the next few decades the long-term full recovery of St Lucia is likely to continue to have a marked effect on the overall health status of South African estuaries.

The Cool Temperate region was found to support estuarine habitat mainly in the fair to poor health categories, especially the small TOCEs near Cape Town and other coastal centres. The Warm Temperate region, on the other hand was characterised by estuarine habitat in good to excellent health, possibly due to the undeveloped nature of large parts of this zone. The Subtropical region had the highest number of estuaries in a poor state, mainly due to direct habitat loss, artificial breaching and intensive sugar cane farming in the catchments and estuary functional zone.

Overall, smaller estuaries tend to be in a better state of health because there are fewer pressures on them. However, these systems may not be as resilient to change as large estuaries, primarily due to their small size and lack of marine “cleansing” brought about by limited tidal exchange.

In contrast larger estuaries are more heavily affected by catchment and direct development pressure, which lead to degradation and a poor health status, but are more resilient due to strong tidal exchange in this type of system. The fact that the physical conditions in estuaries are more dynamic when compared with other aquatic ecosystems means that severe degradation of an estuary may involve a shift from a dynamic to a more stable system. Hence, the loss of dynamic function per se is an important indication of declining estuarine health (DWAF, 1999). In an estuarine health assessment, measures of these different states need to be sufficiently robust so that different practitioners/disciplines will arrive at the same categorisation.

For comparative reasons (with previous assessments) the individual health scores were aggregated as illustrated in Table 2.1. In estuaries, unlike in the terrestrial environment, degradation or loss of habitat seldom means a complete loss of an estuary.

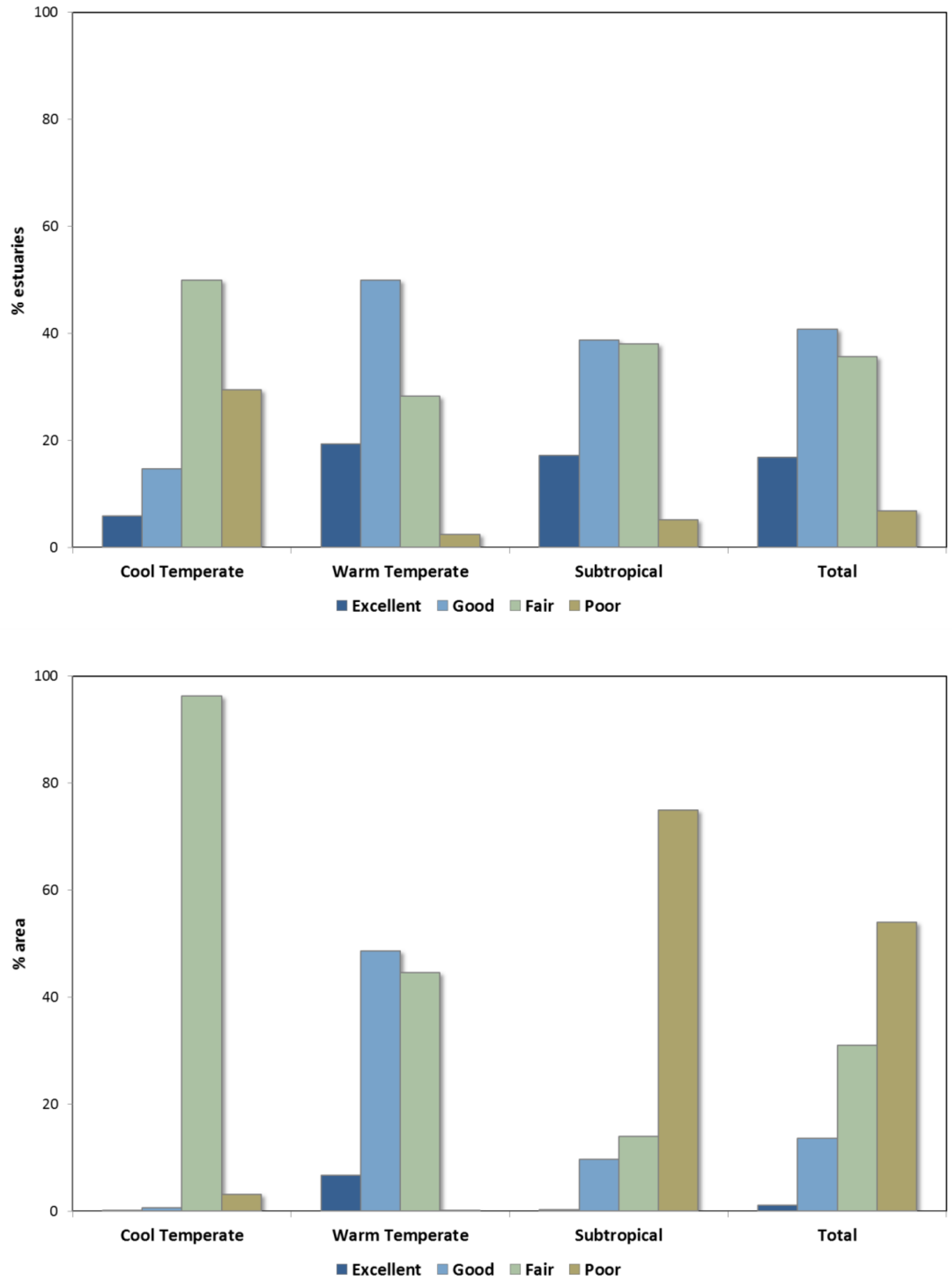


Figure 3.6: Different perspectives arise when the National Health Assessment is presented either as "Percentage estuaries" or "Percentage Area". The percentage area analysis highlights the fact that the majority of South African estuarine area is in a poor to fair state.

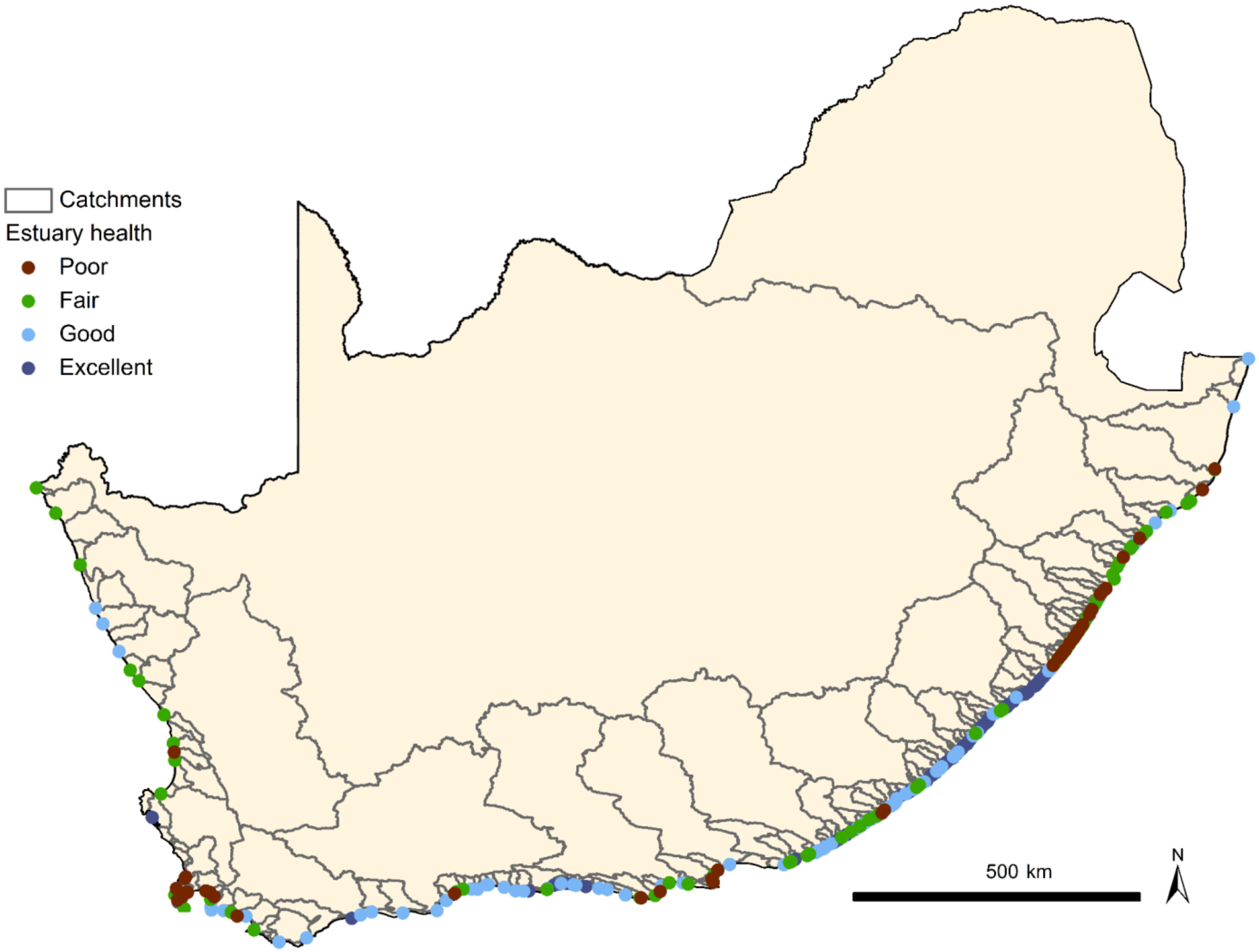


Figure 3.7: Health status of South African estuaries.

This only happens when an estuary becomes completely transformed, e.g. canalized and in-filled to create a parking lot or golf course. In most cases, degradation means the loss of processes or biological functionality, e.g. the estuarine space is filled with a different salinity condition or different species composition. This loss of functionality happens along a continuum, with estuaries retaining more than 90% of their natural processes and biological patterns being rated as excellent and estuaries that are degraded to less than 40% of their natural functionality rated as poor.

3.4.3 Towards informed management of South African estuaries

The information generated as part of this study was assembled in a manner that provides input to a number of management initiatives. The assessment of pressures provided insight into the effectiveness of the various levels and sectors of government (e.g. water resources, fisheries, agriculture, coastal development) and provided a clear indication of where pressures on estuaries were not being addressed effectively.

Key issues such as reduction in freshwater inflow; overexploitation of fish in key nursery systems; the impact of failing waste water treatment works; and poor urban planning in the estuarine functional zone were all highlighted and communicated to the appropriate levels and/or sectors of government. The country-wide assessment also informed a national conservation planning process and highlighted key actions required to be taken by those responsible for biodiversity to ensure adequate protection of biological and physical processes in estuaries

The findings of this study were also aggregated at various management levels, with reporting being conducted by catchment management area and by local municipal area, thus ensuring that all relevant levels and sectors of government can assess how effective their actions have been in the past and where attention needs to be given in future. Special attention was also paid to configuring the findings of the study into the “language” of decision makers using sector specific media releases, glossy documents and ministerial briefs. For example, to provide an overview of estuarine health status in areas of conservation importance (e.g. protected areas, Ramsar sites and Important Bird Areas) the percentage area within each health category was calculated. Seventy-one estuaries form part of national, provincial or municipal protected areas or marine protected areas.

The results showed that there was a lack of estuarine habitat considered to be in excellent and good health within these formally protected areas. The six estuaries within Ramsar sites represent 57 000 ha, of which none is in excellent health (Ramsar, 1971). About 8% of the habitat area is in good health, 9% in a fair state and the majority (83%) in a poor state (Figure 3.8). Similarly estuaries that form part of Important Bird Areas represent about 70 400 ha, of which none is in an excellent health, 7% are in a good state, 26% in a fair state and 67% in a poor state. Collectively, estuaries within marine and other protected areas represent about 65 900 ha, of which only 1% (25 systems) is in excellent health, 13% in good health, 14% in a fair state and 72% in a poor state. The state of the St Lucia system was highlighted since this estuarine lake represents a significant proportion of the habitat comprising Ramsar sites, Important Bird Areas and marine protected areas. The national body charged with biodiversity management in South Africa has incorporated the recommendations regarding Ramsar sites in the integrated report, and is strongly advocating local initiatives that seek formal legal protection of the two remaining unprotected sites in the Cool Temperate region (Orange and Verlorenvlei systems).

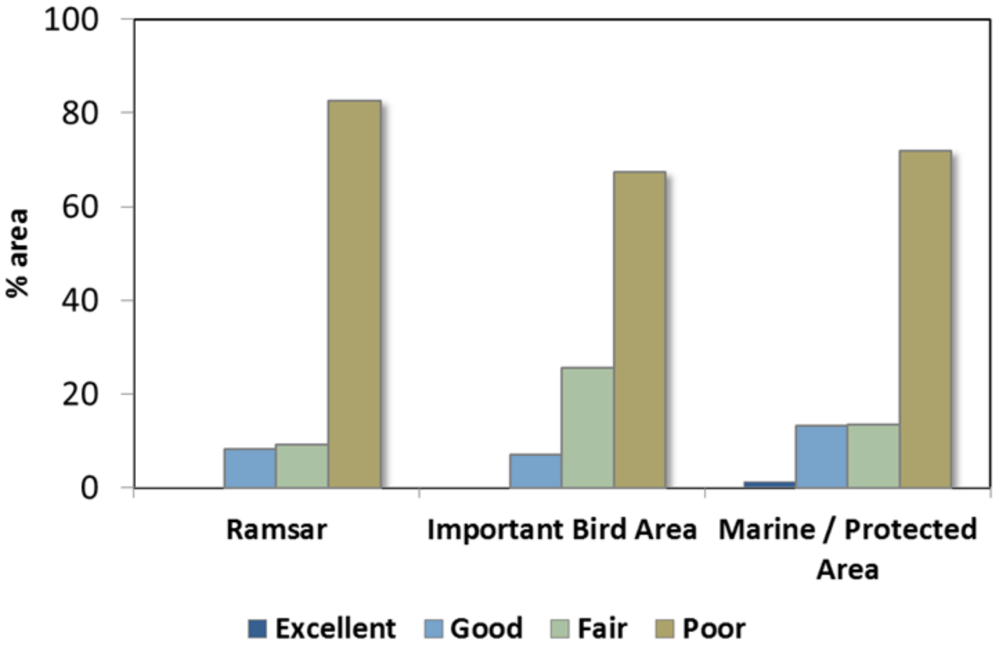
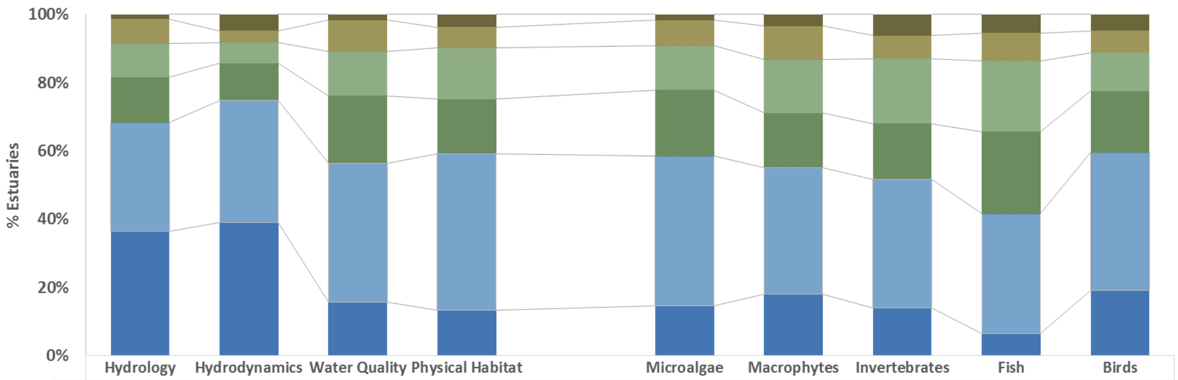


Figure 3.8: The percentage estuarine habitat in areas of conservation concern in an excellent, good, fair or poor state.

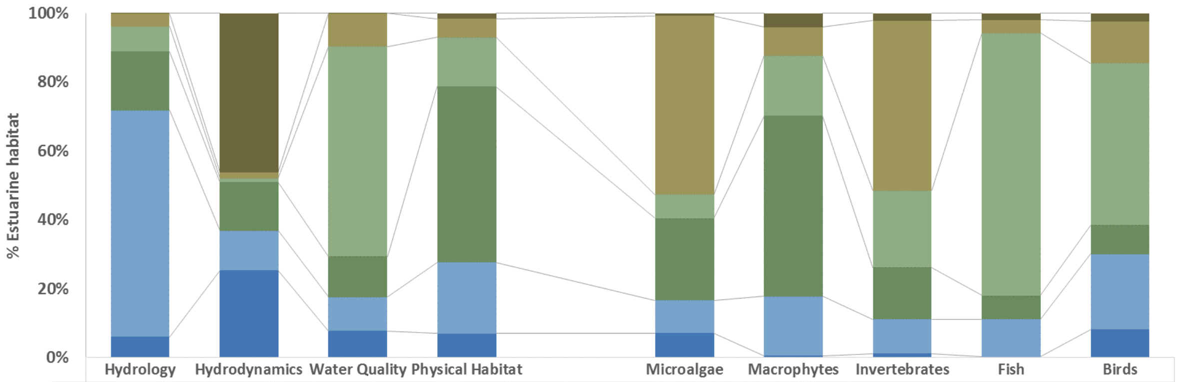
Similarly, the South African National Parks is evaluating its current local management practices for all estuaries located within its jurisdiction against the findings of the national assessment and to ascertain where immediate interventions might prevent further degradation. Overall, while a significant number (58%) of the estuaries in South Africa are in excellent to good health, these are generally small systems in rural areas with few pressures. Smaller estuaries tend to be in a better state of health because there are fewer pressures on them. However, these systems may not be as resilient to change as large estuaries, primarily due to their small size and higher residence time brought about by limited tidal exchange. This is one of the key reasons for the poor conditions of the urban systems.

On the other hand, the larger systems, which are important as fish nursery grounds and of higher economic and ecological importance, are in a fair to poor health due to indirect pressures from the catchment and direct pressures such as development in the estuary functional zone and fishing. Most (85%) of the estuarine habitat in South Africa is in a poor to fair state and there is a risk that this percentage could increase further if appropriate management actions are delayed. The study highlighted the importance of restoring the poor health of the St Lucia Estuary as this system accounts for 56% of the estuarine habitat in South Africa. Fortunately, the St Lucia and uMfolozi systems are in the process of being reconnected, and an adaptive management and monitoring programme has been initiated to assist with the long-term recovery of this World Heritage Site.

Figure 3.9 summarises changes in process and pattern perspective across all South African estuaries. An overview of the abiotic components shows that the hydrological processes are in a good health (in an A or B Category) in about 68% of estuaries. The hydrodynamics component, in turn, shows a 6 % improvement in condition from the hydrological component, alluding to some resilience in this component, i.e. not all flow modification translate directly into shifts in hydrodynamic condition. This is somewhat misleading as a high number of large estuaries, specifically the estuarine lakes, are under severe pressure from mouth manipulation and flow reduction as can be seen from the analysis by estuarine area. The water quality and the physical habitat components, at 57% and 59% respectively, showed a relatively similar pattern in health because of coastal development, with a slightly higher number of degraded systems from a water quality perspective.



	Hydrology	Hydrodynamics	Water Quality	Physical Habitat	Microalgae	Macrophytes	Invertebrates	Fish	Birds
F	1.4	4.8	1.7	3.7	1.7	3.4	6.1	5.4	4.8
E	7.1	3.4	9.2	6.1	7.5	9.9	6.8	8.2	6.5
D	9.9	6.1	12.9	15.0	12.9	15.6	19.0	20.7	11.2
C	13.3	10.9	19.7	16.0	19.4	16.0	16.3	24.1	18.0
B	32.0	35.7	40.8	45.9	43.9	37.1	37.8	35.0	40.5
A	36.4	39.1	15.6	13.3	14.6	18.0	13.9	6.5	19.0



	Hydrology	Hydrodynamics	Water Quality	Physical Habitat	Microalgae	Macrophytes	Invertebrates	Fish	Birds
F	0.2	46.2	0.1	1.6	0.8	4.1	2.1	1.9	2.4
E	3.7	1.7	9.6	5.4	51.9	8.3	49.4	3.8	12.1
D	7.3	1.1	61.1	14.3	6.8	17.4	22.3	76.2	47.1
C	17.1	14.1	11.7	51.1	23.9	52.5	15.1	6.9	8.3
B	65.8	11.6	9.8	20.6	9.5	17.2	9.9	10.9	22.0
A	6.0	25.3	7.8	7.0	7.1	0.6	1.1	0.2	8.1

Figure 3.9: Deteriorating processes and patterns in South African estuaries summarised as percentage estuaries (top) and normalised by area (bottom).

A comparison between the primary producers, the microalgae and macrophyte components of the ecosystem, indicate that roughly 59% and 55% of these communities in South African estuaries are in an A to B Category. Unfortunately, as stated above, associated with the relatively small estuaries. The macrophyte communities include a significant number of large estuaries in fair and poor health systems because of non-flow related pressures, e.g. coastal development and agricultural activities.

Thus from a biotic components perspective the number of estuaries in good health decreases steadily from microalgae (59%), to macrophytes (55%), through the invertebrates (52%), and ultimately to the fish (42%) components, thus reflecting the cumulative effects of flow and non-flow related impacts such as fishing. In contrast, the overall bird component is still in a relatively pristine state with over 60% of estuaries still in an A or B Category, thus highlighting the robustness of the bird community to anthropogenic pressures. Overall, the fish component of the ecosystem fared the worst because of the combined indirect and direct pressures on them.

3.4.4 Conclusion

During the assessment process, estuary experts used the more in-depth environmental flow requirements studies to benchmark their evaluations of the components when working with the more streamlined method of the National Health Assessment. Based on this assessment, specialists indicated that they were consistently overestimating the health of estuaries by about 5-10%, i.e. they generally considered them to be in a better health than they actually are. This was seen as a positive outcome, as the results of this assessment are to be used for planning purposes. In this context, estuaries should not be discounted or ignored if they could contribute to biodiversity targets or prioritised for management interventions. Reasons for the elevated health scores were: lack of good hydrological (inflow) data, accurate land use data, good water quality data; and the large spatial scale at which the study was conducted (i.e. estuaries were evaluated by means of remote sensing imagery rather than field visits). The initial findings of the assessment were further affirmed against a number of more detailed flow requirement studies conducted subsequent to this initial assessment. The results show that the desktop estimates deviated by between 1% and 14% from the more recent in-depth assessments, e.g. Orange (-

5%), Great Berg (+5%), Diep/Rietvlei (-1%); Wildevleovlei (+2%), Zandvlei (-2%), Eerste (-5%), Bot (+10%), Klein (-4%); Duiwenhoks (-10%); Goukou (-2%), Gouritz (-10%), Klein Brak (-8%), Sundays (+1%), Bushmans (+4%), Great Fish (-3), Mzimvubu (+7), Mzimkulu (+9%), Mkomazi (+3), Little aManzimtoti (-10%), uMbokodweni (+2%), uMngeni (-18%), Zotsha (+7%), Mvoti (+9%) (Van Niekerk and Turpie, 2012). The desktop assessments were more accurate if the flow data were accurate, with the degree of deviation being lower in the categories excellent and good, but less accurate in the case of highly modified systems (i.e. categories poor and Heavily Degraded). This was especially the case for small estuaries with high pollution loads. Monitoring of both abiotic and biotic parameters is seen as fundamental to validating the findings of the country-wide assessment. In order to benchmark the findings, monitoring also needs to cover the full spectrum of near-natural to heavily degraded estuaries in all three bioregions following the standardised methods developed for flow requirement studies (DWAF, 1999).

Ideally, research and assessment should be under pinned by modelling studies that fully encompass the functional linkages between ecosystem components and overwhelming pressures on the environment, such as Climate Change and ocean acidification (Borja et al., 2016b). Such modelling would then provide the evidence for setting realistic targets for resource use and thus supporting better long-term resource planning.

In conclusion, South Africa is in the process of improving on this assessment through the development of models (statistical or rule-based) to predict change in the hydrological, physical and water quality health status of estuaries based on land-use. This, in turn, would provide a sound platform for a more systematic approach to the evaluation of change in estuarine processes, patterns and responses on a country-wide scale. This study also provides a template that could be followed by other developing countries that need to assess pressures and the health status of their estuaries.

CHAPTER 4

ASSESSING AND PLANNING FUTURE ESTUARINE RESOURCE USE: A SCENARIO-BASED REGIONAL-SCALE FRESHWATER ALLOCATION APPROACH

4.1 INTRODUCTION

Engineering interventions alone are no longer capable of dealing with the complex challenge of water resource planning and management, particularly the necessity for trade-offs between competing interests and values (Anderson et al., 2008; Pegram et al., 2013). Hence the need for integrated water resources management (IWRM) that promotes the coordinated development and management of water, land and related resources; in order to maximize the resultant economic and social welfare in an equitable manner without compromising the sustainability of vital ecosystems (GWP-TAG, 2000). IWRM culminates in improved water use, and supports economic and social objectives, while sustaining environmental ecosystems (Davis, 2007). This is achieved through strategic and operational planning processes that is integrative, collaborative, and multi-objective in nature. IWRM relies on a multidisciplinary, socio-ecological systems approach which integrates elements such as land and water issues, freshwater and coastal zones, water quantity and quality, differing upstream and downstream interests, and surface water and groundwater interactions (GWP, 2000). The aim is not just to meet straightforward, externally set objectives, but to choose from a series of possible management objectives those that will best contribute to a range of competing economic, social and ecological objectives (GWP, 2000; Davis, 2007). Achieving this typically involves the participation of a range of government bodies and stakeholders, beyond those directly involved with water. IWRM at the catchment scale has the following characteristics (Pegram et al., 2013): 1) trade-offs between alternative economic, social and environmental objectives, and between existing and future demands; 2) a sophisticated approach to recognizing environmental flow requirements and the importance of aquatic ecosystem functioning in providing goods and services; 3) understanding catchment-scale interactions; 4) scenario-based analysis to address uncertainty in future development and climate by assessing alternative hydro-economic scenarios; and 4) prioritization, to identify which of many demands are the key needs for economic development, social justice and environmental protection.

Environmental flow methods are central to IWRM (Dyson et al., 2003; King et al., 2003; Naiman et al., 2006; Olsen et al., 2006). As discussed in Chapter 2, the complexity in these methods has significantly increased over the years. From simple hydrology-hydrodynamic relationships as proxies for assessing ecosystem change (e.g. Alber and Sheldon, 1999; Flannery et al., 2002; Sun and Yang, 2004; Tavassoli et al., 2014; Thompson et al., 2014; Acreman, 2014b) to resource-based approaches where inflows are determined for a desired state of specific resources or ecosystem services, (e.g. Alber, 2002; Doering et al., 2002; Halliday et al., 2003; Halliday and Robins, 2007; Lamberth et al., 2009; Mattson, 2002; Robins et al., 2005; Sun et al., 2012a, Sun et al., 2015). While in more complex ecosystem-based approaches a selection of ecological and socio-economic components/functions are evaluated in order to establish the degree of acceptable change which can be translated into acceptable changes in freshwater inflow (e.g. Adams, 2013; Adams et al., 2002; Gippel et al., 2009; Lloyd et al., 2008; Hardie et al., 2006; Peirson et al., 2001, 2002; Richter et al., 2006; Adams, 2013; Acreman et al., 2014a, 2014b).

South Africa is a water scarce country with a rapidly growing population (DWA, 2013). Rapid urbanisation is causing escalating agricultural growth and industrialisation, especially in coastal regions, resulting in flow modification, pollution, habitat degradation and overexploitation. Water resources are a focal point of concern (DWA, 2013). In South Africa strategic water resources planning and management is primarily governed by the National Water Act (Act No. 36 of 1998) that requires the “Classification” of all water resources. “Classification” outlines the attributes society requires of its water resources and reflects the importance given to protection and/or development of a resource (DWA, 2012). It follows a consultative process that allows stakeholders to negotiate the level of utilisation of water resources in a region. The level of resource utilisation is defined by a future desired ecological state for the different water resources - estuaries, rivers and wetlands - in a region. In summary, there is a requirement for pro-active, regional-scale assessments of change in pattern and process in response to present, and future, resource use to inform planning and allocation.

This chapter describes a planning approach to resource allocation (with a focus on water) at a regional-scale that was developed in a learning-by-doing-manner. The approach borrows from IWRM planning in that it is multi-disciplinary; includes ecological, social and economic objectives; is scenario-based in addressing a range of future development options; uses a multi-criteria evaluation process to assess possible outcomes; and involved an exhaustive stakeholder process with government and private stakeholders to set resource objectives and derive at an optimum solution. The approach is unique in that it applies IWRM principles to multiple catchments within a region (a requirement from an estuarine perspective) versus the traditional application of resource allocation in a single catchment, albeit a very large complex system, with a single estuary at the receiving end (e.g. Hart, 2016). The chapter provides additional clarity in the form of a case study - the first multi-catchment regional estuarine water resource allocation process conducted in South Africa as part of the "Classification of the Mvoti to uMzimkulu Water Management Area (WMA)" (DWS, 2014b, 2014c, 2015a, 2015b, 2015c, 2015d). The chapter concludes with a discussion on the policy implications and future research needs to inform future applications of the approach. The process outlined here may be used in other developing countries to provide guidance to policy makers, planners and decision makers in the water and biodiversity sector attempting strategic resource allocation. The focus here is on estuarine resources, and the research described here does not provide detail on the process followed in the resource allocation for rivers and wetlands or the evaluation of the impact on resource utilization (ecosystems services).

4.2 METHOD DESIGN

This study investigated whether the response of estuaries to escalating future pressures could be quantified on a regional-scale so that this can guide regional-scale planning and estuary freshwater resource allocation. The stages in this research approach represent a design science research method (Bots, 2007), including the development and testing in practice (empirical validation) of a prototype method to a real-world case study. A key requirement was alignment with the water resource policy in South Africa. Therefore the study chose to incorporate existing national methods, where available. For example, South African national government has published methods for determining the ecological freshwater requirements for the country's water resources, including estuaries (e.g. DWAF, 2008). These include an estuary health index for assessing the ecological condition of an estuary, an ecological importance rating system, and guidelines to determine a desired ecological condition.

A public stakeholder process was used to gain oversight, strategic advice and guidance on the process and involved representation from all government sectors and major water users (> 100 representatives) (DWS, 2016a, 2016b). The public participation process was also used to inform the case study, and included report back sessions to smaller technical groups to obtain focussed inputs from the stakeholders. For example, the stakeholder process moderated the ecological recommendations with the parallel findings of a socio-economic assessment via a multi-criteria decision analysis approach.

The development and assessment of future development scenarios was key to the design process. This enabled a creative and flexible approach to dealing with uncertainty, while allowing for the testing of different policy and planning options and their implications (Stewart et al., 2007). Scenario testing provides a robust way of thinking about the future through the consideration of multiple alternative futures when planning over long time horizons with multiple uncertain variables, such as demographic trends and evolving institutions (Stewart et al., 2007).

The approach needed to accommodate both high confidence (e.g. systems targeted for dam infrastructure design) (DWS, 2014a, 2014b, 2015c) and low confidence (DWS, 2015b, 2015d) results as there is a general lack of information on hydro-ecological responses in the region. All results have to be normalised to the same outputs or use the same scales. For the case study relevant data and information were sourced from available scientific literature, and expert opinion was obtained during dedicated specialist workshop sessions (DWS, 2014b, 2015b, 2015c, 2015d).

In the past decade IWRM implementation plans have been developed for large basins across the globe, e.g. Australia, Canada, Netherlands, New Zealand, China (Mitchell., 2006; Mostert., 2006; GWP, 2009; Hart., 2016). The resource allocation approach advocated in this study follows a logical progression of steps, common in IWRM implementation planning studies that ultimately culminates in regional-scale resource allocation, namely:

1. Delineate the study area and agree on individual resource units to be included;
2. Develop coherent future scenarios for a range of development options at a regional-scale;
3. Evaluate level of resource utilisation per resource unit, including a quantitative assessment of the degree of pressure per resource;
4. Determine the ecological health per resource unit;
5. Determine the importance and/or conservation requirements per resource unit;
6. Define the desired ecological conditions for each resource unit;
7. Evaluate consequences of future development scenarios per resource unit (shifts in ecological health and implications for future resource use);
8. Determine "Optimum development scenario configuration" for the region, based on ecological consequences, socio-economic requirements and operational feasibility;
9. Set ecological condition targets and overall managed objectives per resource unit, including future levels of resource use (e.g. detailed freshwater flow allocation; qualitative statement on fishing pressure).

While the above steps may share commonalities with other IWRM implementation planning studies (e.g. Hart et al., 2016), they are unique in their configuration and application scale in this real-world case study. The multi-catchment multi-estuary resource allocation process described here required a high degree of simplification and integration. The major challenge was how to do this, but at the same time not reduce estuarine complexity to the point where change in processes and patterns in individual estuaries could not be detected or reflected. An inherent mismatch between the shape and size of South African estuaries, the processes at play in them, and their associated patterns and responses to change; prevent the application of simple hydrology-hydrodynamic approaches.

The approach that I developed, and applied thus constitutes an ecosystem-based approach that can be used across different estuarine types to allow for change detecton at a range of spatial and temporal scales. The steps and their application to the case study are discussed in detail in the following section (See Figure 4.1 for step followed in the case study).

4.3 RESULTS AND DISCUSSION

The nine steps are described and applied to the Mvoti to Mzimkulu Water Management Area (Table 4.1).

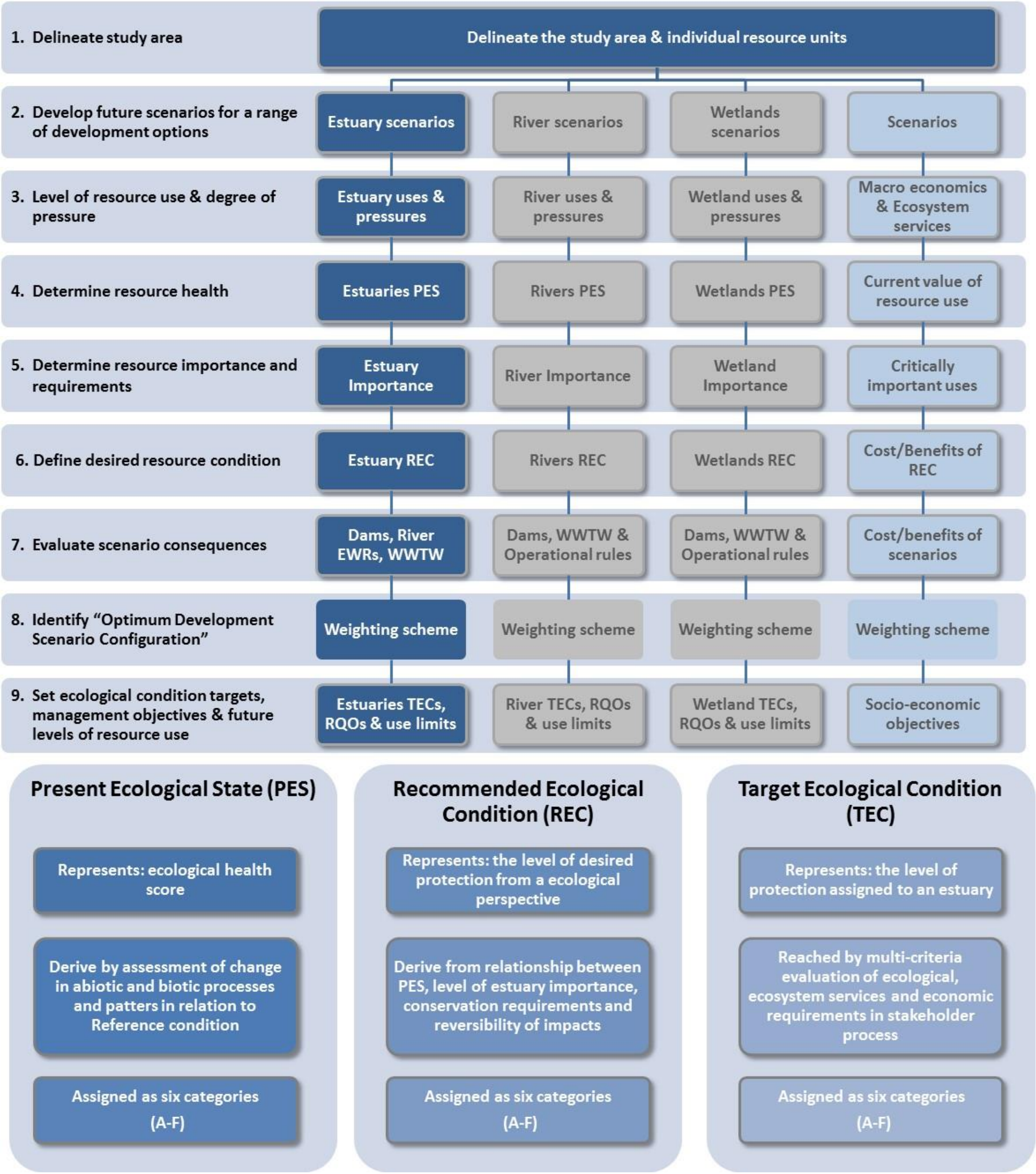


Figure 4.1: The process followed to determine overall level of resource utilization (and associated resource protection) in the Mvoti to uMzimkulu Water Management Area (dark blue blocks represent the steps discussed in this chapter).

4.3.1 Step1: Delineate the study area and agree on individual resource units to be included

The first step in this process is to delineate the extent of the larger study area and clearly define the individual resource units to be evaluated as part of the resource allocation process (Pallero et al., 2017). Ideally, resource units should comprise of all rivers, wetlands, estuaries, groundwater, beaches and freshwater-dependent nearshore coastal environments in the study areas. The boundaries of the study area should preferably be based on geographical or biophysical features, to allow for seamless integration of especially aquatic processes. For example, it is near impossible to do regional-scale resource allocation if you do not include entire primary catchment(s) as you may not be assessing all the drivers of change. However, this does not mean that you cannot disaggregate information and results to fit administrative or even political boundaries to facilitate stakeholder interactions.

The case study was the Mvoti to uMzimkulu WMA that encompasses a total area of approximately 27 000 km^2 and occurs largely within the coastal province of KwaZulu-Natal (Figure 4.2). It extends from Zinkwazi in the north to Port Edward in the south, and inland to the Drakensberg escarpment. The WMA includes 64 river catchments raging in size from 2 to 6 700 km^2 (Figure 4.2), with only a few large catchments - Mvoti, uMngeni, uMkhomazi, uMzimkulu and Mtamvuna - providing the majority of the freshwater flow in the region. Land cover is dominated by grasslands and undeveloped rural land used for agriculture. Urban land is concentrated along the coast from Umhlanga Rocks in the north to Port Edward in the south and the metropolitan areas of Durban and Pietermaritzburg. Agriculture (e.g. sugarcane farming) is predominant along the coast (between Tongaat and KwaDukuza (Stanger) and intermittently in the interior. Forestry is practiced in the vicinity of Greytown to Howick, Richmond and the southeastern portion of the study area. Indigenous forests and wetlands are sparsely distributed across the study area.

Sixty four (64) functional estuaries occur along the 300 km coastline of the WMA (results of this study), 16 of which fall within the highly urbanized coastline (100 km) of the eThekwini Municipality. The study area includes Durban Bay Estuary which includes a large industrial shipping port.

Estuary sizes vary from very small (<2 ha) to large (1 150 ha), but the majority of systems (85%) are smaller than 50 ha and the median size is about 20 ha. The majority of estuaries are classified as temporary open/closed estuaries (TOCEs) with mouth closure occurring on a seasonal basis, during the dry-season winter months. Even the larger predominantly open estuaries are prone to mouth closure under drought conditions. All functional estuaries were evaluated in the study area, with the 5 m lateral boundary taken as indicative of their extent (average tidal range in South Africa is <2.0 m).

Figure 4.2: Map of the Mvoti to uMzimkulu Water Management Area showing drainage boundaries and secondary planning units.

4.3.2 Step2: Develop coherent future scenarios for a range of development options at a regional-scale

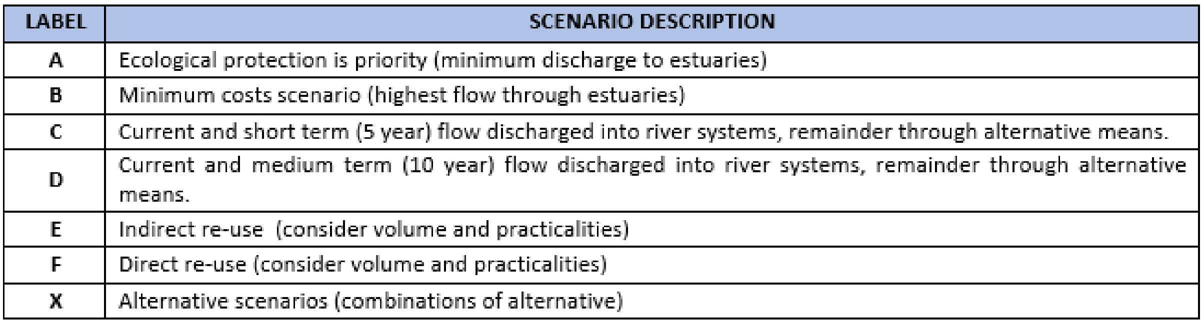
A scenario represents a possible future situation, which is the result of a (hypothetical) combination of events, developments and/or conditions that can used to test possible responses in an uncertain future. “Future scenarios” generally refer to circumstances largely outside the control of the IWRM planning process (such as climate and population growth). “Development scenarios” here refer to future scenarios together with a suite of possible interventions that may be adopted in managing the water resources in the future. “Coherent” within the context of this research means “an internally consistent and plausible description” of a possible future state (IPCC, 2007). Therefore the development of future scenarios should be undertaken in context of prevailing and proposed resource management activities in a region, with a focus on water quantity and quality. Note that these scenarios can also include groundwater resource development amongst others. Municipal wastewater effluents are regulated by setting standards or limits designed to protect the economic, environmental and societal values of water resources (Morris et al., 2017). Traditionally effluents standards focus on physical and chemical water quality parameters within the discharge itself, however these approaches do not adequately account for the sensitivity and responses of receiving environments (Morris et al., 2017). Therefore water quality scenarios (i.e. flow modification and wastewater treatment options) should also from part of the evaluation process if relevant to a region. Scenarios can also be expanded to incorporate the evaluation of direct increase in resource use, e.g. increase in fishing effort or bird disturbance due to increase development (e.g. East Kleinemonde Estuary, Van Niekerk et al., 2008a).

The scenarios should be informed by water resource planning studies and refined through regional stakeholder interactions. Future development scenarios, in the context of water resource management and planning, should comprise plausible definitions of all the variables that influence the water balance and water quality in a catchment and the regional system as a whole. The scenarios should be tested with stakeholders and an agreed list of scenarios finalised for further analyses. Regionally calibrated water resource simulation models should be used to determine the volume of water that is available for economic use per scenario, as well as the volume of water remaining in the natural environment for the purpose of maintain the ecological processes.

In the case study scenarios were developed in collaboration with local authorities and stakeholders for most primary catchments, e.g. ultimate year 2040 development scenario of the greater eThekwini (~ 4 million people), forestry development and decommissioning, river environmental flow requirements, large dam schemes on the uMkhomazi and Mvoti (DWS, 2014e). A key driving factor was that the large dams (e.g. on the Mvoti and uMkhomazi rivers) planned for the region, would increase the available freshwater yield by nearly 20%, which in turn would return to the water cycle predominantly through wastewater discharges and agricultural return flow. A primary set of scenarios was developed along selected themes based on feasible infrastructure configurations (Table 4.1). These were further refined into a host of development permutations to assist with the quest for the optimum balance between water resources yield/assurance, ecological requirements, socio-economic opportunities for growth, infrastructure cost and constraints.

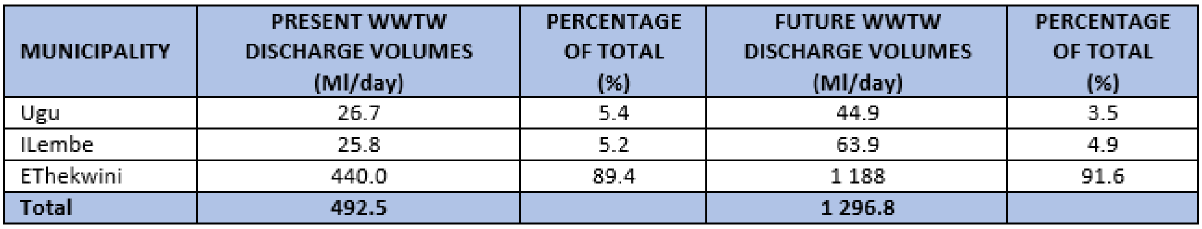
Twenty five of the 64 estuaries were affected by current or potential future wastewater discharge. For each of these, a subset of scenarios were developed that considered management measures such as additional treatment processes to reduce the nutrient pollution load; transferring treated waste from a sensitive estuary to a river and/or estuary system that is able to better assimilate the additional load; discharge of wastewater through sea outfall works (discharges to estuaries are reduced or eliminated); and re-use of treated wastewater (both direct and indirect). All the scenarios were formulated to handle the ultimate future wastewater volumes for the three district municipalities (Ugu = 44.9 Ml/day, eThekwini = 1 188 Ml/day and Ilembe = 63.9 Ml/day) of the region and are summarised in Table 4.2 (DWS 2015b).

Table 4.1: Primary themes defining wastewater management scenarios



LABEL	SCENARIO DESCRIPTION
A	Ecological protection is priority (minimum discharge to estuaries)
B	Minimum costs scenario (highest flow through estuaries)
C	Current and short term (5 year) flow discharged into river systems, remainder through alternative means.
D	Current and medium term (10 year) flow discharged into river systems, remainder through alternative means.
E	Indirect re-use (consider volume and practicalities)
F	Direct re-use (consider volume and practicalities)
X	Alternative scenarios (combinations of alternative)

Table 4.2: Summary of the current and future Wastewater Treatment Works (WWTW) discharge volume as well as the percentage of total daily inflow



MUNICIPALITY	PRESENT WWTW DISCHARGE VOLUMES (Ml/day)	PERCENTAGE OF TOTAL (%)	FUTURE WWTW DISCHARGE VOLUMES (Ml/day)	PERCENTAGE OF TOTAL (%)
Ugu	26.7	5.4	44.9	3.5
ILembe	25.8	5.2	63.9	4.9
EThekwini	440.0	89.4	1 188	91.6
Total	**492.5**		**1 296.8**	

4.3.3 Step 3: Evaluate level of resource utilisation per resource unit, including a quantitative assessment of the degree of pressure per resource

This step determines the level of current resource utilisation on a regional-scale. This can be done through literature reviews, field surveys, spatial data analysis or remote sensing, numerical modelling (hydrological), telephonic surveys, expert workshops or a combination thereof. The level of resource utilization, in turn, needs to be normalised as a level of pressure (e.g. high/medium/low) on each resource unit taking into consideration the individual resource type's ecological sensitivity to specific pressures.

Overall, six key resource uses were identified as major pressures in the case study area: freshwater flow modification; pollution; exploitation of living resources; habitat destruction; sand mining; and manipulation of the tidal inlet (Table 4.3). For example, freshwater inflow to all estuaries was simulated for the present and reference conditions at monthly intervals for a 70-year period using a range of hydrological models (e.g. Water Resource Simulation Model 2000 (WRSM2000), Water Resource Yield Model (WRYM) and Water Resource Planning Model (WRPM) (DWS, 2014a).

Detailed, high confidence hydrological assessments were undertaken for the large river systems using recent land use data (e.g. Mvoti, uMdloti, Tongati, uMgeni, uMkhomazi and uMzimkulu), while low to medium confidence models were developed for the smaller catchments using historical datasets. Results showed that the natural inflow to estuaries in this region (~4 965 x 10^6 m^3) has been reduced by 24% to 3 761 x 10^6 m^3 (Figure 4.3). Google Earth© was used to assess the extent of structural anthropogenic alterations (e.g. canalisation, development, infilling) in the estuary functional zones. To assess pollution, the 2014 land-cover information was initially considered as a proxy for the degree of catchment transformation. However, local experts' knowledge indicated that transformed land was often misrepresented as near natural in the data set. Land-cover information was therefore moderated by local expert opinion in a workshop setting using Google Earth images and information from the river resource assessment conducted as part of the larger study.

Overall, current levels of resource utilisation on individual systems were broadly ranked (high, medium, low, none) as a pressure based on field observations, review of available information (e.g. hydrological modelling, freshwater-use permits issued), spatial analysis, stakeholder interactions and expert opinion (Table 4.3).

The assessment and ranking of the pressures was also confirmed with supporting data extracted from Van Niekerk and Turpie, 2012; Nelson Mandela University Botanical Database (Colloty, 2000; Colloty et al., 1998; Adams et al., 2004; Adams et al., 2012a, 2016), fish survey data (CSIR, unpublished data from Harrison, 2000, 2005; Lamberth and Turpie, 2003), estuarine monitoring reports (Forbes and Demetriades 2009) and ecological flow requirement studies undertaken in the region (6) (DWA, 2011a, 2011b, 2011c, 2011d, 2012; DWAF, 2003). For more detail see Table 4.3 (column 1), specific data sets, or proxies (Table 4.3, column 2), used to assess the extent of pressure impacts on individual estuaries within the region.

4.3.4 Step 4: Determine present ecological health per resource unit

Ideally, the present health of a resource should be expressed as the degree of similarity to its natural state (prior to human interventions). This approach reflects the shift or modification in condition of a resource from its natural (or unimpacted) state. Where development pressures have made it near impossible to hindcast to a natural state (e.g. in parts of the developed world), a "reference state" may be defined based on present development levels or policy objectives (Gu et al., 2017; Zhang et al., 2017; Kendy et al., 2017). See Chapter 3 for more detail on various methods or indices that can be used to determine the present condition (DWAF, 1999; Adams et al., 2002; Van Niekerk et al., 2008a; Adams, 2013).

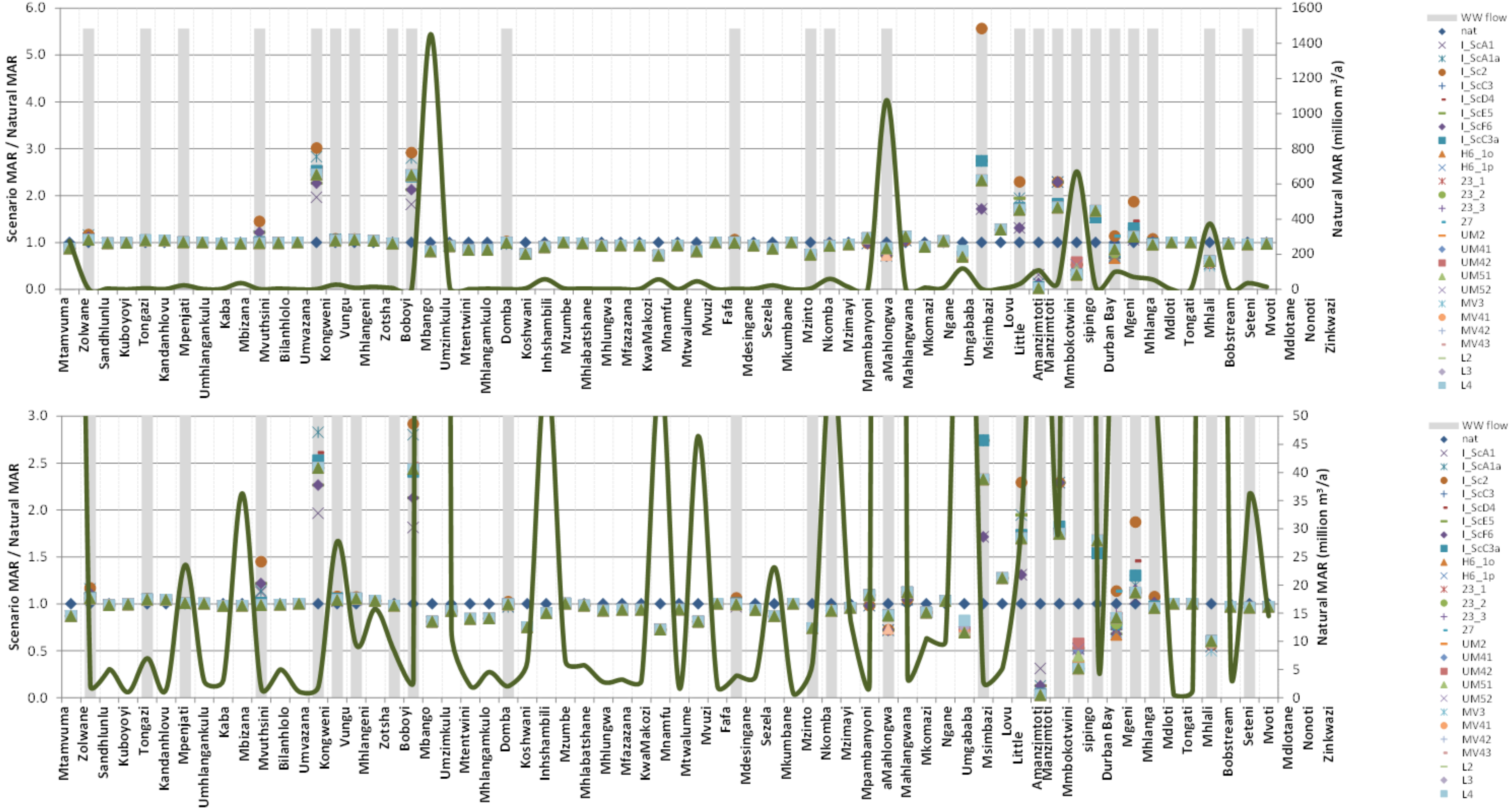


Figure 4.3: Summary of the flow changes under a range of simulated flow conditions for the Mvoti to Mzimkulu WMA estuaries, showing the relative change of the scenarios to the natural Mean Annual Runoff for the full range (top) and the baseflows (bottom). The green lines represent the Mean Annual Runoff (secondary axis).

Table 4.3: Data references for the key pressures on estuaries of the Mvoti to uMzimkulu WMA.

KEY PRESSURE	DATASET	SOURCE
Flow modification	Direct abstraction Dam development Small farm dams Inter-basin transfer schemes Wastewater treatment works Hardening of catchment	• Flow requirement studies (RDM) (Adams et al., 2016) • Field observations • Water Resource Simulation Model 2000 (WRSM 2000), Water Resource Yield Model (WRYM) and Water Resource Planning Model (WRPM) (DWS, 2014a, Van Niekerk et al., 2015) • National Blue drop and Green drop reports (Department of Water and Sanitation)
Pollution	Municipal Wastewater Industrial Wastewater Stormwater runoff Agricultural runoff	• 2008 National land-cover layer (South African National Biodiversity Institute) • Flow requirements studies (RDM)* • De Villiers and Thiart, 2007 • River EWR study (this project) • Forbes and Demetriades, 2009
Exploitation of living resources	Fishing Bait collection	• Lamberth and Turpie, 2003; updated in this study. • Subsistence bait collection (Chapter 3) • Habitat destruction due to bait collection**
Land-use & development (habitat modification)	Bridges Mining Ports & marinas Dredging Low-lying developments Land reclamation	• Spot 5 images • Google Earth • National data sets (2008 National land-cover layer; Colloty, 2000; Colloty et al. 1998) • Flow requirement studies (RDM)* • Field observations** • Begg 1978, 1984 • Forbes and Demetriades, 2009 • Harrison et al., 2000 • Cooper et al., 1993
Mouth manipulation	Artificial breaching Canalisation Redirecting/diversion of the outlet	• KwaZulu-Natal Estuaries database • Flow requirements studies (RDM)* • Field observations** • Begg, 1978, 1984
Sand mining	Locations of mining operations	• Forbes and Demetriades, 2009 • Demetriades, 2007 • CSIR, 2008 • Google Earth

* Based on field observations by estuarine experts / specialists

The South African method for determining the present health (also called the present ecological state (PES)) of an estuary is defined as the extent to which its present state differs from its natural condition. The method used have been applied in detail to more than 50 systems (Adams et al., 2016) and is described in detail in Chapter 2 and 3 (the findings of this study). Estuary health was rated on a continuum from natural (A) to critically modified (F). Estuaries which retain more than 75% of their natural processes and patterns are rated as excellent/good and estuaries degraded to less of 40% of natural functionality are rated as poor. The assessment considered both abiotic and biotic components, namely hydrology, hydrodynamics and mouth condition, water chemistry, sediment processes, microalgae, macrophytes, invertebrates, fish and waterbirds. Assessments were done by a regional multidisciplinary team of specialists and each estuary's health evaluated according to the general characteristics of that system. In the case study the assessments were conducted at a detailed level (medium to high confidence) for the large catchments targeted for dam development and at the desktop level (low confidence) for the remainder (DWS, 2015b).

The overall condition assessment of estuaries in the case study clearly indicated the impact of urbanisation on the small, sensitive estuaries that characterise the region. For most estuaries, the river inflows still resemble that of the reference hydrology, with exceptions occurring in the urbanised systems where discharges from WWTWs have significantly elevated base flows. Therefore, the hydrodynamic processes which influence mouth states and salinity distributions are mostly similar to the natural state. In contrast to the hydrology, the water quality in a large number of estuaries in this region has been modified significantly. This is attributed to diffuse agricultural runoff in rural areas (e.g. introducing fertilizer, herbicides and pesticides) and contaminated stormwater runoff from urban development (delivering nutrients and toxic substances). In 25 of the 64 estuaries water quality has been compromised by effluent discharges from WWTWs, either directly into the estuaries or into rivers just upstream of the estuaries. In the Ugu District Municipality 21 WWTWs were identified which discharge a total volume of 26.7 Ml/day, seven WWTW discharges in the iLembe District Municipality with a total effluent volume of 25.8 Ml/day and 17 WWTW in the eThekwini municipality discharges total a volume of 440 Ml/day. With the exception of the larger estuaries (e.g. the Mtamvuna, uMkhomazi, uMngeni and uMzimkulu) most estuaries along this stretch of coast are relatively small with very little assimilative capacity for nutrient or organic loading. While the overall water quality condition of Durban Bay, the largest estuary in the case study area, is regarded to be fair (Category C) this is largely attributed to tidal flushing of the extensive lower reaches of this system. However, the important remnant estuarine habitats (mangroves, mud and sand banks) in the high-retention upper reaches are subject to extensive contaminated run-off from urban surrounds. Historical and ongoing destruction of habitat for port development, together with poor water quality in the ecologically important upper reaches, significantly threatens the ecological integrity of Durban Bay. Despite being a highly transformed operational port, the size of this estuary and its remaining diversity of habitat still render it an important estuarine resource in need of site-specific interventions.

Urbanisation has led to significant habitat modification in estuaries along this coast (the findings of this study). For example, road and rail infrastructure affect nearly every estuary in the region. Road and rail bridge foundations, abutments and berms have led to infilling and consequential habitat losses. Development across floodplains and channel stabilisation has impacted on natural flow patterns and resulted in localised scouring and deposition. Sugarcane farming along the banks of a large number of systems has led to infilling of floodplains, general constriction of tidal flows and large-scale losses of marginal vegetation and natural vegetation buffers around the estuaries. Poor agricultural practises and overstocking has increased sediment input from catchments in Tribal Trust areas, contributing to sedimentation in the downstream estuaries.

Microalgae show increased production because of increased nutrient loading and concomitant increase in reed habitat (providing additional habitat for epiphytes). However, these effects are somewhat buffered by effective regular flushing of these smaller systems during their open states.

Macrophytes, in most cases, also reflect the effects of urban and agricultural development, with a significant number of estuaries showing severe degradation of floodplain vegetation. In several systems a significant loss of habitat due to the presence of bridge abutments and berms is evident. Disturbed floodplain areas and riparian zones have been invaded by Brazilian pepper tree (*Schinus terebinthifolia*) and *Lantana camara* (Fernandes and Adams, 2016). In many systems, aquatic habitats have been drained to cultivate the floodplain. Overall, this has resulted in woodier vegetation, encroachment by terrestrial vegetation and a loss of aquatic habitat. Modification in freshwater inflow to estuaries and an increase in the frequency and duration of closed mouth conditions is also a threat to macrophytes. Reed encroachment in a number of systems is clear evidence of nutrient enrichment. Increased nutrient input from wastewater treatment and stormwater has caused eutrophication. Emergent species thrive under nutrient-rich conditions and invasive aquatic macrophytes such as water hyacinth (*Eicchornia crassipes*) and water cabbage (*Pistia stratiotes*) outcompete indigenous plants.

Estuarine invertebrate communities have been impacted by alteration and loss of structural and water column habitat, due to development in and around the estuarine systems. In some systems, changes in freshwater inflow have reduced connectivity and recruitment opportunities, with a related decrease in salinity impacting on the overall invertebrate assemblage. The alien invasive snail *Tarebia granifera* has established large populations in many systems and proliferates at the expense of indigenous gastropods and other invertebrates (Jones et al., 2017). Water quality impacts are likely to have played a role in reduced invertebrate abundance in many systems, and certainly to have done so in most estuaries in densely populated urban areas. Although most of the systems in the region exhibit some natural tendency towards depressed dissolved oxygen levels in deeper waters, this has been exacerbated and extends into surface waters in some instances as a result of increased nutrient and organic loading from surrounding land use and WWTW discharges.

Fish communities have responded to changes in freshwater inflow and mouth conditions in some systems. Most, if not all of the systems in the study area have experienced loss of estuarine habitat. Critical fish habitat has been lost in some cases, which has resulted in marked reductions in fish diversity and nursery function. The loss of submerged aquatic vegetation, especially eelgrass *Zostera capensis* from systems like the Sandlundlu, uMgababa, Sipingo, and Durban Bay has undoubtedly played a significant role. Deterioration in water quality (specifically reduction in dissolved oxygen concentrations) is increasing becoming a threat to fish health in these systems, especially those adjacent to densely populated urban areas. In recent years fish kills (attributed to eutrophication and associated low oxygen events) have occurred in 18 of the 64 (28%) estuaries in the study area. In many cases these events have been triggered by malfunctioning WWTWs (due to infrastructure failure and/or overloading). The high number of fish kills recorded in the study area represents about 40% of all recorded fish kills in South Africa, indicating that many estuaries on this coastline are at ecological tipping points (findings of this study). In some cases trophic impacts are likely to have manifested with favoured prey items (e.g. sandprawn *Callichirus kraussi*) either lost or reduced in systems due to habitat loss and alteration, and water quality impacts.

Waterbirds in the smaller estuaries are mostly affected by human disturbance with systems in urban areas showing the most suppressed bird abundances. In many systems, the pressure is further exaggerated by a reduction in suitable habitat and food availability. Decreases in invertebrate-feeding waterbirds, and most especially inter-continental long-distance migrants, are of particular concern due to the ongoing and marked decreases in the populations of these species at a national and likely global scale.

The results were clustered into the three municipal areas of Ugu, eThekwini and Ilembe (Southern, Central and Northern clustered respectively) to reflect the level of use and overall estuary condition. The Ugu and Ilembe clusters occurred in largely rural district municipalities, while the eThekwini cluster covered a large urban metropolitan area with population of 3.5 million people.

4.3.5 Step 5: Determine resource importance and conservation requirements per resource unit

The relative ecological, socio-economic or conservation importance of a resource unit is an important consideration in resource allocation processes (Turpie et al., 2002). Because of the demands for living and non-living resource use in developing countries, it is not practical to ensure the high-quality functioning of all natural resources on a regional-scale (Turpie et al., 2002; Tickner et al., 2017; Rossberg et al., 2017). Thus, it is essential to formulate defensible criteria of prioritising resources, and to use this in the allocation of resources (Rossberg et al., 2017). From a biodiversity standpoint the notion of importance of an area/resource is usually based on rarity (i.e. rare physical types, habitats or species linked to limited abundance or geographical area) and/or abundance (i.e. size, habitat area and diversity, species diversity, population size, and productivity) (Turpie et al., 2002). A third aspect which should be considered in resource allocation is the provision of ecosystem services (e.g. nursery areas for fish, key bird watching) (Rossberg et al., 2017). Formal protected areas (or desired formal protected areas) generally require a higher degree of resource protection that inherently limits the allocation of resources (living and non-living) to protect processes and patterns. It is also possible to extend this task to include important socio-economic (e.g. important recreational areas) or cultural (i.e. sacred bathing area) uses through an expanded weighting scheme.

In South Africa, estuary biodiversity importance is based on the importance of an estuary for plants, invertebrates, fish and birds, using rarity indices (Turpie et al., 2002). The Estuary Importance Rating takes size, the rarity of the estuary type within its biographical zone, habitat and the biodiversity importance of the estuary into account (Turpie et al., 2002, Appendix B). These ratings have been determined for all South African estuaries, but to address gaps in the national assessment and increased sensitivity to change, the case study estuaries were also evaluated on a regional-scale (the findings of this study). The regional importance of macrophytes considered mangroves and submerged macrophytes. The uMngeni and Durban Bay estuaries were very important as they supported all of these habitat types. In the case of fish the Maree et al., *(*2003) Fish Importance Rating was adjusted for new information and then normalised. This assessment showed that 10 estuaries in the region were of high importance to fish, with Durban Bay being the most important. The regional importance for birds was based on the findings of Ryan et al., (1986), but were adjusted for new information and then normalised on the same scale. This assessment showed that 23 estuaries in the region were of relative importance to birds

The National Estuarine Biodiversity Plan prioritises estuaries for partial or full estuarine protected status (Turpie et al., 2012b; Van Niekerk and Turpie, 2012). This plan followed a systematic approach that took pattern, process and biodiversity persistence into account. Estuary health was used as a surrogate for social and economic costs and benefits, because estuaries where the opportunity costs of protection are likely to be high are also likely to be heavily-utilised systems in a lower state of health. The plan indicates that 21 of the estuaries in the region, require some level of formal protection and required that these systems be in a high functional state (i.e. near pristine condition as express by A or B category). Where this is not possible, remedial actions should be undertaken to improve estuarine functionality in order to contribute to biodiversity targets.

All of the above is critical in formation in the setting of the desired state (Step 6), determining the optimum development scenario configuration (Step 8), and the setting of ecological condition targets (Step 9).

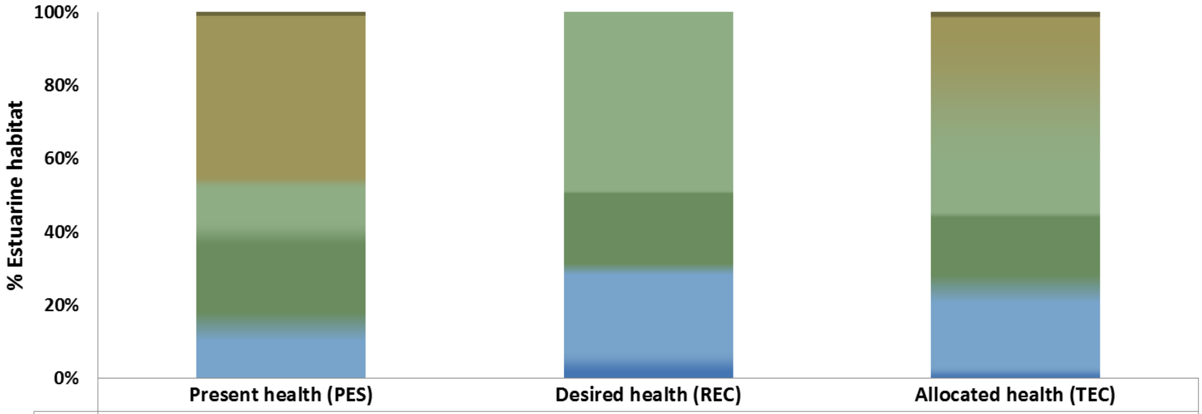
4.3.6 Step 6: Define desired ecological state for each resource unit

The desired condition of a resource is typically a function of its present health, its importance, protection status and/or other important resources uses (DWAF, 1999; Adams et al., 2002; Turpie et al., 2002; Hardie et al., 2006; Halliday and Robins, 2007; Van Niekerk et al., 2008a; Elliott et al., 2016; Hart et al., 2016). In theory, the present health (Step 4) sets the minimum condition a resource should be maintained at. The degree to which the desired condition needs to be elevated above the present health should depend on the importance (e.g. ecological, contribution to food production, tourism value) and the (desired) protection status of a particular resource.

Generally the more important a resource, the “healthier” the desired health condition (or resource protection status). Thus, important estuaries should be in a “good” condition. Protocols may also stipulate a minimum desired condition. The approach can also be used to define a desired condition for a specific estuary parameter or component to facilitate optimum resource use, e.g. enhance nursery function for important fisheries species or define mouth state for recreational use (Sun et al.., 2015; Elliott et al., 2016; Rossberg et al., 2017). However, the desired condition needs to be realistic with consideration given to the reversibility of current impacts and current uses, i.e. harbours cannot be restored, but sugarcane can be removed and riparian vegetation rehabilitated (Borja et al., 2010; Elliott et al., 2016).

The case study found that only 10% of the total estuarine habitat (area) in the region is presently in a “good state” (B Category) and none is in an excellent condition (Figure 4.4). Therefore, to meet biodiversity targets it was recommended that 29% of the estuarine area be in a “good state” of which 8% should be restored to near natural (A or A/B). In South Africa a “fair” category is viewed as the minimum functional condition for any water resource, where systems in a worse condition have to be restored to at least meet this criteria (Adams et al., 2002).

Based on policy guidelines 32 (50%) of the estuaries needed to improve in condition to meet national biodiversity targets and assist with stock recovery of collapsed fish species (Figure 4.4, Appendix C). For the majority of the systems the mitigation revolved around restoration of riparian habitat and improved water quality. Appendix C provides a summary of the proposed mitigation required to achieve the so-called recommended ecological conditions (REC).



	Present health (PES)	Desired health (REC)	Allocated health (TEC)
■ F	1	0	1
■ E/F	0	0	1
■ E	44	0	1
■ D/E	4	0	42
■ D	8	49	10
■ C/D	8	1	2
■ C	17	19	15
■ B/C	8	3	8
■ B	10	21	18
■ A/B	0	7	3
■ A	0	1	0

Figure 4.4: Summary of overall estuarine health (expressed as percentage area) at present (represented by the PES), recommended to achieve biodiversity targets (represented by the REC); and under the negotiated near- to mid-future allocated resource utilisation levels (represented by the TECs).

4.3.7 Step 7: Evaluate consequences of future development scenarios per resource unit;

Once the current health and desired ecological condition is determined, future development scenarios are evaluated to determine the resource unit responses to future resource use levels. The overarching aim of the scenario evaluation process is to find the appropriate balance between the level of resource protection and resource utilisation to sustain socio-economic development. There are three main aspects to consider in this balance, namely ecological functioning, current resource utilisation, and future economic benefits that can be derived from the use of the water resources in a region.

The scenario-evaluation process therefore estimates the consequences of the scenarios on these aspects by quantifying selected metrics that allows for the comparison of the scenarios on a relative basis with one another. For natural resources (i.e. estuaries, rivers and wetlands), the metric is ecological health.

In the case study the ecological consequences of the operational scenarios were evaluated at the estuaries targeted for infrastructure development or wastewater discharges and the results translated into a broad ecological health category (DWS 2014e). The process consists of analysing the individual scenarios flow and quality regime, determining the degree of change in the abiotic processes and predicting the change biotic responses to these changes. Table 4.4 provides an example of how the individual systems were evaluated to establish their sensitivity to flow and water quality changes. In this example, the uMdloti system was evaluated for nine different flow permutations (i.e. increase and decrease in MAR) and three different wastewater nutrient treatment levels (L1, L2 and L2a) at escalating processing cost.

While degradation of habitat was an important contributing factor in the poor health state of a large number of the smaller systems in the region, overall the driving factor on a regional-scale was poor water quality and changes in mouth state (Figure 4.4). This was associated with increased volumes and nutrient loading from WWTWs, as well as poor water quality entering from the catchments. As a result of their relative small assimilative capacity the smaller systems are at a high risk of becoming eutrophic under the future scenarios, especially when their mouths close during low flow and drought conditions.

Table 4.4: An example of an estuary scenario consequence assessment to changes in both wastewater volume and treatment option (uMdloti Estuary: Ecological Categories for each ecosystem component and overall estuary health associated with selected scenarios themes (A, C, D and X) at increasing levels of effluent treatment (L1, L2, L2a))

SCENARIO TYPE CODE (WW treatment level)	MAR (x 10^6 m/a)	WWTW VOLUME (Ml/d)	HYDROLOGY	HYDRODYNAMICS	WATER QUALITY	PHYSICAL HABITAT ALTERATION	ABIOTIC HEALTH SCORE	MICROALGAE	MACROPHYTES	INVERTEBRATES	FISH	BIRDS	BIOTIC HEALTH SCORE	ECOLOGICAL CATEGORY
Present	85.03	7.53	D	D	E	C	**D**	E	D	D	D	F	**E**	D
X_6_1o	67.02	7.53	D	E	E	D	**D**	E	E	D	D	F	**E**	D/E
A_1	68.02	0	D	E	E	D	**D**	E	E	D	D	F	**E**	D/E
X_6_1p	70.12	7.53	D	D	E	D	**D**	E	D	D	D	F	**E**	D/E
A_1a (L1)	72.40	12	C	D	E	D	**D**	E	E	D	D	F	**E**	D/E
C_3 (l1)	77.88	27	B	D	E	D	**D**	E	E	D	D	F	**E**	D
C_3 (L2)	77.88	27	B	D	E	D	**D**	E	E	D	D	F	**E**	D
X_23_2 (L2)	78.97	30	B	D	E	D	**D**	E	E	D	D	F	**E**	D
X_23_2 (L2a)	78.97	30	B	D	E	D	**D**	E	E	D	D	F	**E**	D
D_4 (L2a)	89.93	60	B	F	E	C	**D**	E	F	E	E	E	**E**	D/E
X_2 (L1)	113.68	12)	C	F	E	C	**D**	F	F	F	E	E	**E**	E
X_2 (L2a)	113.68	125	C	F	E	C	**D**	F	F	F	E	F	**E**	E

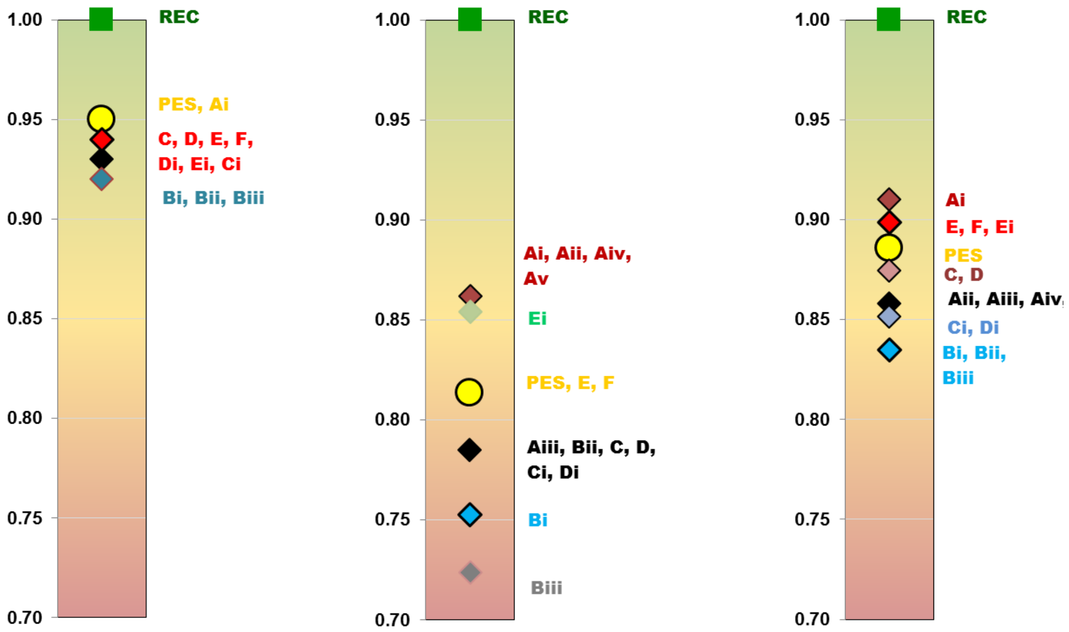
In turn, die-off of vegetation potentially result in high detrital loads, causing reduced dissolved oxygen levels which negatively impact invertebrates, fish and waterbirds. Fish kills are likely to be the end result and are indicative of the ecosystems reaching ecological tipping points.

As this research's focus is on the estuary resource requirements, it does not report in detail on the other metrics. They are merely included to show how the findings of the parallel assessments influence the overall estuary resource allocation. For example, the cost of the alternative management measures as represented by the various scenarios themes were also fed into the socio-economic implication of each scenario, and was later used to moderate the ecological recommendations.

4.3.8 Step 8: Determine “optimum development scenario configuration” for the region, based on ecological consequences, socio-economic requirements and operational feasibility

The regional-scale “Optimum Development Scenario configuration” is determined, following the integration of the ecological and socio-economic implications of resource use and development. The scenarios consequences should be expressed numerically per resource unit and compared separately for changes in ecological health, deviation from current levels of resource use (i.e. impacts on ecosystem services such as fisheries production or recreational use) and economic benefits. The scenarios should be ranked, first, per resource unit and, secondly, in an overall integrated regional-scale ranking by means of a weighting scheme (e.g. using a multi-criteria analysis approach). Weighting factors can be used to reflect that certain resources are more important than others or that variables may differ in their relative importance between water resources. All calculations should be normalised, e.g. presented as % of total resource area in a good/fair/poor ecological condition.

In the case study the different scenarios were assessed using the ecological responses (outcome of Step 7); Gross Domestic Product (GDP); and current levels of resource uses (i.e. ecosystem services) (DWS 2014e) as proxy indicators of the impact of the development scenarios on each resource unit. The overall regional-scale evaluation indicated that some of the scenarios were more favourable from an economic point of view, while others were more beneficial from an ecological perspective (DWS 2014d). The scenario which yields the highest benefits in Gross Domestic Product was the “Minimum cost scenarios” (Scenario theme B), which represent the highest volumes of estuarine WWTW discharges at prevailing nutrient removal treatment processes. The “Direct Re-use scenario” (Scenario theme F) yielded the lowest economic benefits (Table 4.1). Most of the difference was a result of changes to the construction and operational costs of the wastewater treatment options. In contrast, changes in current levels of resource utilisation were found to follow a close response to estuarine health. For example, recreational fishing would improve if regional estuarine health improves as a result of increased oxygen levels. The results of the 64 estuaries in the study area were “artificially” aggregated into the three management clusters that aligned with the boundaries of the three district municipalities, and therefore streamlined stakeholder interactions (Figure 4.6).



Ugu Cluster **eThekwini Cluster** **Ilembe Cluster**

Figure 4.5: Graphic summary of the operational scenario consequences in relation to the desired state represented by the REC for the estuaries of the Mvoti-uMzimkulu WMA. (See Table 4.1 for scenarios themes A to F descriptions, smaller permutation are indicated by roman numerals)

Clustering also allowed for the pragmatic separation of sections of the coast that were still in relatively good condition from the central area that hosted the large number of poor-condition estuaries in the Durban Metropolitan area. The overall results indicated that it is feasible to develop an “Optimum resource use scenario” configuration which is beneficial to the environment, without resulting in severe negative economic constraints. Of the 64 estuaries occurring in the region, 30% (19 estuaries) had significant flow related pressures on them, while 78% (50 estuaries) were under significant water quality pressure. More than 90% (58 estuaries) had undergone significant habitat destruction. All of the estuaries could benefit from some remedial actions and/or more proactive management of the main vectors of change. In some of the systems, additional water resource development would be possible, as long as the baseflow (low flow regime) is maintained, e.g. the inflowing river can be targeted for off-channel development or runoff river abstraction.

The case study showed that the majority of the catchments in the region are small and linked to small temporarily open/closed estuaries that require a high percentage of their natural runoff to maintain their required condition. Any increase or decrease in runoff to this type of system rapidly leads to changes in mouth state and related ecological degradation (Whitfield et al., 2008). When their estuary mouths close to the sea from time to time, the systems are very sensitive to nutrient loading from their catchment or the direct surrounding environment.

Similar to Morris et al. (2017), the study showed that the assessment of WWTWs nutrient discharges into estuaries should consider the impact on the receiving environment rather than relying on adherence to permitted discharge standards. If WWTW permit guidelines are applied across the board, the impact of the associated nutrients and organic material on the TOCE estuaries is not mitigated for. The small estuaries of the case study region retain and accumulate nutrients during closure periods, with consequent impacts on water quality, microalgae and macrophytes, and cascading ripple effects on all other trophic levels. The study clearly showed that the present wastewater treatment levels in South Africa are insufficient to prevent a deterioration in overall estuarine health in TOCEs and the application of a receiving water quality evaluation is advocated when assessing the impacts of discharges on these systems. It is also recommended that intermittently open estuaries not be used as conduits for wastewater disposal.

4.3.9 Step 9: Set ecological condition targets and managed objectives per resource unit, including future levels resource uses

Based on the “Optimum Development Scenario Configuration” an achievable resource condition target is defined for each resource unit. These targets are derived from the impact of the selected “Optimum Development Scenario Configuration” on each resource in the region. The proposed targets can be further moderated through stakeholder engagement on the feasibility of recommendation/mitigation/remedial actions associated with the “Optimum Development Scenario Configuration”. These resource targets should be disaggregated to levels that sets clearly define required resource condition and constraints for future resource use, e.g. flow allocation, wastewater discharges, fishing effort, riparian development (Rossberg et al., 2017).

In the case study, the level of future resource utilisation is defined by the future desired ecological state (called the Target Ecological Categories (TEC)) for each resource unit in the region, i.e. all estuaries, rivers and wetlands. Table 4.5 provide an example of the future levels of resource allocation for the central eThekwini cluster. To meet biodiversity targets and ecosystem service requirements the study recommended that 32% of the estuarine habitat (area) in the region be in a “good state”, with a subset of 8% of estuarine habitat restored to a near natural state (A or A/B Category), thus signifying a substantial improvement on the 10% of estuarine habitat presently in a good condition (B Category) (Figure 4.4). However, as a result of economic constraints (which preclude potential–increases in baseflows or removal of all waste water discharges) only 27% of estuarine area will be managed to a “good condition” in future, with only 3% restored too near natural functionality (See TEC summary in Figure 4.4 and Figure 4.5).

Table 4.5: An example of the allocated future levels of resource utilisation in the Central eThekwini cluster after integration with ecosystems services and socio economic considerations

OVERALL LEVELS OF RESOURCE UTILISATION IN THE ETHEKWINI CENTRAL CLUSTER (16 ESTUARIES)		
Present health (PES) ≥ D: not achieve	**Overall ecological recommendation (REC) = Heavily used**	**Overall cluster allocation (TEC) = Heavily used**
The TEC are an improvement over the PES for 10 estuaries, with the TEC achieving the REC at six and partially achieving the REC at four. The TEC is the same as the PES and does not meet the REC at four estuaries. The TEC falls within the poor (E or F) category in three estuaries (currently all in a very poor condition). Non-flow related measures must be applied to achieve the TEC at the uMhlanga, uMngeni, Amanzimtoti, uMahlongwana and uMhlongwa estuaries. The EWR must be implemented at uMngeni and the pumping scheme must be operated to achieve the existing EWR for uMhlanga. At the ecologically important uMkomazi no further waste must be put into the estuary. The proposed Smithfield Dam with appropriate operating rule will comply to the TEC. For two small estuaries, the Little Amanzimtoti and Mbokodweni, cost to improve these estuaries to a D is significant and the estuaries are of lower importance than others. Further waste water input was therefore deemed to be accommodated, but the estuary water quality must still comply with all required human health standards. This means that criteria other than ecological becomes the driving criteria. In the case of the uMdloti estuary increased wastewater can be discharged in estuary and still maintain it current category, but the exact volume still need to be established through adaptive monitoring. In the short term, the TEC may drop while Hazelmere Dam is being raised and fully utilised and the long-term TEC achieved. The uThonghati Estuary was targeted for the re-use of all wastewater (via pumping scheme to Hazelmere Dam). In the long term, the TEC will therefore be met. In the short term, further discharge may be allowed in the estuary while alternative options for waste are being developed. This means that it the short term, the estuary will stay in a poor (E/F) category, but will then improve in the long-term to the TEC.		

Furthermore, under the “Optimum Development Scenario Configuration” six systems will remain in a poor condition (low/non-functional/ <D Category), with two being deemed of low restoration potential to natural functionality (i.e. Durban Port and Isipingo with catchment diverted for international airport and target for future port expansion).The remaining four small estuaries are predicted to decline further in condition as a result of increased wastewater discharges to the systems. Overall, the TEC was set as the desired state (represented by the REC) for 44 estuaries (69%), which means that the condition is to be improved for 22 of the 64 estuaries (34%) in the case study (Figure 4.4).

In most cases, the proposed increase in health requires the restoration of the riparian habitat, improving water quality (catchment and/or stormwater) and reducing fishing pressure. Estuaries where improved condition (REC > PES) was dependant on increased baseflows were not targeted for improvement as existing legal licences are deemed irreversible from a regulatory perspective.

The exception to this are the two systems for which new large dam infrastructure is being planned over the next decade. For the Mvoti and uMkomazi estuaries operational rules were developed that would assist in maintaining open mouth conditions and protect baseflows.

The individual resource TECs were also “translated” into measurable management goals (called Resource Quality Objectives) for each resource (DWS, 2015a). These objectives give direction to resource administrators as to how the resource needs to be managed moving forward. Resource Quality Objectives provide numerical and/or descriptive statements about the biological, chemical and physical attributes that characterise a resource associated with the level of protection defined by its TEC. It includes the associated water quantity and quality requirements. The TEC for the individual resources provide detailed ecological conditions for habitat and biota; and managed actions required to achieve the TEC (e.g. reduce fishing effort, restore riparian areas). The present condition (PES), recommend configuration from an ecological perspective (REC), as well as the resulting overall resource utilisation levels are summarised in Appendix B and C. The implications of the resource allocation process and associated targeted estuary condition configuration are listed in Appendix C.

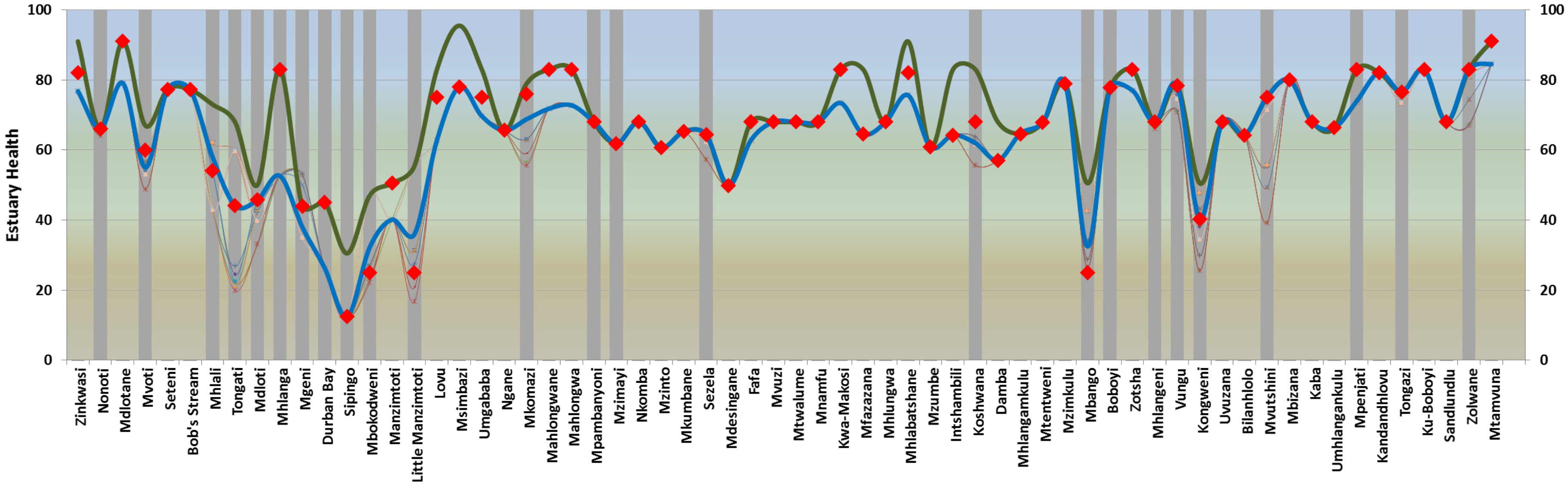


Figure 4.6: Graphic summary of the present health (PES= blue line), desired state (REC = green line) and allocated targets (TEC = Red maker) as well as the responses to different flow scenarios (in fine lines) for the estuaries of the case study. System that receive wastewater are indicated with a grey bar.

4.4 CONCLUSIONS AND RECOMMENDATIONS

Overall the regional-scale scenario assessment and resource allocation process developed, and executed, in this study was sound. It allowed for the detection of changes in estuarine processes and patterns over near- to mid-future temporal scales. It also successfully facilitated resource allocation across multiple catchments in a large coastal region (64 catchments with 64 estuaries), compared with the “single” catchment-scale application (one catchment with one estuary). The study followed a learning-by-doing approach, borrowing from a strong suite of tools that have been developed in the South African water sector and in the international arena. The study met most of the criteria of IWRM, incorporated international best practice (e.g. stakeholder involvement, scenario based), and used available resources as innovatively as possible within the constraints of the official methods (a legal requirement) - all within the constraints of a data limited environment.

The method accommodated both high and low confidence results, with the more detailed focus on the resource targeted for large infrastructure (seen as irreversible impacts). Only the high confidence results were incorporated in legal instruments (government gazettes) leaving room for future improvement in low confidence findings moving forward. However, from this study I have identified some policy implications and research gaps that should to be addressed moving forward with this type of assessment.

4.4.1 Policy implications

The study had a number of policy implications for the government sectors that deal with natural resource management, i.e. water, biodiversity, coastal management and fisheries.

Need to align policy aspirations with socio-economic reality in a transparent manner: The case study showed that restoring all estuaries in a developed region to an “ecological functional” level is not feasible (e.g. South African policy target: All estuaries must be in D Category or higher vs. requirements of an estuary-port). It also showed that restoration in some of the systems would carry very high economic consequences, e.g. require removal of all wastewater and restoration of catchment water quality. Therefore, in striving for a balance between socio-economic concerns and biodiversity requirements, some of the smaller systems will be targeted for additional wastewater disposal, which means that they will decline further in condition. This in contrary to international best practice, the current water resource protection guidelines and South African estuaries conservation plan (Turpie et al., 2012b; Morris et al., 2017), but it does reflect the economic reality in a developing country. It is therefore recommended that clear policy guidelines be developed to assist with decision-making and stakeholder engagement where biodiversity obligations are to be overridden in future. The non-adherence to international obligations has legal implications and transfers opportunity costs to other forms of resource utilisation in the long-term, e.g. reduced fishing effort to compensate for flow reduction pressures.

Sound pollution policy guidelines should be developed, and then adhered to, to ensure a clean future: International best practice dictates that wastewater discharges should be allowed in high retention, high value coastal systems such as estuaries (Morris et al., 2017). Shortly before conducting this case study South Africa developed new policy guidelines in line with international best practice (i.e. no new wastewater discharges to be allowed in estuaries as they degrade these habitats and pose a serious risk for human health). It is unfortunate that these principles will be eroded before they can be entrenched in general sector practices. The wastewater scenarios that deal with recycling, reuse and disposal through a sea outfall were met with significant resistance from some pressure groups, i.e. civil society and the public sector. This speaks to the fact that South Africa does not yet acknowledge that it is a water-scarce country and that disposing of wastewater in the present manner may be cheaper in the short-term, but is becoming an ill-affordable luxury in the long-term. Preferably, wastewater should be recycled and reused, but if stakeholders cannot be convinced of this, the next preferable option would be to dispose of it at sea where the general public will not be exposed to pathogens on a regular basis. Recent severe droughts and related water shortage in the region are going some way towards driving these concepts home. The TEC configuration allows for a short-term decrease in health in some smaller systems, but with a long-term requirement for more appropriate effluent disposal. However, a stronger policy stance by the relevant authorities on the reuse option, supported by the key lead agents would have culminated in more pro-active planning in line with the initial study recommendation. Strong policy and political will is needed to ensure a clean future in developing countries otherwise short-term, local level benefits will erode long-term regional-scale benefits.

Develop processes and structures that can implement the recommended improvements or constraints on current levels of resource use: Generally, recommended improvements to resource condition require both flow and non-flow interventions. In the case study, a large number of interventions focus on restoration of riparian habitat, control of artificial breaching and management of catchment water quality (driven by stormwater and informal settlement runoff). In South Africa, these mitigations will have to be implemented as part of formal estuary management plans. While the project outputs were tailored to facilitate this cross-sectorial collaboration, on the ground implementation will require significantly more resources and political will to achieve. This collaboration should be fostered early in future studies for a seamless rollout of identified remedial actions. In countries where such structures do not exist, it will be near impossible to achieve non-flow related intervention without first establishing co-operative governance structures.

To achieve IWRM all sectors need to control the various types of resource utilization, and in some cases it may even require redressing historical resource uses: While the South African Water Act speaks to protection of the water resources, the water sector currently sees existing legal licenses as non-negotiable. This unfortunately means that none of the interventions needed for restoration of baseflows, a critical aspect in maintaining estuarine processes and functioning, will be implemented. If large dam developments were to go ahead, flow releases are proposed as part of the dam operating rules to maintain open mouth conditions at the Mvoti and Mkomazi estuaries, but a concern remains that this will not be implemented as the current legal allocation of baseflow to the uMgeni system is not being released. Similarly, during the 2010/11 drought environmental flows to the Great Brak Estuary were not released to ensure water supply to a nearby refinery. The water sector is critical in the maintenance of aquatic ecosystem health and the provision of ecosystem services, the sector therefore needs to be held accountable and not just pass on remedial action to other line functions.

Monitoring is key to track change and to achieving resource targets/objectives: Ultimately, future changes in resource utilisation will result in changes in resource condition. For example, in the case study a large number of estuaries are set to improve in condition (TECs an improvement on PES). It is therefore very important to launch a regional-scale monitoring programme to track if: limits are being adhered too; mitigation measure are initiated; and overall targets are being achieved. Regional-scale monitoring programmes will be more cost effective versus the ad hoc style monitoring that typifies data collection in developing countries such as South Africa and generally results in a relatively low confidence assessment. Regional monitoring programmes require interdepartmental cooperation in both the data collection aspects and in the report of monitoring results against the targets set. For example, although there is a national waterbird count scheme (the Co-ordinated Waterbird Count, CWAC) in South Africa, this scheme is poorly funded and understaffed. As a result, this monitoring effort is haphazard, incomplete in coverage and with little data analysis occurring. To be able to accurately and precisely monitor the avian component of estuarine biodiversity, a more targeted and consistent system of waterbird counts at coastal estuaries is required, coupled with more indepth studies of waterbird-estuary functional relationships.

4.4.2 Future research required to support the regional-scale resource allocation studies

A major shortcoming of the approach was the lack of sensitivity to the requirements of the large number of small estuaries in the case study area. Future research that will improve regional-scale resource allocation and the setting of management objectives is outlined below.

The health of your neighbour matters. If increasing coastal development is inevitable, the net result is a continuous escalation of pressures on estuaries. A policy decision, backed by science, needs to be a made on whether estuarine degradation should be spread over the region or focussed on a few compromised systems while some retain their natural state. For example, should wastewater be disposed to a number of adjacent systems (but systems must remain at the functional level), or collected at a central point and discharged into a single targeted system. While most researchers support the idea of targeted estuaries (especially if they are of limited ecological/social importance and/or poor current condition), existing policy is driving the opposite behaviour, with the result that development pressure is spread along the coast, i.e. a form of ribbon development.

Need for research on estuarine connectivity and inter-estuary recruitment. In the case of a network of small systems that collectively add up to significant estuarine area in a region, the functional gap(s) forming as a result of poor condition systems (e.g. declining low oxygen) along a coast is worrying. Unfortunately, no scientific support is available to guide planners in what are the consequences for estuarine connectivity. In short, the "health of your neighbour matters" as it ensures overall resilience to the network of estuaries along a coast, but the science is lacking to show the degree to which the health of adjacent estuaries influence each other. In future biodiversity recapture, telemetry and genetics studies will assist in "making the case for estuarine connectivity" and the development of guidelines for regional resource allocation.

Nutrient responses: The small estuaries are very sensitive to nutrient loading. There is a need to better understand the role of the different nutrient species in microalgae and macrophyte production to be able to predict tipping points and current/future condition assessments. This will require dedicated research on eutrophic systems in the region to inform managed decision making, especially as restoration comes at significant infrastructure cost.

This study has shown that the sensitivity of estuaries to future pressures such as change in the quantity and quality of freshwater inflow can be quantified on a regional-scale. In addition, policy implications have been identified to influence regional-scale planning and estuary resource allocation as a whole. This is a new approach developed specifically for South Africa, but has similarities to IWRM in countries such as Australia, Canada, the Netherlands, New Zealand and China.

CHAPTER 5

A REVIEW AND SYNTHESIS OF THE VULNERABILITY OF SOUTH AFRICAN ESTUARIES TO CLIMATE CHANGE

5.1 INTRODUCTION

Climate Change is a measurable reality and South Africa is especially susceptible to its impacts (DEA, 2010, 2013). South Africa has an economically divided society due to a number of socio-economic disparities; and as a result its population is characterized by a vulnerable majority with a high reliance on ecosystem services. Therefore, adaptation to Climate Change impacts becomes even more important in building societal resilience in the face of change.

The concept of vulnerability has become increasingly important in Climate Change research, with extensive developments taking place in the vulnerability assessment field over the last few decades (Jones and Preston, 2011). The Intergovernmental Panel on Climate Change (IPCC) defines Climate Change vulnerability as the degree to which a system is susceptible to, or unable to cope with adverse effects including climate variability and extremes (IPCC, 2001, 2012, 2014). Vulnerability is a function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity (IPCC, 2001). The IPCC fourth Assessment Report (AR4) stresses the importance of providing a socio-economic perspective (e.g. resource use implication) and the need for assessing scenarios that assume no restriction on greenhouse gases (GHG) in contrast with those assuming GHG stabilisation (Carter et al., 2007).

The term ‘vulnerability’ may refer to the vulnerable system itself, the impact to this system, or the mechanism causing these impacts. In this context, exposure deals with climate-related stressors and there is thus an overlap with hazards, which can be seen as the process or phenomenon to which an estuary is exposed to in the form of events or trends. Sensitivity relates to the degree to which an ecosystem or community is affected. Assessing vulnerability thus requires consideration of the health and functioning of the ecosystem (Carter et al., 2007). Adaptive capacity relates to the ability to adjust to change and is thus harder to measure than exposure and sensitivity. The complexity involved in defining and measuring the various geographical, spatial, temporal and social dimensions of vulnerability has resulted in a multitude of methods (Carter et al., 2007). However, in South Africa, there is no standard approach or best practise guidelines for measuring Climate Change vulnerability (DEA, 2013). This makes monitoring of vulnerability and the evaluation of adaptation measures challenging, and precludes comparing different sectors or localities as well as assessing vulnerability over time (DEA, 2017). This study strives to address that gap for the estuaries of South Africa.

Internationally estuaries have been the focus of a number of comprehensive Climate Change vulnerability assessments in recent years. For example, Day et al., (2008, 2011), Gillanders et al., (2011), and Robins et al., (2016) have investigated regional responses to Climate Change drivers in the United States of America (USA), Australia and the United Kingdom (UK) to provide a broad framework for anticipated changes. The following effects of Climate Change were globally identified as important drivers of change in estuarine environments: change in oceanic circulation processes; modification of terrestrial climatic and hydrologic processes; ocean acidification; sea level rise; and an increase in sea storminess (Day et al., 2008; Day et al., 2011; Gillanders et al., 2011; Newton et al., 2014; Robins et al., 2016). This growing body of work is supported by ongoing detailed, controlled laboratory studies and *in situ* observations on estuarine sensitivity to changes, e.g. ocean acidification and temperature (e.g. Duarte et al., 2013; Vizzini et al., 2013; Kerfahi et al., 2014; Milazzo et al., 2014; Ge et al., 2017; Rees et al., 2017; Laurent et al., 2017). More recently, downscaling of the global climate model by regional climate models has allowed for the development of site-specific dynamic models that can assist with evaluating the responses to Climate Change in a more systematic manner. Examples include assessments of the impacts of increased storminess and sea level rise on estuarine processes in Australia, USA, UK, Europe and Sri Lanka (e.g. Brito et al., 2012; Ranasinghe et al., 2013; Prandle and Lane, 2015; Duong et al., 2015, 2017; Brown et. al., 2016a; House et al., 2017; Goodwin et al., 2017). Site-specific models have also been developed to evaluate ecophysiological metrics (e.g. increase temperature changes) to assess climate change effects on organisms of conservation concern in the USA (Brown et. al., 2016b). All of these models are data hungry and would take considerably effort to apply in South Africa’s data limited environment.

Key to understanding the vulnerability of South African estuaries to Climate Change are their physical features. These estuaries are highly variable in size, shape, degree of marine/fluvial influence and catchment characteristics (Reddering, 1988). The estuaries of the region also represent highly variable habitats in which conditions such as mouth state, water depth, salinity, temperature, turbidity and dissolved oxygen concentrations can fluctuate rapidly, both temporally and spatially (Day, 1981). The role of estuaries as fish and prawn nursery grounds and important feeding areas for migrant birds are of particular importance as they contain much of the only sheltered habitat along the highly exposed linear coastline (Beckley, 1984). South Africa’s coast spans three biogeographical regions (or climatic zones), namely the cool temperate west coast, warm temperate south and east coast and Subtropical east coast (Emanuel et al., 1992; Harrison, 2002; Turpie et al., 2000)(see Figure 5.1).

Transition zones between the biogeographical regions are shaped by oceanographic and climatic features such as currents, bathymetry and, terrestrial runoff. Therefore, these transitional zones vary according to El niňo - La niňa events and related wet-dry cycles (Dieppois et al., 2015). Freshwater inflow to estuaries is determined by climatic conditions, as well as the size and shape of the catchment, the latter controlling the magnitude and flow distribution of runoff (Reddering and Rust, 1990). The relatively small South African estuaries are wave-dominated, shallow (water depth 2–3 m) and microtidal (<2 m) (Cooper, 2001). The resulting low tidal flows, coupled with comparative low freshwater inflow, results in a limited ability to maintain inlet stability (i.e. open mouth conditions). The effect of strong wave action and high sediment availability is that more than 90% of estuaries have restricted inlets, with more than 75% closing for varying periods of time when a sandbar forms across the mouth (Cooper, 2001; Whitfield, 1992; the findings of this study).

Overall, estuary size thus influences a number of estuarine physical characteristics, including tidal flows, dependency on river inflow; and associated mouth regimes. Size also acts as a predictor of community composition and abundance, with smaller systems having fewer species and lower absolute abundance (Whitfield, 1980a, 1980b).

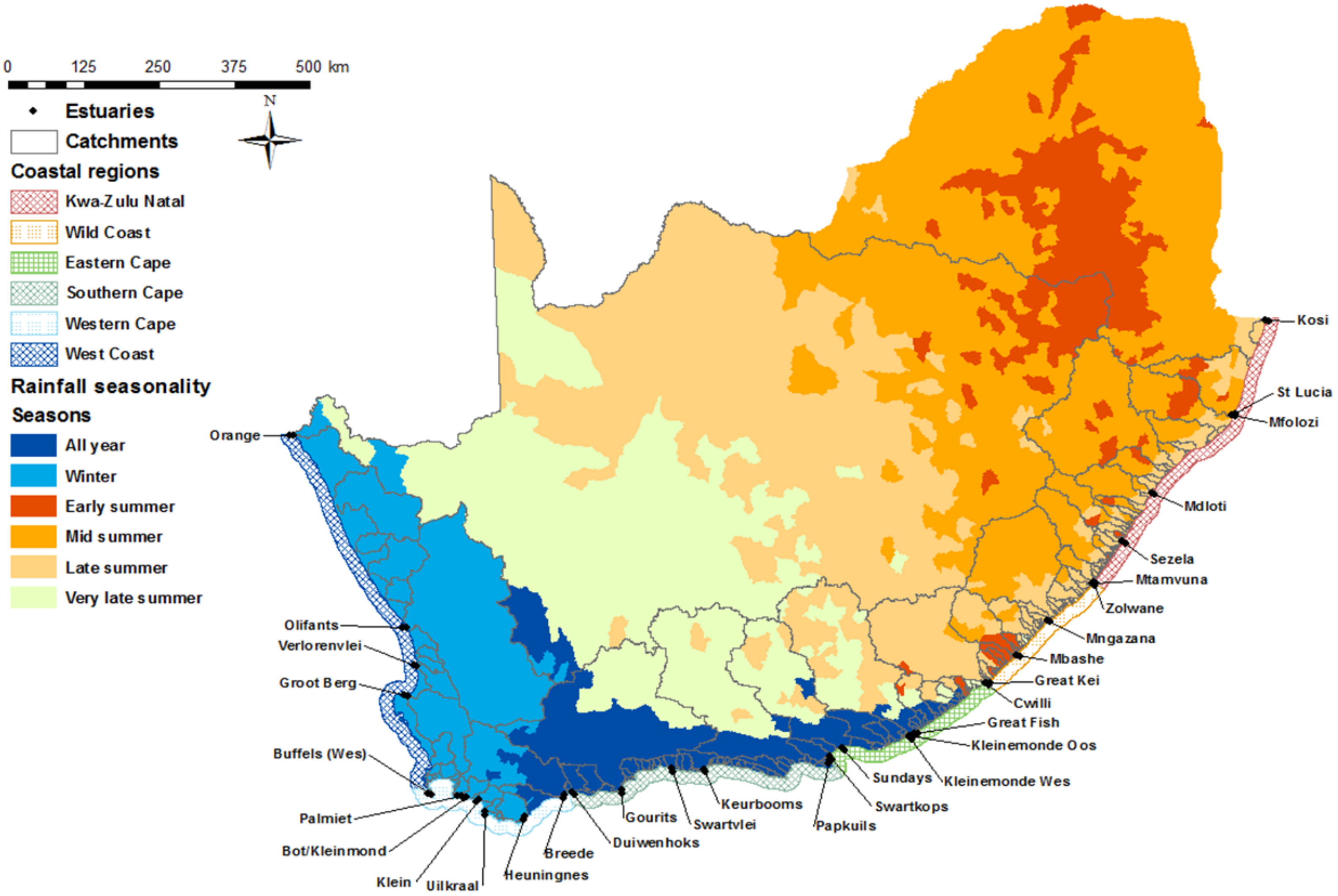


Figure 5.1: Map showing the six coastal regions, relative catchment size and rainfall seasonality for South Africa (Modified from Schulze, 2007).

Larger estuaries also tend to have a higher diversity of habitat types (water column and substrate) than smaller systems (Lamberth and Turpie, 2003; Van Niekerk and Turpie, 2012; the findings of this study). Estuary responses to Climate Change processes will vary according to estuarine type. For example, large and small estuaries tend to respond differently to major resetting events. In South Africa, large estuaries tend to be more buffered against flood scouring as they have greater storage capacity relative to flow, which translates into less loss of substrate, habitat and biota whilst smaller systems may be subject to a complete reset of substrate and biotic composition during a similar size event (e.g. 1 in 5 year flood). In addition, estuarine habitats are significantly degraded (primarily through freshwater reduction, habitat destruction, nutrient pollution and overexploitation of living resources) with the consequent effects on related ecosystem services (e.g. nursery function) widely acknowledged (Chapter 3). These impacts reduces the capacity of these ecosystems to buffer the effects of change, albeit natural or anthropogenic.

This chapter sets out to explore the vulnerability of South African estuaries to Climate Change, based on their known characteristics. It synthesises the projected Climate Change stressors with a focus on the near-future (2016-2035) and mid-future (2040-2060) affects. The study ranks the regional vulnerability of the estuaries and concludes with identifying priority adaptation strategies to mitigate and plan for the effects of Climate Change.

5.2 METHODS

There is a constantly growing body of knowledge on Climate Change vulnerability In South Africa. The country saw an expansion of information from the Second National Communication (DEA, 2010) to the much more detailed and in-depth Long Term Adaptation Scenarios (LTAS) assessment (DEA, 2013), including the analysis done for the National Biodiversity Assessment (Driver et al., 2012; Van Niekerk and Turpie, 2012). This assessment draws on the author’s experience in contributing to this body of knowledge and a review of existing regional research on estuarine sensitivity to change. For this assessment, estuaries were subdivided into six coastal regions that were relatively homogenous with respects to rainfall and catchment characteristics, coastal topography, beach slope, the dominant mouth position when closed, and estuary size (Table 5.1). Local and international literature was then reviewed to develop an overview of what key Climate Change stressors may affect the estuaries in the various coastal regions. The following stressors were considered critical:

- Change in oceanic circulation processes;
- Modification of terrestrial climatic and hydrologic processes (temperature, precipitation and run-off regime shifts);
- Ocean acidification;
- Sea Level Rise; and
- Increase in the frequency and intensity of sea storms.

The estuaries of the six coastal regions were assessed at a broad scale to determine the potential impact on ecosystem processes and patterns based on their regional sensitivity to each stressor. A change rating (low=largely similar, medium= some change from present, high = significant change is expected) was then applied to indicate where the most change is projected to occur in the near-future and mid-future.

The alarming implications of the extreme far-future scenarios were not considered here as much work is still needed on how temperature changes and related stream flow reduction will be impacted on. This will be the work of future studies. The interaction between Climate Change stressors, estuarine processes and anticipated biotic response was summarised and implications for the different regions highlighted. The biotic response section has a strong emphasis on fish as community composition, range expansion and physiological aspects have been well studied compared to other taxa. The chapter concluded with a section on priority mitigation and adaptation strategies

5.3 RESULTS AND DISCUSSION

5.3.1 Key Climate Change stressors on South African Estuaries

5.3.1.1 Changing ocean circulation processes

Two large scale ocean currents running very close to the shore strongly influences South Africa’s coastal climates, i.e. the Agulhas Current along the east and south coasts and the Benguela Current along the west coast.

Table 5.1: Summary of the key physical features of South African estuaries that defines their vulnerability to Climate Change

BIOGEOGRAPHICAL REGION	COOL TEMPERATE	WARM & COOL TEMPERATE TRANSITION ZONE	WARM TEMPERATE		SUBTROPICAL-WARM TEMPERATE TRANSITION ZONE	SUBTROPICAL
COASTAL REGION	**West Coast** Orange-Krom n= 17	**Western Cape** Buffels (Wes)-Breede n=20	**Southern Cape** Duiwenhoks - Papenkuils n= 37	**Eastern Cape** Swartkops – Cwili n=58	**Wild Coast** Great Kei - Umtamvuna n= 85	**KwaZulu Natal** Zolwane - Kosi n = 74
Coastal energy	High energy wave dominated coast					
Rainfall seasonality	Winter (Note: Orange catchment Mid/Late Summer)	Predominantly Winter	All year, peaks in spring and autumn. Very late summer in larger catchments	Late summer to All year	Late summer rainfall	Mid to Late summer, Early summer in larger catchments
Mean annual precipitation (mm)	200 - <100	200 – 600 (mountains >1000)	200 - 800	200 – 800	400 - 800	600 – 1200
Dominant catchment size	Three very large catchments, rest small catchments	Small to large catchment	Small to large catchments	Small catchments interspersed with large catchments	Numerous small catchments	Numerous small catchments
Coastal topography	Coastal plain	Vary from steeply incised to coastal plain	Vary from steeply incised to coastal plain	Vary from steeply incised to coastal plain	Steeply incised	Steeply incised, Coastal plain in northern parts
Dominant closed mouth position	Mostly perched	Mostly not perched	Mostly not perched	Mostly not perched	Mostly not perched	Mostly perched
% Estuaries	%	%	%	%	%	%
- **Very small: <50 ha**	58.8	70.0	62.2	63.8	81.2	78.4
- **Small: 50- 100 ha**	5.9	0.0	5.4	17.2	8.2	9.5
- **Medium: 100-500 ha**	17.6	15.0	21.6	17.2	10.6	4.1
- **Large: >500 ha**	17.6	15.0	10.8	1.7	0.0	8.1

The Agulhas Current, flowing along the eastern shores of South Africa, is the strongest western boundary current in the southern hemisphere (Beal et al., 2011). From Port Edward (30°S) to Port Elizabeth (34°S) and is generally found within 20 to 50 km from the coast (Gründlingh, 1983; Bryden et al., 2005; Goschen and Schumann, 1990; Rouault and Penven, 2011). The position of the Agulhas Current is influenced by offshore cyclonic meanders (referred to as "Natal Pulses") that can force its core 200 km offshore up to 4 times per year driving localized upwelling and contributing to the dispersion and transport of pollutants or fish larvae (Bryden et al., 2005; Rouault and Penven, 2011; Krug et al., 2014; Beal et al., 2015). Natal Pulses also influence the downstream variability of the current and the leakage of warm, salty water into the Atlantic. The pulses are linked to the formation of Agulhas Rings and Early Retroflections when the current retroflects upstream of its usual location and interrupt the Agulhas Leakage (Lutjeharms and van Ballegooyen, 1988; van Leeuwen and de Ruijter, 2000; Rouault et a., 2010). Most of the inter-ocean transfer of heat and salt between the Indian and Atlantic oceans is associated with the Agulhas Leakage (Gordon et al., 1987; Matano and Beier, 2003). Changes in Agulhas Leakage influence the Benguela Current Large Marine Ecosystem and its coastal climate thus impacting on river run-off and estuarine dynamics. Recent work suggests that meso-scale variability in the greater Agulhas Current system has intensified with the northern Agulhas Current (north of about Coffee Bay) experiencing a strengthening of the mean current; while the southern Agulhas Current appears to be slowing down, but meandering more (Backeberg et al., 2012). Overall, stronger Agulhas Current transport has been predicted due to global warming which will effect inshore upwelling cells as well as shelf-edge upwelling which in turn may impact coastal ecology (Backeberg et al., 2012). The impact of a stronger Agulhas Current on the retroflection mode is still unclear. Cai et al. (2007) and Rouault et al. (2009) indicate that an increase in Agulhas Current transport will lead to stronger Agulhas Leakage with more warm Indian Ocean water passing along the southern and western coasts of South Africa. While Van Sebille et al. (2009) found that an increase in Agulhas Current transport may lead to a higher frequency of Upstream Retroflection with a concomitant decrease in Agulhas leakage. Either way, the impact of a stronger Agulhas Current will have definitive effects on the coastal climate of South Africa. In addition, close to the coast, winds play an important role in determining the ocean temperatures through wind driven upwelling. Rouault et al. (2010) reports a cooling trend along South

Africa's south coast and in the Port Elizabeth/Port Alfred region associated with an increase in upwelling-favourable easterly winds, suggesting that the cooling trends are both due to an intensification of the Agulhas Current as well as increased upwelling favourable winds.

Greenhouse gas (GHG) induced global warming and the anthropogenic ozone hole has caused an intensification and southwards shift of the Southern Hemisphere Sub-tropical gyres over the last 40 years (Cai, 2006, and references therein). On the western coast of South Africa the Benguela Current is likely to intensify and lead to more intense upwelling due to the speeding up of the Supergyre (Saenko et al., 2005; Roemich, 2007). This will induce much lower sea surface temperatures along the west coasts of South Africa than at present. Agulhas Rings sometimes drift very close inshore up the west coast, raising the temperature of nearshore waters and occasionally interacting with upwelling plumes, both of which have important consequences for fish recruitment including that into the nearshore and estuarine environments (Duncombe Rae et al., 1992). How robust the upwelling trends in the Benguela Upwelling System is remains unclear (Hagen et al., 2001; Lutjeharms et al., 2001; Bakun et al., 2010; Rouault et al., 2010; Dufois and Rouault, 2012). Changes in ocean circulation processes and associated temperature regime shifts is likely to impact on biotic processes and patterns, e.g. primary production, habitat forming plants, community composition and species range expansions, recruitment and nursery function, and other behavioural responses.

5.3.1.2 Modification of terrestrial climatic and hydrological processes

Global temperatures have increased by about 0.8 °C over the last century, in response to the enhanced greenhouse effect. However, recent climate trend analyses indicate that South Africa has been warming more than twice the global rate of temperature increase over the past five decades (Jones et al., 2012; Kruger and Sekele, 2012; MacKellar et al., 2014; Engelbrecht et al., 2015; Kruger & Nxumalo, 2016). The largest and smallest increases in maximum temperature have been recorded during winter and autumn, and summer respectively. There is strong evidence of statistically significant increases in rainfall occurring over the southern interior regions, extending from the western interior of the Eastern Cape and eastern interior of the Western Cape northwards into the central interior region of the Northern Cape (Kruger, 2006;

MacKellar et al., 2014). Extreme daily rainfall events have increased over these same areas.

This study is largely based on the outputs of the global climate model analysed in Assessment Report Five (AR5) and downscaling within regional climate models and the Coordinated Regional Downscaling Experiment (CORDEX) of the World Climate Research Programme. For South Africa, projected Climate Change futures were derived using both statistical and dynamical downscaling techniques. The projections were developed for both low-mitigation (RCP8.5) and high-mitigation (RCP4.5) futures, and for near-future (2016-2035), mid-future (2036-2065) and far-future (2066-2099) time scales (Note: temporal time-frames vary ± 10 years between models) Examples of such model results are shown in Figure 5.2 and Figure 5.3. These projections make feasible the identification of plausible climate futures for South Africa and the identification of adaptation actions. These assessments have largely focussed on the near to near- to mid- future impacts as these are where the complexities in estuarine responses reside.

Far-future projections hold devastating impacts for South African estuaries, with little options for adaptation. South Africa is likely to experience much hotter, drier conditions that will for example result in a decline in freshwater inflow and extensive estuarine mouth closure. The projected far-future warming ranges from - 4.5 °C (with localised increases of 6°C in some projections) with much drier conditions and more frequent occurrence of droughts likely over most of the interior (see Figure 5.2)(SAWS, 2017).

Climate Change may also manifest itself over a particular region through changes in the frequency of occurrence of severe weather events (in addition to potential changes in the long-term averages of variables such as rainfall and temperature). An increase in extreme rainfall events is projected to occur along the Southern, Eastern Cape and KwaZulu-Natal coasts during spring and summer, with a reduction in such events projected for winter and autumn (e.g. Christensen et al., 2007; Engelbrecht et al., 2009; Engelbrecht et al., 2013).

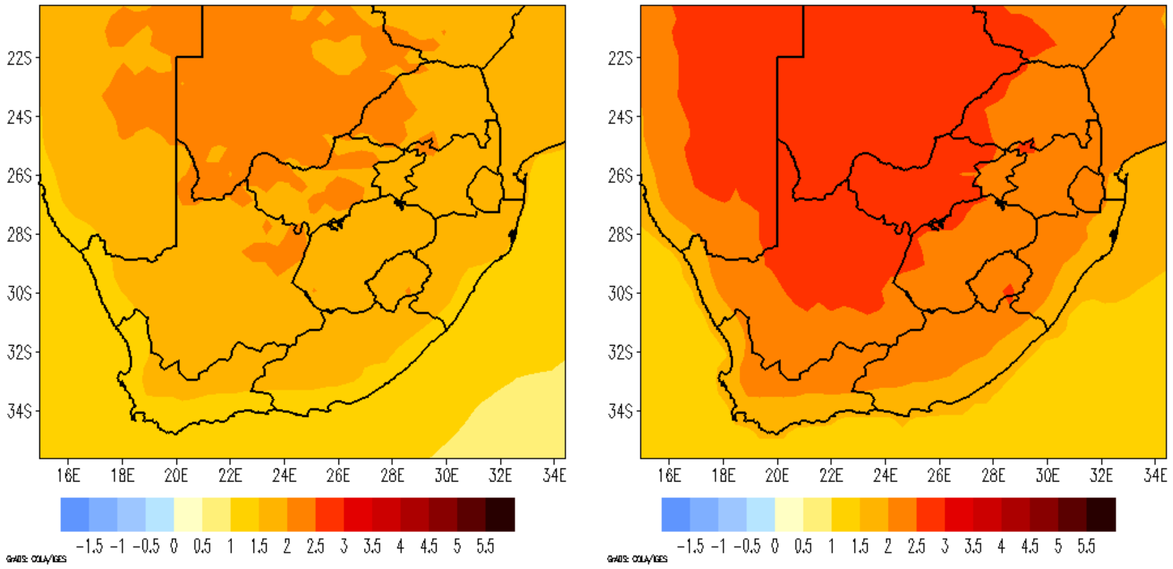
An increase in extreme rainfall events is associated with an upsurge in the frequency of occurrence of cut-off lows and more frequent occurrence of tropical-temperate cloud bands over the region (e.g. Engelbrecht et al., 2009, 2010). Tropical cyclone tracks are projected to shift northward, bringing more flood events to northern Mozambique and fewer to the Limpopo and KwaZulu provinces in South Africa (Malherbe et al., 2013). Statistical models also show an increase in extreme precipitation events in the summer over the east coast of KwaZulu-Natal along with an increase in rain-days for much of the country, excepting possibly the extreme west / southwest (Hewitson et al., 2005).

In summary, Climate Change in the near to mid-future in southern Africa will alter precipitation patterns which will affect the quality, rate, magnitude and timing of freshwater runoff to estuaries and will exacerbate existing human modifications of river inflows (Alber, 2002; USEPA, 2009; Bunn, 2016; SAWS, 2017). Along the Subtropical and warm temperate biogeographical region the combination of generally wetter conditions and heavy precipitation events would result in more runoff being generated (Figure 5.3). While a decrease in rainfall in the Cool Temperate bioregion, with the related possibility of a slight increase in inter-annual variability, would result in a decrease in flows and an increase in flow variability, as changes in precipitation are amplified in the hydrological cycle (Hewitson and Crane, 2006; Engelbrecht et al., 2009; 2011; Lumsden et al., 2009). The exception to this is the Orange River, which drains more than half of the country and with most of the catchment falling in the summer rainfall area. The frequency and magnitude of large floods are expected to increase in this system as are the intensity and duration of drought or zero-flow periods. The impact of these changes on marine and estuarine habitats and biota are likely to be significant as this catchment provides more than 75 % of the flow into the sea on the west coast (the findings of Chapter 3).

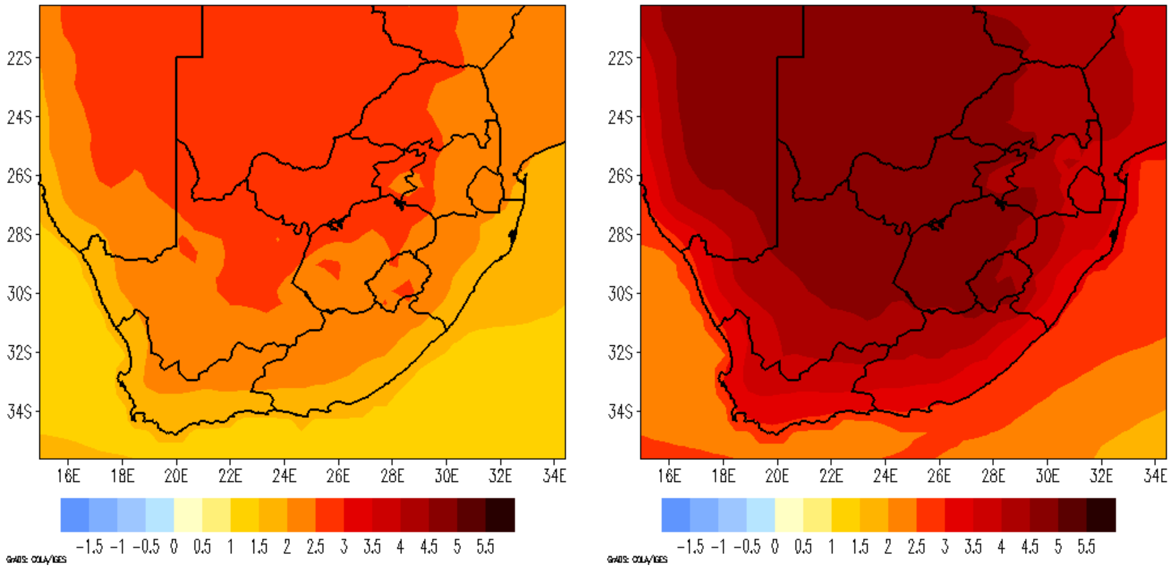
Estuarine functioning is strongly influenced by the magnitude and timing of freshwater runoff (Meynecke et al., 2006). Changes in precipitation and runoff ultimately drive changes in mouth state, and nutrient and sediment supply to estuaries and the coast. These will also influence human adaptation strategies to reduce risk, e.g. river impoundment and land-use change that will increase the rate of change in primary inputs (flow, sediment and nutrients) to estuaries and the coast.

Scenario RCP4.5 (GHG 560 pmm by 2100) **Scenario RCP8.5 (GHG 950 pmm by 2100)**

2036-2065 **2036-2065**



2066-2095 **2066-2095**

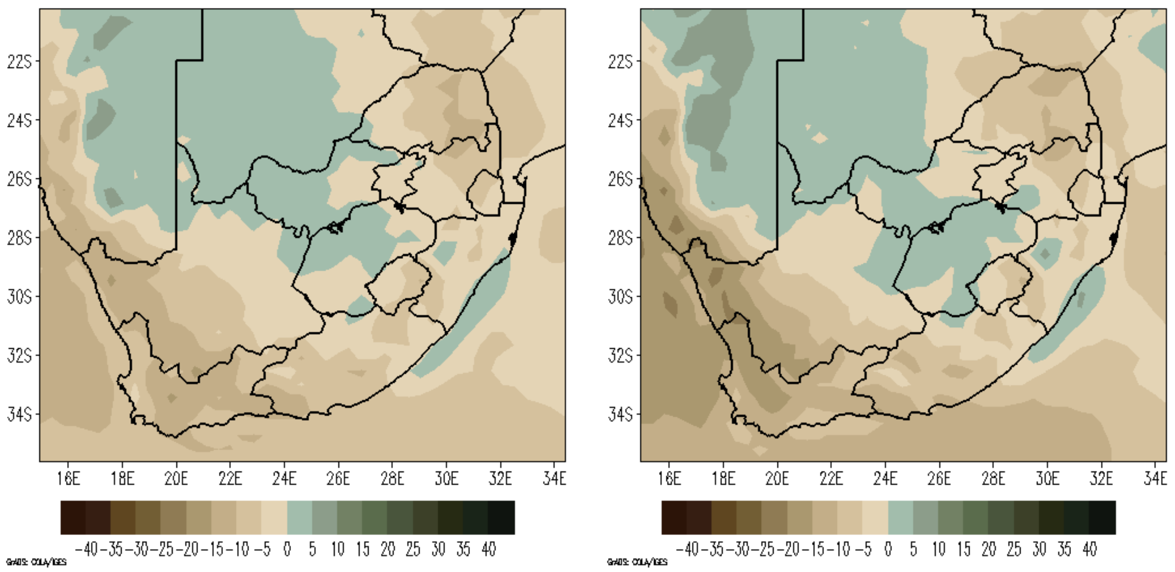


Median annual mean temperature change (ºC) relative to 1976-2005 (SAWS, 2017)

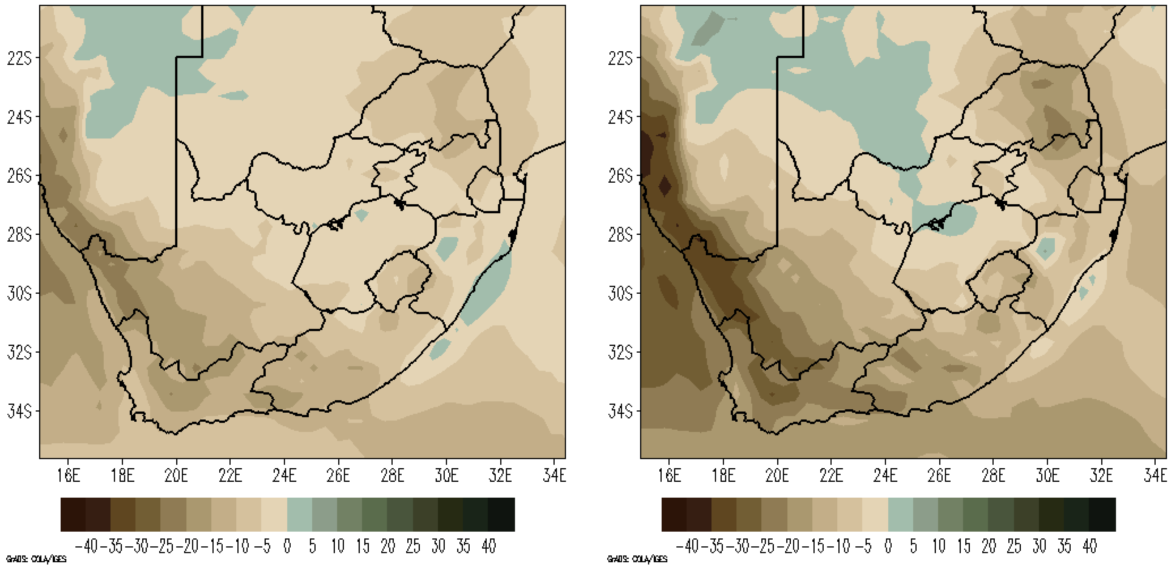
Figure 5.2: Annual mean near-surface (2m) temperature (°C) change from the median projected for 2036-2065 (top) and 2066-2095 (bottom), relative to present (1976-2005), under conditions of the RCP 4.5 (left) and RCP 8.5 (right) pathway.

Scenario RCP4.5 (GHG 560 pmm by 2100) **Scenario RCP8.5 (GHG 950 pmm by 2100)**

2036-2065 **2036-2065**



2066-2095 **2066-2095**



Annual percentage (%) change in total rainfall - relative to 1975-2005 (SAWS, 2017)

Figure 5.3: Annual total rainfall percentage (%) change from the median projected for 2036-2065 (top) and 2066-2095 (bottom), relative to present (1976-2005), under conditions of the RCP 4.5 (left) and RCP 8.5 (right) pathways.

5.3.1.3 Sea level rise (SLR)

Recent calibrated observations from satellites show that global sea level rise over the last decade has been 3.3+/- 0.4 mm.yr^{-1} (Rahmstorf et al., 2007). The IPCC AR5 SPM 2013 (IPCC, 2013; Church et al., 2013) concludes that anthropogenic warming and sea level rise will continue for centuries due to the timescales associated with climate processes and feedbacks, even if greenhouse gas concentrations are stabilised. Comparisons between approximately 30 years of South African tide-gauge records and the longer-term records elsewhere, show substantial agreement with global trends (Theron, 2007). A recent analysis of sea water levels recorded at Durban confirms that the local rate of sea level rise falls within the range of global trends (Mather 2008). Present South African sea level rise rates are approximately: west coast +1.9 mm.yr^{-1}, south coast +1.5 mm.yr^{-1}, and east coast +2.7 mm.yr^{-1} (Mather et al., 2009; Mather and Stretch, 2012). The probability of sudden rises in sea level (possibly several metres) due to catastrophic failure of large ice-shelves (e.g. Church and White, 2006) is still considered unlikely this century, but events in Greenland (e.g. Gregory, 2004) and Antarctica (e.g. Thomas et al., 2004) may soon force a re-evaluation of this assessment. In the longer-term the large-scale melting of ice-masses is inevitable. Recent literature (subsequent to IPCC 2007) give a wide range of SLR scenarios, but most “physics/process based” projections for 2100 are in the 0.5 to 2 m range (Pfeffer et al., 2008; Milne et al., 2009; Rossouw and Theron, 2009; Nicholls and Cazenave, 2010; SWIPA, 2011; Church et al., 2013).

Based on the above literature and findings, it is concluded that the best estimate (or ‘central estimate/mid scenario’) of sea level rise by 2100 is around 1 m, with a plausible worst-case scenario of 2 m and a best-case scenario (low estimate) of 0.5 m. The corresponding best estimate (mid-scenario) projections for 2030 and 2050 are 0.15 m and 0.35 m, respectively (Theron et al., 2012). Sea level rise of 1 to 3 m per degree of warming is projected if the warming is sustained for several millennia, with ultimate projections over millennia indicating a 7 m increase (Church et al., 2013). This in turn, will drive change in critical estuarine processes such as sediment dynamics, mouth state, and salinity regime shifts; with associated responses in biotic processes and patterns, e.g. primary production and eutrophication, biotic habitat structure, changes in recruitment, nursery function and community composition.

5.3.1.4 Increase in the frequency and intensity of sea storms

The Fourth Assessment Report of the IPCC predicts an increasing frequency and intensity of extreme weather events in the 21st Century (IPCC, 2007). The frequency and magnitude of severe weather events such as tropical cyclones, hailstorms, droughts and floods appears to be on the increase globally (IPCC 2007). In South Africa, increases in either intensity or frequency, or changes in seasonal storm intensity have been reported at a local scale albeit on a very short time-scale (Guastella and Rossouw, 2012; Harris, 2010). Preliminary findings indicate that there may be long-term trends in the regional metocean climate, while sea level rise alone will greatly increase the impacts associated with extreme sea-storm events (Theron, 2007). The regional variation in global wave climate was demonstrated by Mori et al. (2010), who, in simulating future trends, predicted that mean wave height might generally increase in the regions of the mid-latitudes (both hemispheres) and the Antarctic ocean, while decreasing towards the equator. Wang et al. (2004), Komar and Allan (2008) and Ruggerio et al. (2010) provide further evidence of a general wave height increase and increasing storm intensities in the Northern Hemisphere. Such changes in the regional metocean climates are expected to have significant impacts on local coastal areas. It is therefore important to investigate possible future climatic changes off the southern African coastline as well as the expected associated impacts. As can be anticipated, a more severe wave climate (or related oceanic wind climate) will result in more storm erosion, potentially more coastal sediment transport, and greater coastal impacts.

Preliminary analyses found that the annual mean significant wave height (Hm_0) for the wave data collected off Richards Bay and Cape Town indicate no real progressive increase (Rossouw and Theron, 2009). This may appear to contradict the findings of the IPCC, as presented in PIANC (2008), but the South African results may reflect a regional aspect of the impact of Climate Change. Although the averages appear to remain constant, there seems to be some change in the individual storms. For example, considering the peaks of individual storms off Cape Town during the more extreme winter period (June to August), an increase of about 0.5 m over 14 years is observed. This result may be indicative of a significant increase in the “storminess” over the next few decades. It is also worth noting that the opposite occurs during summer: there has been a general decrease over the last 14 years with regard to individual storms off Cape Town. However, the South African wave-record is too short to make any firm conclusions at present. To some extent it could be said that the preliminary "trend" indicated by the South African wave-data is supported by model predictions of Mori et al. (2010), which appear to show an increase in wave height for the South African coast of roughly 6% for extreme events (Theron et al., 2010).

Wave climate and conditions are determined by ocean winds. Predicted values for potential changes in oceanic wind regimes off southern African are lacking. In view of this shortcoming and to enable an assessment of the potential impacts of stronger winds, a relatively modest increase of 10% could be assumed. Thus, a modest 10% increase in wind speed, means a 12% increase in wind stress, a 26% increase in wave height, and as much as an 80% increase in wave power (Theron, 2007). This means that a modest 10% increase in wind speed could also result in a potentially significant increase in coastal sediment transport rates and consequently impact on estuarine mouth regimes and associated salinity regimes. These changes in turn will drive change in the responses of key biotic processes and patterns, particularly changes in recruitment processes of fish and invertebrates linked to mouth state and overwash.

5.3.1.5 Ocean acidification

Fossil fuel burning and anthropogenic land-use changes have caused the atmospheric CO_2 concentrations to rise from 280 ppm to about 387 ppm (Le Quéré et al., 2009). The oceans have absorbed approximately 30% of these total anthropogenic carbon dioxide emissions from the atmosphere (Canadell et al., 2007; IPCC, 2014). When seawater absorbs CO_2, chemical reactions occur that reduce the pH of seawater, the concentration of carbonate ion, and the saturation states of the bio-minerals aragonite and calcite in a process called "ocean acidification" (Feely et al., 2010). Over the past 250 years, the pH of the ocean surface waters has decreased by about 0.1, corresponding to a 26% increase in acidity (Feely et al., 2010; IPCC, 2014). By the end of this century, surface ocean pH is expected to decrease by another 0.2 to 0.4 units (Feely et al., 2004, 2009; Doney et al., 2009; IPCC, 2014). Globally the aragonite saturation state from preindustrial to present has decreased below the envelope of natural variability (Hauri et al., 2013). Southern African upwelling systems have a naturally lower pH and a considerably lower carbonate saturation state (Gruber et al., 2012). The pH levels in the Southern Benguela currently range from 7.60 to 8.25, depending on the season, but have an annual average pH of ~8.1 (Gregor, 2012). This system is predicted to have a pH of approximately 7.8 to 7.5 units by year 2100 and an even lower pH of 7.3 to 6.7 units by year 2300 (Caldeira and Wicket, 2005). Ocean acidification will ultimately result in change in pH and oxygen in estuaries, with a related response in biotic processes such as community composition, nursery function and behavioural responses. However, natural variability in estuarine pH should be taken into account when effects of ocean acidification are considered. Natural fluctuation in pH may play a large role in the development of resilience in estuarine populations. On the other hand, it may combine with the effects of ocean acidification to produce even more extreme events resulting in even greater impact on the biota (Hoffman et al., 2011).

5.3.2 Quantification and mapping of vulnerability

5.3.2.1 Changing ocean circulation processes

Upwelling and biogeochemical inputs

Predicted changes in ocean circulation process such as current location and velocity (Section 5.3.1.1) will strongly influence key marine-driven biogeochemical inputs such as dissolved oxygen and nutrients to the coast. Coastal biogeochemical processes in turn, influence permanently open, marine dominated estuaries to a larger extent than TOCEs or freshwater-dominated systems. In terms of biogeochemical shifts linked to ocean circulation and upwelling, it is expected that estuaries adjacent to upwelling systems will be most affected (Figure 5.4). More intense upwelling and tidal advection of upwelled water will increase nutrient availability in estuaries. This phenomenon will mostly influence the large permanently open Orange, Olifants and Great Berg estuaries along the West Coast. In the case of the Great Berg Estuary (situated within St Helena Bay) more frequent upwelling induced “black tides” and advection of anoxic hydrogen-sulphide waters may pose additional risk (Lamberth et al., 2010). Figure 5.4 indicates that there will be some change (medium) for these estuaries as well as for open systems in KwaZulu-Natal and Wild Coast. An increase in shelf upwelling will increase nutrient input and primary production in the nearshore and lower reaches of open estuaries.

Temperature shifts

Estuaries will have a high vulnerability to increases in land temperatures (Figure 5.). Projected temperature increases in the average global surface atmosphere range from a low scenario of 1 to 3°C with a potential upper range of 6°C by 2100 (indicated as high in all regions on Figure 5.2 and Figure 5.4). Shallow -water aquatic systems such as South African rivers and estuaries will exhibit greater increases in temperature than deeper waters (Rijnsdorp et al., 2009; James et al., 2013).

Overall, the large numbers of shallow, small TOCEs that characterise the South African coast are likely to be very sensitive to terrestrial temperature increases predicted under far-future Climate Change predictions.

Larger, permanently open estuaries on the other hand, will be more likely to respond to shifts in temperature due to changes in ocean currents and upwelling conditions whilst the influence of terrestrial heating will be mostly confined to the upper reaches where river processes dominate. Indicted as medium (decrease) along the West Coast and Western Cape, and medium (increase) along the Southern and Eastern Cape in Figure 5.4.

This means that South African estuaries will be subject to changes in the alongshore coastal temperature gradient and along a land-sea gradient (Wooldridge and Dyzel, 2012).

Biological responses: Land-sea temperature gradients

Wooldridge and Deyzel, (2012) show that where species are at the edge of their range they can arrange themselves longitudinally according to the land-sea temperature gradient. As predicted land temperatures rise the upper reaches of temperate estuaries are likely to support more tropical species due to increased temperature gradients between estuaries and the sea. Thus, while there will be low degree change in Subtropical KwaZulu-Natal estuaries, but a medium degree in the other regions (Figure 5.2).

Change in coastal /ocean circulation patterns and temperature regimes

Feature/process	West Coast	Western Cape	Southern Cape	Eastern Cape	Wild Coast	KwaZulu Natal
a. Current location and velocity	L	L	M	M	M	M
b. Upwelling	M	M	L	L	M	M
c. Land temperatures	H	H	H	H	H	H
d. Sea temperatures	M^{-}	M^{-}	M^{+}	M^{+}	M^{+}	L
e. Biological responses: Land-sea gradient	M	M	M	M	M	L
f. Biological responses: Along-coast gradients	L	L	M	H	H	H

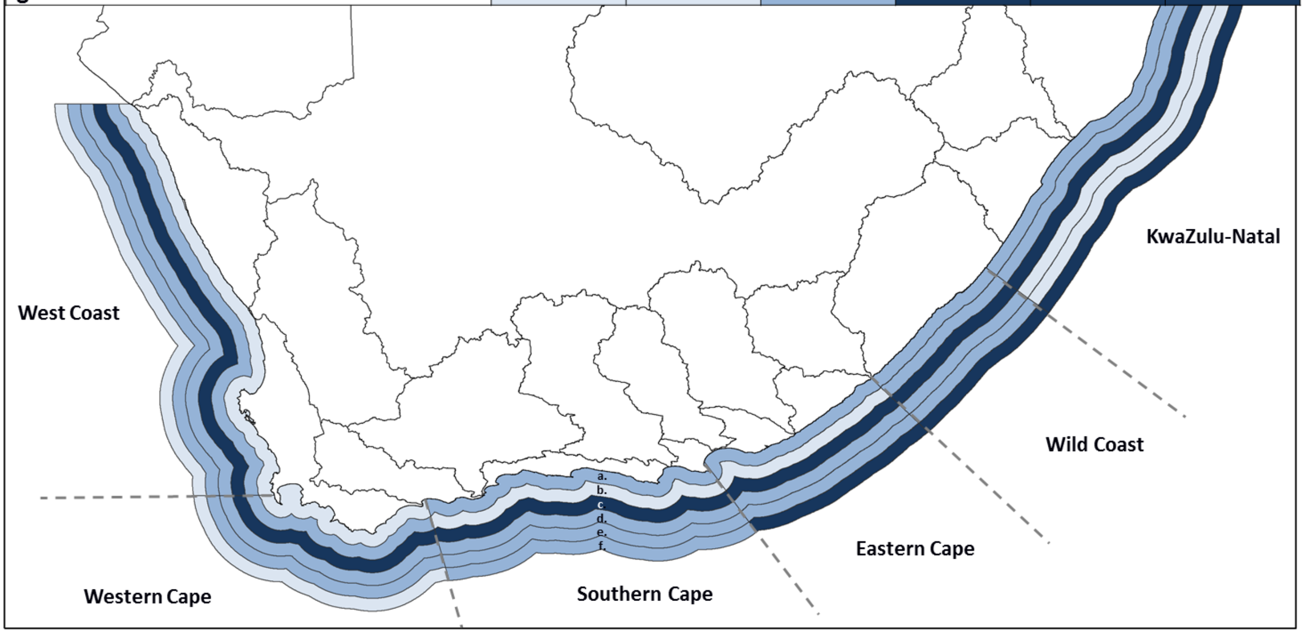


Figure 5.4: Regional summary of changes in ocean circulation patterns and shifts in temperature regimes and the influence on the community structure, abundance and distribution of estuarine species. Vulnerability is indicated as high/medium/low shifts from west to east with potential change a. to f. depicted by moving outward from the coast.

Biological responses: Along-coast gradients

Higher temperatures on the east coast may result in the expansion of the Subtropical bioregion south-westwards compacting the warm temperate region against the cooling southern Benguela and expansion of Cool Temperate waters and species to the east (Blamey et al., 2015; Whitfield et al., 2016). A significant change (indicated as high) is therefore expected for Eastern Cape, Wild Coast and KwaZulu-Natal estuaries (Figure 5.2). Temperature will influence community composition and species distribution as well as reproduction, growth, behaviour, mortality, predator-prey and parasite-host relationships and competition for resources. Species are adapted to, and distributed within, specific environmental temperature ranges (Maree et al., 2000; Elliott, 2002; Harrison and Whitfield, 2006) and tend to be more stressed near the edge of their distribution (Sorte and Hoffman, 2004). As temperature changes, the geographical distribution of species, depending on their tolerances or preferences, may contract or expand, leading to new and unpredictable species interactions (Murawski, 1993; Perry et al., 2005; Clark, 2006; Harley, et al. 2006; USEPA, 2009).

While many species of fish in estuaries are tolerant of extreme temperatures, changes in the distribution and abundance of especially the marine species in estuaries are likely to be linked to coastal temperatures because of spawning and larval development taking place in the marine environment. Thermal windows are narrow in the early life stages of fish (eggs and larvae) and then widen in juveniles and young adults (Pörtner and Knust, 2007; Pörtner and Peck, 2010). In recent years a number of estuarine-associated Subtropical species as well as some tropical reef species have extended their ranges 200 to 1000 km south to the Warm / Cool Temperate transition zone (Lamberth et al., 2013). Furthermore, the increased occurrence of tropical fish species in estuaries along the East Coast of South Africa (e.g. East Kleinemonde and Mngazana) has not displaced the numbers of temperate species, thus resulting in an increase in species richness (James et al., 2008b, 2008c; Mbande et al., 2005). Range expansion may be accompanied by behavioural changes. Expansion of *Pomadasy commersonnii* into the warm-cool temperate bioregion transition zone has culminated in stock separation, loss of return migration and the establishment of a spawning population in its new range (Lamberth et al., 2013). Less mobile or sessile species that are less able to escape or compete with encroaching species for resources, may face local or global extinction. Communities do not shift their distribution as a unit. Movement into new habitat depends on: 1) the abundance of reproductively active adults available in the original habitat and their capacity to produce young; 2) enough potential colonisers; 3) their ability to move into new habitats; 4) the survival of a viable and effective population size in the new habitat to produce succeeding generations (Kennedy et al., 2002). Thus, the loss of species from an estuary that has become too warm may reduce species diversity in that estuary in the short term with recovery depending on the mobility of new colonizers, their ability to tolerate higher temperatures and their tolerance of higher salinities in the marine environment.

Changes in temperature will also affect coastal vegetation with more Subtropical species moving further south most notably the invasion of salt marsh habitats by mangroves the latter being tropical and sub-tropical in nature and ideal indicators of global warming (Steinke, 1999; Adam, 2002; Gilman et al., 2008; Hoppe-Speer et al., 2015a). Introduced mangroves survive in warm temperate estuaries as far south as East London and as temperatures increase they will expand (Hoppe-Speer et al., 2015a, 2015b; Whitfield et al., 2016). The only inhibitor of mangrove expansion appears to be the unavailability of estuarine habitat due to dominance of temporarily open-closed estuaries to the west. Frost may also play a role but in most cases, frost and plant cell damage are dampened in estuaries and the nearshore zone (de Lange and de Lange, 1994; Whitfield et al., 2016). There are a number of mangrove-associated invertebrates that have already shifted further than mangroves and colonised “surrogate” salt marsh and sedge habitat to the south. This includes the tropical fiddler crab *Uca annulipes* and mangrove snail *Cerithidea decollate* in the Knysna Estuary a new southernmost limit for both genera (Hodgson and Dickens, 2012; Peer et al., 2015).

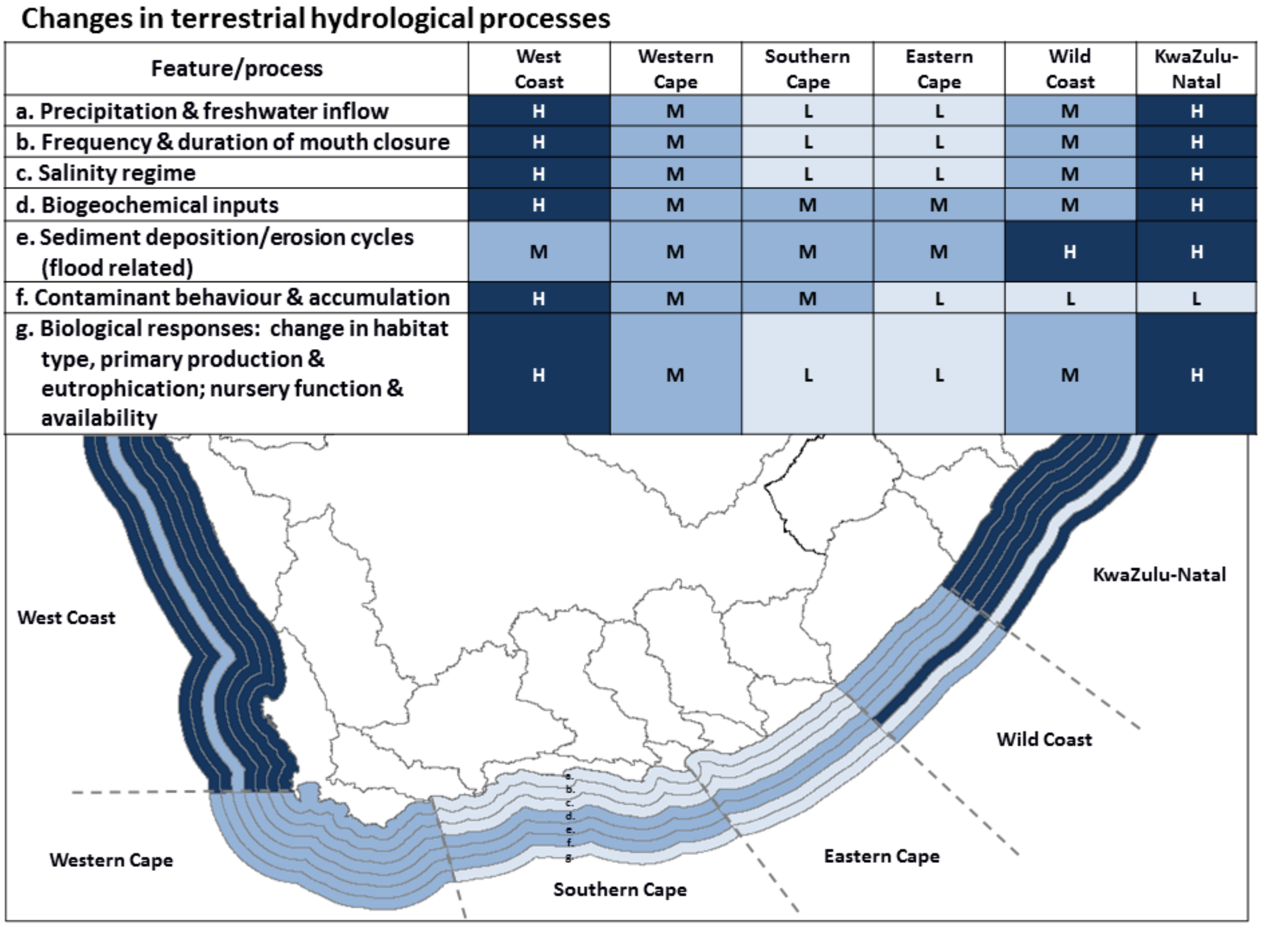
5.3.2.2 Modification of terrestrial climatic and hydrological processes

Precipitation and freshwater inflow

In principle, all estuaries are sensitive to changes in precipitation and associated freshwater inflow. This is especially true of the relatively small South African estuaries, which depend on river inflow to offset the high wave energy that causes mouth closure along a relatively exposed coast (Cooper, 2001, this study). The five major consequences of modifications in freshwater inflow are changes in: the frequency and duration of mouth closure; the extent of saline intrusion; land-derived biogeochemical inputs (suspended solids, nutrients, POM, dissolved oxygen); sediment dynamics; and contaminant behaviour and accumulation (e.g. toxic substances). Vulnerability is high for these features for the West Coast and KwaZulu-Natal (Figure 5.3).

Changes in the frequency and duration of mouth closure

TOCEs become isolated from the sea by the formation of a sand berm across the mouth during periods of low or no river inflow. Such estuaries stay closed until their basins fill up and their berms are breached by increased river flow. A foremost consequence of river flow modification albeit reduction or increase, is a change in the frequency and duration of estuary mouth closure in TOCEs (Whitfield et al., 2008). In extreme cases, freshwater inflow reduction can cause permanent mouth closure or a significant flow increase can prevent the mouth from closing. Permanently or predominantly open estuaries may also experience closure and switch to being TOCEs. Figure 5.5 shows that mouth closure responds to precipitation and run-off with the same response pattern around the coast for different regions.



Changes in terrestrial hydrological processes

Feature/process	West Coast	Western Cape	Southern Cape	Eastern Cape	Wild Coast	KwaZulu-Natal
a. Precipitation & freshwater inflow	H	M	L	L	M	H
b. Frequency & duration of mouth closure	H	M	L	L	M	H
c. Salinity regime	H	M	L	L	M	H
d. Biogeochemical inputs	H	M	M	M	M	H
e. Sediment deposition/erosion cycles (flood related)	M	M	M	M	H	H
f. Contaminant behaviour & accumulation	H	M	M	L	L	L
g. Biological responses: change in habitat type, primary production & eutrophication; nursery function & availability	H	M	L	L	M	H

Figure 5.5: Regional summary of the consequences of changes in precipitation on key estuarine processes – mouth state, salinity regime, nutrient inputs, floods and sediment depositional cycles, contaminant behaviour, habitat type and nursery function. Vulnerability is indicated as high/medium/low shifts from west to east with potential change a. to g. depicted by moving outward from the coast.

The significant decrease in runoff along the West Coast (High) and Western Cape (Medium) is likely to cause a significant increase in closed conditions in temporarily open systems along this coastline. Average flow conditions are predicted to remain largely similar for the present along the Southern Cape (possible slight decrease) and Eastern Cape (possible slight increase) in most regional climate models (indicated by low in Figure 5.5), however extreme events such as cut-off lows are predicted to increase. However, this is only likely to lead to a small change in closed mouth conditions in TOCEs depending on the size of the system and the inflow regime (indicated by low in Figure 5.5). Wild Coast TOCEs are likely to show slight reductions in closed mouth conditions as a result of increased river flow. However, these flow-driven increases in open mouth state could be offset by increased sedimentation from the highly erodible, but severely degraded Wild Coast catchments (Le Roux et al., 2008). KwaZulu-Natal TOCEs have a high vulnerability as a predicted increase in precipitation will result in the mouth closing less often thus reducing the periods of high productivity associated with closed-mouth conditions (indicated by high in Figure 5.5) (Nozais et al., 2005; Thomas et al., 2005).

Riddin and Adams (2008, 2010 and 2012) show that changes in the mouth state, water levels and salinity of TOCEs result in changes in estuary habitat type, e.g. an increase in closed mouth conditions can reduce submerged macrophytes cover and increase macroalgal cover. Associated high water levels can reduce supratidal salt marsh, reed and sedge cover. Loss of these habitats may result in bank destabilisation and erosion, while a loss of submerged macrophytes affects faunal composition and abundance and on the subsequent functioning of temporarily open/closed estuaries. The most vulnerable regions are West Coast and KwaZulu-Natal as indicated by high in Figure 5.5.

Changes in mouth condition has serious ecological implications since these estuaries represent 70% of the different types of estuaries found in South Africa. For example the mudprawn *Upogebia africana* has an obligatory marine phase of development during the larval stages. Estuary mouth closure, particularly for extended periods (e.g. >1 year), disrupts the life cycle and can result in local extirpation (Wooldridge and Loubser, 1996). Some demersal zooplankton species exhibit tidally-phased migratory behaviour (Schlacher and Wooldridge, 1995). Mouth closure removes the tidal signal disrupting the life cycles of these organisms. Extended mouth closure coupled with dilution or evaporation can lead to hypo or hypersalinity respectively with impacts on biota linked to their salinity preferences or tolerances (indicated by high and medium for West Coast and Western Cape respectively in Figure 5.5). Reproduction may be interrupted in species that breed in estuaries e.g. *Callichirus kraussi* or mass mortalities may result in species unable to escape intolerable conditions in a system (Whitfield et al., 2006). Prolonged mouth closure in TOCEs results in low recruitment potential for juvenile marine fish and effectively prevents the emigration of adults back to sea (Vorwerk et al., 2003). During extended closure, fish populations may also decrease considerably due to predation by other fishes, birds and mammals including humans. For example, predation by piscivorous birds reduced the Cape stumpnose *Rhabdosargus holubi* population in the West Kleinemonde Estuary between 20 and 80% over a six month period (Blaber, 1973). In severe cases, predation will once the mouth reopens, result in little or no recruitment to the adult population in the sea. Some fishes may live out their life in a closed estuary without ever having had the opportunity to breed.

With birds, mouth closure will lead to a loss of tidal action which, in turn, will adversely affect the quantity and availability of intertidal benthic organisms to waders that forage mainly on intertidal mudflats (Whitfield et al., 2008). Many of these waders are Palaearctic migrants; so mouth closure can have a global impact on their population. Other effects of reduced freshwater inflow includes the loss of shallow water habitats, favoured by herons, flamingos and other wading birds, and the loss of islands, which provide roosts and breeding sites safe from terrestrial predators. Under extreme Climate Change scenarios, increased mouth closure results in loss of connectivity with the marine environment and adjacent estuaries, increased population isolation and allopatric speciation.

Changes in the salinity regime

The degree to which seawater enters an estuary is dependent on river inflow and the bathymetry of the system, i.e. seawater penetration is often constrained by river inflow in the shallow, constricted upper reaches of South African estuaries, but penetrates and mixes with relative ease into the deeper middle reaches whilst the lower reaches are generally dominated by tidal flows. Thus the middle reaches of an estuary show the most sensitivity to changes in flow (river and tidal) as they can shift from a more brackish character to a more fresh (increase flow) or marine (increase sea level or decrease flow) state. For example, in large systems flow reduction may initially result in a reduction in the extent of the estuarine mixed zone i.e. that section of an estuary with salinity between 10 and 20. Further reduction in stream flow can result in the complete elimination of this mixed zone so that, effectively, the system functionally becomes an arm of the sea e.g. the Kromme Estuary (Bate and Adams, 2000). If there is no inflow at all, a reverse salinity gradient may develop, where the salinity at the head of the estuary exceeds that of seawater e.g. the Kariega Estuary (Bate et al., 2002; Paterson and Whitfield, 2003).

Reduced freshwater inflow reduces the primary productivity of an estuary, thereby reducing the food available to juvenile fishes (Strydom and Whitfield, 2000; Snow and Adams, 2006). This will impact growth, survival and production or recruitment into the adult population (Strydom, 2015). Reduction in freshwater inflow into TOCEs may lead, paradoxically, to a reduction in salinity in many small systems. If the mouth is closed and, provided that the river inflow still exceeds evaporation and seepage losses, a progressive freshening of the estuary occurs until such time as rising water levels lead to a breaching of the berm closing the mouth, e.g. Groot Brak. The impact is an almost complete loss of marine species with only a few euryhaline estuarine and freshwater species remaining (Whitfield, 2005). Mass mortalities of marine fish species occurred in the closed Bot Estuary when salinities declined to 2- 3 and temperature to below 18°C (Bennett, 1985).

West Coast and Western Cape estuaries will show a significant increase in salinity penetration (indicated by high and medium respectively in Figure 5.5) in large permanently open estuaries especially during the summer low-flow period, but some freshening (decline in average salinity) of TOCEs is likely under increased closed mouth conditions as they will remain closed for longer periods under the influence of limited river inflow and continuous seepage losses through the berm. Southern Cape estuaries are likely to remain similar to present (indicated by low in Figure 5.5), but may show a limited increase in salinity penetration in some large permanently open estuaries during the low flow season. Eastern Cape systems are also predicted to remain similar to present (indicated by low in Figure 5.5), but could have a slight decrease in salinity penetration in some large open estuaries due to an increase in resetting events. In the smaller Eastern Cape TOCEs, the predicted slight increases in flow could cause an increase in open mouth conditions with a concomitant increase in average salinity depending on estuarine size and shape. The Wild Coast is likely to see some reduction in salinity penetration in permanently open systems as a result of increased freshwater flows (indicated by medium in Figure 5.5), whilst the slight increase in open mouth state in TOCEs may facilitate increased tidal action and related salinity penetration. Overall predicted increases in precipitation in KwaZulu-Natal are likely to dilute the average salinity in the numerous small perched TOCEs (< 10), whilst increased open states in the deeper TOCEs and estuarine lakes will facilitate a shift to more saline conditions (10 -20) than present. The large permanently open systems are expected to become fresher under increased flow conditions. A significant change is thus expected for KwaZulu-Natal estuaries (indicated by high in Figure 5.5).

Changes in biochemical inputs (suspended solids, nutrients, POM, dissolved oxygen)

While estuary biogeochemistry is strongly influenced by freshwater inflow and marine inputs, *in situ* hydrodynamic processes (e.g. mixing, flushing, residence time and stratification) and biogeochemical processes (e.g. flocculation, remineralisation and primary production) also play a role (Taljaard et al., 2009a; 2009b). Overall the expected changes in biochemical inputs largely follows changes in freshwater inflow, albeit median flow conditions or/and increase in floods, thus showing a high degree of change along the West Coast and Subtropical regions Figure 5.5). These ratings were a precautionary aggregate of predicted responses in suspended solids (SS) (or turbidity), particulate organic matter (POM), dissolved inorganic nutrients, and dissolved oxygen, with the highest rating allocated to the combined grouping of biochemical inputs.

River inflow usually introduces suspended solids to estuaries, especially in highly erodible catchments. Therefore, estuaries situated in regions where river inflow is projected to decrease, mainly the West Coast and Western Cape, will become generally less turbid, while systems where an increase in extreme events is expected will become more turbid, mainly KwaZulu-Natal and, to some extent the Wild Coast region. Vulnerability is indicated as high for these regions (Figure 5.3). This, in turn, may affect important factors such as light attenuation (e.g. linked to primary production) and visibility (e.g. predator-prey relationships), that will decrease in systems becoming more turbid and increase in the less turbid systems (Whitfield, 1998; Lemley et al., 2017).

POM is affected by input from the river and *in situ* biological processes (e.g. primary production, eutrophication) and anthropogenic input (e.g. wastewater discharges and contaminated runoff) (McCallister et al., 2006; De Villiers and Thiart, 2007; He et al., 2014; Lemley et al., 2017). However, changes in freshwater inflow are viewed to be the key stressor, as river inflow introduces significant amounts of POM to estuaries during high flow events. Systems situated in regions where a decrease in flow is projected, West coast and Western Cape regions, will generally receive less catchment-derived POM, while in regions where flows and/or floods are expected to increase POM will become higher compared with present, mainly KwaZulu-Natal and, to some extent the Wild Coast region.

Nutrients in estuaries are naturally derived from river inflow, upwelling (see ocean circulation processes), as well as *in situ* processes such as remineralisation and primary production (e.g. De Villiers and Thiart, 2007; Taljaard et al., 2009a; Gillanders et al., 2011). However, anthropogenic sources have increased nutrient input to South African estuaries (findings of Chapter 3). Estuarine ecosystems are no longer able to assimilate nutrient loads resulting in eutrophication (Lemley et al., 2015, 2017). Climate Change driven nutrient dynamics will be superimposed on the existing impacts, i.e. highly impacted urban estuaries around Cape Town, Mossel Bay, Port Elizabeth and Durban, and the large permanently open systems subject to agricultural return flow (e.g. Great Berg, Olifants, Breede, Sundays, uMfolozi). Expected change in processes and patterns will be similar to that of suspended solids and POM. Along the West Coast and Western Cape the decrease in river inflow and associated increase in residence time will allow for more effective utilisation of nutrients benefit in situ processes, thus increased primary production (Taljaard et al., 2009a; Human et al., 2015). In contrast, increase flow along the KwaZulu-Natal coastline will reduce retention and associated increase in primary production.

Dissolved oxygen levels in estuaries are influenced by temperature, salinity, nutrient loading, residence time and stratification (Taljaard et al., 2009b; Gillander et al., 2011;

Human et al., 2015). Increased temperatures increases primary production and remineralisation rates, thus increasing fluctuations in dissolved oxygen (Justic et al., 2007). Thus, higher temperatures (Figure 5.4), shifts in residence time (e.g. change mouth closure in Figure 5.5) and nutrient input will increase dissolved oxygen stress in South African estuaries, especially in the smaller TOCEs (O'Boyle et al., 2013; Wallace et al., 2014). This is especially the case along the West Coast (high) and Western Cape (medium) regions as a result of the significant reduction in freshwater input. The highly enriched, smaller urban TOCE would be most at risk. Only small shifts in freshwater inflow is predicted for the Southern Cape and Eastern Cape regions, thus while some overall decline in dissolved oxygen is expected it would not be as severe as West Coast and Western Cape. Along the Wild Coast (indicated as medium in Figure 5.5) the predicted increase in river inflow will somewhat offset the general increase in dissolved oxygen stress because of warming and increase primary production. While in KwaZulu-Natal increased river inflow will reducing residence time. As a result, the effects of nutrient enrichment on DO levels will be less persistent, i.e. these systems will flush more often. However the large lake systems in this region (e.g. Kosi Bay) comprising naturally deep, highly-resident water bodies, will not benefit from this mechanism and can become enriched over time with predicted higher river inflow (indicated as high in Figure 5.5).

All of the above changes in water quality will result in changes in estuary primary production and eutrophication, resulting in an overall decline in the species richness and abundance of estuarine resident taxa (indicated as high for West Coast and KwaZulu-Natal in Figure 5.5). For example, in the Sezela Estuary in KwaZulu-Natal, which was subject to chronic industrial pollution in the 1980s, a maximum of two estuarine resident fish species was recorded in the system between 1984 and 1986. Subsequent improvements in water quality resulted in an increase in the number of estuarine-resident fish species recorded to a maximum of 16 species in 2001 (Whitfield, 1995; Harrison and Whitfield, 2004).

Sediment deposition / erosion cycles and floods

Floods in estuaries scour sediment deposited during periods of lower flow. This accumulated sediment is both catchment derived and brought in from the sea by flood tides. Soil erosion in catchments poses a major threat to estuaries, particularly those in Wild Coast and KwaZulu-Natal (see Figure 1.1) (Le Roux et al., 2008; Morant and Quinn, 1999). The potential denuding of vegetation in arid catchments (i.e. increasing the erodibility of soils) coupled with an increase in the frequency of high intensity rain events due to Climate Change will lead to a significant increase in the deposition of sediment in estuaries (indicated by high in Figure 5.5).

Whilst the Western Cape is likely to experience only small increase in flood events, the arid nature of the land and sparse land cover will make it highly vulnerable to erosion especially in areas subjected to poor land-use. Western Cape and Southern Cape estuaries fed by rivers draining Table Mountain Sandstone tend to be sediment starved, and will therefore be somewhat buffered from the above mentioned effects. The Southern Cape and Eastern Cape systems will see some increase in the occurrence of flooding and substrate instability, hence indicated as medium low in Figure 5.5). Along the Wild Coast the predicted increase in the frequency and magnitude of flood events will, exacerbated by current land use, result in greater catchment erosion. This will lead to more infilling, changes of sandy to muddy habitats and a decline in substrate stability, resulting in changes to biotic community structure. In KwaZulu-Natal small incised estuaries, increased flooding will negatively influence substrate stability resulting in depauperate biotic communities as there is little intertidal and lower floodplain habitat available for colonization. Significant change (high) is thus expected in Wild Coast and KwaZulu-Natal estuaries (Figure 5.3).

Large dams have the effect of capturing freshets and attenuating major flood peaks. The degree to which this will occur depends on the ratio of dam volume to MAR, the level in the dam preceding the flood, and the size of the flood. A decline in these type of resetting events will increase sediment deposition in estuaries and overall reduce their volume and surface area. Higher temperatures, with the related increase in evaporation, will not only increase the need to build more dams but will also exacerbate the impact of existing dams on the aquatic environment (Bunn, 2016). Therefore catchments that are heavily utilised may see a general reduction in floods and associated sediment transport, e.g. uMgeni and Great Brak.

Contaminant behaviour and accumulation (e.g. toxic substances)

Contaminants (e.g. metals, polyaromatic hydrocarbons, pesticides, herbicides and pathogens) are introduced through wastewater discharges, stormwater runoff, agricultural return flow and atmospheric deposition. Climate Change stressors can cause changes in chemical behaviour (e.g. associated with changes in temperature, pH and oxygen), and the remobilisation and/or flushing of such contaminants (Kennedy, et al., 2002; Schiedek et al., 2007).

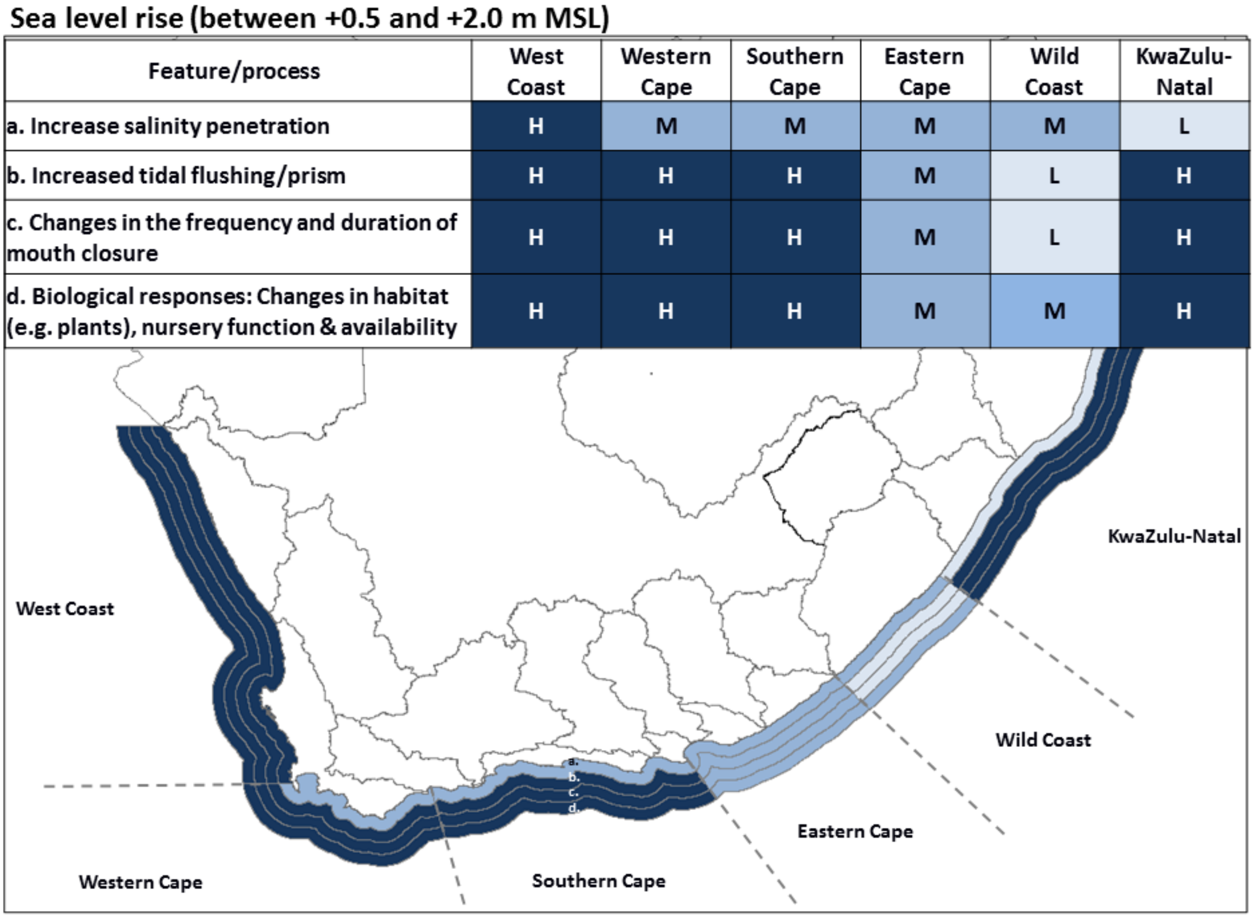
For example, changes in pH and dissolved oxygen may result in contaminants becoming bio-available with ripple effects on estuarine biota. Toxic substances (e.g. metal and persistent organic pollutants) adsorb onto fine sediment particles and POM, which settle as a result of a decrease in flow and/or open mouth conditions. The re-suspension and flushing of settled contaminants from estuarine systems is largely influenced by high river flows and extreme events. The predicted increases in temperature are also expected to increase the bioavailability of some toxins, but this is an area that needs further research.

Because of reduced inflow, and increased retention, West Coast and Western Cape estuaries may experience an increase in average pollutant concentrations with a high and medium vulnerability indicated in Figure 5.5 respectively. As water resources become more developed return flow (e.g. agriculture and wastewater) is expected to make up a larger percentage of the baseflows in especially the West Coast, Western and Southern Cape thus contributing to pollution loads. Contaminant behaviour with the exception of temperature induced aspects, is expected to remain similar to present along the Eastern Cape and relative pristine Wild Coast. Along the KwaZulu-Natal coast, a high number of urban estuaries (e.g. Durban, Richards Bay) are likely to experience a significant increase in the flushing of pollutants from the water column and sediment thus “buffering” against the effect Climate Change (indicated by a low in Figure 5.5)). Decrease in retention will also assist in reducing the average contaminant concentration.

5.3.2.3 Sea level rise

Sea level rise can either counteract the reduction in runoff to an estuary or exacerbate the effect depending on the size of the estuary, sediment availability, and wave energy near or at its mouth. In the case of small, temporarily open/closed estuaries sea level rise could assist in maintaining open mouth conditions through increasing the tidal prism, particularly if the system is sheltered from wave action and/or little sediment is available near its mouth. Alternatively, sea level rise could merely reset the level at which an estuary closes to the same relative height above mean sea-level, without significantly affecting the frequency or duration of mouth closure. However, an increase in storminess might actually increase the frequency and or duration of the mouth closure due to increased marine sediment transport into the mouth area during sea storms. Sea level rise can also dampen the barrier effect (i.e. protection) provided by submerged rocky platforms in dissipating wave action and maintaining open mouth conditions under low flows. In the case of permanently open estuaries, sea level rise may lead to an increase in saline penetration (especially in the middle reaches) and require additional freshwater inflow to maintain the present salinity gradient, i.e. it may be necessary to increase ecological flow requirements to maintain present ecological health.

West Coast and Western Cape estuaries will see a significant increase in tidal flows as the less steep topography of this region facilitates the formation of large permanently open systems (e.g. 70 km long Great Berg Estuary). The increased tidal prisms in the medium to larger temporarily open systems will assist with maintaining open mouth conditions, and associated salinity penetration, in the face of flow reductions, but the benefits of increased sea level rise may be offset by changes in mouth protection (indicated by high in Figure 5.5). The net result is that the estuaries along this coastline may become more saline as salinity penetration becomes more effective. Southern Cape estuaries will also show a significant increase in tidal flows due to a gentle topography of the large estuarine lakes, bays and permanently open systems of the region. Even the smaller systems may show an increase in tidal amplitude, tidal prisms and associated salinity penetration as sediment is often limiting along this coast, thus preventing estuary berms from resetting to their potential levels. The nett result is that increased tidal prisms in medium to larger temporarily open systems and estuarine lakes will assist with maintaining open mouth conditions and longitudinal salinity gradients. Significant changes (high) are thus expected for the West Coast, Western and Southern Cape (Figure 5.6). In the Eastern Cape larger permanently-open estuaries may experience a substantial increase (>1.0 m) in tidal flows, while that of the smaller systems with generally steeper topography will be similar to the present day. Increased tidal prisms in medium to larger temporarily open systems will assist with maintaining open mouth conditions and increase salinity intrusion (indicated by medium in Figure 5.6). The tidal amplitudes, and flows (tidal prism), of Wild Coast estuaries will remain fairly similar to present as the region has predominantly small systems with steep topography.



Sea level rise (between +0.5 and +2.0 m MSL)

Feature/process	West Coast	Western Cape	Southern Cape	Eastern Cape	Wild Coast	KwaZulu-Natal
a. Increase salinity penetration	H	M	M	M	M	L
b. Increased tidal flushing/prism	H	H	H	M	L	H
c. Changes in the frequency and duration of mouth closure	H	H	H	M	L	H
d. Biological responses: Changes in habitat (e.g. plants), nursery function & availability	H	H	H	M	M	H

Figure 5.6: Regional summary of the consequences of sea level rise on key estuarine processes – salinity penetration, tidal flushing and mouth state. Vulnerability is indicated as high/medium/low shifts from west to east with potential change a. to g. depicted by moving outward from the coast.

An increase in open mouth conditions and related salinity regimes will mostly be driven by increased inflow as tidal prisms will only increase marginally as the systems reset to a new equilibrium. Once again, the exceptions to the rule are the larger permanently open systems with floodplain areas. It is expected that estuary berm heights along the KwaZulu-Natal Coast will reset themselves to a new elevated equilibrium and so the effects of sea level rise on mouth state and tidal amplitudes in the estuaries of this region are seen as limited (Figure 5.6). Thus, tidal amplitudes, tidal prisms and associated salinity regimes, of the KwaZulu-Natal estuaries are likely to remain very similar to present as the region has predominantly small, perched systems with steep topography. However, the exceptions to this rule are the large estuarine lakes and bays, which have extensive floodplains (i.e. St Lucia Lake system comprising more than half of South Africa's estuarine area). The combination of increased tidal prisms in the estuarine lakes, together with amplified inflow, will lead to an increase in open mouth conditions and salinity penetration for these important systems. Hence, the overall high rating given to the Kwa-Zulu-Natal region in Figure 5.6, notwithstanding the smaller system largely remaining similar to present.

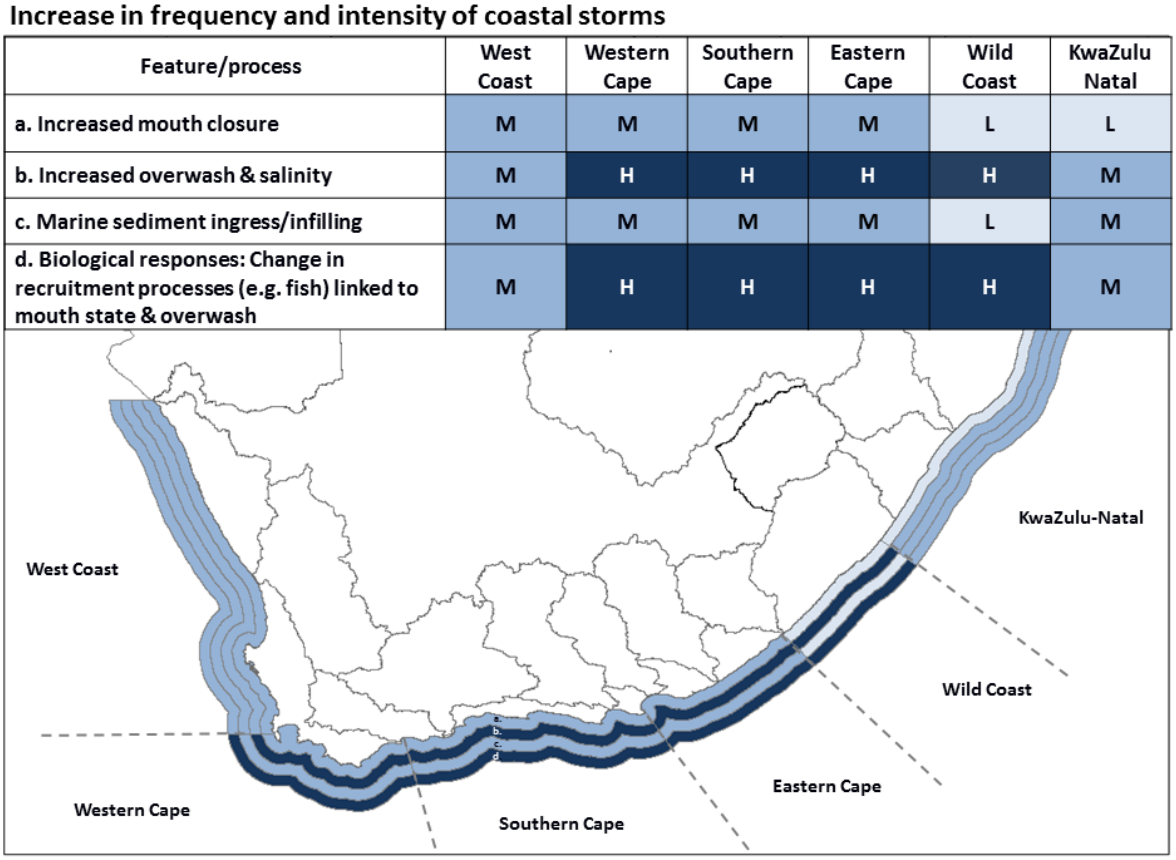
Climate Change and sea level rise will intensify pressure on management agencies to implement assisted (and often premature) breaching as increasingly low-lying properties will be at risk of flooding. The response of humans to sea level rise are often damaging to estuaries and estuarine biota, e.g. armouring the coastline with berms / dykes that prevent biological systems from adjusting naturally (i.e. inland retreat of wetlands). This could lead to the loss of salt marsh and mangroves leading to a decrease in estuarine habitat and food supply. An indirect impact is an increase in turbidity, as the fringing vegetation around an estuary no longer traps sediment. This, in turn, reduces light penetration thus causing a decrease in primary production by microalgae, whilst filter and "tactile" feeders will benefit at the expense of "visual" feeders (e.g. estuarine round herring *Gilchristella aestuaria* vs Cape silverside *Atherina breviceps*). Furthermore, some mangrove and salt marsh systems may not be able to keep pace with more rapid levels of sea-level rise. Mangroves may out-compete salt marshes in Subtropical areas in response to rising sea levels (Adams, 2002).

5.3.2.4 Increase in the frequency and intensity of sea storms

A number of small to medium sized estuaries (e.g. Great Brak) show great sensitivity to increased wave action (e.g. DWS tidal gauge K2T004). In general, large storms at sea generate the wave conditions that close such estuaries, unless there is significant river flow to maintain the open mouth condition. An increase in storminess due to Climate Change would therefore increase the occurrence of mouth closure and transport more marine sediment into an estuary than at present. In the absence of freshwater inflow changes, estuaries along an exposed, sediment rich coastline such as KwaZulu-Natal would be more likely to close than estuaries that are fairly protected, or those located on marine sediment starved coastlines such as the Wild Coast. However these generalisation are tempered by aspects such as beach slope, protection against wave action and changes in freshwater inflow.

Along the West Coast and Western Cape mouth closure will increase (indicated by medium in Figure 5.7), but note that a number of the smaller arid systems are predominantly closed due to a lack of inflow, while larger systems such as the Olifants and Great Berg should remain open as a result of significant tidal flows. While the steeper beach slopes along West Coast are likely to buffer against a significant increased overwash, overwash is likely to increase salinity in more the sheltered systems, with lower berms, of the Western Cape (indicated as high in Figure 5.7). The average berm height which is estimated between 2.5– 3.5 m MSL can increase by 0.5 – 1.0 m where sediment is available as a result of increased sediment transport potential. As sediment is generally not a limiting factor along most of the Southern and Eastern Cape, increased storminess is likely to translate into increased mouth closure and an ingress of marine sediment at exposed systems (indicated by medium in Figure 5.5).

The exception is the Tsitsikamma coastline in the Southern Cape region where there is limited sediment. Overwash events are also likely to occur more frequently especially in systems where limited marine sediment availably retards, or prevents, berm growth (indicated by medium to high in Figure 5.5). The net result is that some of the estuaries may experience a net increase in salinity during periods of low flow or during drought years.



Increase in frequency and intensity of coastal storms

Feature/process	West Coast	Western Cape	Southern Cape	Eastern Cape	Wild Coast	KwaZulu Natal
a. Increased mouth closure	M	M	M	M	L	L
b. Increased overwash & salinity	M	H	H	H	H	M
c. Marine sediment ingress/infilling	M	M	M	M	L	M
d. Biological responses: Change in recruitment processes (e.g. fish) linked to mouth state & overwash	M	H	H	H	H	M

Figure 5.7: Regional summary of the consequences of increased frequency and intensity of sea storms on estuary mouth state, overwash and marine sediment processes. Vulnerability is indicated as high/medium/low shifts from west to east with potential change a. to d. depicted by moving outward from the coast.

Wild Coast estuaries are mostly very sheltered with limited marine sediment availability, future mouth conditions is thus likely to be very similar to present (indicated by low in Figure 5.5), particularly given that a slight increase in river inflow is predicted for this region. At present average berm heights are estimated at 2.5 to 3.0 m MSL, but may rise by 0.5 – 1.0 m depending on overwash, increased sediment transport potential and available sediment. KwaZulu-Natal estuaries are somewhat buffered against the potential effects of increased storminess as the coast is characteristically wave dominated resulting in most estuaries being “perched” high on the beach profile and subsequently less vulnerable to increased storminess (Figure 5.5). The predicted increase in closure along this coastline is also likely to be offset by increased inflow. In KwaZulu-Natal, present berm heights are relatively high at about 3 to 3.5 m MSL and could build up even more by 0.5 to 1.0 m by a combination of the predicted increases in overwash and sediment transport potential.

The change in biological recruitment such as fish follows the same pattern as mouth state and overwash (Figure 5.7). Overall predicted increase in overwash could offset some of the impacts of mouth closure along Western and Southern Cape and increase connectivity along the Eastern Cape and Wild Coast (indicated as high on Figure 5.7).

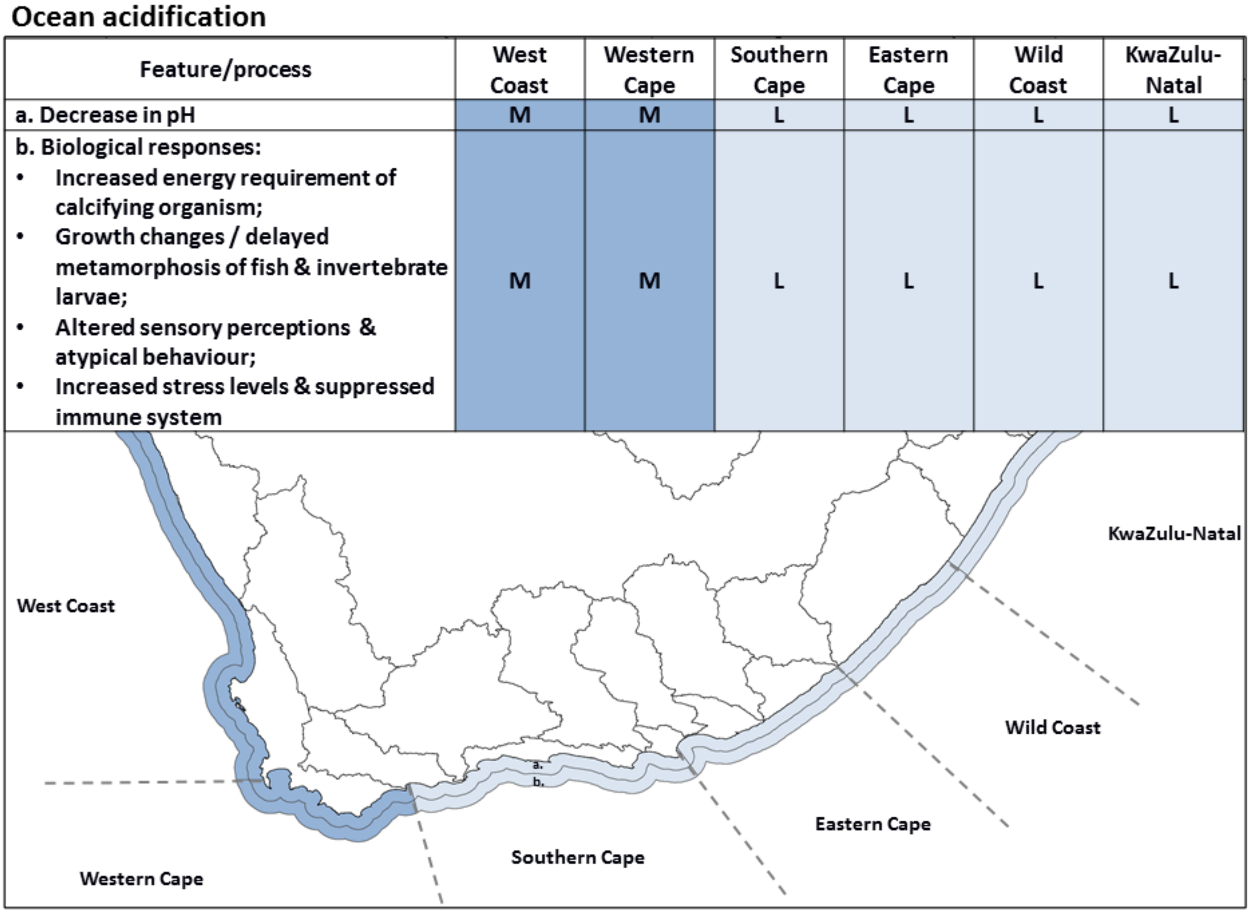
In addition, to the direct effects of increased storminess on estuary mouth state, are the indirect effects on human behaviour and pressure on estuary resources utilisation. For example, increased wind speeds have resulted in a significant decline in sea-days for the commercial marine linefishery on the southern Cape coast (Augustyn et al., 2017). In an attempt to maintain fishing effort and catch levels, fishers are likely to build larger vessels (i.e. maintain fishing effort at sea) or find calmer waters elsewhere, resulting in a displacement of fishing effort into calmer estuarine waters. This has already happened in the Bot Estuary with the resultant overexploitation and user conflict.

5.3.2.5 Ocean acidification and estuarine pH shifts

Estuarine pH levels are strongly dependent on coastal upwelling; catchment geology and land-use; freshwater inflow; nutrient input; primary production and decomposition (Freely et al., 2010; Zeng et al., 2015; Laurent et al., 2017). Changes in land-use can result in changes in freshwater alkalinity and CO_2 fluxes up to 0.5 units (Howland et al., 2000; Aufdenkampe et al., 2011; Cia et al., 2011; Duarte et al., 2013; Zeng et al., 2015; Laurent et al., 2017). In South Africa, many rivers are acidic (e.g. pristine rivers of Western Cape Table Mountain Sandstone fynbos region have pH<6), and have saturation states for aragonite (Ω) lower than receiving ocean waters (Midgley and Schafer, 1992). However, as a result of anthropogenic interference (e.g. riparian clearing, agricultural return flow), many of these weakly buffered systems have lost their strong acidic character and pH levels can now exceed that of sea waters, e.g. Palmiet Estuary (Chapter 3; DWA, 2010). Dynamic gradients in pH and saturation states are driven by estuary mixing processes, but *in situ* metabolic processes can causing deviation from these gradients (Howland et al., 2000; Salisbury et al., 2008; Cai et al., 2011; Duarte et al., 2013; Laurent et al., 2017). The pH in estuarine habitats (e.g. mangroves, salt marshes and macroalgal beds) reveal site-specific diel, semi-diurnal and stochastic patterns of varying amplitudes as high as 1.0 unit (Spilling, 2007; Hofmann et al., 2011; Wallace et al., 2014; Hendriks et al., 2014; Baumann et al., 2015). Nutrient enrichment stimulates primary production and eutrophication (e.g. phytoplankton blooms increase pH to 9.0); however once die-off occurs, organic matter is remineralized, leading to potential hypoxia and lower pH (Freely et al., 2010; Wallace et al., 2014; Zeng et al., 2015; Laerent et al., 2017). See Chapter 3 for detail on systems subjected to anthropogenic enrichments. Deeper, stratified estuaries (e.g. Klein, Swartvlei, Sundays) are more vulnerable to the effects of remineralisation compared with shallower, well-mixed systems. However, shallower systems (e.g. uMdloti) are more vulnerable to large diurnal variations in pH depending on the level of nutrient loading (Baumann et al., 2015). Increased residence times are likely to exacerbate remineralisation and the lowering of pH (O'Boyle et al., 2013; Wallace et al., 2014).

The pH of surface ocean waters may decrease by 0.3-0.4 units by 2100 under the influence of rising atmospheric CO_2 levels (Caldeira and Wickett, 2003). Thus, by the end of this century, ocean acidification may become the dominant process in permanently open estuaries as the acidification process continues, especially the West Coast and Western Cape estuaries (indicated by medium in Figure 5.8) will be vulnerable as they are subjected to regular upwelling (Figure 5.4). In the smaller, temporarily open/closed estuaries of these regions, reduced inflow and longer closure may also intensify the effects of existing anthropogenic enrichment. In the KwaZulu-Natal region, and to a lesser extent the Wild Coast region, increased flows and more frequent openings in the small temporarily open/closed estuaries, may reduce the existing effects of anthropogenic enrichment through more regular flushing. Most at risk are the systems that are currently subject to significant pH shifts, i.e. smaller, temporarily open/closed systems in the urban nodes and permanently open systems receiving agricultural runoff (see Chapter 3).

Lower pH will affect all calcifying organisms (indicated by medium in Figure 5.8), as structures made of calcium carbonate dissolve requiring more metabolic energy for an organism to maintain the integrity of its exoskeleton (Azevedo et al., 2015).



Ocean acidification

Feature/process	West Coast	Western Cape	Southern Cape	Eastern Cape	Wild Coast	KwaZulu-Natal
a. Decrease in pH	M	M	L	L	L	L
b. Biological responses: • Increased energy requirement of calcifying organism; • Growth changes / delayed metamorphosis of fish & invertebrate larvae; • Altered sensory perceptions & atypical behaviour; • Increased stress levels & suppressed immune system	M	M	L	L	L	L

Figure 5.8: Regional summary of the vulnerability to ocean acidification and the possible consequences on calcifying species. Vulnerability is indicated as high/medium/low shifts from west to east with potential change a. to b. depicted by moving outward from the coast.

Estuarine organisms that may be affected include coralline algae, echinoderms, crustaceans and molluscs (USEPA, 2009; James et al., 2013; Azevedo et al., 2015; Zeng et al., 2015). Calcifiers residing in cold water habitats such as upwelling systems are at a higher risk to ocean acidification and decreased seawater carbonate saturation, as their environment is only just supersaturated with respect to the carbonate phases they excrete (Andersson et al., 2008).

The extent of these potential impacts will depend on organisms' ability to adjust their acid–base balance as well as their ability to increase their calcification rates, whilst the ability to withstand or adapt to these changes over long periods of time would clearly be beneficial (Fabry et al., 2008). Acidification will likely impact various life stages differently as CO_2 tolerance varies between life stages of organisms (Pörtner et al., 2004). For most fish species, egg and larval phases are more sensitive to elevated CO_2 compared to the juvenile and adult stages (Ishimatsu et al., 2004). Increases in CO_2 levels may lead to hypercapnia (elevated CO_2 partial pressure) and acidosis in the blood and tissues of fishes (Pörtner et al., 2004). Ocean acidification will not only have a direct impact, but will possibly indirectly influence the ability of organisms to deal with local phenomena. Estuary-dependent species with a pelagic life-history stage will be particularly vulnerable.

Slower growth and delayed metamorphosis of fish and invertebrate larvae may result in recruitment failure if these animals miss the brief recruitment window typical of most temporarily open-closed systems along the South African coastline. In some fish species, slow development and changes in the physical and chemical structure of otoliths (and other bone structure) may alter sensory perceptions and their ability to communicate, avoid danger or detect prey (indicated by medium in Figure 5.8) (Potts et al., 2015). Acid-induced otolith malformation led to atypical behaviour such as reliance on visual rather than sound stimuli, as well as to increased cortisol levels, stress levels and suppressed immune systems in the Sciaenid *Sciaenops ocellatus* (indicated by medium in Figure 5.8) (Browning et al., 2012). However, not all species will react in the same way to ocean acidification and an understanding of the process driving the different responses by fish is critical for future prediction (Potts et al., 2015).

Anomalous to the above in South African estuaries is the alkalinisation of acidic blackwater catchments (along the Western Cape and Southern Cape) brought about by riparian clearing, agricultural return flow and other bad land-use practices some estuarine pH levels exceeding that of marine inflow (Lamberth unpublished). While, several species have enough physiological plasticity to cope with acidification, many may not be able to cope with the two extremes of acidity and alkalinity in the marine and estuarine environment. Abrupt changes and increases in pH and other environmental extremes raise the susceptibility of fish and invertebrates to disease (Huchzermeyer and van der Waal, 2012). The invasive potential of these pathogens and their vectors also increases (Conn, 2014). Furthermore, the estuarine invasive potential of alien species e.g. Pacific oyster *Crassostrea gigas* may increase in response to rising pH whilst they die-off in an acidic sea (Keightley et al., 2015).

However, it may be possible to mitigate the continued development and impacts of corrosive conditions by addressing and reducing the land-derived anthropogenic pressures that contribute to their formation, such as increased nutrient and sediment inputs associated with land-use change and urbanization (Kelly et al., 2011).

5.3.2.6 Summary of impact of Climate Change stressors on critical South African estuarine processes and variables

The interaction between Climate Change stressors, estuarine processes and associated biotic response are complex. With multiple interactions which can both amplify and moderate responses. In summary, the impacts of Climate Change on South African estuaries include changes in: 1) Ocean circulation patterns resulting in shifts in temperature regimes and coastal connectivity; 2) Terrestrial climatic/hydrological processes forcing changes in: freshwater inflow and associated inputs; shifts in the frequency and duration of estuary mouth closure; modifications in salinity regimes; changes in biochemical inputs; changes in sediment deposition/erosion cycles including accumulation of POM; and changes in contaminant behaviour and accumulation; 3) Sea level rise and related impact on salinity regime and mouth state; and 4) Increase in frequency and intensity of coastal storms also impacting on salinity regimes and mouth state; and 5) Ocean Acidification amplifying existing pH fluctuations.

These changes in estuarine processes and variables will drive a range of biotic responses changes such as shifts in primary production with a focus on structure/habitat forming plants and eutrophication; species range contraction/expansion in response to marine and terrestrial temperature regime shifts; changes in recruitment and estuary nursery function, shifts in community composition, and general behavioural responses. A summary of these complex interactions is provided in Table 5.2 with large and small circles indicating key estuarine processes that have a high to medium vulnerability to Climate Change stressors.

The above information in turn provides guidance on where priority mitigation and adaption strategies are required to ensure estuarine resilience to Climate Change.

Table 5.2: A summary of the impact of Climate Change stressors on critical South African estuarine processes and variables, which in turn drive a range of key biotic responses. (Large/Small Circle = High/Medium degree of change or vulnerability)

CLIMATE CHANGE STRESSOR					KEY ESTUARINE ASSOCIATED PROCESSES/ VARIABLES	KEY BIOTIC RESPONSES							
Ocean circulation	Climatic and hydrological	Sea level rise	Storminess	Ocean acidification		Primary production	Habitat forming plants	Eutrophication	Range contraction/expansion	Recruitment	Nursery function	Community composition	Behavioural responses
●					Coastal connectivity	●	●		●	●	●	●	●
	●				Freshwater inflow	●	●	•		●	●	●	●
	●	●	●		Mouth State	●	●			●	●	●	●
	●	●	•		Salinity regime		●	●			●	●	
●	●		•		Nutrients	●	•	●			●	●	
●	●				Temperature	•	•		●	•	•	•	●
•	●			●	Oxygen						●	●	●
●	●			●	pH						●	●	●
	●	●	●		Sediment dynamics & organic accumulation	•	●	●			•	●	
	●				Particulate Organic Matter & Suspended Solids		•	•			•		
	●				Contaminants (Toxins)			●			●	●	

5.4 SYNOPSIS AND THE WAY FORWARD

5.4.1 Priority Mitigation and Adaptation Strategies

Accelerated Climate Change is one of many pressures acting on estuaries and should be viewed as an additional form of anthropogenic stress in an already stressed ecosystem. It is necessary to understand the potential amplification of variability that Climate Change may have on existing freshwater resources, potential impact on estuarine and marine production, as well as the harvesting of resources in the marine and estuarine environments. It is thus necessary to integrate Climate Change and non-Climate Change threats. Climate Change should be seen as a catalyst to fast-track sustainable resource allocation processes, e.g. allocations of environmental flows (Bunn, 2016).

The ability to predict the response of estuaries to Climate Change and to plan mitigation and adaptation strategies is still hindered by a lack of good prediction tools and the lack of a fundamental understanding of many of the effects of climate variability on the physical, chemical and biological characteristics (Meyer et al., 1999; Thompson et al., 2014). We are limited by the availability of both data (e.g. long-term flow data, temperature data, mouth conditions, wave height, species data) and models (e.g. flow changes, linking hydrological regimes to ecosystem processes and large-scale ocean current changes).

At the same time, this uncertainty around forecasting change should not be seen as an impossible obstacle to understanding and developing adaptation mechanisms to reduce the effects of Climate Change on estuarine resources. Accurate forecasting is not obligatory to begin the process of adapting to Climate Change as major trends are often evident enough for meaningful actions to be planned and implemented. Priority adaptation and mitigation strategies that should be included in future Estuarine Management Plans (a legal requirement in South Africa) are discussed below and summarised in Figure 5.9.

To accommodate projected changes in estuarine functioning and production as a result of changes in ocean circulation and terrestrial climatic processes it is important to reduce fishing and harvesting pressures to sustainable levels to allow for resilience to natural and anthropogenic resetting events. Marine Protected Areas (MPAs) are producing larger, healthier fish with higher thermal tolerances and resilience (Potts et al., 2017). The current network of estuarine and marine protected areas needs to be expanded to cover all bioregions and estuarine types.

In addition, it is important to preserve coastal connectivity to ensure recruitment from healthy neighbouring systems in the event of natural/man-made disasters. In order to accommodate sea storms and sea level rise the estuary functional zone (i.e. estuary floodplain and supporting habitats) must be protected from developments to increase resilience to extreme flooding (and allow for lateral channel movement), negate the need for premature artificial breaching, and prevent coastal squeeze of estuarine habitats. Future setback/flood lines determinations should include sea level rise (+0.5 to +2.0 m) and projected increase in flood magnitudes.

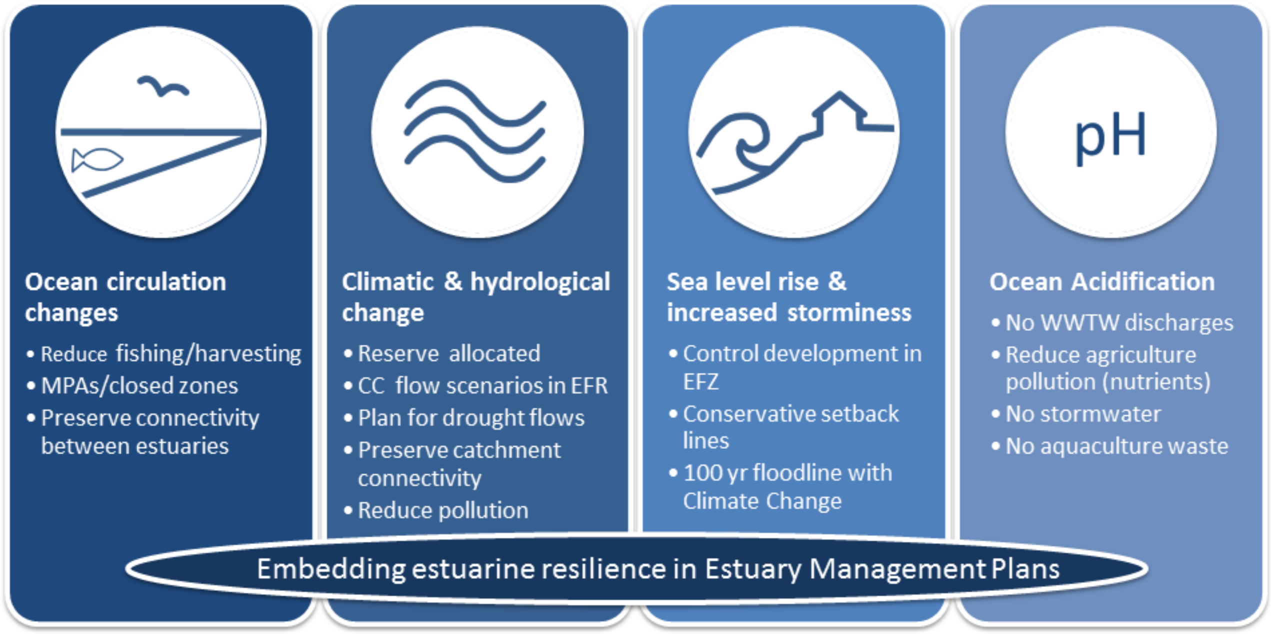


Figure 5.9: Embedding estuarine resilience to Climate Change by incorporating predicted effects of Climate Change into current planning and managed approaches.

The determination and implementation of estuarine environmental flow requirements is critical in ensuring health and productivity in the face of change in the hydrological processes. Environmental flow requirement studies should therefore include projected “Climate Change operational scenarios” to determine future catchment yields and ecological requirements. The duration and extent of future droughts needs to be explicitly evaluated and planned for in arid countries such as South Africa. Catchment connectivity is critical to ensuring adaptation to future climate shifts, therefore structures such as dams, bridges and weirs should ideally not be planned in, or near, estuaries. Urgent interventions are needed to curb nutrient loading to ensure resilience during the low flow season as reduced baseflow and an increase in water retention time can lead to hypoxia / anoxia.

Eutrophication resulting from nutrient pollution can also severely amplify the potential ocean acidification signal. It is therefore critical that current sources of nutrient pollution in estuaries be addressed and no additional future inputs planned, i.e. no additional Waste Water Treatment Works (WWTW) discharges; improve agricultural practises and urban agricultural return flow; eliminate storm water runoff; and no marine aquaculture waste discharges should be allowed in high retention environments such as estuaries.

In summary, it is essential that Climate Change, and the projected effects thereof, be integrated into current plans and policies dealing with management and governance of estuaries, specifically, the fishing, water and coastal management sectors. Current planning tools need to focus on integration of the synergistic effects of global change. In addition, adaptation includes adjusting to situations, developing coping strategies and impact responses. Adaptation may be behavioural or involve mitigation such as engineering solutions. This requires an adaptive management approach that is supported by monitoring and frequent review.

5.4.2 Conclusion

Overall, this analysis showed that KwaZulu-Natal and West Coast estuaries will be the most influenced by Climate Change from a structural and functional perspective. This may appear contrary to the current monitoring and research programmes which focus on biotic responses in the biogeographic transition zones (e.g. Wild Coast and Southern Cape) but the latter were chosen due to less behavioural noise and greater ease of measuring biological responses at the edge of species' ranges. In KwaZulu-Natal, the major driver of change is increased runoff into the numerous small, perched temporarily open/closed estuaries, resulting in more open mouth conditions, a decrease in retention time and a related decrease in primary productivity and nursery function. Similar to KwaZulu-Natal, West Coast estuaries will also experience a decline in primary production and loss of nursery function, but as a result of reduced freshwater input. Whilst Wild Coast, Eastern and Southern Cape estuaries will show some shifts in mouth state, nutrient supply, salinity regime and ultimately production. The most obvious impacts of Climate Change along these coastal regions will be the change in temperature (nearshore and land), associated species range expansions / contractions and changes in community structure.

The effect of sea level rise, and related increase in tidal prisms, will be less apparent along the KwaZulu-Natal coastline, where with the exception of estuarine lakes and bays, the majority of estuaries are perched whilst it will be more apparent along the Southern and Western Cape coast with their more extended coastal floodplains. The effects of ocean acidification in the short term will be negligible in comparison with the terrestrial signal (e.g. eutrophication resulting from urban runoff and agricultural return flow). Systems subjected to regular upwelling or increased upwelling, e.g. along the West Coast are likely to display the effects of ocean acidification first. South Africa is a wave dominated coast sensitive to increased sea storminess. However highly protected (e.g. Wild Coast) or very exposed (along the KwaZulu-Natal) estuaries are less likely to change character, whereas smaller estuaries along the Western, Southern and Eastern Cape may be very sensitive to this change.

The far-future scenarios under both the high and low-mitigation pathways, hold severe consequences for South African estuaries. Their relative small size and low freshwater inflow make them extremely vulnerable to hydrological Climate Change stressors - stream flow reduction, temperature increases and associated evaporation. All the coastal regions will be subject to extreme change under these projections. Under the far-future scenarios estuary mouth closure will become prevalent along the entire coastline with some systems not connecting to the coast on decadal scales (e.g. Verlorenvlei, Uilkraals). The occurrence of hypersalinity (>35) will become ubiquitous in most permanently open systems and a large number of open systems may close in the future (e.g. Olifants, Great Fish, Keurbooms, Kosi estuaries). Some smaller estuaries may dry out in their entirety, similar to Holgat and Brak on the west coast, while the estuarine lakes are likely to show extreme shifts in open water area on decadal scales (St Lucia, Bot, Swartvlei). Thus, while the trajectory is clear, much research is still needed to establish the extent to which individual systems will respond to such drastic change – making extreme predictions without more rigorous investigations will only be interpreted as alarmist.

CHAPTER 6

DISCUSSION AND CONCLUSIONS

The objective of this study was to develop and apply approaches for detecting change in pattern and processes in South African estuaries, i.e. what is the current and future responses of South African estuaries to key pressures? I did this by addressing the following four key questions:

- How can we quantify the response of estuaries to key pressures, with a focus on freshwater inflow modification?
- What is the condition of South African estuaries in response to current anthropogenic pressures?
- Can the response of estuaries to escalating future pressures, related to flow and water quality, be quantified on a regional-scale so that this can guide regional-scale planning and estuary resource allocation? (Chapter 4)
- How vulnerable are South African estuaries to Climate Change?

This thesis adds substantively to the body of knowledge on South African estuaries. It makes an original contribution to the study area and field of research as it successfully investigated change dynamics in South African estuaries with a focus on processes, patterns, and long-term trajectories. This required the development of new methods, or the application of existing approaches in new or unique ways. In most cases methods/approaches had to accommodate the general paucity of long-term datasets in South Africa.

6.1 QUESTION 1: HOW CAN WE QUANTIFY THE RESPONSE OF SA ESTUARIES TO KEY PRESSURES, WITH A FOCUS ON FLOW MODIFICATION? (CHAPTER 2)

This thesis sets out to develop an approach for change detection in estuarine ecosystems with a focus on integrating multiple-scale hydrological and complex ecosystem processes. It describes a method developed for determining estuarine environmental flows in South Africa that enables coupling between river inflow (hydrology) and the downstream chemical and biological ecosystem processes in an estuary based on ecohydrology and ecosystem-based approaches. Specifically, it addresses the challenge of mismatched temporal and spatial scales prevalent in the linking of abiotic and biotic processes in estuaries. This challenge was overcome by simplifying and aggregating the complexities of abiotic processes to appropriate scales suitable for analysis of biotic responses, using concepts such as physical states (where distinct hydrodynamic and biogeochemical characteristics were linked to typical freshwater inflow ranges) and zoning (simplified representation of homogenous areas).

The small, temporarily open Palmiet Estuary was used as a case study to demonstrate the application of the method. The method is especially flexible in terms of data richness and can use a range of statistical or numerical methods. It can be applied in systems with very limited data using largely expert opinion/judgment to data-rich systems using sophisticated modelling techniques. As a result of its flexibility the method can be applied globally to a wide range of estuarine types, from large, tidal dominated systems to small, wave dominated systems using regionally calibrated hydrological models and locally developed change detection estuarine health indexes. I have applied this approach to more than 50 estuaries as part of ecological flow requirements studies (e.g. East Kleinemonde Estuary (Van Niekerk et al., 2008a); Keurbooms (Van Niekerk et al., 2008b); Great Brak (DWA, 2009a); Goukamma (DWA, 2009b); Palmiet (DWA, 2010); Great Fish (Van Niekerk et al., 2013b); Mvoti (DWS, 2015c), uMkhomazi (DWS, 2014b) and the learning from this was incorporated in this thesis

The method shares significant commonalities with that of other international approaches, e.g. simulating river inflows as the basis of an evaluation; identifying homogenous regions; deciding on the desired condition (Peirson et al., 2001, 2002; Adams et al., 2002; Richter et al., 2006; Lloyd et al., 2008; Gippel et al., 2009; Hardie et al. 2006; Adams, 2013). However, a unique feature of the method is the identification of physical states and the evaluation of the annual/seasonal distribution in physical states and associated biotic responses, which couples the river flow (hydrology) and the downstream chemical and biological ecosystem processes in a predictive manner, embracing both the ecohydrological and ecosystem-based approaches. Specifically, it addressed the challenge of mismatching scales in the linking of abiotic and biotic processes.

By promoting the natural state as a standard for expressing the present and desired condition, the latter conditions reflect the absolute shift or modification in an estuary from its un-impacted state. In addition to being an important requirement for biodiversity and conservation planning processes, this fixed starting point prevents “creeping normality” or “shifting baseline” syndromes and incremental deterioration of ecosystem function.

The method is especially flexible in terms of data richness and can use a range of statistical or numerical methods. It can be applied in systems with very limited data using largely expert opinion/judgment to data-rich systems using sophisticated modelling technologies, indicating degree of certainty by confidence ratings. However, whilst the method accommodates data poor environments and can be applied at various levels of data availability, monitoring is viewed as an essential component in the overall process. This is needed to increase confidence over time and assess whether flow allocations are achieving the desired state and associated ecosystem services. The method’s flexibility in data requirements also lends itself to applications in countries that are either data limited or have large discrepancies in data quality between systems (e.g. South Africa, Australia and Portugal). As a result of its flexibility the method can be applied in a wide range of estuarine types, from large tidal dominated systems (e.g. United States of America) to small, microtidal systems along wave dominated coasts (e.g. South Africa and Australia).

While the method focused on river flow in the modification and restoration of estuarine ecosystem function, it is not the only factor that contributes to such modification. It is also important to have a sound understanding of other global change pressures. These include pollution (e.g. wastewater discharges), living resource exploitation (e.g. over-fishing) or physical destruction of habitat (e.g. construction of bridges, causeways, jetties and developments in floodplains) (Whitfield et al., 2012; Van Niekerk et al., 2013a). The cumulative or synergistic impact of all influences must be understood in order to set a realistic environmental flow, e.g. the desired condition may not be achieved for a particular system by only adjusting the river flow.

The shortest time scales the current application of the method resolves is monthly increments. However, while this resolution adequately reflects the longer time scales that the larger, permanently open estuaries or lake systems cycles through, it should be noted that a limitation of the method is that the small, temporarily open / closed estuaries may require weekly, or even daily time scales, to detect change. Unfortunately, while the method is flexible enough to accommodate this requirement, the supporting hydrological tools are not currently readily available. Using monthly time steps on such small systems equates to averaging out important hydrological stressors (e.g. no flow days, freshettes, floods). Thus, reducing our resolution at which we can detect change in small system. The challenge moving forward would be to refine the method to accommodate much shorter timeframes.

6.2 QUESTION 2: WHAT IS THE CONDITION OF SOUTH AFRICAN ESTUARIES IN RESPONSE TO CURRENT ANTHROPOGENIC PRESSURES? (CHAPTER 3)

Population and development pressures increase the need for proactive strategic management on a regional or country-wide scale – reactively protecting ecosystems on an estuary-by-estuary basis against multiple pressures is ‘resource hungry’ and not feasible. Proactive management requires a strategic assessment of health so that optimum resource allocation can be achieved against desired estuarine condition and associated ecosystem services. The approach used in Chapter 2 was therefore scaled-up to a country-wide assessment of the nearly 300 functional South African estuaries. The assessment examined both key pressures (freshwater inflow modification, water quality, artificial breaching of temporarily open/closed systems, habitat modification and exploitation of living resources) and health state.

The approach promoted here allowed for the assessment of the type and level of the different pressures, as well as the ecological health status of a large number of estuaries in a data limited environment. Key pressures and the ecological condition of estuaries on a national scale were summarised. The approach may also be used to provide guidance to coastal researchers attempting to inform management in other developing countries. The assessment was primarily aimed at decision makers both inside and outside the biodiversity sector. A key starting point was to delineate spatially the estuary functional zone (area) for every system. In addition, available data on pressures impacting estuaries on a national scale were collated.

A desktop national health assessment, based on an Estuarine Health Index (DWA, 2008) developed for South African ecological water requirement studies, was applied systematically to all estuaries in the country. National experts, all familiar with the index evaluated the estuaries in their region. Individual estuarine health assessment scores were then translated into health categories that reflect the overall status of South African estuaries.

The results showed that estuaries in the Warm Temperate biogeographical zone are healthier than those in the Cool Temperate and Subtropical zones, largely reflecting the country's demographics and developmental pressures. A major finding was that, while a large number of South African estuaries are still in an excellent to good condition, they tend to represent very small systems (< 150 ha in size) in rural areas with few pressures. Larger systems, which are more important as nursery grounds because of their size, and also of higher economic and ecological importance, are in a fair to poor condition. This was due to pressures within the catchments influencing these downstream systems, and degradation as a result of direct development within the estuary functional zone.

The research highlighted the need for long-term data sets to populate the assessment and calibrate models. This lack of information / models were a serious limitation in improving the overall confidence of the study and highlighted the need for on-going research and development of models (statistical or rule-based) to predict change in the hydrological, physical and water quality health status of estuaries based on land-use. There has been some progress in regional modelling of hydrology, development of statistical approaches to determine mouth state (Van Niekerk et al., 2015), and a screening model for assessing water quality in small, dynamic estuaries (Taljaard et al., 2017).

Moving forward, improved abilities in the prediction of shifts in regional estuarine abiotic processes would provide a sound platform for a more systematic approach in the evaluation of biological responses on a country-wide scale.

6.3 QUESTION 3: CAN THE RESPONSE OF ESTUARIES TO ESCALATING FUTURE PRESSURES, RELATED TO FLOW AND WATER QUALITY, BE QUANTIFIED ON A REGIONAL-SCALE SO THAT THIS CAN GUIDE REGIONAL-SCALE PLANNING AND RESOURCE ALLOCATION? (CHAPTER 4)

Based on the understanding developed in the above applications, a scenario-based regional-scale estuarine resource allocation process was designed and applied to assess potential changes to key drivers, namely modification of freshwater inflow and further degradation in water quality. This regional-scale case study included 64 estuaries for which estuarine health, biodiversity importance and resilience to key anthropogenic pressures were evaluated against future development scenarios as a means of optimising freshwater allocations while maintaining estuarine health and associated ecosystem services.

Projected population growth was integrated into a range of coherent future dam development and municipal wastewater discharge scenarios. Each estuary was then screened to assess its projected health state under the range of scenarios. This assessment highlighted that the characteristically small estuaries in this region had very little resilience to changes in freshwater quantity and quality, particularly where there were discharges from wastewater treatment works. In contrast, larger systems – generally targeted for dam development - only showed sensitivity during low-flow periods and droughts when flow reduction caused mouth closure and increased sensitivity to changes in nutrient cycling.

Through this approach it was possible to directly evaluate socio-economic development scenarios against the consequences of estuarine condition. Broadly, the research strived to find a balance between ecological requirements and socio-economic development in a region, which meant that maintaining the larger systems in relatively good condition would be at the expense of smaller systems that are currently in a poor condition. However, the overall negative trajectories are clear and indisputable.

The approach dictates a logical progression of steps, with the results largely being determined by the quality of the input data – something that is in short supply in South

Africa. While the steps themselves are not new (i.e. they share commonalities with international IWRM best practise), they are unique in the way they have been aligned in this application. Again, the approach promoted here is scalable and can accommodate various levels of input data, thus making it globally applicable to other data poor environments such as South America or Africa.

However, a major deficiency of the approach was the lack of sensitivity to the trade-offs required among the large number of small estuaries in the case study area. If coastal development is taken as inevitable, the net result is a continuous escalation of pressures on estuaries. A policy decision, backed by science, needs to be a made on whether estuarine degradation should be spread over the region or focussed on a few compromised systems. For example, should wastewater be disposed to a number of adjacent systems (but systems must remain at the functional level), or collected at a central point and discharged into a single targeted system. While most researchers support the idea of targeted systems (especially if they are of limited ecological/social importance and/or in poor current condition), existing policy in South Africa is driving the opposite behaviour, with the result that development pressure is spread along the coast, resulting in a form of “ribbon development”.

In the case of a network of small estuaries that collectively add up to significant estuarine system, the ever increasing “gaps” forming along the coastline as a result of a large number of poor condition systems adjacent to each other is worrying. Unfortunately, at present, little hard science is available on the direct consequences of declining estuary condition on overall connectivity and the ability to absorb/recover from events. In short, the “health of your neighbour matters” as it ensures the overall resilience of a regional network of estuaries, but the science is lacking to show the degree to which the health of adjacent estuaries influence each other. In future, biodiversity recapture studies, telemetry and genetics studies will assist in “making the case for estuarine connectivity” and the development of guidelines for regional resource allocation.

6.4 QUESTION 4: HOW VULNERABLE ARE SOUTH AFRICAN ESTUARIES TO CLIMATE CHANGE? (CHAPTER 5)

Given the understanding developed in the preceding endeavours the final challenge was to synthesise how vulnerable South African estuaries are to Climate Change. Estuaries form an interface between the land and sea and are strongly influenced by terrestrial, coastal and atmospheric processes. Unfortunately, given the level of information available on climate related stressors it was not possible at this stage to provide an estuary-by-estuary response, however based on my understanding of the physical processes at play in South African estuaries it was possible to project a regional response. The assessment was conducted on a regional-scale and is primarily based on known physical characteristics of South African estuaries and predicted or measured change in the drivers of estuary condition. In addition, my research also highlights possible estuarine ecosystem responses extrapolated from current known responses. I found that the major estuarine drivers in order of importance are precipitation /inflow; ocean processes; and temperature regime shifts; sea level rise; and intensity of sea storms; and acidification. Flow related ecosystem responses include modifications in the extent of saline water intrusion; changes in the frequency and duration of mouth closure; decrease or increase in nutrients fluxes; and changes in the magnitude and frequency of floods and related sediment deposition/erosion cycles.

The analysis of the regional vulnerability of the estuaries of South Africa to Climate Change provides a summary of the key shifts (scaled as high, medium, low) in the drivers of estuary condition. As expected, the analysis shows that change in marine current configuration seem to be driving shifts in the nearshore temperature regimes of the transitional zones, with a related ecological responses (e.g. range expansion). Transitional zones often show the response to change the clearest as the noise from biological / behavioural interactions is at a minimum. However, the largest structural and functional changes are expected along the arid cool temperate and Subtropical biogeographical regions of South Africa. This could lead to notable shifts in frequency and duration of mouth closure and salinity regimes, which in turn will impact on estuary ecosystem services such as nursery function. The chapter concludes with broad recommendations on monitoring and adaptation strategies for South African estuaries.

Moving forward, Climate Change is likely to accelerate ecosystem degradation in synergy with present pressures on South African estuaries. Thus, there is a need to enhance our scientific understanding of the long-term biophysical cycles of estuarine systems with the focus on predicting their vulnerability to Climate Change related stressors. This would require the down-scaling of existing global/regional-scale models outputs (IPCC, 2014) for application at the primary estuary catchment-scale. Key vectors of Climate Change that should be considered for down scaling include shifts in seasonal rainfall and associated change in inflow (monthly time steps), changes in magnitude and frequency of floods, detail on predicted increases in droughts, and a seasonal breakdown of projected increase in terrestrial temperature regimes. In addition, dynamic/conceptual models will need to be refined and/or developed of the biophysical cycles of South African estuaries (e.g. temporarily open/closed and permanently open systems). This will broaden our understanding of their responses to Climate Change in a more systematic manner such as was done in Australia, America or UK (e.g. similar to Ranasinghe et al., 2013; Prandle and Lane, 2015; Brown et al., 2016). To address limitations of the current approach, an estuary specific Climate Change Vulnerability Analysis should be conducted on South African systems focussing on change in processes, patterns and associated important ecosystem services (e.g. fishery nursery function and production, carbon sequestration, flood mitigation). This would allow for the development of detailed mitigation and adaptation strategies for the estuaries of South Africa, and to coordinate these with current management actions and interventions addressing existing global change pressures (e.g. resource harvesting, freshwater abstraction, pollution).

6.5 CONCLUSION

Combining the size and health data, the picture that emerges from this research shows that it is predominately small estuaries that are still in an excellent or good condition (Figure 6.1). With the exception of the Kosi Estuary most of the larger systems are in a fair state. This also means that while we still have representative pattern and process in the smaller temporarily open/closed type of systems, biophysical processes are being transformed in the larger systems with cascading effects in the associated biota. It is also clear from this assessment that the smaller estuaries are somewhat “binary” in their responses, i.e. they can maintain an excellent/good condition when in protected and/or relative under developed areas (e.g. Table Mountain Park or Wild Coast), but are very sensitive to pressures and degrade rapidly once pressure is exerted on them. Hence, the wide spread in health from near natural to highly degraded in this type of system. The analysis of their sensitivity to future pressures (e.g. flow modification and increase nutrient loading) supports this finding. In contrast, the larger permanently open estuaries, estuarine lakes and bay systems show more resilience to change and maintain a fair state in the face of ongoing pressures. This resilience is largely related to either the “buffering effect” of a continuous input from the sea (e.g. compensate for loss of freshwater flow, provide additional flushing mechanism) and/or related to their large volumes that “buffers” against the effects of *in situ* process such as remineralisation.

In summary, I conclude that while data may be a limiting factor in the assessment of change in the processes and patterns of South African estuaries; sufficient information is now available to accurately determine the present responses and future trajectories to Global Change pressures. The methods developed, and applied here, are robust enough to accommodate both data rich and data poor parameters/estuaries. Despite the fact that more monitoring and research will improve our confidence in the assessments and predictions set out in this thesis, there is satisfactory evidence here to determine overall vulnerability to change and future trajectories.

This thesis clearly shows that estuarine health and productivity is in decline in South Africa. It thus directs future research towards quantifying critical pressures, such as flow modification and deteriorating water quality, in a more systematic manner and the need for understanding the responses of the more vulnerable systems (e.g. small temporarily open/closed estuaries and lake systems) to said pressures. Further, research is also required on the restoration potential of South African estuaries, i.e. how do we stop the ongoing decline in condition?

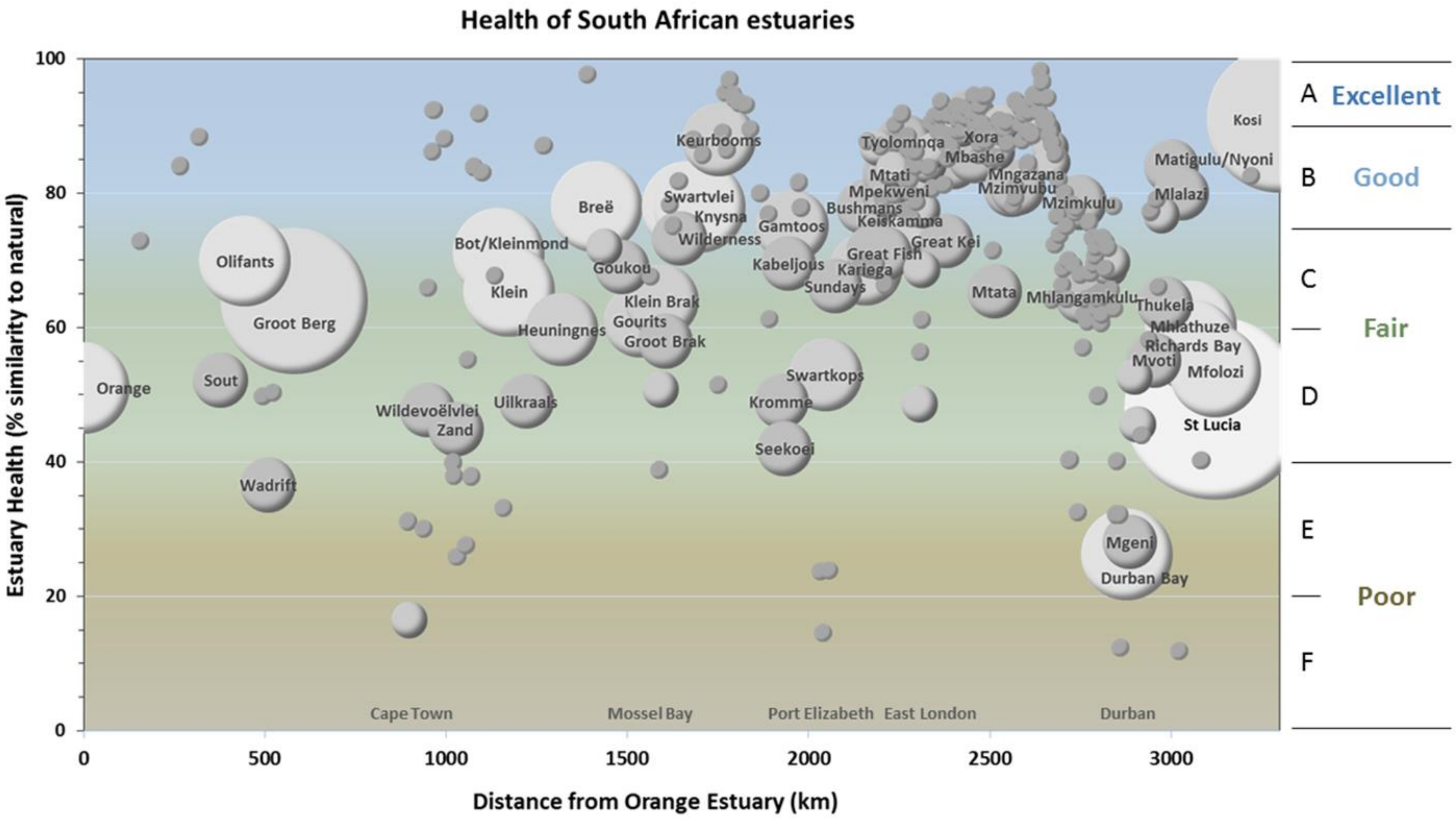


Figure 6.1: Bubble plot of South African estuaries from west to east showing health (% similarity to natural) and relative size. (Total Estuarine habitat area grouped into six categories: Very Large: > 10 000 ha, Large: 5 000 – 10 000 ha, Medium – Large: 1 000 – 5 000 ha, Medium: 500 -1 000 ha, Small: 100 – 500 ha, Very small: < 50 ha).

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APPENDICES

Appendix A: South African Desktop National Health Assessment

Table A.1 South African Desktop National Health Assessment, with individual ecological components graded from Excellent (dark blue), good (blue), fair (green) to poor (brown). A Provisional Present Ecological Status is also provided. Pressure levels are indicated as very high (VH), high (H), medium (M) or low (L). A blank indicates the absence of a pressure.

	Pressures								Health Condition												
NAME	Change in flow	Pollution	Habitat loss	Mining	Artificial Breaching	Fishing Effort	Fishing Effort (Catches in tones)	Bait collection	Hydrology	Hydrodynamics	Water Quality	Physical habitat	Habitat State	Microalgae	Macrophytes	Invertebrates	Fish Final	Birds	Biological State	Estuary Health State	Ecological Category
Orange (Gariep)	M	L	M		Y	L	5.0	Y	58	50	72	86	67	50	50	40	60	26	45	56	D
Buffels	L	M	M	Y	Y	L	0.1	Y	80	75	58	60	68	64	60	65	55	80	65	66	C
Spoeg	L	L	L			L	0.1	Y	80	75	82	80	79	83	95	90	75	90	87	83	B
Groen	L	L	L			L	0.1	Y	80	75	76	80	78	79	95	80	75	95	85	81	B
Sout	M	L	M				0.0		50	60	74	40	56	71	50	40	10	50	44	50	D
Olifants	M	M	M			VH	121.1	Y	69	100	50	78	74	70	58	65	40	95	66	70	C
Jakkalsvlei	H	M	L			L	0.1	Y	40	30	48	60	45	47	80	60	35	80	60	52	D
Wadrift	H	M	H			L	0.1	Y	30	0	48	40	30	27	30	40	25	70	38	34	E
Verlorenvlei	M	M	M		Y	M	10.0	Y	50	30	76	70	57	40	50	50	30	90	52	54	D
Great Berg	M	H	M			VH	511.0	Y	54	95	44	55	62	44	50	45	70	70	56	59	D
Rietvlei/Diep	M	H	H		Y	L	0.1	Y	70	30	24	30	39	26	30	15	10	50	26	32	E
Sout (Wes)	H	H	H			L	0.1		40	10	10	5	16	9	0	0	0	0	2	9	F
Houtbaai	L	H	H			L	1.0	Y	80	30	18	30	40	23	40	30	0	30	25	32	E
Wildevoëlvlei	M	H	M			L	0.0	Y	60	40	22	55	44	29	50	40	55	60	47	46	D
Bokramspruit	L	H	L				0.0		80	60	36	60	59	47	85	85	30	70	63	61	C
Schuster	L	L	L				0.0		95	90	90	90	91	90	90	90	90	95	91	91	A
Krom	L	L	L				0.0		95	90	90	95	93	91	95	95	95	100	95	94	A
Buffels Wes	L	H	H				0.0		90	10	10	10	30	10	10	10	10	10	10	20	F
Elsies	L	H	H			L	0.1		90	10	16	30	37	16	30	10	0	30	17	27	E
Silvermine	L	H	H		Y	L	20.0	Y	80	50	28	40	50	37	40	30	55	50	42	46	D
Sand	M	H	M		Y	M	0.1	Y	70	30	40	40	45	36	50	50	45	60	48	47	D
Zeekoei	M	H	H			L	0.1	Y	50	30	20	20	30	26	30	40	15	30	28	29	E
Eerste	M	H	H			L	0.1	Y	65	30	24	40	40	27	40	20	0	40	25	33	E
Lourens	L	H	M			L	0.1	Y	90	80	44	60	69	54	60	60	55	70	60	64	C
Sir Lowry's Pass	M	H	H			L	1.0	Y	70	70	36	30	52	44	10	10	15	20	20	36	E
Steenbras	H	L				L	0.1	Y	30	100	68	90	72	92	100	95	85	90	92	82	B
Rooiels	L	L	L			L	0.1	Y	95	90	90	85	90	90	90	90	90	90	90	90	B
Buffels (Oos)	L	L	L			L	0.2	Y	85	70	75	80	78	79	95	90	85	95	89	83	B
Palmiet	M	L	M			L	70.0	Y	67	50	75	78	67	74	45	60	80	81	68	68	C
Bot/Kleinmond	M	M	M		Y	VH	0.1	Y	75	55	56	65	63	58	60	60	35	80	59	61	C
Onrus	H	H	H			L	80.0	Y	40	30	18	50	35	23	40	50	40	60	43	39	E
Klein	M	M	M		Y	H	2.1	Y	75	60	66	80	70	65	70	70	60	80	69	70	C
Uilkraals	M	M	M			M	0.1	Y	50	0	62	70	46	35	70	70	65	80	64	55	D

NAME	Pressures								Health Condition												
	Change in flow	Pollution	Habitat loss	Mining	Artificial Breaching	Fishing Effort	Fishing Effort (Catches in tones)	Bait collection	Hydrology	Hydrodynamics	Water Quality	Physical habitat	Habitat State	Microalgae	Macrophytes	Invertebrates	Fish Final	Birds	Biological State	Estuary Health State	Ecological Category
Ratel	M	M	L			L	10.0	Y	60	40	66	85	63	56	80	80	85	100	80	71	C
Heuningnes	M	M	M		Y	M	0.0	Y	50	50	62	75	59	59	60	45	50	80	59	59	D
Klipdrifsfontein	L	L					80.0		95	90	95	95	94	93	100	100	100	100	99	96	A
Breëde	M	L	L			H	20.0	Y	66	100	72	90	82	90	80	80	80	85	83	78	B
Duiwenhoks	M	L	L			H	13.0	Y	75	100	70	90	84	79	90	75	65	90	80	82	B
Goukou (Kaffirkui	M	M	M			H	20.0	Y	75	95	58	70	75	69	70	65	55	80	68	71	C
Gouritz	M	M	M			H	0.1	Y	60	100	62	70	73	65	70	65	65	80	69	71	C
Blinde	L	M	L			L	2.1	Y	90	70	74	80	79	71	80	70	65	90	75	77	B
Hartenbos	M	H	M		Y	L	10.0	Y	50	10	24	40	31	19	60	60	55	60	51	41	D
Klein Brak	L	M	M			M	0.0	Y	80	70	70	70	73	70	70	75	60	80	71	72	C
Groot Brak	M	M	H		Y	M	1.0	Y	67	56	50	83	64	60	40	50	40	68	52	58	D
Maalgate	L	L				L	1.0	Y	90	80	84	95	87	80	100	50	95	100	85	86	B
Gwaing	L	M	L			L	0.0	Y	93	100	66	95	89	55	80	70	50	80	67	77	B
Kaaimans	L	L	L				0.0	Y	80	100	80	80	85	80	90	60	90	90	82	84	B
Wilderness (Touws)	L	M	M		Y		0.0	Y	80	60	74	80	74	66	75	80	80	90	78	76	B
Swartvlei	L	L	M		Y		4.1	Y	79	73	77	86	79	80	75	80	75	75	77	78	B
Goukamma	L	L	L		Y	M	70.4	Y	91	84	86	90	88	87	87	90	90	90	89	88	B
Knysna	L	M	L			H	0.2	Y	92	100	72	80	86	70	80	75	60	65	70	78	B
Noetsie	L	L	L			L	0.1	Y	85	70	80	95	83	80	90	60	95	90	83	83	B
Piesang	L	M	M			L	10.0	Y	85	70	64	50	67	64	50	50	65	50	56	62	C
Keurbooms	L	L	L			L	0.1	Y	98	99	90	97	96	95	85	95	75	83	87	91	A
Matjies	L	L	L			L	0.5	Y	93	75	83	95	87	85	90	90	95	90	90	89	B
Sout (Oos)	L	L				L	2.9	Y	97	100	90	95	96	90	100	100	90	95	95	95	A
Groot (Wes)	M	L	L			L	1.0	Y	75	60	74	80	72	70	80	85	75	90	80	76	B
Bloukrans	L	L				L	0.2	Y	90	100	80	95	91	92	100	95	85	95	93	92	A
Lottering	L	L				L	0.2	Y	85	100	78	95	90	92	100	95	85	95	93	91	A
Elandsbos	L	L	L			L	0.1	Y	85	100	78	95	90	92	95	95	85	95	92	91	A
Storms	L	L	L			L	0.1		80	100	78	95	88	92	95	95	85	95	92	90	A
Elands	L	L	L			L	0.1	Y	80	80	78	95	83	82	95	95	85	95	90	87	B
Groot (Oos)	M	M	L			L	1.8	Y	65	65	64	90	71	70	90	95	85	95	87	79	B
Tsitsikamma	M	M	L			L	0.1	Y	70	70	64	96	75	70	90	80	90	95	85	80	B
Klipdrif	M	M	M			L	0.1	Y	65	40	56	50	53	50	60	60	55	65	58	55	D
Slang	M	M	M			L	22.1	Y	65	30	56	50	50	45	60	60	45	55	53	52	D
Krom Oos (Kromme)	H	H	M			H	1.0	Y	34	100	34	70	60	17	50	20	40	70	39	49	D
Seekoei	M	M	H			L	2.0	Y	58	40	40	61	50	35	35	30	35	40	35	42	D
Kabeljous	L	M	M			L	19.3	Y	80	60	62	70	68	61	70	70	65	85	70	69	C
Gamtoos	M	M	M			H	2.1	Y	65	90	54	80	72	60	70	80	75	90	75	74	C
Van Stadens	L	L	L			L	0.1	Y	80	60	76	80	74	70	80	80	85	90	81	78	B
Maitland	L	M	M			L	0.1	Y	80	60	64	80	71	61	70	75	65	80	70	71	C
Baakens	M	H	H			L	0.1	Y	70	40	36	10	39	29	10	5	5	10	12	25	E

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Papenkuils	M	H	H			L	35.0	Y	70	10	10	0	23	9	0	0	5	0	3	13	F
Swartkops	L	H	H			H	10.0	Y	90	100	44	50	71	57	40	50	45	70	52	62	C
Coega (Ngcura)	M	H	H			L	9.0	Y	75	0	10	10	24	25	10	0	0	20	11	17	F
Sundays	M	H	M			H	0.3	Y	75	100	36	89	75	37	50	50	70	80	57	66	C
Boknes	L	L	L			L	11.5	Y	80	60	72	80	73	70	80	70	65	70	71	72	C
Bushmans	L	M	M			H	0.1	Y	85	95	66	70	79	78	70	65	55	80	70	74	C
Kariega	M	L	M			L	2.2	Y	60	95	68	70	73	69	70	60	65	80	69	71	C
Kasuka	L	L	L			L	2.0	Y	90	80	80	75	81	81	90	90	85	90	87	84	B
Kowie	M	M	M			L	0.0	Y	70	100	56	60	72	61	60	60	85	80	69	70	C
Rufane	M	M	M				0.1	Y	60	40	58	60	55	55	70	70	70	70	67	61	C
Riet	L	L	L			L	2.2	Y	95	90	86	85	89	90	90	85	85	80	86	88	B
Kleinemond Wes	L	M	L			L	2.0	Y	95	90	72	85	86	78	85	90	90	85	86	86	B
Kleinemond Oos	L	M	L			L	0.0	Y	95	90	78	85	87	80	85	90	90	85	86	87	B
Klein Palmiet	H	M	M			L	30.0	Y	40	0	50	50	35	35	70	70	45	50	54	45	D
Great Fish	M	M	M			H	0.1	Y	70	100	62	70	76	71	75	70	55	90	72	74	C
Old Womans	L	M	M			L	2.2	Y	95	80	72	65	78	71	70	75	65	70	70	74	C
Mpekweni	L	M	L			M	3.0	Y	90	80	76	80	82	77	85	80	80	70	78	80	B
Mtati	L	L	L			L	3.5	Y	90	80	82	80	83	81	90	90	85	90	87	85	B
Mgwalana	L	L	L			L	8.5	Y	90	80	82	80	83	81	90	90	85	90	87	85	B
Bira	L	L	L			L	0.2	Y	95	90	90	90	91	90	85	90	85	90	88	90	B
Gqutywa	L	L	L			L	0.1	Y	90	80	80	90	85	80	80	80	85	90	83	84	B
Ngculura	L	L	L			L	0.0		85	70	84	90	82	79	80	90	65	90	81	82	B
Blue Krans	L	L	L			L	2.1		95	90	90	90	91	90	90	90	85	90	89	90	A
Mtana	L	M	L			L	50.0	Y	90	80	74	85	82	77	90	85	85	90	85	84	B
Keiskamma	L	M	M			H	0.1	Y	80	100	58	70	77	70	70	70	75	80	73	75	C
Ngqinisa	L	M	L			L	2.0	Y	95	90	78	85	87	82	85	90	85	90	86	87	B
Kiwane	L	L	L			L	20.0	Y	95	90	90	85	90	90	90	90	85	90	89	90	B
Tyolomnqa	L	L	L			M	0.1	Y	90	80	80	80	83	80	80	90	80	90	84	83	B
Shelbertsstroom	L	M	L			L	0.1	Y	90	80	68	60	75	73	85	75	65	75	75	75	C
Lilyvale	L	M	L			L	0.1	Y	80	70	58	75	71	64	90	80	85	80	80	75	B
Ross' Creek	L	M	L			L	2.3	Y	90	80	74	70	79	77	90	80	85	80	82	80	B
Ncera	L	M	L			L	0.1	Y	90	80	74	85	82	77	90	85	85	90	85	84	B
Mlele	L	M	L			L	0.1	Y	90	80	74	60	76	77	85	75	85	75	79	78	B
Mcantsi	L	M	M			L	3.2	Y	90	80	62	70	76	67	70	75	85	75	74	75	C
Gxulu	L	L	L			L	1.0	Y	90	80	86	70	82	84	80	75	85	70	79	80	B
Goda	L	L	L			L	0.1	Y	90	80	86	85	85	85	90	85	85	90	87	86	B
Hlozi	L	L	L			L	0.1	Y	85	70	84	80	80	80	90	90	85	90	87	83	B
Hickman's	L	M	L			L	0.1	Y	95	90	78	85	87	82	90	85	75	80	82	85	B
Mvubukazi	L	M	L			L	0.0	Y	95	90	72	90	87	78	90	85	75	80	82	84	B
Ngqenga	L	H	L			L	20.0		90	80	50	60	70	61	90	85	75	80	78	74	C

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Buffalo	H	H	L			L	0.1	Y	40	90	46	40	54	41	85	70	65	60	64	59	D
Blind	L	H	L			L	0.1	Y	80	70	46	70	67	56	85	60	75	60	67	67	C
Hlaze	L	M	L			L	7.4	Y	80	70	64	90	76	68	85	70	75	70	74	75	C
Nahoon	M	H	M			H	2.0	Y	72	100	40	85	74	60	70	60	35	70	59	67	C
Qinira	L	M	L			M	7.7	Y	90	90	68	70	80	77	80	70	70	70	73	76	B
Gqunube	L	M	L			M	8.0	Y	90	100	68	70	82	78	85	70	70	70	75	78	B
Kwelera	L	L	L			H	2.0	Y	95	100	84	70	87	88	80	75	75	90	82	84	B
Bulura	L	M	L			H	0.1	Y	95	90	78	80	86	81	80	75	65	80	76	81	B
Cunge	L	L	L			L	3.5	Y	95	90	90	90	91	90	90	90	85	90	89	90	A
Cintsa	L	M	L			L	3.1	Y	80	65	70	50	66	69	80	80	75	80	77	71	C
Cefane	L	L	L			L	3.5	Y	95	90	84	85	89	86	85	85	85	85	85	87	B
Kwenxura	L	L	L			L	0.2	Y	95	90	90	85	90	90	90	90	85	90	89	90	B
Nyara	L	L				L	0.1	Y	95	90	90	90	91	91	100	90	85	90	91	91	A
Mtwendwe	L	L	L			L	1.0	Y	95	90	90	80	89	90	90	75	85	90	86	87	B
Haga-haga	L	L	L			L	0.1	Y	90	80	86	80	84	85	90	75	85	90	85	85	B
Mtendwe	L	L	L			L	3.8	Y	95	90	90	80	89	90	90	75	65	80	80	84	B
Quko	L	L	L			L	2.6	Y	95	90	90	80	89	90	90	90	95	95	92	90	A
Morgan	L	M	L			L	0.1	Y	80	80	70	70	75	77	90	60	65	70	72	74	C
Cwili	L	M	L			L	30.0	Y	95	90	78	75	85	82	90	70	85	85	82	83	B
Great Kei	L	M	L			H	2.3	Y	85	100	72	60	79	60	85	60	35	60	60	70	C
Gxara	L	L	L			L	0.1	Y	95	90	84	75	86	86	90	90	85	90	88	87	B
Ngogwane	L	L	L			L	1.7	Y	95	90	84	75	86	86	90	85	65	85	82	84	B
Qolora	L	L	L			L	0.1	Y	95	90	84	75	86	86	85	90	85	90	87	87	B
Ncizele	L	L	L			L	0.1	Y	95	90	84	75	86	86	90	90	85	90	88	87	B
Timba	L	L	L			L	6.0		95	90	90	90	91	90	90	90	85	90	89	90	A
Kobonqaba	L	L	L			L	3.0	Y	95	100	84	80	90	88	80	80	85	85	84	87	B
Nxaxo/Ngqusi	L	L	M			L	2.4	Y	95	90	84	80	87	84	70	75	75	80	77	82	B
Cebe	L	L	L			L	2.4	Y	95	90	84	85	89	86	90	90	85	90	88	88	B
Gqunqe	L	L	L			L	1.5	Y	95	90	90	90	91	90	90	95	95	95	93	92	A
Zalu	L	L	L			L	2.4	Y	95	90	90	85	90	90	90	90	95	95	92	91	A
Ngqwara	L	L	L			L	1.5	Y	95	90	90	85	90	90	90	90	95	95	92	91	A
Sihlontlweni/Gcin	L	L	L			L	0.0	Y	95	90	90	85	90	90	90	90	85	90	89	90	B
Nebelele	L	L					7.0		95	90	90	80	89	91	100	100	100	100	98	93	A
Qora	L	L	L			L	1.3	Y	95	100	84	80	90	89	90	90	75	90	87	88	B
Jujura	L	L	L			L	1.5	Y	95	90	90	80	89	90	90	90	85	90	89	89	B
Ngadla	L	L	L			L	2.5	Y	95	90	90	90	91	90	90	90	85	90	89	90	A
Shixini	L	L	L			L	0.0	Y	95	100	90	80	91	93	90	90	75	90	88	89	B
Beechamwood		L					0.0		100	100	97	90	97	98	100	100	100	100	100	98	A
Unnamed		L					0.0		100	100	97	90	97	98	100	100	100	100	100	98	A
Kwa-Goqo		L					0.0		100	100	97	90	97	98	100	100	100	100	100	98	A

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Ku-Nocekedwa		L					8.4		100	100	97	90	97	98	100	100	100	100	100	98	A
Nqabara/Nqabarana	L	L	L			L	1.0	Y	95	100	84	75	89	88	80	90	85	90	87	88	B
Ngoma/Kobule	L	L	L			L	1.0	Y	95	90	90	90	91	90	90	90	95	90	91	91	A
Mendu	L	L	L			L	0.0	Y	95	90	90	90	91	90	90	90	95	100	93	92	A
Mendwana	L	L	L				15.0		95	90	90	90	91	90	90	90	90	90	90	91	A
Mbashe	L	M	L			H	0.1	Y	90	80	68	60	75	70	85	60	55	70	68	71	C
Ku-Mpenzu	L	L	L			L	0.2	Y	95	90	84	75	86	87	95	90	95	95	92	89	B
Ku-Bhula/Mbhanyana	L	L				L	0.1	Y	95	90	90	90	91	91	100	90	85	90	91	91	A
Kwa-Suka	L	L				L	0.5	Y	95	90	90	90	91	91	100	85	75	85	87	89	B
Ntlonyane	L	M	M			L	0.1	Y	95	90	72	75	83	75	55	75	70	75	70	76	B
Nkanya	L	M	L	Y		L	0.0	Y	95	90	78	85	87	82	90	75	80	80	81	84	B
Sundwana		L				L	7.0		100	100	97	95	98	98	100	90	95	95	96	97	A
Xora	L	L	L			L	0.2	Y	95	100	84	80	90	88	80	90	85	90	87	88	B
Bulungula	L	L	L			L	0.0	Y	95	90	90	90	91	89	80	80	85	90	85	88	B
Ku-Amanzimuzama	L	L	L			L	0.0		95	90	89	90	91	92	90	90	85	90	89	90	A
Nqakanqa		L	L				0.0		100	100	97	95	98	97	90	90	90	90	91	95	A
Unnamed2		L	L				2.0		100	100	97	95	98	97	90	90	90	90	91	95	A
Mncwasa	L	L	L			L	0.5	Y	95	90	84	80	87	85	80	80	85	90	84	86	B
Mpako	L	L	L			L	0.1	Y	95	90	84	85	89	85	80	75	75	80	79	84	B
Nenga	L	M	M			L	0.1	Y	95	90	72	60	79	74	50	50	85	85	69	74	C
Mapuzi	L	M	L			L	5.5	Y	95	90	78	80	86	82	90	85	75	80	82	84	B
Mtata	M	H	M			H	0.1	Y	46	100	31	88	66	39	60	40	45	60	49	58	D
Tshani	L	M	L			L	5.0	Y	95	90	78	80	86	82	90	80	75	80	81	84	B
Mdumbi	L	L	M			H	0.1	Y	95	100	84	80	90	87	75	80	70	80	78	84	B
Lwandilana	L	L	L			L	1.0	Y	95	90	93	90	92	92	90	90	90	90	90	91	A
Lwandile	L	L	L			L	5.2	Y	95	90	86	90	90	90	90	90	90	90	90	90	A
Mtakatye	L	L	L			H	0.1	Y	90	100	80	80	88	85	80	85	75	90	83	85	B
Hluleka/Majusini	L	L	L			L	6.0	Y	95	90	90	80	89	90	90	85	95	100	92	90	A
Mnenu	L	M	L			L	0.1	Y	95	90	81	85	88	84	90	85	85	90	87	87	B
Mtonga	L	L	L			L	0.1	Y	95	90	84	80	87	86	90	85	85	90	87	87	B
Mpande	L	L				L	1.0	Y	95	90	84	85	89	87	100	85	95	90	91	90	B
Sinangwana	L	L	L			L	6.7	Y	95	90	84	70	85	85	80	85	75	80	81	83	B
Mngazana	L	M	M			H	6.0	Y	95	100	72	80	87	79	70	50	55	80	67	77	B
Mngazi	L	M	L			L	0.1	Y	85	70	64	80	75	67	80	60	65	70	68	72	C
Gxwaleni	L	L				L	0.1	Y	95	90	93	85	91	93	100	75	95	95	92	91	A
Bulolo	L	L	L			L	0.0	Y	95	90	90	75	88	89	80	60	85	90	81	84	B
Mtumbane	L	L	L			L	35.2		95	90	90	80	89	90	90	60	85	80	81	85	B
Mzimvubu	L	M	L			H	0.0	Y	90	100	72	80	86	70	90	40	45	70	63	74	C
Ntlupeni	L	L	L			L	1.0		95	90	84	80	87	86	90	90	85	90	88	88	B
Nkodusweni	L	L	L			L	4.1	Y	95	90	80	80	86	86	90	80	75	80	82	84	B

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Mntafufu	L	L	M			H	3.8	Y	95	100	84	80	90	87	75	70	75	90	79	85	B
Mzintlava	L	M	L			H	0.0	Y	95	100	78	70	86	85	90	85	65	80	81	83	B
Mzimpunzi	L	L	L				0.1		95	90	84	95	91	86	90	85	90	90	88	90	B
Kwa-Nyambalala	L	L	L			L	2.0	Y	95	90	90	85	90	90	90	80	75	85	84	87	B
Mbotyi	L	L	L			L	0.0	Y	95	90	90	80	89	90	90	80	75	85	84	86	B
Mkozi	L	L	L				0.0		95	90	84	90	90	86	90	100	100	100	95	92	A
Myekane	L	L					0.0		95	90	90	90	91	91	100	100	100	100	98	95	A
Sitatsha	L	L					0.0		95	90	90	90	91	91	100	100	100	100	98	95	A
Lupatana	L	L					0.0		95	90	90	90	91	91	100	100	100	100	98	95	A
Mkweni	L	L					3.2		95	90	90	90	91	91	100	100	100	100	98	95	A
Msikaba	L	M				H	0.0	Y	95	100	78	90	91	86	100	100	75	100	92	91	A
Butsha			L				0.1		100	100	100	90	98	99	90	95	100	100	97	97	A
Mgwegwe						L	0.1	Y	100	100	100	100	100	100	100	100	95	100	99	100	A
Mgwetyana						L	4.5	Y	100	100	100	100	100	100	100	100	95	100	99	100	A
Mtentu	L	L	L			H	1.0	Y	95	95	90	90	93	92	80	95	85	95	89	91	A
Sikombe	L	L				L	0.1	Y	95	90	90	90	91	91	100	90	95	90	93	92	A
Kwanyana	L	L	L			L	0.1	Y	95	90	90	90	91	89	80	90	85	90	87	89	B
Mtolane	L	L				L	3.5	Y	95	90	90	90	91	91	100	90	85	90	91	91	A
Mnyameni	L	L	M			L	0.1	Y	95	95	84	90	91	87	70	90	85	90	84	88	B
Mpahlanyana	L	L				L	0.1	Y	95	90	90	90	91	91	100	80	85	90	89	90	A
Mpahlane	L	L				L	3.7	Y	95	90	90	90	91	91	100	80	85	90	89	90	A
Mzamba	L	M	L			H	0.0	Y	95	100	78	80	88	85	90	75	75	90	83	86	B
Mtentwana	L	M	H				2.5	Y	80	60	64	80	71	58	40	60	60	90	62	66	C
Mtamvuna	L	L	L		?	L	0.1	Y	85	80	78	90	83	80	80	75	75	85	79	81	B
Zolwane	L	L	M		Y	L	0.2	Y	95	90	84	95	91	84	70	70	70	80	75	83	B
Sandlundlu	L	M	M	Y	Y	L	0.2	Y	95	90	69	70	81	72	50	60	55	50	57	69	C
Ku-Boboyi	L	M	M			L	0.0	Y	95	90	81	90	89	81	60	70	65	65	68	79	B
Tongazi	L	M	M				0.2	Y	95	90	78	80	86	80	70	70	70	70	72	79	B
Kandandhlovu	L	M	M			L	0.3	Y	95	90	78	70	83	79	60	60	65	75	68	76	B
Mpenjati	L	M	M	Y	Y	L	0.3	Y	95	85	78	85	86	78	70	70	70	80	74	80	B
Umhlangankulu	L	M	M		Y	L	0.2	Y	95	80	66	50	73	65	50	50	55	65	57	65	C
Kaba	L	M	M			L	0.6	Y	95	90	78	80	86	80	70	70	65	90	75	80	B
Mbizana	L	M	M	Y	?	L	0.2	Y	95	80	78	70	81	75	70	70	70	85	74	77	B
Mvutshini	L	M	M		Y	L	0.2	Y	90	70	74	80	79	71	75	70	65	80	72	75	B
Bilanhlolo	L	M	M		Y	L	0.2	Y	90	70	62	60	71	61	55	50	50	60	55	63	C
Uvuzana	L	M	M		Y	L	0.2	Y	90	70	68	80	77	66	70	60	55	60	62	70	C
Kongweni	L	M	H		Y	L	0.0	Y	90	70	62	60	71	59	40	50	55	60	53	62	C
Vungu	L	M	L				0.2		90	80	62	90	81	68	80	80	75	70	75	78	B
Mhlangeni	L	M	M		Y	L	0.7	Y	90	70	62	60	71	62	70	70	65	80	69	70	C
Zotsha	L	M	M	Y	Y	L	0.2	Y	90	80	74	50	74	73	50	70	65	80	68	71	C

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Boboyi	L	H	M			L	0.1	Y	90	80	56	50	69	63	70	65	70	65	67	68	C
Mbango	M	H	H			L	4.0	Y	70	60	27	50	52	36	40	10	0	30	23	37	E
uMzimkulu	M	M	M	Y	Y	H	0.2	Y	75	70	66	70	70	70	70	75	55	80	70	70	C
Mtentweni	L	M	M			L	0.2	Y	90	80	65	60	74	68	60	60	55	60	61	67	C
Mhlangamkulu	L	M	M			L	0.2	Y	90	80	62	70	76	66	60	50	65	85	65	70	C
Damba	L	M	M		Y	L	0.2	Y	90	70	68	60	72	64	50	50	55	70	58	65	C
Koshwana	L	M	M			L	0.2	Y	90	80	62	60	73	66	60	60	65	70	64	69	C
Intshambili	L	L	M			L	0.3	Y	90	80	80	70	80	78	60	80	65	80	73	76	B
Mzumbe	L	M	H	Y		L	0.2	Y	95	90	78	40	76	77	40	30	25	40	42	59	D
Mhlabatshane	L	L	M			L	0.8	Y	95	90	84	70	85	83	60	65	65	80	71	78	B
Mhlungwa	L	M	M			L	0.5	Y	95	90	78	40	76	78	50	60	60	65	63	69	C
Mfazazana	L	M	H			L	0.4	Y	95	90	78	60	81	76	30	40	65	70	56	68	C
Kwa-Makosi	L	M	M			L	0.2	Y	95	90	81	80	87	83	75	70	65	80	75	81	B
Mnamfu	L	M	M			L	0.2	Y	95	90	72	70	82	76	70	60	60	70	67	74	C
Mtwalume	L	M	M	Y		L	0.2	Y	85	70	66	50	68	64	50	40	35	50	48	58	D
Mvuzi	L	M	M			L	0.8	Y	80	60	72	50	66	64	60	75	70	80	70	68	C
Fafa	L	M	M	Y	Y	L	0.1	Y	80	50	66	40	59	56	70	60	55	60	60	60	D
Mdesingane	L	M	H			L	0.0	Y	90	80	62	50	71	64	40	50	45	60	52	61	C
Sezela	L	H	M		Y		0.2		90	70	44	50	64	49	60	25	30	30	39	51	D
Mkumbane	L	M	M			L	0.6	Y	85	70	68	70	73	65	60	40	50	60	55	64	C
Mzinto	L	M	M		?	L	0.0	Y	90	80	68	60	75	69	50	50	50	60	56	65	C
Nkomba	L	M	H			L	0.2		90	80	74	50	74	72	40	60	45	70	57	65	C
Mzimayi	L	M	M			L	0.1	Y	90	80	74	70	79	74	60	60	55	70	64	71	C
Mpambanyoni	L	M	M	Y	?	L	7.6	Y	90	70	68	70	75	65	60	30	45	50	50	62	C
Mahlongwa	L	M	M	Y	Y	M	0.4	Y	95	80	78	50	76	74	60	70	60	80	69	72	C
Mahlongwane	L	M	M		?	L	7.0		95	90	72	60	79	75	60	80	75	80	74	77	B
uMkomazi	L	M	M	Y	Y	H	1.9	Y	85	60	72	60	69	64	60	70	55	60	62	66	C
Ngane	L	L	M		?	L	0.0	Y	90	80	86	90	87	83	70	85	70	80	78	82	B
Umgababa	L	L	M		Y		0.0		80	70	80	80	78	74	70	85	85	90	81	79	B
Msimbazi	L	L	L				0.0		90	80	86	90	87	84	80	90	90	90	87	87	B
Lovu	M	M	M	Y	Y		0.0		75	50	62	50	59	55	60	65	70	80	66	63	C
Little Manzimtoti	M	H	H		Y		0.0		70	60	36	75	60	41	30	10	20	20	24	42	D
Manzimtoti	L	H	H	Y	Y		0.0		90	70	50	60	68	50	30	10	30	30	30	49	D
Mbokodweni	M	H	H	Y	Y		0.0		50	30	28	40	37	25	20	20	40	50	31	34	E
Sipingo	H	H	H				53.0		1	1	10	15	7	8	30	5	10	40	19	13	F
Durban Bay	M	H	H			H	3.7	Y	70	100	42	20	58	48	10	20	25	5	22	40	E
uMgeni	M	H	H	Y	Y	L	0.1	Y	50	50	28	50	45	37	40	40	55	70	48	46	D
uMhlanga	M	H	M		Y	L	1.0	Y	50	30	36	60	44	40	65	40	40	40	45	45	D
uMdloti	L	H	H	Y	Y	L	0.6	Y	78	70	30	68	62	17	25	17	25	20	21	41	D
Tongati	L	H	H	Y	Y	L	0.6	Y	85	60	0	45	48	40	50	25	25	20	31	39	E

NAME	Pressures								Health Condition												
	Change in flow	Pollution	Habitat loss	Mining	Artificial Breaching	Fishing Effort	Fishing Effort (Catches in tones)	Bait collection	Hydrology	Hydrodynamics	Water Quality	Physical habitat	Habitat State	Microalgae	Macrophytes	Invertebrates	Fish Final	Birds	Biological State	Estuary Health State	Ecological Category
Mhlali	M	H	M	Y	Y	L	0.0	Y	75	80	44	60	65	58	60	70	55	70	63	64	**C**
Bob's Stream	M	M	M				0.1	Y	60	50	65	60	59	61	60	50	75	80	65	62	**C**
Seteni	M	M	M			L	1.0	Y	75	80	71	60	72	76	60	50	75	80	68	70	**C**
Mvoti	M	H	M	Y	Y	L	0.2	Y	75	70	32	60	59	44	50	20	30	20	33	46	**D**
Mdlotane	L	L	M			L	0.6	Y	95	90	90	95	93	88	70	85	80	90	83	88	**B**
Nonoti	L	M	M	Y	Y	L	3.0	Y	95	90	75	75	84	77	60	70	65	75	69	77	**B**
Zinkwasi	L	M	H	Y	Y	L	17.0	Y	90	80	74	75	80	70	20	60	65	60	55	67	**C**
Thukela	L	H	M	Y	Y	H	15.0	Y	87	80	46	75	72	65	60	50	50	50	55	64	**C**
Matigulu/Nyoni	L	L	L			H	0.1	Y	90	80	83	80	83	87	80	80	55	85	77	80	**B**
Siyaya	H	H	H			L	18.0		10	10	16	20	14	14	10	10	10	5	10	12	**F**
Mlalazi	L	M	M		Y	H	80.0	Y	90	90	81	90	88	80	50	80	55	80	69	78	**B**
Mhlathuze	L	M	H	Y		H	88.0	Y	80	100	62	30	68	72	40	60	50	40	52	60	**C**
Richards Bay	L	M	H			H	0.0	Y	80	100	56	30	67	66	20	30	45	80	48	57	**D**
Nhlabane (Present)	M	L	H	Y			0.0		65	10	52	10	34	41	40	50	40	60	46	40	**D**
Msunduzi	L	M	M				8.0		80	90	58	40	67	70	50	40	60	70	58	63	**C**
uMfolozi	L	H	H	Y	Y	H	10.0	Y	80	70	46	60	64	50	30	50	45	40	43	54	**D**
St Lucia	H	M	H		Y	H	4.0	Y	35	40	57	65	49	30	30	10	40	40	30	40	**E**
Mgobezeleni	L	L	L		Y	M	300.0		85	70	87	85	82	82	90	90	60	95	83	83	**B**
Kosi	L	L	M			VH	0.0	Y	85	90	89	80	86	88	70	90	70	70	78	82	**B**

* *Ecological Category was determined by an ecological water requirement study, otherwise determined by desktop study.*

Appendix B: Key physical features, estuary health, present health category (PES), estuarine importance, desired state (REC), allocated health (TEC) and key pressures for the estuaries of Mvoti to uMzimkulu WMA

Table B.1 The Key physical features, estuary health, present health category (PES), estuarine importance, desired state (REC), allocated health (TEC) and key pressures for the estuaries of Mvoti to **uMzimkulu** WMA.

ESTUARY	KEY PHYSICAL FEATURES				ESTUARY HEALTH												IMPORTANCE (5=Higi,1=Low)					KEY PRESSURE		
	Estuary habitat (ha)	Natural MAR (million m^3/a)	Present MAR (million m^3/a)	% Open (1993 – 2013 (excluding drought))	Hydrology	Hydrodynamics	Water Quality	Physical habitat	Habitat Score	Microalgae	Macrophytes	Invertebrates	Fish	Birds	Estuary Health (Total)	Present Health (PES)	Conservation	Estuary (Biodiversity)	Fish Nursery	Desired State (REC)	Allocated State (TEC)	Flow	Water Quality	Non-Flow
Mtamvuna	64	275	239	95	81	95	86	90	88	85	80	80	75	85	81	B	5	4	5	A/B	A/B			
Zolwane	2	2	2	81	98	95	88	90	93	89	80	80	75	85	82	B	1	1	1	B	B			
Sandlundlu	11	5	5	60	94	95	86	70	86	87	70	45	40	50	58	C	1	2	1	C	C			●
Ku-Boboyi	5	1	1	53	100	90	88	90	92	89	80	80	75	75	80	B	1	1	1	B	B			
Tongazi	7	7	7	91	92	90	79	80	85	80	70	65	60	65	68	B/C	1	2	1	B/C	B/C			●
Kandandhlovu	5	2	2	54	100	95	77	70	85	84	80	80	75	75	79	B	1	2	3	B	B		●	●
Mpenjati	33	24	24	71	98	90	79	60	82	79	50	60	60	80	66	B/C	5	3	3	B	B		●	●
Umhlangankulu	16	3	3	33	98	95	54	50	74	68	75	40	45	65	59	C	1	3	3	C	C		●	●
Kaba	15	3	3	27	95	95	54	70	78	65	60	60	55	55	59	C	1	2	1	C	C		●	●
Mbizana	28	36	36	54	94	95	79	70	85	82	70	70	70	85	75	B	1	3	1	B	B			●
Mvutshini	4	2	2	42	96	85	66	80	82	72	70	70	65	65	68	B/C	1	1	1	B/C	B/C		●	●
Bilanhlolo	17	5	5	47	96	93	66	50	76	71	40	50	50	50	52	C	1	3	3	C	C		●	●
Uvuzana	6	1	1	32	100	100	46	70	79	61	70	60	55	60	61	C	1	1	1	C	C		●	●
Kongweni	7	2	3	49	25	55	30	50	40	28	40	50	35	50	41	E	1	2	3	D	E/F	●	●	●
Vungu	7	28	29	96	90	90	66	90	84	73	80	70	75	65	73	B	1	2	1	B	B		●	

ESTUARY	KEY PHYSICAL FEATURES				ESTUARY HEALTH											Present Health (PES)	IMPORTANCE (5=Higi,1=Low)			Desired State (REC)	Allocated State (TEC)	KEY PRESSURE		
	Estuary habitat (ha)	Natural MAR (million m^3/a)	Present MAR (million m^3/a)	% Open (1993 – 2013 (excluding drought))	Hydrology	Hydrodynamics	Water Quality	Physical habitat	Habitat Score	Microalgae	Macrophytes	Invertebrates	Fish	Birds	Estuary Health (Total)		Conservation	Estuary (Biodiversity)	Fish Nursery			Flow	Water Quality	Non-Flow
Mhlangeni	16	9	10	55	86	80	73	60	75	75	60	60	55	70	64	C	1	2	1	C	C		●	●
Zotsha	29	16	16	76	89	70	66	84	77	80	65	75	85	80	77	B/C	5	3	3	B	B		●	●
Boboyi	14	8	8	94	87	95	79	70	83	80	70	80	70	65	73	B/C	1	2	1	B/C	B/C		●	●
Mbango	13	3	7	86	26	50	38	50	41	35	40	10	5	30	24	E	1	2	1	D	E/F	●	●	●
uMzimkulu	118	1452	1175	97	84	78	72	75	77	90	80	70	80	80	80	B	5	4	5	B	B			
uMthente	18	12	11	40	75	85	62	60	70	66	60	65	65	70	65	C	1	3	1	C	C	●	●	●
Mhlangamkulu	13	2	2	19	48	63	60	70	60	55	75	75	70	70	69	C	1	1	3	C	C	●		●
Damba	20	5	4	28	50	50	60	60	55	51	60	65	55	65	59	D	5	2	1	C	D	●		●
Koshwana	18	2	2	26	90	80	50	60	70	60	50	55	45	60	54	C/D	5	2	1	B	C	●	●	●
Intshambili	10	6	5	42	30	60	73	70	58	57	70	80	70	75	70	C	5	2	1	B	C	●	●	●
Mzumbe	36	59	54	74	81	70	75	50	69	69	40	60	55	40	53	C/D	1	3	1	C	C		●	●
Mhlabatshane	19	6	6	50	90	90	66	70	79	72	65	75	75	75	72	B/C	5	2	3	A/B	B			●
Mhlungwa	17	6	6	29	90	90	75	40	74	77	50	60	60	65	62	C	1	2	1	C	C		●	●
Mfazazana	16	3	3	24	77	70	64	60	68	62	50	60	60	75	61	C	5	3	1	B	C		●	●
Kwa-Makosi	15	3	3	37	82	90	73	65	77	77	70	65	65	70	69	B/C	5	3	1	B	B		●	●
Mnamfu	14	3	3	42	82	80	62	70	73	67	70	60	60	70	65	C	1	2	1	C	C		●	●
Mtwalume	39	58	43	71	85	75	73	65	74	74	70	65	60	65	67	C	1	3	1	C	C		●	●
Mvuzi	18	2	2	23	85	75	73	60	73	74	65	75	65	75	71	C	1	2	1	C	C		●	●
Fafa	51	46	38	45	68	71	75	55	67	67	50	60	55	60	58	C/D	1	4	3	C	C	●	●	●
Mdesingane	7	2	2	58	95	60	52	40	62	55	40	30	25	40	38	D	1	1	1	D	D		●	●
Sezela	28	4	4	19	90	90	52	60	73	63	60	50	50	55	56	C	1	3	1	C	C		•	•
Mkumbane	12	4	4	8	80	90	66	60	74	68	50	55	55	55	57	C	1	2	1	C	C		•	•
uMuziwezinto	30	23	20	15	64	70	60	60	63	59	60	55	55	60	58	C/D	1	3	1	C/D	C/D	•	•	•

ESTUARY	KEY PHYSICAL FEATURES				ESTUARY HEALTH											Present Health (PES)	IMPORTANCE (5=Higi,1=Low)			Desired State (REC)	Allocated State (TEC)	KEY PRESSURE		
	Estuary habitat (ha)	Natural MAR (million m³/a)	Present MAR (million m³/a)	% Open (1993 – 2013 (excluding drought))	Hydrology	Hydrodynamics	Water Quality	Physical habitat	Habitat Score	Microalgae	Macrophytes	Invertebrates	Fish	Birds	Estuary Health (Total)		Conservation	Estuary (Biodiversity)	Fish Nursery			Flow	Water Quality	Non-Flow
Nkomba	13	1	1	10	97	95	70	70	83	74	60	60	65	60	64	B/C	1	1	1	B/C	B/C		•	•
Mzimayi	<1	6	5	20	55	60	58	70	61	55	65	60	65	70	63	C/D	1	2	1	C/D	C/D	•	•	•
Mpambanyoni	13	60	55	78	90	85	68	60	76	70	60	60	70	50	62	C	1	2	1	C	C		•	•
Mahlongwa	14	14	13	22	89	93	66	60	77	73	70	70	65	65	69	C	5	2	1	B	B		•	•
Mahlongwane	21	3	3	13	90	90	66	60	76	71	60	70	65	70	67	C	5	3	1	B	B		•	•
uMkhomazi	75	1078	926	99	66	95	67	78	76	90	21	75	60	60	61	C	5	4	5	B	B/C		•	•
Ngane	8	4	4	54	83	75	71	50	70	73	60	60	55	60	62	C	1	2	1	C	C		•	•
Umgababa	47	11	10	46	74	70	73	65	71	69	60	70	65	80	69	C	5	3	3	B	B/C	•	•	•
Msimbazi	28	10	10	36	97	95	77	70	85	81	60	80	65	70	71	B	5	3	1	A	B		•	•
Lovu	40	119	73	77	54	70	69	50	61	64	60	65	65	70	65	C/D	5	3	3	B	B/C	•	•	•
Little aManzimtoti	10	3	7	72	40	24	40	53	39	28	45	5	30	20	25	E	1	2	1	D	E	•	•	•
aManzimtoti	21	5	7	44	74	65	32	45	54	42	30	15	15	30	26	D/E	1	3	1	D	D	•	•	•
Mbokodweni	18	32	54	86	53	35	39	45	43	20	30	10	30	17	21	E	1	3	1	D	E	•	•	•
Sipingo	27	109	3	5	1	1	16	20	10	12	30	20	5	10	15	F	1	3	1	D	F	•	•	•
Durban Bay	1148	36	63	100	49	40	53	10	38	33	10	10	5	15	15	E	5	5	5	D	E	•	•	•
uMngeni	83	671	263	95	44	0	39	30	28	55	20	10	20	35	28	D/E	5	4	3	D	D	•	•	•
Mhlanga	83	13	22	48	50	60	44	60	54	54	65	40	40	60	52	D	5	4	3	B	B	•	•	•
uMdloti	58	100	72	40	57	53	40	68	54	31	45	45	45	20	37	D	1	4	3	C	D	•	•	•
uThongathi	37	71	71	84	61	81	37	43	55	35	50	30	30	20	33	D	1	4	1	C	D	•	•	•
Mhlali	42	56	54	48	62	88	62	60	68	50	51	40	60	40	48	C/D	5	4	3	B/C	D	•	•	•
Bob's Stream	<1	1	1	20	95	95	68	60	80	75	70	80	80	70	75	B/C	1	1	1	B/C	B/C		•	•
Seteni	7	1	1	35	100	100	70	60	83	76	60	80	80	65	72	B/C	1	2	1	B/C	B/C		•	•

ESTUARY	KEY PHYSICAL FEATURES				ESTUARY HEALTH											Present Health (PES)	IMPORTANCE (5=Higi,1=Low)			Desired State (REC)	Allocated State (TEC)	KEY PRESSURE		
	Estuary habitat (ha)	Natural MAR (million m^3/a)	Present MAR (million m^3/a)	% Open (1993 – 2013 (excluding drought))	Hydrology	Hydrodynamics	Water Quality	Physical habitat	Habitat Score	Microalgae	Macrophytes	Invertebrates	Fish	Birds	Estuary Health (Total)		Conservation	Estuary (Biodiversity)	Fish Nursery			Flow	Water Quality	Non-Flow
Mvoti	22	375	420	99	53	95	58	73	70	80	32	25	55	10	40	D	5	3	1	C	C/D	•	•	•
Mdlotane	25	6	6	14	94	90	66	80	82	74	80	75	70	80	76	B	5	4	1	A/B	A/B		•	
Nonoti	27	36	35	18	89	90	64	65	77	70	55	65	25	60	55	C	1	3	1	C	C		•	•
Zinkwasi	71	14	14	28	94	95	75	70	83	81	65	70	75	60	70	B/C	5	4	3	A/B	B		•	•

Appendix C: Recommended mitigations and resource use constraints to achieve management objectives (as defined by TEC) for the estuaries of Mvoti to uMzimkulu WMA

Table C.1 Summary of present health (PES), the desired health (REC) and allocated health (TEC) with recommended mitigations and resource use constraints to achieve management objectives (as defined by TEC) for the estuaries of Mvoti to uMzimkulu WMA.

ESTUARY	PES	REC	TEC	MITIGATIONS and Constraints to TO ACHIEVE THE TEC
Mtamvuma	**B**	**A/B**	**A/B**	Interventions required to achieve the REC of an A/B: • Restoration of estuarine riparian habitat; • Reduce/control fishing high pressure; • Protect baseflows to estuary to maintain mouth state and salinity profile. A/B TEC is immediately applicable.
Zolwane	**B**	**B**	**B**	B TEC is immediately applicable. Scenarios that result in a B will be acceptable.
Sandhlunlu	**C**	**C**	**C**	TEC set to maintain the PES and REC and is immediately applicable.
Kuboyoyi	**B**	**B**	**B**	TEC set to maintain the PES and REC and is immediately applicable.
Tongazi	**B/C**	**B/C**	**B/C**	TEC set to maintain the PES and REC and is immediately applicable. Scenarios that comply to the TEC are acceptable.
Kandanhlovu	**B**	**B**	**B**	TEC set to maintain the PES and REC and is immediately applicable.
Mpenjati	**B/C**	**B**	**B**	Interventions required to achieve the REC: • Remove/reduce impact of sand mining; • Improve water quality; • Restore estuarine riparian habitat. The B TEC is immediately applicable if the above non-flow related activities are addressed. Water quality should also be improved and standards for existing situation and future scenarios should be investigated to allow for improvement.
Umhlangankulu	**C**	**C**	**C**	TEC set to maintain the PES and REC and is immediately applicable.
Kaba	**C**	**C**	**C**	TEC set to maintain the PES and REC and is immediately applicable.
Mbizana	**B**	**B**	**B**	TEC set to maintain the PES and REC and is immediately applicable.
Mvuthsini	**B/C**	**B/C**	**B/C**	TEC set to maintain the PES and REC and is immediately applicable. Any scenario that achieves the TEC (eg Sc C themes) is acceptable.
Bilanhlolo	**C**	**C**	**C**	TEC set to maintain the PES and REC and is immediately applicable.
Umvazana	**C**	**C**	**C**	TEC set to maintain the PES and REC and is immediately applicable.
Kongweni	**E**	**D**	**E/F**	Interventions required to achieve the REC: • Restoration of estuarine riparian habitat; • Improve water quality. • Reduce baseflows to estuary to maintain mouth state and salinity profile. The D can be achieved under current situation by removing half the waste and flow of current discharges. This has socio-economic implications and will be difficult to do. Therefore, the TEC is set to maintain the D/E.
Vungu	**B**	**B**	**B**	TEC set to maintain the PES and REC and is immediately applicable. Any scenario that achieves the B is acceptable.
Mhlangeni	**C**	**C**	**C**	TEC set to maintain the PES and REC and is immediately applicable.
Zotsha	**B/C**	**B**	**B**	Interventions required to achieve the REC: • Restoration of estuarine riparian habitat; • Improve water quality. TEC set to achieve the REC and is immediately applicable. No future waste scenarios should be considered for this system.
Boboyi	**B/C**	**B/C**	**B/C**	TEC set to maintain the PES and REC and is immediately applicable.
Mbango	**E**	**D**	**E/F**	Interventions required to maintain the REC: • Restore baseflows to estuary to maintain mouth state and salinity profile • Maintain water quality; and • Partial restoration of estuarine habitat. The D can be achieved under current situation by removing half the waste and flow of current discharges. This has socio-economic implications and will be difficult to do. Therefore, the TEC is set to maintain the E.

ESTUARY	PES	REC	TEC	MITIGATIONS and Constraints to TO ACHIEVE THE TEC
uMzimkulu	B	B	B	Interventions required to counteract the downward trajedtory the REC/TEC: • eradicate invasive alien vegetation • remove derelict, redundant and old quays, jetties, wharfs and revetments; and rehabilitate banks; • prohibit dredge spoil dumping in inappropriate areas; • manage agricultural and industrial practices in the catchment.
Mtentwini	C	C	C	TEC set to maintain the PES and REC and is immediately applicable.
Mhlangamkulo	C	C	C	TEC set to maintain the PES and REC and is immediately applicable.
Domba	D	C	D	Interventions required to achieve the REC: • Restore baseflows to estuary to maintain mouth state and salinity profile • Maintain water quality; and • Partial restoration of estuarine habitat. The PES is to be maintained as the TEC in the short term as restoration of baseflows have potential socio-economic implications. Further investigations can be undertaken as part of the estuarine management plans to determine whether improvement is possible even to a C/D by addressing non-flow measurements. No further scenarios should be considered as this could compromise potential improvement and as water quality must be maintained in its present state.
Koshwani	C/D	B	C	Interventions required to achieve the REC: • Restore baseflows to estuary to increase mouth state and salinity profile. • Improve water quality; and • Partial restoration of estuarine habitat. There is uncertainty regarding the capacity and discharge of the WWM works. To improve the estuary would either require removal of waste water and/or improvement of the treatment work to the required standard. Due to these uncertainties and the uncertainty around the implications of improvement, the TEC has been set to a C only. Once more information is available, the TEC can be reviewed.
Inhshambili	C	B	C	Interventions required to achieve the REC: • Restore baseflows to estuary to maintain mouth state and salinity profile. • Improve water quality; and • Partial restoration of estuarine habitat. The PES is to be maintained as the TEC in the short term as information is not available on the increased baseflows required. Restoration of base flows are the key parameter which require improvement. Further investigations can be undertaken as part of the estuarine management plans to determine whether improvement is possible even to a B/C by addressing non-flow measurements. No scenarios should be considered.
Mzumbe	C/D	C	C	
Mhlabatshane	B/C	A/B	B	Interventions required to achieve the REC: • Catchment water quality; and • Restoration of estuarine habitat (riparian). As it is assumed that addressing catchment water quality may be difficult and not possible on the short term, it was evaluated whether only addressing the estuarine habitat will achieve an improvement. Improvement will be to a B which is set as the TEC and immediately applicable. The TEC therefore represents an improvement, but not to the REC.
Mhlungwa	C	C	C	TEC set to maintain the PES and REC and is immediately applicable.
Mfazazana	C	B	C	Interventions required to achieve the REC: • Improve baseflows to estuary to maintain mouth state and salinity profile. • Improve water quality; and • Partial restoration of estuarine riparian habitat. The PES is to be maintained as the TEC in the short term as restoration of baseflows have potential socio-economic implications. Further investigations can be undertaken as part of the estuarine management plans to determine whether improvement is possible even to a B/C by addressing non-flow measurements.

ESTUARY	PES	REC	TEC	MITIGATIONS and Constraints to TO ACHIEVE THE TEC
KwaMakozi	**B/C**	**B**	**B**	Interventions required to achieve the REC/TEC: • Protect baseflows to estuary to maintain mouth state and salinity profile. • Improve water quality; and • Partial restoration of estuarine habitat. The TEC is set to improve to a B.
Mnamfu	**C**	**C**	**C**	TEC set to maintain the PES and REC and is immediately applicable.
Mtwalume	**C**	**C**	**C**	TEC set to maintain the PES and REC and is immediately applicable.
Mvuzi	**C**	**C**	**C**	TEC set to maintain the PES and REC and is immediately applicable.
Fafa	**C/D**	**C**	**C**	Interventions required to achieve the REC: • Restore estuarine riparian habitat. The C TEC is immediately applicable if the above non-flow related activities are addressed.
Mdesingane	**D**	**D**	**D**	TEC set to maintain the PES and REC and is immediately applicable.
Sezela	**C**	**C**	**C**	TEC set to maintain the PES and REC and is immediately applicable. Scenarios that comply to the TEC are acceptable.
Mkumbane	**C**	**C**	**C**	TEC set to maintain the PES and REC and is immediately applicable.
Mzinto	**C/D**	**C/D**	**C/D**	TEC set to maintain the PES and REC and is immediately applicable.
Nkomba	**B/C**	**B/C**	**B/C**	TEC set to maintain the PES and REC and is immediately applicable.
Mzimayi	**C/D**	**C/D**	**C/D**	TEC set to maintain the PES and REC and is immediately applicable.
Mpambanyoni	**C**	**C**	**C**	TEC set to maintain the PES and REC and is immediately applicable.
aMahlongwa	**C**	**B**	**B**	Interventions required to achieve the REC: • Protect baseflows to estuary to maintain mouth state and salinity profile. • Improve water quality; • Partial restoration estuarine riparian habitat • Control and reduce fishing pressure. B TEC is immediately applicable.
Mahlangwana	**C**	**B**	**B**	Interventions required to achieve the REC: • Protect baseflows to estuary to maintain mouth state and salinity profile. • Improve water quality; • Partial restoration estuarine riparian habitat B TEC is immediately applicable.
Mkomazi	**C**	**B**	**B/C**	Interventions required to achieve the REC: • Remove sandmining from the upper reaches below the Sappi Weir; • Restoration of vegetation in the upper reaches and along the northern bank in the middle and lower reaches; • Curb recreational activities in lower reaches; • Reduce/remove cast netting in the mouth area • Relocate upstream, or remove, the Sappi Weir. • Restore baseflows to estuary to maintain mouth state and salinity profile. The TEC of a B/C is immediately applicable and excludes the relocation of the SAPPI weir (as it may have economic consequences) and restoration of baseflows (difficult without a dam). The same anthropogenic measures under medium to long-term option Sc21 (includes the dam) as well as Sc Ci and Di, will also achieve the B/C. However, putting any additional waste whatsoever in the Mkomazi should be avoided due to the risk of mouth closure (especially pre-dam) and other options should be sought
Ngane	**C**	**C**	**C**	TEC set to maintain the PES and REC and is immediately applicable.
Umgababa	**C**	**B**	**B/C**	Interventions required to achieve the REC: • Restore baseflows to estuary to maintain mouth state and salinity profile. • Improve water quality; and • Partial restoration of estuarine habitat. Without information on the baseflow requirements (and a way to supply it), the REC cannot be achieved in the short term. The TEC therefore represents an improvement, but not to the REC. Water quality and estuarine habitat must be improved to achieve the TEC which is immediately applicable. Once higher confidence information is available on this estuary, the TEC can be improved to a B. No waste water must be put into this system as it will then not make it possible to improve to the REC in the long term.

ESTUARY	PES	REC	TEC	MITIGATIONS and Constraints to TO ACHIEVE THE TEC
Msimbazi	**B**	**A**	**B**	Interventions required to achieve the REC: • Protect baseflows to estuary to maintain mouth state and salinity profile. • Improve water quality. • Partial restoration of estuarine habitat. The TEC is set to maintain the PES. Improvement to the A will be difficult as one would have to remove some development in the catchment.
Lovu	**C/D**	**B**	**B/C**	Interventions required to achieve the REC: • Restore baseflows to estuary to improve mouth state and salinity profile. (Scenario L4) • Improve water quality; and • Partial restoration of estuarine habitat. Significant decrease in forestry and irrigation may meet REC. Socio economic implications of this scenarios are significant and the immediately applicable TEC is set at a B/C by applying non-flow related measures. Further improvement may require measurements that have significant socio-economic consequences.
Little Amanzimtoti	**E**	**D**	**E**	Interventions required to achieve the REC: • Restore baseflows to estuary to improve mouth state and salinity profile. • Significant improvement in water quality; and • Partial restoration of estuarine habitat. Immediate applicable maintain PES, as it is very difficult (costly) to achieve the D as this would require removing all waste. Further WW scenarios can therefore be considered as long as the estuary does not become a health hazard and there is compliance to other relevant legal requirements.
Manzimtoti	**D/E**	**D**	**D**	Interventions required to achieve the REC: Catchment water quality. Riparian habitat. REC of a D is immediately applicable
Mmbokotwini	**E**	**D**	**E**	Interventions required to achieve the REC: • Restore baseflows to estuary to improve mouth state and salinity profile. • Significant improvement in water quality; and • Partial restoration of estuarine habitat. Immediate applicable maintain PES, as it is very difficult (costly) to achieve the D as this would require removing all waste. Further WW scenarios can therefore be considered as long as the estuary does not become a health hazard and there is compliance to other relevant legal requirements.
Sipingo	**F**	**D**	**F**	Interventions required to achieve the REC: • Restore as much as possible baseflows to estuary to improve mouth state and salinity profile. • A significant improvement in water quality (storm water) needed. • Partial restoration of estuarine habitat. It is not possible to improve the estuary to a D as there is limited restoration potential. It must be noted that the mangrove habitat should not be compromised within the estuary. Stormwater the overriding problem should be addressed.
Durban Bay Shallow water and interidal zone	**E**	**D**	**D/E**	Interventions required to restore functionality to Durban Bay applicable to the specific important areas within the bay: • Protect baseflows to estuary to maintain mouth state and salinity profile. • Improve water quality (storm water management); • Reduce fishing effort, and • Partial restoration of estuarine habitat in upper reaches. The restoration of this area requires a TEC of a D and is immediately applicable.

ESTUARY	PES	REC	TEC	MITIGATIONS and Constraints to TO ACHIEVE THE TEC
uMgeni	**D/E**	**D**	**D**	Interventions required to achieve the REC/TEC: • Restoration of macrophytes: removal of alien plant species, replanting/ reintroduction with indigenous species (some of which is already occurring) • Wetland engineering (creation of new wetland habitats in close proximity to the uMngeni River banks,. • Implement flow allocation in an estuary friendly manner • Review the current breaching policy that only requires breaching after 2 to 3 weeks, this poses a risk to plant communities and birds. • Develop an Estuary Management Plan The above interventions can achieve the TEC which is immediately applicable. Any scenarios that result in a D TEC are acceptable.
Mhlanga	**D**	**B**	**B**	Interventions required to achieve the REC: • Restore baseflows to estuary to improve mouth state and salinity profile. • A significant improvement in water quality needed. • Partial restoration of estuarine habitat. If the existing pumping scheme comes into operation, it should achieve REC. The TEC is therefore set as the REC and is immediately applicable.
uMdloti	**D**	**C**	**D**	Interventions required to achieve the REC: • Restore baseflows to estuary to improve mouth state and salinity profile. • A significant improvement in water quality needed; and • Partial restoration of estuarine habitat. Further investigation need to be conducted to see to what extend the catchment quality can be improved to meet the REC. The importance rating should also be reviewed as it is likely that improvement to a C may not be required. The TEC that is therefore immediately applicable is set to maintain the PES. A scenario that includes more waste water to a specific limit must be investigated as this could achieve the TEC.
Tongati	**D**	**C**	**D**	Improvement is based on low confidence importance which cannot be refined (1 point). Based on this, the immediate applicable TEC is set as a D and all scenarios apart from Aiii will maintain the present state.
Mhlali	**C/D**	**B/C**	**D**	Interventions required to achieve the REC: • Reduce the nutrient input from the WWTW and catchment to control growth of reeds and aquatic invasive plants; • Remove the sugarcane from the Estuary Functional Zone (below 5 m contour); • Removal of vegetation from main river channel in upper reaches, including invasive aliens plants; • Ensure that the estuary is not artificial breached; and • Remove the old saltwater weir from middle reaches of system. Intervention without removal of WW will achieve a C, but not REC. However, infrastructure has already been constructed and licenses awared for an increases in waste (from .8 to 6 Ml/D) (Sc D). Any increase of waste from current is likely to result in a decreased (from PES) state as nutrients are the key factor in this estuary.
Bobstream	**B/C**	**B/C**	**B/C**	TEC set to maintain the PES and REC and is immediately applicable.
Seteni	**B/C**	**B/C**	**B/C**	TEC set to maintain the PES and REC and is immediately applicable.
Mvoti	**D**	**C**	**C/D**	Interventions required to achieve the REC: • Improvement of oxygen levels in the estuary, through for example, removal of the high organic content from the Sappi Stanger effluent; • Reduce the nutrient input from the catchment by 20%. • Remove the sugarcane from the Estuary Functional Zone (below 5 m contour). If the Sappi effluent is retained, but other interventions applied TEC = C/D. The proposed dam development scenarios will also achieve the TEC with the above measures. Limited increase in WW to this system is not likely to degrade it below a D as long as the system remains open. The TEC is set as a C/D which can be maintained with a new dam, possibly limited increases in waste water, and by addressing the interventions above without the removal or organic content from the SAPPI effluent.

ESTUARY	PES	REC	TEC	MITIGATIONS and Constraints to TO ACHIEVE THE TEC
Mdlotane	**B**	**A/B**	**A/B**	Interventions required to achieve the REC: • Improve water quality; and • Partial restoration of estuarine habitat. The TEC is set as an A/B.
Nonoti	**C**	**C**	**C**	TEC set to maintain the PES and REC and is immediately applicable.
Zinkwazi	**B/C**	**A/B**	**B**	Interventions required to achieve the REC/TEC: • Protect baseflows to estuary to ensure mouth state and salinity regime. • Improve water quality; and • Partial restoration of estuarine habitat. Measures should be put in place to improve to a B and the TEC of a B is immediately applicable. It is felt that achieving an A/B will required a scale of interventions that is difficult and with negative socio-economic implications.