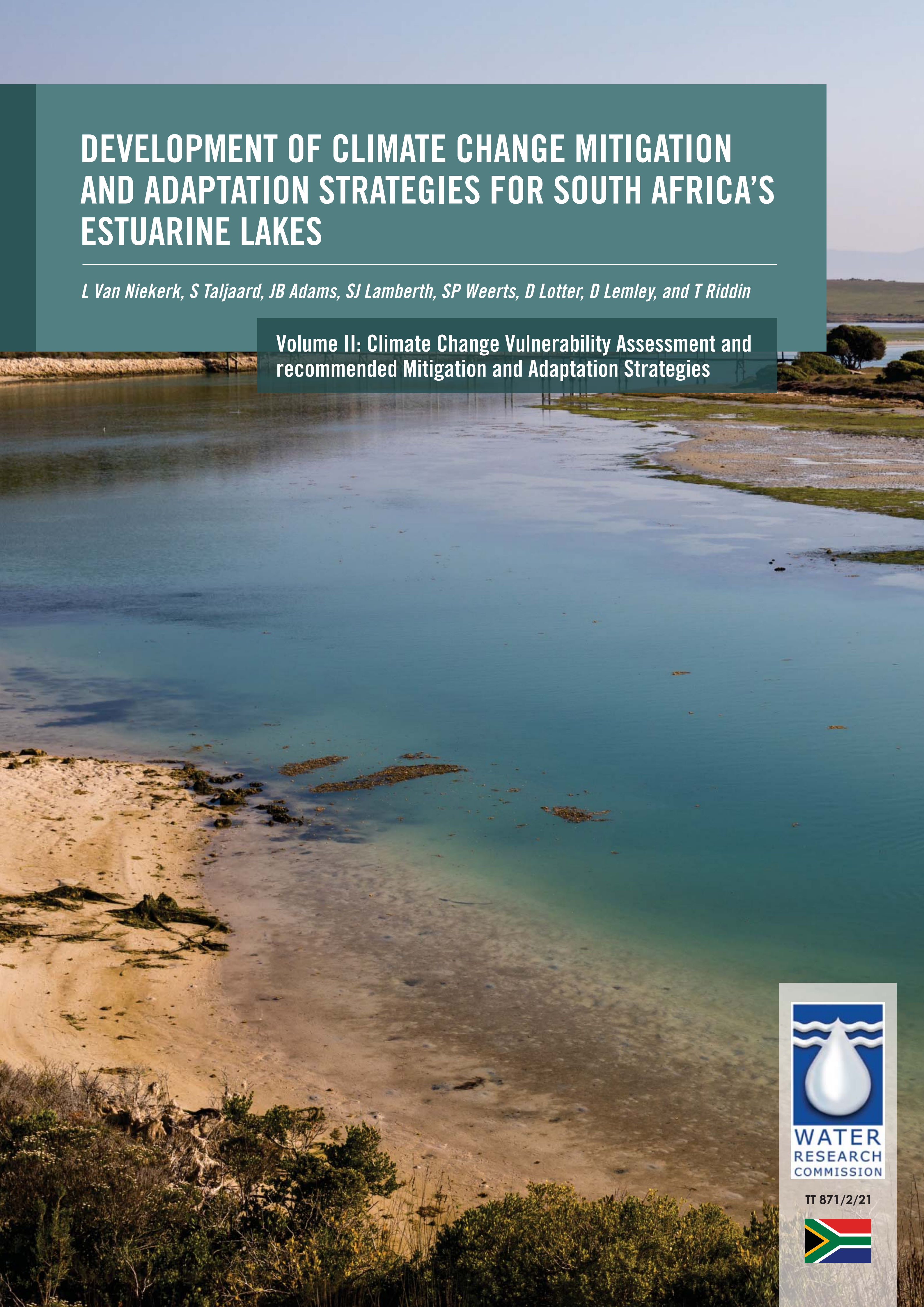

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L Van Niekerk, S Taljaard, JB Adams, SJ Lamberth, SP Weerts, D Lotter, D Lemley, and T Riddin

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WATER RESEARCH COMMISSION

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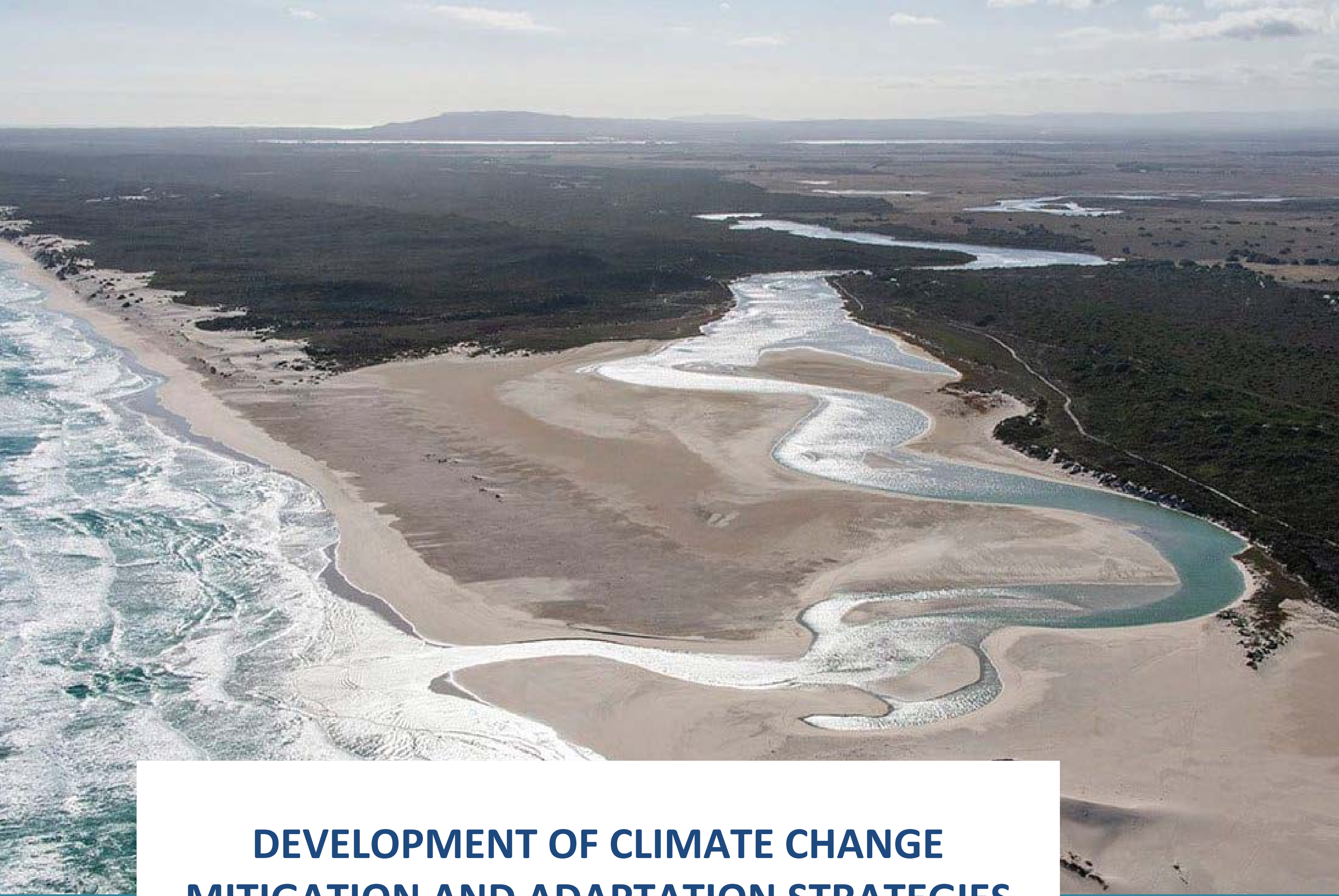

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CSIR

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4 Daventry Street, Lynnwood Manor, Pretoria
SOUTH AFRICA
0081

orders@wrc.org.za or download from www.wrc.org.za

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The researchers contributed to this report:

SPECIALIST	AFFILIATION
Dr L van Niekerk (Project leader)	CSIR, Stellenbosch
Dr S Taljaard	CSIR, Stellenbosch
Prof JB Adams	Nelson Mandela University
Dr S J Lamberth	Department of Environment, Forestry and Fisheries
SP Weerts	CSIR, Durban
Dr D Lotter	CSIR, Stellenbosch
Dr T Riddin	Nelson Mandela University

The following students and post-docs received funding/participated in this study:

STUDENT/POST-DOC	AFFILIATION
Dr D Lemley	Nelson Mandela University
V Tsipa	Nelson Mandela University
C Julie	Nelson Mandela University
J Wasserman	Nelson Mandela University

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REFERENCE GROUP MEMBER	AFFILIATION
Dr B Petja	Water Research Commission (Chairperson)
Dr N James	South African Institute of Aquatic Biodiversity (SAIAB)
Dr G Cilliers	Department of Forestry, Fisheries and Environment (DFFE)
Dr J Malherbe	Agricultural Research Council (ARC)
Dr S Mgquba	Department of Water and Sanitation (DWS)
N Madlokazi	Department of Forestry, Fisheries and Environment (DFFE)

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ATTENDEES	ORGANISATION
P de Villiers	Cape Nature
S Bachoo	Ezemvelo KZN Wildlife
F MacKay	Oceanographic Research Institute
Dr S Taljaard	Council for Scientific and Industrial Research
J Nhleko	Department of Forestry, Fisheries and the Environment
R Pillay	Department of Forestry, Fisheries and the Environment
C George	Western Cape Government (DEADP)
Dr N James	South African Institute for Aquatic Biodiversity
Dr S Lamberth	Department of Forestry, Fisheries and the Environment
Prof J Adams	Nelson Mandela University
Dr S Taljaard	CSIR
Dr L van Niekerk	CSIR

EXECUTIVE SUMMARY

Study Rationale

Estuaries form an interface between the land and sea and are strongly influenced by climatic, hydrological, and oceanic processes. Approximately 90% of South Africa's 290 estuaries are small, dynamic temporarily closed estuaries or seasonally driven predominantly open systems. However, a small percentage (< 4%) are large estuarine lake systems. While these estuarine lakes constitute a small percentage of systems numerically, collectively they cover more than 60% of South Africa's estuarine habitat. Undoubtedly these systems face future climate change pressures, but very few have been the focal point of long-term biophysical research that could inform climate change response strategies.

Estuarine lakes typically have large surface area:volume ratios, comparatively low mean annual runoff, and intermittent connectivity to the sea (e.g. mouths can close for extended periods), resulting in relatively low flushing rates and a larger influence of *in situ* processes on estuarine characteristics relative to other estuary types. They are therefore less resilient to change as their biophysical processes function over long timescales (i.e. annual to decadal cycles) and their re-setting mechanisms are relatively weak in comparison with the smaller systems. Thus, estuarine lakes are vulnerable to catchment land-use and development pressures. This also makes them vulnerable to the vectors of global change, including climate change (e.g. shifts in seasonal rainfall, intensification of drought cycles, increase in the occurrence of floods, as well as increasing temperatures and evaporation).

Ever-increasing anthropogenic impacts on estuarine systems already pose serious threats to the biodiversity and ecosystem services we derive from these ecosystems (e.g. carbon sequestration, flood attenuation, fisheries, provision of sustainable livelihoods, and eco-tourism). Climate change is likely to add to, and possibly exacerbate existing pressures, accelerating the degradation of estuaries. In fact, several estuarine lakes are already recognised as systems in transition from estuarine lakes to coastal lakes due to human interferences such as reduction in freshwater inflows, barriers at their outlets and low-lying development. Timeous planning to mitigate and adapt to climate change is critical for sustaining these valuable ecosystem assets. Management and climate change strategies for these systems may require unique and dedicated interventions to ensure future resilience in the face of ongoing change.

Climate change is a measurable reality and South Africa is especially vulnerable to its impacts. Key drivers of change have been identified as: modification of terrestrial climatic (e.g. temperature and rainfall) and hydrological processes; changes in the oceanic circulation; ocean acidification; sea-level rise; increased sea storminess. However, this study focussed specifically on the critical *terrestrial climatic and hydrological vectors associated with climate change*, and their anticipated effects on the key processes in the estuarine lakes of South Africa, as well as the key biotic responses, and their consequences on the ecological health of these valuable systems.

Study Area

Thirteen estuarine lakes systems occur in four biogeographical regions along South Africa's coast, namely Verlorenvlei, Zeekoevlei, Klein, Bot/Kleinmond, Heuningnes, Touw/Wilderness, Swartvlei, uMhlathuze, St Lucia, uMgobezeleni and Kosi (Figure 1). This study focussed on the lakes systems that were still retaining natural functionality.

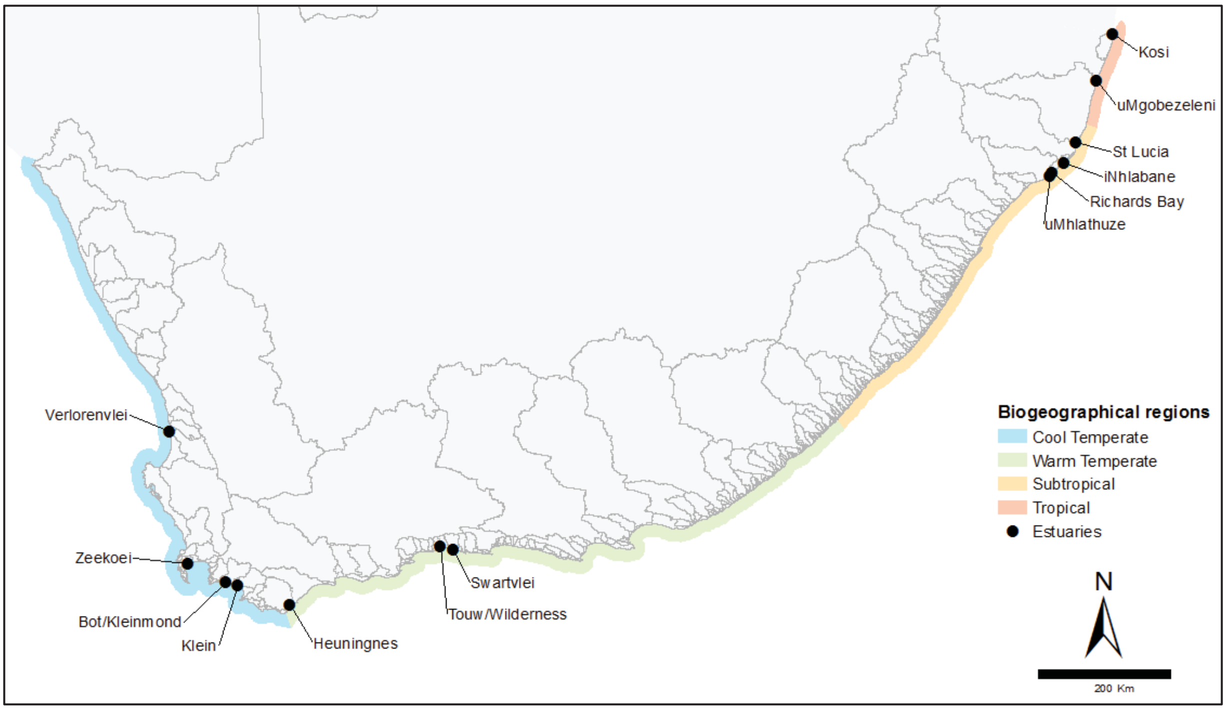

Figure 1: Location of South Africa's Estuarine Lakes

Estuarine lake connectivity ranges from near-permanently open (e.g. Kosi), through systems that are open on annual time scales (e.g. Swartvlei), to predominantly closed (e.g. Bot/Kleinmond and St Lucia). The extent and duration of marine connectivity influence the salinity regime in these lake systems, which can range from fresh to hypersaline. Estuarine lakes have unique system-specific characteristics relating to connectivity, morphological complexity, and salinity regimes. Connectivity to the sea can occur via constricted inlet channels, fully functional estuaries, or in some cases, large estuarine lakes can be directly connected to the sea with no clearly defined channels (e.g. Klein). Most lakes are brackish to fresh, but some show a tendency to become hypersaline during dry periods (Table 1). This complexity is further compounded by the occurrence of a wide range of abiotic states that are observed in estuarine lake systems over long timescales. In total, seven open and five closed abiotic states were recognised in the lakes systems that largely maintain natural functionality. Table 2 provides a summary of typical abiotic conditions associated with each of these states, focussing on mouth state, salinity regime, and water levels as key distinguishing characteristics. While there are differences amongst lakes in the states as a result of the interplay between bathymetry and freshwater input, some common features could be grouped into the 12 states.

The low flushing rates and intermittent connection to the sea make South Africa's estuarine lakes vulnerable to catchment and development pressures and contribute to more than 84% of estuarine lake habitat already being in a poor condition from catchment and development pressures. This reduces their ability to provide key ecosystem services such as flood regulation, nutrient cycling, nursery habitat, and has compromised recreational and tourism benefits derived from these systems.

Catchment development is increasing, resulting in reduced inflow (either surface or groundwater) into many lakes, with Kosi being a good example. South Africa's estuarine lakes are already subject to extensive anthropogenic pressures that go beyond the influence of climate change. The key pressures acting on each of the country's estuarine lake systems are indicated in Table 2.

Table 1: Description of generic abiotic states occurring in South Africa's estuarine lake systems

ESTUARY	OPEN ABIOTIC STATES							CLOSED ABIOTIC STATES					
	Fresh	Marine/ Fresh	Gradient	Marine/ Brackish	Marine	Marine/ Hypersaline	Hypersaline	Fresh	Brackish	Gradient	Marine/ Brackish	Marine	Hypersaline
Verlorenvlei	●							●	●				
Zeekoevlei	●												
Bot/Kleinmond					●			●	●			●	●
Klein	●		●		●				●			●	
Heuningnes	●		●		●		●		●				●
Touw/Wilderness	●		●					●	●		●		
Swartvlei	●		●						●	●		●	
St Lucia/uMfolozi					●	●	●	●		●			●
iNhlabane	●							●					
uMhlathuze			●		●								
uMgobezeleni	●							●					
Kosi	●	●	●	●							●		

ABIOTIC STATE		STATE DESCRIPTION
OPEN	Fresh	Mouth is open and the system is (nearly) fresh throughout. Average water levels. Can have elevated water levels due to flooding for short periods.
OPEN	Marine/ Fresh	Mouth is open with limited salinity penetration in lower reaches (estuarine zone), while lakes are generally fresh. Average water levels.
OPEN	Gradient	Mouth is open and full salinity gradient is observed throughout the system. Average water levels.
OPEN	Marine/ Brackish	Mouth is open and salinity varies from marine (near mouth) to brackish. Average water levels.
OPEN	Marine	Mouth is open and a marine salinity regime is observed throughout the system. Average water levels.
OPEN	Marine/ Hypersaline	Mouth is open and the salinity regime varies from marine to hypersaline in parts of the system. Average to low water levels. Some parts of the system may become isolated.
OPEN	Hypersaline	Mouth is open and the majority of lake system is hypersaline. Very low water levels.
CLOSED	Fresh	Mouth is closed and the system is nearly fresh throughout. High to very high-water levels.
CLOSED	Brackish	Mouth is closed and the system is brackish throughout. High water levels.
CLOSED	Gradient	The mouth is closed, and partial longitudinal salinity gradient is observed. High water levels.
CLOSED	Marine/ Brackish	Mouth is closed and salinity regime varies from marine to brackish in parts of the system. Low water levels.
CLOSED	Marine/ Hypersaline	Mouth is closed and salinity regime varies from marine to hypersaline in parts of the system. Very low water levels, some littoral habitats may be exposed, or parts of lakes isolated from larger system.

Approach and Methods

An ensemble of high-resolution climate model simulations of present-day climate and projections of future climate change over South Africa has been performed as part of the "Green Book" project. Scenarios were developed for Representative Concentration Pathways 4.5 and 8.5 (RCP 4.5 and 8.5). The simulations span the period 1960-2100, with the period 1960 to 1990 representing the baseline, 2021-2050 (mid-future) and 2070-2099 (far-future). RCP4.5 is a high mitigation scenario, whilst RCP8.5 is a low mitigation scenario.

Since measured inflow data into estuaries are typically not available due to sparse observation networks, rainfall-runoff models were used to simulate hydrological data. No new hydrological modelling was undertaken as part of this study, and available simulated data for Reference and Present (i.e. accounting for existing anthropogenic pressures, but not climate change pressures) were sourced from the historical studies. Given that the climate model ensemble outputs do not span the required >70-year simulation periods, available simulated monthly present inflows were scaled according to the predicted relative shifts in monthly rainfall for the catchments and directly onto the estuaries using a delta-change approach moderated by published literature.

Table 2: Key anthropogenic pressures on South Africa's Estuarine Lakes

SYSTEM	PRESSURE																
	Overall Pressure Level	Reduced base flows	Reduced floods	Reduced groundwater input	Poor water Quality: Stormwater/floodplain drainage	Poor water quality : River water quality	Poor water quality: WWTWdischarges	Reduced connectivity/ hydrodynamic functioning	Artificial mouth management/breaching	Loss/degraded riparian areas/ wetlands	Alien vegetation	Grazing (sheep, cattle, goats)	Mangrove harvesting	Recreational activities impacting birds	High fishing pressure/ bait collection	Alien or translocated fish	Mining
Verlorenvlei	H	●		●		Agric		●	●	●		●			●*	●	
Zeekoevlei	VH	●			Urban	Urban	●	●	●		●			●		●	
Bot/Kleinmond	M	●				Agric	●		●		●			●	●	●	
Klein	M	●			Urban	Agric	●		●		●			●	●*	●	
Heuningnes	H	●			Agric	Agric		●	●	●	●	●		●	●	●	
Touw/ Wilderness	M	●						●	●		●			●	●	●	
Swartvlei	L	●				Agric		●	●		●			●			
uMhlathuze	VH	●	●		Agric	Agric/ Urban		●	●	●	●		●	●	●*	●	●
iNhlabane	VH	●	●					●		●	●	●			●*		●
St Lucia/uMfolozi	H	●	●					●			●		●		●*		
uMgobezeleni	M			●	Agric/ Urban			●	●				●		●*		
Kosi	L	●		●							●		●		●*		

**Illegal gillnetting impacting nursery function & food security*

An ecosystem-based approach was adopted whereby conceptual models, of typical biophysical patterns in each of the estuarine lakes were constructed from the generic seven open and five closed abiotic states. These conceptual models distinguished between dominant open-closed cycles, and drought and flood events (Figure 2).

Condition (% of natural)	≥91%	90-75	75 - 61	60 - 41	40-21	≤20
Ecological condition Category	A Natural	B Largely natural / few changes	C Moderately modified	D Largely modified	E Highly degraded	F Extremely degraded
Ecological State	NATURAL	NEAR NATURAL	MODERATE	HEAVILY	SEVERE/CRITICAL	
Functionality	Retain Process & Pattern (Representation)		Some loss of Process & Pattern	Significant loss of Process & Pattern	Little remaining Process & Pattern	

Table 3: Estuary health scoring system indicating the relationship between the six Ecological Categories and the loss of ecosystem condition and functionality.

To ensure alignment with existing estuarine health assessments of South African estuaries (e.g. NBA 2019, Table 3), the Estuary Health Index (EHI), developed under the National Water Act was used to integrate assessment results. The index considers an array of abiotic and biotic components. For this study, the abiotic components were simplified to three indicators, namely hydrology, hydrodynamics (mouth state and water level), and water quality (including salinity and nutrients), while the biotic indicators were simplified to three, namely microalgae, macrophytes and fish. The indicators were each categorised from natural (A) to critically modified (F) based on expected changes under each of the climate change scenarios.

Vulnerability to Climate Change

One of the key findings that emerged from the Estuarine Lake Vulnerability Assessment was that the maximum potential shift in estuarine state varied between 9% and 22% from present functionality under the RCP 4.5 and RCP 8.5 Climate scenarios (see Figure 2). In all cases, the maximum degree of change was induced by the RCP 8.5 Far-future Scenario. RCP 8.5 Far-future conditions were *very likely* to cause major impacts on estuarine connectivity and associated functioning, with related impacts on biotic productivity and composition.

The responses to the RCP 4.5 scenarios were generally grouped around the present state, with some scenarios even representing a shift towards natural conditions because of increased freshwater input in the mid-future scenarios. In most cases, the estuarine lakes were somewhat buffered against slight shifts in connectivity, water levels or salinity regimes as they are generally weekly connected to the sea and subjected to long periods of closure.

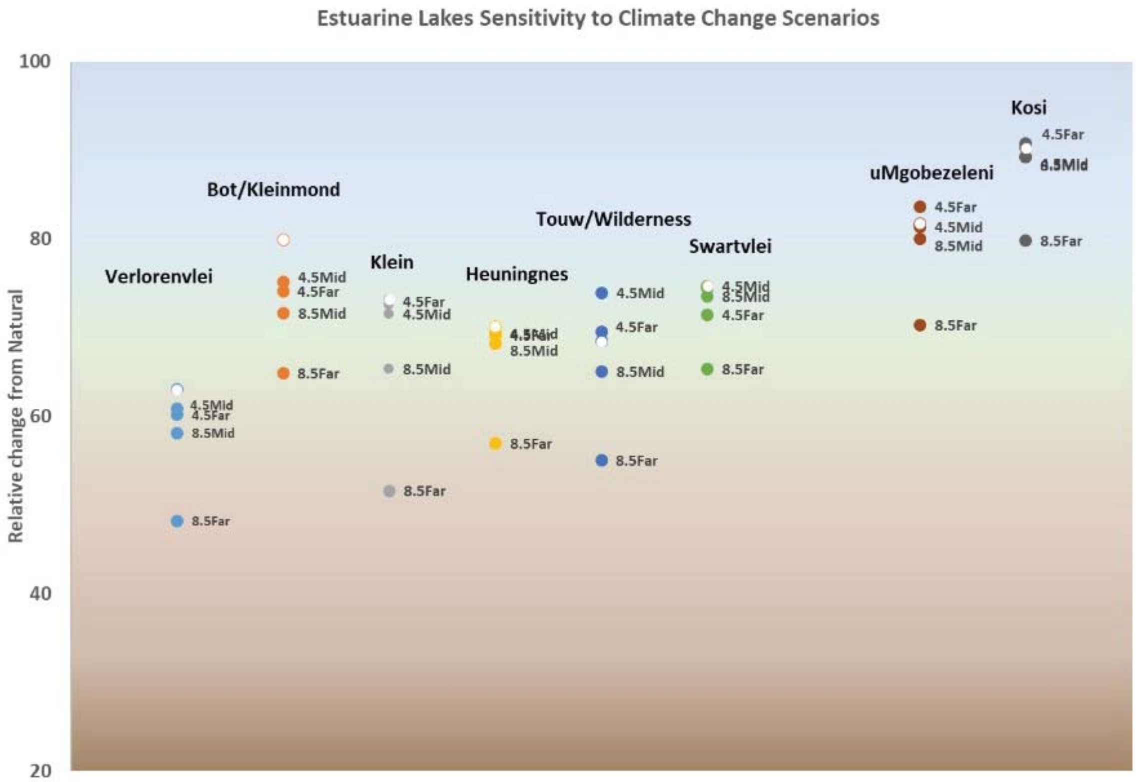

Figure 2: Relative sensitivity of the estuarine lakes of South Africa to RCP 4.5 and RCP 8.5 Climate Change Scenarios

Climate Change versus Anthropogenic Change

An important finding of the assessment was that in all systems assessed, except for Kosi, anthropogenic-induced change exceeded climate-induced shifts in estuary functioning (see Figure 3), highlighting the degree of transformation the estuarine lakes have already experienced. In the case of Kosi (near-natural in its present state), the relative shifts were similar in magnitude.

Given that estuarine lakes are nutrient sinks that cannot be flushed by floods like other systems, the present water quality was a good predictor of future resilience, with enriched systems more likely to decline further in condition under hotter and/or drier future conditions. For example, the Klein that receives continuous wastewater input, is expected to become significantly more degraded under warmer climatic conditions. Increased mouth closure, lower water levels and warmer temperatures are *very likely* to drive an increase in harmful algal blooms and concomitant lower oxygen levels. Thus, v*ery likely* to increase the occurrence of fish kills in the system. In contrast, Kosi with near-natural water quality, mostly only responded to shifts in water levels and salinity regimes.

Relatively shallow lake systems, such as Verlorenvlei, Bot/Kleinmond and Heuningnes tend to be more vulnerable to the impact of reduced flows and/or the impact of drought conditions. In this type of system, event-scale droughts tend to dry out a large part of the lake beds and surrounding estuarine vegetation. Depending on the degree of marine connectivity, this type may also develop extreme hypersalinity in some parts of the system. This effect could be further amplified if the system was already subjected to enrichment, with harmful algal blooms often associated with this type of conditions. In some systems like Verlorenvlei, blue-green algal blooms are associated with fish developing lesions during the breeding season. While in Botvlei and Soetendalsvlei (Heuningnes) drought conditions are associated with extensive reed die-off due to low water levels and hypersalinity.

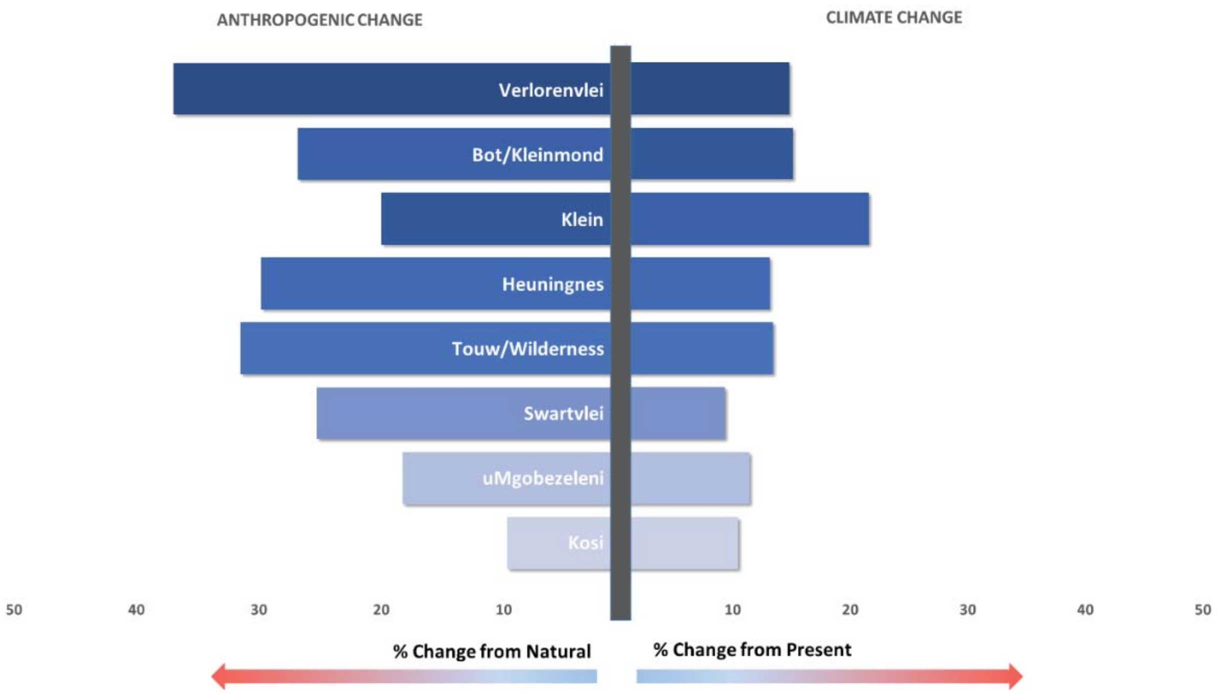

Figure 3: Graphic representation of the degree of anthropogenically-induced versus climate-induced change in the Estuarine Lakes of South Africa

Recommended Mitigation and Adaptation Strategies for Estuarine Lakes

Mitigation is defined as “human intervention to reduce the sources or enhance the sinks of greenhouse gases”, while climate change adaptation focuses on actions to face the consequences of climate change. Adaptation thus refers to changes in ecological, social, or economic systems because of existing or anticipated climatic stressors, as well as their ramifications or consequences.

The study showed that **we have strong legislative measures (“good tools in the toolbox”)** to support the rollout of climate change mitigation and adaptation strategies for estuarine lakes, but we **need to “sharpen” them and increase their efficacy** (e.g. implementation and compliance). Table 4 list the key recommendations

Table 4: Recommended mitigation and adaptations strategies to ensure Climate Change resilience of South Africa's Estuarine Lakes

Mitigation Strategies to protect estuarine lakes and blue /teal carbon habitats
Use existing international and national processes and structures to protect all remaining blue and teal carbon habitats in the Estuary Functional Zone of estuarine lake systems (in agreement with the United Nations Framework Convention on Climate Change and the Paris Agreement). Follow an ecosystem-based approach that protects abiotic and biotic processes and ensure functional estuaries. Increase protection through a combination of enhanced formal protection (e.g. parks) and initiating less formal approaches such as implementing Other Effective Conservation Measures at lower priority / smaller estuaries. Identify and protect ecologically significant ("critical") areas such as nursery grounds, feeding grounds, and areas of high species diversity and abundance to ensure that supporting biotic processes and feed-back loops are retained. Clearly define land ownership within the EFZ area so that state-owned land can be proclaimed as protected, or to identify as areas suitable for stewardship. Develop a land acquisition programme – purchase coastal land that is damaged or prone to regular flooding and use it for protection of estuarine habitats (e.g. blue and teal carbon) and estuarine processes.
Mitigation Strategies to restore estuarine lakes and blue /teal carbon habitats
Use existing international and national processes and structures to restore all disturbed blue and teal carbon habitats in the Estuary Functional Zone of estuarine lake systems. Develop a national restoration programme for estuaries with clear restoration targets that are integrated into provincial and local coastal management programmes. Blue and teal carbon habitats and water quality should be a key focus of such a restoration programme. Conserve and restore the structural complexity and biodiversity of vegetation in salt marshes, seagrass, and mangroves of estuarine lakes.
Land-use and Instream Infrastructure adaptation strategies
Commit to active retreat below the 2.5 m MSL to allow natural processes to re-establish critical habitats under future climate conditions. Discourage all developments and future land-use change below the 5 m MSL contour. Incorporate consideration of climate change impacts into all planning for new infrastructure. Develop overarching policies/strategies and reporting mechanisms that will ensure the persistence of blue and teal carbon ecosystems and avoid future losses and maintain CO_2 sinks, focussing on land use practices. Return disturbed land to natural process to allow for wetland accretion (accommodation space). Develop a land-exchange programme to reclaim 'accommodation space'. Acquire all fallow and agricultural land below the 2.5 m MSL contour. Avoid further habitat degradation and soil disturbance within the EFZ by elevating it as a listed activity under the NEMA EIA Regulations (2014), i.e. list the clearing/infilling of estuarine habitat within EFZ under Listing Notice 1, currently in Listing Notice 3. Avoid all mining-related activities within EFZs as these have irreversible impacts on carbon storage and sequestration. Develop a policy that does not permit mining for sand, diamonds, minerals, or establishment of salt works within a 1 km buffer of the EFZ. Reduce the impact of boating activities.
Flow modification adaptation strategies
Protect /restore freshwater inflows to the estuarine lakes of South Africa through freshwater flow allocations ('Reserves') targeted at the maintenance of critical estuarine processes and carbon ecosystems. Assessments should explicitly incorporate requirements of blue and teal carbon habitats in the determination of 'Reserves' and 'Resource Quality Objectives' gazetted by DWS. Estuaries with significant blue carbon habitats (and/or key teal carbon habitats, i.e. swamp forest) should have medium to high confidence 'Reserves' determinations, including drought allocations. This should be supported by increased compliance monitoring of the implementation of Ecological Water Requirements. Clear invasive alien plants in catchments to restore critical base flows and freshwater input to estuaries. Prevent over-abstraction and lowering of groundwater table and ensure all groundwater abstraction activities are licensed and do not impact estuaries. Develop and implement a policy to phase out/ not permit commercial forest plantations within a 2 km buffer of EFZ to protect groundwater table. Do not permit mining within EFZ given the high risk of disturbance of the groundwater table and additional risk of wind-blown dust and pollution. Evaluate mining within 2 km radius of an estuary to ensure mitigation of impacts to groundwater table.
Pollution adaptation strategies
Improve the overall water quality of estuarine lake systems to enhance resilience to future warmer and drier conditions. Estuarine lakes are nutrient sinks it is thus critical that all wastewater discharges be removed from these systems. During the phasing out process, reduce effluent and improve water quality from existing wastewater treatment works, with the intent of recycling or reusing effluent in the long term. Control/reduce the impact of agricultural runoff on estuarine lakes. Develop agriculture best practice guidelines and generate awareness of the impact of over fertilisation on wetlands and estuaries. Control and discourage the use of herbicide and pesticide inputs in and around estuaries. Control/reduce the impact of stormwater runoff on estuarine lakes.
Over-exploitation adaptation strategies
Reduce fishing pressure to ensure a self-maintaining population that is resilient to future climate conditions. Increase formal protection of estuarine living resources, e.g. through the establishment of Marine Protected Areas, closed area zonation, IUCN Red Listing of Threatened Species. Institute catch/gear control measures to ensure sustainable fishing levels. Invest in effective compliance measures, e.g. remote tracking systems, human resources. Develop estuarine resource monitoring programmes that can feed into management strategies and country-level indicators. Create public awareness of the risk over-exploitation poses to estuary function and societal benefits. Control/reduce fishing effort levels in Kosi by implementing an existing fisheries management plan for the Kosi Fish traps. Reduce pollution pressure to increase resilience to droughts and periods of low connectivity to the sea.
Artificial Breaching adaptation strategies
Commit to active retreat below the 5 m MSL to allow natural processes to re-establish critical habitats under future climate conditions. Discourage all developments and future land-use change below the 5 m MSL contour. Develop a National Artificial Breaching Protocol for estuaries. Ensure that conservative flood line assessments are in place that highlights the impact of 1:100 year flood event under future climate conditions and incorporate into municipal Integrated Development Plans and local Estuary Management Plans. Prohibit the development of new hard infrastructure (especially access roads) within the EFZ. Development Mouth Management Plans nested within the objectives of relevant Estuary Management Plans. Where artificial breaching is deemed needed, develop a Maintenance Management Plan to achieve the highest possible breaching level and guide breaching practices. Return agricultural land to natural process to allow for wetland accretion (accommodation space). Engage with National and Provincial Disaster Risk agencies to highlight the risk poor breaching practices pose to estuarine/ carbon ecosystems. Develop a land acquisition programme – purchase coastal land that is damaged or prone to regular flooding and use it for the protection of estuarine habitats (e.g. blue and teal carbon) and processes.
Invasive alien plants **adaptation strategies**
Manage/eradicate invasive alien plant species in estuaries and their associated catchments. Develop protocols/procedures for early detection, risk assessment, and management of invasive alien plant species. Prevent the introduction of new species through agriculture or aquaculture. Develop protocols for monitoring the spread of invasive alien plant species in estuaries. Introduce nutrient control strategies to control growth. Develop long-term catchment clearing programmes (e.g. in collaboration with Working for Water / Wetlands). Create

public awareness among civil society and researchers of the risk invasive species pose to estuaries and the need to clean gear and boats. Invest in the research of alien invasive species.
Alien invasive or extralimital fish and invertebrate species adaptation strategies
Manage/eradicate alien invasive or extralimital fish and invertebrate species in estuaries or their associated catchments. Prevent the introduction of new species through agriculture or aquaculture. Develop protocols/procedures for early detection, risk assessment, and management of invasive alien fish and invertebrate species. Prevent the establishment of aquaculture facilities near estuarine lake systems. Control aquarium trade and aquaculture introduction pathways through permitting system(s) and detailed EIA studies. Investigate the option of a controlled fishery to remove larger aliens/translocated fish. Create public awareness among civil society and researchers of the risk invasive species pose to estuaries and the need to clean gear and boats. Invest in research of invasive alien species to develop an understanding of the risk they pose to estuarine functionality and ecosystem services. Prevent the discharge of ballast water in ports (especially those in or near estuaries).

There is a need to sharply increase our efforts towards estuary protection, especially for those systems that support extensive blue and teal carbon habitats to ensure ongoing contribution to South Africa's climate mitigation strategies. **Adaptation strategies need to be developed within a broad, holistic socio-ecological systems context especially in areas governed by Traditional Authorities**. Strategies need to be developed across land- and seascapes – where there are many competing interests to be considered. The impacts of Climate Change need to be embedded within the context of a wide array of existing stressors and need to consider the multiple ways in which any action can impact other facets of the socio-ecological system at a range of temporal and spatial scales.

The **focus should be on the whole-of-the-system and long-term outcomes**. The maximum public benefit accrues from maintaining and restoring resilient ecosystems that provide healthy human living environments, support optimal biodiversity and underpin robust and productive fisheries. This is best achieved by focussing on long-term transformative outcomes at a whole-of-system scale that provides on-going benefits by enhancing resilience and reducing vulnerability into the future. **Key to this is generating awareness and protecting the complex natural cycles (i.e. drought-flood/open-closed) that occur in estuarine lakes at decadal temporal scales.**

Opportunities need to be investigated to "**retrofit" current approved resource uses to accommodate future climate change requirements** to ensure the protection of estuaries moving forward (e.g. drought flow allocations in DWS Classification).

'Managed Retreat' should be actively encouraged to allow estuarine processes (and associated blue and teal carbon habitats) to re-establish under a changing climate. The passive "do nothing/wait and see" approaches will have immense ecological impacts with cascading implications for critical ecosystem services such as carbon sequestration and nursery function.

Future Research Needs

The development of the abiotic and biotic conceptual models as an explicit step in the vulnerability assessment method allowed for the identification of commonalities and differences across estuarine lake systems and assists with bridging data gaps and extrapolating findings. The selected assessment approach was sensitive to change and allowed for the detection of climate-induced shifts in estuary function and productivity. It is thus recommended that **similar conceptual models be further developed for other types of estuaries**, e.g. Estuarine Bays, Fluvially dominate estuaries, Predominantly open). The generic identification of abiotic states and associated conceptual models also have wider application in flow requirement studies and estuary condition assessment.

More effort should be made to develop coupled rainfall-runoff yield models specifically geared to better resolve climate change projections on river flows. Given the high degree of flow modification many estuary catchments are subjected to at present, it is not appropriate to merely superimpose climate change impacts on natural flow regimes. The impact of Climate Change needs to be reflected in conjunction with present levels of use (i.e. exploitation). Given the importance of evaporation in the development of water balance models for large water bodies such as the estuarine lakes, ongoing efforts in this regard should be supported. Groundwater is often ignored in these assessments, but under a hotter climate, this relative stable input parameter may change and needs to be considered in future studies as it plays a key role in maintaining lake levels in drought conditions. Given that many of the tools utilised in the estuarine lake vulnerability assessment have been set up and automated, e.g. estimating a change in mouth state, water quality and microalgae; should more detailed runoff, evaporation rates, or groundwater input datasets become available; it is recommended that the predicted abiotic state shifts be re-evaluated, and if need be, the vulnerability assessment workshop repeated.

The impact of droughts is of special concern. More effort should be made to develop measures that reflect the increase in the occurrence and duration of droughts explicitly (some broad measures were included in this estuarine lake study). It is also recommended that all estuary conceptual models in future explicitly develop a ‘drought state’ (even if only based on theoretical understanding and/or extrapolated from similar systems). This will assist with developing a more informed understanding of the impact and risk associated with severe droughts on estuaries moving forward.

The impact of increasing temperatures on primary producers (e.g. algae and macrophytes) is not well understood and thus poorly coupled to predictions of change, especially under the RCP 8.5 far-future scenarios. This results in a low confidence assessment. More research needs to be done to inform predictions. Similarly, more research is needed on the impact of elevated temperatures on estuarine fish and the protection deeper refugia offer in the face of rising temperatures.

The concomitant impact of sea level rise was not included in this estuarine vulnerability assessment. It is recommended that where detailed topographical (e.g. LiDAR) information is available more systematic evaluation be undertaken of the impact of sea level rise on key estuarine habitats. Finally, it is recommended that the approach adopted in this study for estuarine lakes be expanded to other estuarine types in South Africa (e.g. predominantly open, and temporarily closed systems) to assess vulnerability to climate change at the country-level for all estuarine types.

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LIST OF SYMBOLS AND ABBREVIATIONS

BAS	Best Attainable State
CARA	Conservation of Agricultural Resources Act (No 43 of 1983)
Carbon Tax Act	Carbon Tax Act (No 15 of 2019)
CD	Chief Directorate
CMA	Catchment Management Agency
CPUE	Catch-per-unit-effort
CSIR	Council for Scientific and Industrial Research
CSIR	Council for Scientific and Industrial Research
DEA	Department of Environmental Affairs
DFFE	Department of Forestry, Fisheries and Environmental
DIN	Dissolved Inorganic Nitrogen
DIP	Dissolved Inorganic Phosphate
DO	Dissolved Oxygen
DRP	Dissolved Reactive Phosphate
DRS	Dissolved Reactive Silicate
DWA	Department of Water Affairs (now DWS)
DWAF	Department of Water Affairs and Forestry (now DWS)
DWS	Department of Water and Sanitation
EFR	Ecological Flow Requirement
EFZ	Estuary Functional Zone
EHI	Estuarine Health Index
EMP	Estuarine Management Plan
ERC	Ecological Reserve Category
EWR	Ecological Water Requirement
H	High
ICM	Integrated Coastal Management Act (No 24 of 2008)
IDP	Integrated Development Plan
L	Low
M	Medium
MAR	Mean Annual Runoff
Maritime Safety Authority Act	Maritime Safety Authority Act (No. 5 of 1998)
MCM	Million Cubic Metres
MCM/a	Million Cubic Metres per annum
Minerals Act	Mineral and Petroleum Resources Development Act (No. 28 of 2002)
MLRA	Marine Living Resources Act (No. 18 of 1998)
MPA	Marine Protected Area
MSL	Mean Sea Level
Municipal Systems Act	Local Government: Municipal Systems Act (No. 32 of 2000)
National Buildings Regulations	National Buildings Regulations and Building Standards Act (No. 103 of 1977)
NBA	National Biodiversity Assessment
NEMA	National Environmental Management Act (No. 107 of 1998)
NEMBA	National Environmental Management: Biodiversity Act (No 10 of 2004)
NEMP	National Estuarine Management Protocol
NEMPA	National Environmental Management: Protected Areas Act (No. 57 of 2003)
NMU	Nelson Mandela University
NWA	National Water Act (No. 36 of 1998)
NWRS	National Water Resources Strategies
PES	Present Ecological Status
RDM	Resource Directed Measures
REC	Recommended Ecological Category
REI	River-Estuary Interface
RQO	Resource Quality Objectives
SA	South Africa
SPLUMA	Spatial Planning and Land Use Management Act (No. 16 of 2013)
VH	Very high

VL	Very low
Waste Act	National Environmental Management: Waste Act (No. 59 of 2008)
Water Services Act	Water Services Act (No. 108 of 1997)
WMA	Water Management Area

1. INTRODUCTION

1.1 Aim and Objectives of this Study

This Water Research Commission study aims to develop **Climate Change mitigation and adaptation strategies focussing on South Africa's estuarine lake systems** for consideration in resource allocation, planning and management and inclusion in related government policies (e.g. prioritising estuarine lakes Water Resource Classification under the National Water Act). This was achieved through the following tasks:

1. Literature review on South Africa's estuarine lake systems;
2. Down-scale global model results of Climate Change scenarios;
3. Develop conceptual (biophysical) models for estuarine lakes;
4. Conduct Climate Change Vulnerability Analysis of estuarine lakes; and
5. Prepare Climate Change Mitigation and Adaptation Strategies for South Africa's estuarine lakes (Deliverable 5 – Workshop Proceedings).

This document represents the final report for this study, consolidating the outputs across all deliverables.

1.2 Expected influence of Climate Change on Estuarine lakes

Climate change is a measurable reality and South Africa is especially vulnerable to its impacts (DEA 2010, 2013), including estuarine lakes. Recently estuaries have been the focus of several comprehensive Climate Change Vulnerability Assessments (Day et al. 2008, 2011, Gillanders et al. 2011, Newton et al. 2014). Key drivers of change have been identified as (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):

- **Modification of terrestrial climatic and hydrologic processes (the focus of this study)**
- Changes in oceanic circulation;
- Ocean acidification;
- Sea level rise; and
- Increased sea storminess.

1.2.1 Modification of terrestrial climatic and hydrologic processes

While global *temperatures* have increased by about 0.8°C over the last century in response to the enhanced greenhouse effect, recent analyses indicate that South Africa has been warming at more than twice the global rate over the past five decades (Jones et al. 2012; Kruger and Sekele 2012; MacKellar et al. 2014; Engelbrecht et al. 2015; Kruger and Nxumalo 2016). Climate change in southern Africa will change precipitation patterns, which in turn will affect the quantity, quality, and seasonality of hydrological flows to estuaries and exacerbate existing human modifications of river inflows (Alber 2002; USEPA 2009; James et al. 2013, Bunn 2016; SAWS 2017). Climate change may also manifest through changes in the frequency of severe weather events. On the subtropical and warm temperate coasts, the combination of generally wetter conditions and increased intensity of precipitation events will result in increased runoff. An anticipated decrease in rainfall in the cool temperate region, with a minor increase in inter-annual variability, will result in a decrease in freshwater flows and an intensification of the wet-dry cycles, as shifts in precipitation are strengthened in the hydrological cycle in most instances (Hewitson and Crane 2006; Engelbrecht et al. 2009; 2011; Lumsden et al. 2009, James et al. 2013). An increase in extreme events is projected for the Southern, Eastern Cape and KwaZulu-Natal coasts during spring and summer, with a reduction projected for winter and autumn (e.g. Christensen et al. 2007; Engelbrecht et al. 2009; Engelbrecht et al. 2013).

While the focus in this study is on *terrestrial climatic and hydrological vectors of climate change,* there have been complementary studies in South Africa that provides greater insight on the potential effects of ocean driven vectors of climate change. This chapter provides a brief overview of such assessments for consideration in the proposed climate change mitigation and adaptation strategies presented in Chapter 6.

1.2.2 Changes in Ocean Currents

South Africa's coastal climate is strongly influenced by *two large scale ocean currents*. The Agulhas Current, flowing along the east coast, is the strongest western boundary current in the southern hemisphere (Beal et al. 2011). 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 will also influence the ecosytems of the Benguela Current including its coastal climate, thus impacting on river run-off and estuarine dynamics. Overall, a stronger Agulhas Current transport has been predicted due to global warming, which will affect inshore upwelling cells as well as shelf-edge upwelling which in turn may impact coastal and estuarine ecology along South Africa's coast (Backeberg et al. 2012). On the west coast, the Benguela Current is likely to intensify and lead to more intense upwelling due to the acceleration of the Supergyre (Saenko et al. 2005; Roemich 2007). How robust the upwelling trends in the Benguela Upwelling System will remain unclear (Hagen et al. 2001; Lutjeharms et al. 2001; Bakun et al. 2010; Rouault et al. 2010; Dufois and Rouault 2012).

1.2.3 Sea Level Rise

Present South African *sea level rise* rates are estimated as: west coast +1.9mm per annum, south coast +1.5 mm per annum and east coast +2.7mm per annum (Mather et al. 2009; Mather et al. 2019). The effect of sea level rise, and related increase in tidal prisms, will be less apparent along the KwaZulu-Natal coastline, where except for estuarine lakes and bays, most estuaries are perched. However, it will be more apparent in estuarine systems along the Southern and Western Cape characterised by more extended coastal floodplains.

1.2.4 Increased Storminess

South Africa is a wave-dominated coast sensitive to *increased sea storminess*. 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 timescale (Guastella and Rossouw 2012; Harris 2010). Preliminary findings indicate that there may be long-term trends in the regional metocean climate (Theron 2007). Mori et al. (2010) 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. 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. 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.

1.2.5 Ocean Acidification

Ocean acidification will ultimately result in a 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 considered when the effects of ocean acidification are considered. Natural fluctuation in pH may play a large role in the development of resilience in estuarine biological populations (Sorte and Hofmann 2004). On the other hand, it may combine with the effects of ocean acidification to produce more extreme events that result in an even greater impact on the biota (Hofmann et al. 2011). 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.

1.2.6 *Potential responses vectors of climate change*

Table 1.1 provides an overview of the expected influence of these climate change stressors on key estuarine processes.

Table 1.1: Vulnerability of key estuarine processes to various climate change stressors

ESTUARINE PROCESSES	STRESSOR				
	Terrestrial Climatic & hydrological processes	Ocean circulation	Ocean acidification	Sea level rise	Storminess
Coastal connectivity (alongshore)		●			
Land-sea connectivity (mouth state)	●			●	●
Salinity regime	●			●	•
Temperature	●	●			
Biogeochemistry (water quality)	●	●	●	•	
Biological cues (flow to sea)	●		•		

This study on estuarine lakes will focus specifically on the most critical *terrestrial climatic and hydrological vectors* associated with climate change, and its anticipated effects on the key estuarine processes, as well as the key biotic responses, and its consequences on the ecological health condition and important ecosystem services supplied by these systems.

1.2.6.1 *Potential responses of abiotic indicators to terrestrial climatic and hydrological vectors of climate change*

Climate change pressures (shifts in seasonal rainfall, increased drought and flood events, increased temperature, and evaporation) together with anthropogenic influences (increased pollution and water abstraction, development) put pressures on the estuarine lakes. Water level in lakes fluctuates annually and inter annually as a natural response to local climate and rainfall events. These fluctuations are expected to amplify under climate change as rainfall reduces and abstraction for human consumption increases, aggravated by is the issue of increased sea storms and SLR with consequent saline water intrusion. Table 1.2 summarises some of the impacts of climate change-driven temperature and rainfall shifts may have on key abiotic processes in estuarine lakes (distilled from a review of available Information – Van Niekerk et al. 2022).

Table 1.2: Overview of the possible influence of Climate Change vectors linked to changes in temperature and rainfall on key abiotic response indicators in estuarine lake systems

CLIMATE CHANGE VECTOR	INFLUENCE ON ABIOTIC PROCESSES
Temperature	Water levels: An increase in temperature is likely to increase evaporation rates and decrease lake water levels during the closed phase (e.g. Verlorenvlei, Bot, St Lucia). This will particularly be a problem during drought conditions.
	Mouth state: Rising temperatures and evaporation rates are likely to increase evaporation rates, decrease lake level and thus also decrease opportunities for open mouth conditions due to high evaporative losses. This will particularly be a problem under drought conditions.
	Salinity: Rising temperatures and evaporation rates may lead to hypersalinity developing in some lakes systems (Klein) or increase duration and intensity of existing hypersalinity cycles (e.g. St Lucia). However, in some systems, like the Bot/Kleinmond, it could lead to a freshening of the lake system under prolonged closed conditions due to seepage losses and outflow through Kleinmond.
Rainfall	Water levels: An increase/decrease in direct rainfall on the lakes will be a related increase/decrease on lake water levels as these systems have large surface areas and can be sensitive to direct input. The larger the system the more sensitive it will be to rainfall changes.
	Mouth state: An increase/decrease in direct rainfall on the lakes will have an impact on breaching frequencies. The larger the system the more sensitive it will be to rainfall changes.
	Interactive effects: Increased rainfall cold result in increased breaching and prolonged open mouth states that decreased water levels
River runoff	Nearshore marine environment: A decrease /increase in runoff will have a related impact on the fluvially dependant nearshore marine habitats that rely on river inflow for salinity and turbidity fronts, nutrient input, sediment supply and detritus (organic matter).

CLIMATE CHANGE VECTOR	INFLUENCE ON ABIOTIC PROCESSES
Floods	Mouth dynamics: An increase/decrease in floods will increase/decrease opportunities for mouth breaching, which, in turn, will change connectivity with the marine environment.
	Sediment dynamics: An increase/decrease in floods will change the sediment equilibrium in lake systems. In many cases lakes are sediment sinks and thus sensitive to increased sediment input.
	Salinity: During a flood event salinity can be fresh or nearly fresh. However, after a flood event salinity tend to increase significantly due to increasing tidal amplitude and related seawater flushing. Thus, an increase in floods and related scouring of the mouth area, can result in an increase in salinities post a flood event. Systems such as Swartvlei may thus experience an increase in the maximum salinity achieved during the open cycle if floods were to intensify.
	Water levels: Low tide levels can be dramatically lower after a flood event, reducing subtidal habitat and causing dieback /desiccation of submerged vegetation that is now exposed. Thus, reduction in habitat can impact biota such as fish.
Droughts	Water levels: An increase in droughts is likely to decrease lake water levels under extreme conditions.
	Mouth state: An increase in droughts is likely to decrease marine connectivity (less open mouth conditions).
	Salinity: An increase in droughts is likely to increase the likelihood of hypersalinity developing (Klein) or increase the duration and intensity of exiting hypersalinity cycles (St Lucia). However, in some systems, long closed periods may lead to freshening of the lake system.
	Lake connectivity: Drastically reduced lake levels are likely to isolate parts of the estuarine lake systems from each other (e.g. Rondevlei).

1.2.6.2 *Potential responses of biotic indicators to terrestrial climatic and hydrological vectors of climate change*

Microalgae

The effect of abiotic characteristics and processes, and other biotic components, on microalgae is described in Table 1.3 (distilled from a review of available Information – Van Niekerk et al. 2022). This information can be used to estimate the ecological health of the microalgae component in estuaries.

Studies have shown that at moderate levels of water level disturbance littoral habitats and their biota are affected (Zohary and Ostrovsky 2011). The littoral zone usually extends to a depth of between 1 and 5 m. This littoral zone usually has high species diversity because it acts as an ecotone between the terrestrial and aquatic habitats. At higher disturbance, keystone species weaken, invasive species increase, biodiversity is reduced and microalgal blooms increase even in the absence of nutrient loading. The latter is due to internal nutrient recycling.

Table 1.3: Effect of abiotic characteristics and processes, as well as other biotic components on microalgae

PROCESS	MICROALGAE
Mouth condition (temporal implications where applicable)	Once the berm at the estuary mouth is breached, there is a major outflow of estuarine water to sea that results in a rapid drop in the water level. Previously submerged sand and/or mud banks becoming exposed for long periods (weeks to years). The exposure of previously inundated sediments has a profound impact on the available microphytobenthic habitat within a lake system, impacting on higher trophic levels (e.g. providing a food source to intertidal crab species).
Retention times of water masses	Short water retention times favour the dominance of chlorophyte and diatom taxa in phytoplankton of the upper and middle reaches of estuaries. The efficient intrusion of marine water replenishes oxygen-rich water in the lower reaches of estuaries, preventing cyanobacteria from becoming dominant and favouring the prevalence of marine diatoms and flagellated life-forms that require vertical stratification (e.g. dinoflagellates, cryptophytes, raphidophytes). The intrusion of oxygen-poor groundwater typically supports cyanobacteria in the microphytobenthos, a process that also can dominate in some lake systems.
Flow velocities (e.g. tidal velocities or river inflow velocities)	In the upper reaches of lakes under high river flow, the phytoplankton is typically dominated by the chlorophytes, diatoms, and euglenophytes. As river flow decreases flagellated life-forms (e.g. dinoflagellates, cryptophytes, raphidophytes) become dominant in the middle reaches of estuaries where the water column is stratified, particularly in nutrient-rich water. Small phytoplankton, the picophytoplankton (<2 µm), occur when river flow is low. If there is very little exchange of water in the estuary and there is a high oxygen demand, then conditions favour the presence of cyanobacteria in the phytoplankton and in the microphytobenthos.
Total volume and/or estimated volume of different salinity ranges	When a lake is breached, the reduction in water level causes a decrease in the volume of water occupied by phytoplankton, limiting the potential area for colonisation of microalgae as well as overall primary production throughout the estuary.
Floods	Large-scale floods are important in scouring accumulated sediment, organic material, and 'old' water from estuaries, effectively resetting the system. The flood itself as well as the improved tidal exchange following the event support the presence of chlorophytes and diatoms in the water column and provide intertidal habitat for microphytobenthos.
Salinity	Distinct communities containing microalgae, both phytoplankton and microphytobenthos, are present in marine and freshwater environments. The presence of either of these two communities in an estuarine lake system is dependent on the hydrodynamics (e.g. tidal intrusion and freshwater flow).

PROCESS	MICROALGAE
Turbidity	Microalgal primary production is light-dependent and an increase in turbidity is likely to inhibit this, resulting in a decrease in the biomass of microalgae, particularly phytoplankton.
Dissolved oxygen	Dissolved oxygen is a function of several variables including organic loading, water exchange (through river flow or tidal exchange), and the presence of primary producers, etc. If there is a high oxygen demand and poor water exchange, then the resulting oxygen-poor environment is likely to support microalgal communities dominated by cyanobacteria.
Nutrients	High nutrient loads in estuarine lakes support high microalgal biomass (phytoplankton chlorophyll *a* > 20 µg.l-1, and benthic microalgal chlorophyll *a* > 100 $mg.m^{-2}$). Strong stratification in a nutrient-rich estuarine lake is likely to support a dinoflagellate and/or raphidophyte dominated phytoplankton community. Extended periods of low river flow and limited, or no, tidal exchange in a nutrient-rich system will accelerate the process of eutrophication, resulting in an organic-rich and oxygen-poor environment that supports a cyanobacteria dominated microalgal community.
Sediment characteristics (including sedimentation)	The accumulation of fine sediment (silt and clay) provides an ideal benthic habitat for epipelic microphytobenthos. This can be a very productive environment supporting a complex food chain (e.g. mobile diatoms, polychaete worms, intertidal crabs, mud prawns). However, if there is a high organic content then the sediment environment is likely to become anoxic to the sediment surface in extreme cases and is likely to be dominated by cyanobacteria. Sedimentation by fine sediment is unlikely in environments exposed to strong flow. These environments are typically dominated by coarse sediment, and exposed rocks and boulders providing suitable habitat for episammic and epilithic microalgal taxa.
Other biotic components	The dominance of microalgae in an estuary is influenced by the presence of other biotic components. In a recently flushed estuary, the fast-growing microalgae are perfectly adapted to colonise the environment, with little competition for space and resources. However, with time the higher trophic levels begin to recover, and herbivory increases, particularly from the invertebrates, impacting on microalgal biomass. In addition, the presence of macrophytes and macroalgae impact on the microalgae, fringing vegetation and submerged aquatic vegetation provide habitat for epiphytic microalgae (at the expense of epipelic microalgae) but fast-growing macroalgae (e.g. *Cladophora glomorata* and *Ulva intestinalis*) compete with microalgae for light and nutrients.

Macrophytes

Macrophyte habitats provide important ecosystem services such as filtering and bank stabilisation. They cycle nutrients by taking them up and releasing them again through decomposition processes. They provide a habitat for fish and invertebrates. Salt marsh, mangrove and reed and sedge wetlands protect the land from floods and sea storms, sequester carbon and serve as a source of raw materials for humans. A diversity of macrophyte habitats creates sites desirable for recreation, tourism, and research. A summary of the effect of abiotic processes, as well as other biotic components on macrophyte habitats, are described in Table 1.4 (distilled from a review of available Information – Van Niekerk et al. 2022).

Table 1.4: Effect of abiotic characteristics and processes, well as other biotic components on macrophyte habitats

PROCESS	MACROPHYTES
Mouth condition (temporal implications where applicable)	Open mouth conditions create intertidal habitat. Salt marsh species occur along a tidal inundation gradient. Closed mouth conditions would promote the growth and proliferation of macroalgae. Prolonged mouth closure could result in the die back of intertidal salt marsh species.
Retention times of water masses	Greater water retention time would provide better opportunities for nutrient uptake by macrophytes thereby favouring their abundance.
Water levels	High water level: result in some flooding of macrophyte habitats. Macroalgae and submerged macrophytes flourish in this state. Mangroves and swamp forest are sensitive to flooding, standing water and anoxic conditions and will not survive prolonged inundation (months).
Water level fluctuations	Lakeshores are ecotones (a transitional zone between terrestrial and aquatic habitats) characterized by fluctuations in water levels. Any rapid changes in water level will result in vegetation changes. Stable water levels can also cause an expansion of macrophytes such as reeds and sedges.
Wave action	The edges of the estuarine lakes are defined by distinct zones of emergent macrophytes, which act as a wave barrier for submerged macrophytes that grow in the shelter of these plants. Wind-driven wave action can prevent the establishment of submerged macrophytes in shallow areas.
Flow velocities (e.g. tidal velocities or river inflow velocities)	High flow prevents the establishment of large submerged macrophyte beds. Currents less than 0.1 m s^{-1} favour the growth and establishment of submerged macrophytes such as *Stuckenia pectinata* (pondweed). Low flow conditions could cause the expansion of reeds and sedges into the water channel further reducing flow.
Total volume and/or estimated volume of different salinity ranges	The longitudinal salinity gradient promotes species richness, different macrophyte habitats are distributed along the length of the estuarine lake system, e.g. salt marsh in the lower reaches and reeds and sedges in the upper reaches.
Floods	Large floods are important in flushing out salts from the salt marsh area and preventing the encroachment of reeds and sedges into the main river channel. Hypersaline sediments caused by evaporation and infrequent flooding will result in dry bare patches in the supratidal areas. High groundwater levels and freshwater flooding maintain suitable moisture conditions for plant growth in salt marshes. Floods are important for resetting the estuary and removing accumulated sediment and macrophyte growth from inflowing channels. Floods would also deposit rich organic mud in estuaries and thus floods have an important nitrifying effect.
Salinity	A change in salinity will influence the macrophyte habitats, e.g. reeds and sedges grow better in brackish water whereas salt marsh and seagrass grow better in salinity close to seawater. Development and runoff can often decrease salinity leading to reed expansion. Reeds and sedges are sensitive to increases in salinity but can survive if their roots and rhizomes are in salinity less than 20. However, if freshwater seepage is reduced then it may lead to die back. Freshwater inflow dilutes salts, preventing hypersaline conditions, in systems prone to developing this state such as salt marshes. Rainfall and evaporation on the marsh, groundwater seepage from adjacent land and the salinity of the tidal water

PROCESS	MACROPHYTES
	that inundates the marsh control the sediment salinity. Hypersaline sediments caused by evaporation and infrequent flooding will result in dry bare patches in the supratidal areas.
Turbidity	Increased sediment load within the water column results in a reduction in the photic zone and will limit submerged macrophyte establishment and distribution. Submerged macrophyte growth is naturally limited in turbid estuaries, however, catchment degradation can increase silt load.
Dissolved oxygen	Accumulations of macroalgae can reduce the water quality of estuaries, not only by depleting the oxygen in the water column upon decomposition but also by causing anoxic sediment conditions when large mats rest on the sediment under low flow conditions.
Nutrients	Increased nutrient inputs would increase macrophyte growth particularly in areas of freshwater seepage (i.e. reeds and sedges). Eutrophication responses are an increase in plant growth, e.g. expansion of reeds, blooms of macroalgae or invasive aquatic floating macrophytes such as *Azolla*. Inorganic nutrients (especially N and P) are known to stimulate the abundance of ephemeral and epiphytic macroalgae. *Ulva* and *Cladophora* often form accumulations due to their filamentous nature and higher nutrient uptake rates than macroalgae with thicker thalli. These accumulations can reduce the water quality of estuaries, by depleting the oxygen in the water column upon decomposition.
Sediment characteristics (including sedimentation)	Catchment degradation and sediment input can lead to unnatural expansion of macrophyte habitats, e.g. reed encroachment into previous open water channel habitats.
Other biotic components	Invasive species reduce biodiversity and change the habitat structure. Disturbed floodplains or estuary riparian zones are rapidly colonized margins by invasive plants. Grazing, browsing and trampling by cattle and goats is a significant pressure in some estuaries.
Groundwater seepage	Seepage shorelines where reeds, sedges and swamp forest occur are sensitive to changes in groundwater input.

As freshwater inflow is an important determinant of the structure and function of estuarine lakes, any changes to this, influence macrophytes. Changes in flow velocity and subsequent sedimentation mostly results in macrophytes encroaching into open water areas. Changes in mouth state and water level can cause dieback of macrophytes. Salinity influences species richness, biomass, and community composition. In an estuary with a longitudinal salinity gradient, different macrophytes will be distributed along the gradient. Deterioration in water quality is an increasing problem in South African estuaries and estuarine lakes. This results in reed expansion, increases in macroalgal blooms and invasive aquatics such as water hyacinth. Floating invasive aquatics frequently occur in the upper reaches of estuaries in response to agricultural return flow and nutrient enrichment.

Most estuarine habitat in South Africa has been lost due to residential and industrial developments. In many systems agriculture also takes place within the 5 m contour line. Grazing and associated trampling by livestock is a pressure in some lake systems, e.g. Verlorenvlei. Mangroves are harvested for building material and fuel wood. Reeds and sedges are also harvested but this activity is more common in subtropical compared to Warm-Temperate estuaries, e.g. *Juncus kraussii* (ncema) and *Phragmites australis* (common reed), are commonly used in KwaZulu-Natal by the local community for mats and basketry.

Alien vegetation also displaces estuarine macrophytes. This particularly occurs along the boundaries of estuaries where the ecotone between the terrestrial and estuarine habitat has been disturbed. In the Temperate estuaries, common invasives are *Acacia cyclops*, *Acacia longifolia*, *Acacia mearnsii*, *Lantana camara*, *Solanum americanum* and *Ricinus communis.* Common reed *Phragmites australis* can spread and colonise disturbed ecotones characterised by low sediment and groundwater conductivity from adjacent development and freshwater runoff. Other impacts are activities influencing submerged macrophytes such as bait digging, damage by boats and dredging (Adams et al. 1999). As many estuarine lakes in South Africa contain large beds of submerged macrophytes, often lacking in the other estuarine types, an understanding of estuarine lakes and the consequences of climate change impacts is crucial for their conservation and management. The loss of submerged macrophytes following an extended period of mouth opening in the Swartvlei is likely to become a more common event in these estuarine lakes and increased sea storms and SLR potentially alter mouth dynamics and salinity intrusion into the lakes.

Fish

Many biotic and abiotic factors influence the abundance and diversity of estuarine-associated fishes, including latitude, seasonality, catchment size, estuary size, salinity gradients, habitat diversity, mouth condition, dissolved oxygen levels, turbidity, food resources, flooding, and anthropogenic impacts. The last of these can be direct, such as pollution, dredging, bait collection and fishing; or indirect, such as upstream impoundments, water abstraction and marine fishing. Impoundments trap sediment, reduce freshwater flow and obstruct the upstream migration of catadromous species, reduce the spatial extent and strength of migration cues for larvae and juveniles of estuarine-associated fishes in marine environments, whereas overexploitation in the marine environment reduces spawning stock of estuarine-associated species into estuaries.

The response of estuarine fish assemblages to environmental and ecological change makes them good indicators of anthropogenic stress. In all, fish response varies according to the life-history characteristics of the individual species concerned. The life-history characteristics of most of South Africa's estuarine fish are known. The following response table (Table 1.5) was constructed to reflect the change that can occur in fish communities in response to the shifts in abiotic and biotic components (distilled from a review of available Information – Van Niekerk et al. 2022).

Table 1.5: Effect of abiotic characteristics and processes, as well as other biotic components on fish groupings

DRIVER	IA. ESTUARINE RESIDENTS (BREED ONLY IN ESTUARIES)	IB. ESTUARINE RESIDENTS (BREED IN ESTUARIES AND SEA)	IIA. ESTUARY DEPENDENT MARINE SPECIES	IIB AND C. ESTUARY ASSOCIATED SPECIES	III. MARINE MIGRANTS	IV. EURYHALINE FRESHWATER SPECIES
Mouth condition	Mouth dynamics govern connectivity between estuarine lake habitats and marine waters. Mouth closure prevents recruitment of marine spawned fish into the system and may also prevent movement (migration) of fishes within the system towards the mouth during spawning periods. It also results in loss of tidal currents and water movement in the system and a loss of salinity gradients that govern fish (and prey and habitat) distributions across the system. Intertidal area, already limited in most coastal lakes is lost, with implications for the productivity of intertidal habitats, and trophic effects to the fish community. Prolonged closure will result in vegetation changes and die off which could, in turn, result in oxygen depletion and fish kills. Increased mouth opening and strong scouring could result in opposite effects, increasing tidal fluctuation, exposing open banks on a tidal basis, stimulating microphytobenthic production to the benefit of some components of the fish assemblage (e.g. Mugilidae), but the detriment of others either through direct loss of habitat (e.g. loss of shallow submerged vegetation such as Zoster beds as preferred or even critical – in the case of pipefish and seahorses – habitat) and/or through trophic effects (e.g. loss of benthic invertebrate productivity, sand prawns).					
Retention times of water masses	Increased retention of water favours phytoplankton production and allows greater opportunity for macrophytes development. This is dependent on nutrient inflows, uptake rates in the different compartments and cycling between compartments. Shifts in trophic pathways could occur, in extreme cases with the food base shifting from the water column to the benthos (or vice versa).					
Flow velocities (e.g. tidal velocities or river inflow velocities)	Persistently higher tidal flows impact the estuarine sections of estuarine lake systems, reducing productivity and habitat availability for most estuarine associated fishes. Increased river flows also reduce the penetration of most estuarine associated fishes into fluvial coastal freshwaters. Lake basins are protected from the effects of increased flow velocities to a large degree, depending on their morphologies. Increased flow through the whole system has the porosity to influence water chemistry, and nutrient cycling, and therefore effect trophic dynamics (including fishes). Impacts will be specific to system (type) and flow change scenarios.					
Total volume and/or estimated volume of different salinity ranges	Higher lake volumes increase potential fish habitat area. Fishes that reside in the water column clearly benefit from greater habitat, but volume increases mostly (***but not always***) lead to increased shoreline and shallow water habitat. In saline and brackish water most marine estuarine associated fish benefit from additional open water habitat. These include Mugilidae, Gerridae, *Pomadasys commersonnii*, and predatory Carangidae and Sphyraenidae. In freshwater however, these benefits are reduced. Some estuarine resident species, notably the *G. aestuaria* and *A. breviceps* benefit from open habitat, but most freshwater species have a high affinity for vegetated habitats (especially in clear water systems). These species only benefit from increased volume if it results in an increase in vegetated habitat, which is mostly the case in the longer term.					
Floods	Flood results in the movement of fishes, in response to salinity changes, or to remain in the system, or to leave it. Estuarine resident species typically adopt strategies to prevent being washed out of the system in floods, either moving up the system away from the mouth, or into marginal habitats where they gain protection from strong outflows. Estuarine associated marine species may move down the system cued by floodwaters, in spawning migrations to marine waters. Some freshwater species similarly use floods as an opportunity to gain access to spawning areas. *Clarias gariepinus* for example undertakes spawning aggregations in newly flood marginal areas.					
Salinities	The salinity of a primary driver of fish distribution in estuarine lakes, either directly as different species have different salinity preferences, or indirectly, through affecting prey and habitat distribution. Most estuarine dependant fishes are tolerant of low rather than high salinity and several freshwater species can tolerate slight (or even marked) elevations in salinity. Distribution across wider estuarine lakes system is therefore possible by most fish species in these systems. Biological interactions become important considerations (predation risk, prey availability, habitat availability).					
Turbidity	Turbidity is an important determinant of phytoplankton and therefore zooplankton productivity, and therefore affects the food base in estuarine lakes. This has implications for the fish community. Visual fish predators are more effective in clear waters. Turbidity also plays an important role in the value of estuarine lake water as a predation refuge for fish themselves. In turbid systems fishes distribute widely across the systems and over areas of open water, whereas in very clear systems fishes are much more guarded and hold in structured vegetated habitats in littoral and shallow areas.					
Dissolved oxygen	Most fishes become stressed when oxygen levels drop below 4 mg/ℓ. While many estuary-associated fish use surface breathing as an adaptation to hypoxia, and some can also adapt by skin respiration, eutrophication and persistent night-time low oxygen levels may exhaust fish to an extent that mass mortalities occur. Low oxygen levels in very deep areas of some systems (e.g. Kosi) preclude their use by fishes (and their prey). Overturn events are rare but can result in fish kills naturally. Cold temperature can have a similar or exacerbating effect. Freshwater species *O. mossambicus* and *C. gariepinus* are generally the most tolerant members of the estuarine lake fish community to persistent low oxygen concentrations. Fish health impacts from oxygen saturation can also					

DRIVER	IA. ESTUARINE RESIDENTS (BREED ONLY IN ESTUARIES)	IB. ESTUARINE RESIDENTS (BREED IN ESTUARIES AND SEA)	IIA. ESTUARY DEPENDENT MARINE SPECIES	IIB AND C. ESTUARY ASSOCIATED SPECIES	III. MARINE MIGRANTS	IV. EURYHALINE FRESHWATER SPECIES
	occur. Although less documented in South African systems (than occurrence and impacts of low oxygen events) fish health impacts can occur at levels as low as 120% saturation, a level that is easily attained in waters in the proximity of algal beds or submerged aquatic macrophytes.					
Subtidal, intertidal and supratidal habitat	Open water habitat is used by the planktivorous estuarine dependent species that live in the water column, but several most of the goby species have a close association with sand (or mud) substrates, sometimes co-inhabiting with crustaceans in burrows. Submerged aquatic macrophytes are also important for some estuarine resident species (notable pipefishes and seahorses, but also gobies and blennies). These habitats, in estuarine lakes, are typically shallow subtidal. Intertidal habitats are limited, but where they occur are important for estuarine dependant marine species, particularly members of the Mugulidae that feed of tidal microphytobenthic productivity. Shallow water subtidal habitat is also important to these species. Deeper intertidal habitat is also used as a refuge from predation by wading birds and to the extent that it offers productive feeding grounds (for example in supporting Callianasa banks). Very deep subtidal areas in estuarine lakes are likely to have quite distinct water quality characteristics, including low oxygen levels, that might preclude use by fishes.					
Other abiotic components	Low temperatures increase tolerance to hypoxia and low salinities and lower risk of mass mortality. Greater volumes maintain lower temperatures and thermoclines develop in the water column. Sex ratios can be skewed in fish where sex determination is temperature related. Temperature increases tend to skew towards males, decreases towards females. Consequently, climate change and local scale anthropogenic influences on temperature could have a profound impact on fish populations. Growth rates and gonadal development tend to decrease on either side of the optimal temperatures for individual species. Fish move according to their preferred temperature, constraints more in temporarily open/closed than permanently open estuaries. Many of the fish in southwestern Cape estuaries are tolerant of low pH inflow of black water systems, e.g. *Myxus capensis*. Shallow marginal areas tend to be warmer than deeper channel areas and are thus favourable for metabolic processes. Juveniles and small adults also use shallow water as a predation refuge. Indigenous fish adapted to low pH whereas introduced ones originate from high pH waters. Consequently, agricultural runoff raises pH to the advantage of the introduced species.					
Sediment characteristics (including sedimentation)	Individual species preferences are highly variable and often related to preferred food sources. The burying ability and crypsis of some fish (e.g. sole *Heteromycteris capensis*) are governed by sediment characteristics. Some fish are directly and indirectly impacted, e.g. *Psammogobius knysnaensis* and *Croilia mossambica* are psammophyllic but have commensal/mutual relationships with burrowing invertebrates which are distributed according to their burrowing ability and sediment characteristics. Members of the Mugilidae feed over areas of different grain size and in so doing reduce competition for food resources. *O. mossambicus* prefers sandy substrata for nesting					
Phytoplankton biomass	High phytoplankton production contributes to turbidity in estuaries and probably favours those species with higher turbidity preferences. Phytoplankton is also a food source for filter-feeding fish, e.g. *G. aestuaria* and invertebrates. Fish also benefit indirectly from the proliferation of invertebrates that feed on phytoplankton. Omnivorous filter-feeding fish will out-compete selective feeders during periods of high phytoplankton biomass. Harmful algal blooms in estuaries, usually a result of eutrophication, have several direct (toxicity) and indirect (e.g. hypoxia) impacts on fish. Blue-green *Microcystis* blooms, common in SA estuaries, can cause skin and/or organ lesions in fish resulting in poor health, reduced reproductive success and mortalities. Golden algae *Prymnesium parvum*, an invasive species recorded in Zandvlei, causes fatal gill haemorrhaging and induces abortion and premature spawning in fish.					
Benthic micro-algae biomass	Benthic microalgae are an important contributor to the food base of many estuarine lakes, supporting a wide range of fishes directly, and indirectly. *G. aestuaria* and *A. breviceps* may both selectively feed/graze on benthic diatoms. Mugillidae feed extensively on benthic micro-algae. These fishes are a dominant part of the fish biomass in South African estuarine lakes and therefore overall fish biomass is largely reflective of benthic algal biomass.					
Zooplankton biomass	Zooplankton is the primary food source for most estuarine resident species, although many can feed opportunistically on benthic invertebrates. Zooplankton also supports most marine estuarine associated fishes in the early life stages, before they move onto larges benthic prey items.					
Aquatic macrophyte cover	Several estuarine resident species have a critical dependence on vegetated habitats. This includes several pipefishes and seahorses, bennies and gobies. *Zostera* is especially important, although other vegetation can be used, including *Ruppia* and *Potamegeton* in lower salinities and freshwaters. Marine estuarine dependant species are less dependent on structured (vegetated) habitats, although some forms may have life stages that do have strong preferences for submerged aquatic vegetation. *Rhabdosargus holubi* for example, occurs predominantly in *Zostera* beds, if available, as small juveniles < 50 mm SL, before moving onto open sandbanks. Moonies, *Monodactylus* spp. associate with structured habitat as a matter of preference throughout their lifecycle. In clear water systems especially, fishes have a high dependency on vegetation as a predation refuge, especially during daylight hours. In turbid systems, habitat associations with structured habitats are weaker.					
Benthic invertebrate biomass	Benthic invertebrates are the main source of prey for most fishes once they have passed through their very early life stages. Even estuarine resident species that are otherwise plantivorous will feed opportunistically on benthic prey items if they are available in good numbers. *Callianassa* is important in several estuarine lake systems. They can occur in high biomass and support large specialist invertebrate feeders such as *Pomadasys commersonni*.					
Fish biomass	*G. aestuaria, A. breviceps* and *Ambassis* spp. are fodder-fish and comprise a high proportion of the fish biomass in the estuary and support piscivorous fishes and avifauna. High predator biomass can suppress abundance of these fodder fish. The value of benthic estuarine resident species (e.g. gobies) in playing a similar role in supporting piscivorous fishes and birds is probably underrated					

1.3 Assumptions and Limitations

The following assumption pertains to this report:

- Climate change is a measurable reality and South Africa is especially vulnerable to its impacts. Globally key drivers of change have been identified as (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): modification of terrestrial climatic (e.g. temperature and rainfall) and hydrologic processes; changes in the oceanic circulation; ocean acidification; sea-level rise; and increased sea storminess. However, this study focussed specifically on the critical *terrestrial climatic and hydrological vectors associated with climate change*, and its anticipated effects on the key estuarine processes in the estuarine lakes of South Africa, as well as the key biotic responses, and their consequences on the ecological health of these valuable systems.
- The vulnerability assessment did not consider the highly modified estuarine lake systems which as a result of severe human intervention, e.g. harbour development (e.g. Richards Bay/uMhlathuze) and development of dividing weirs (e.g. Zeekoevlei and iNhlabane), are no longer functioning as estuarine lake systems. It also did not include St Lucia/uMfolozi system as it has been the focus of the previous assessment.
- For this study, four abiotic indicators (water levels, mouth state, water levels, temperature, salinity, and water quality [nutrients]), and three biotic indicators (microalgae, macrophytes and fish) were selected to assess the responses of estuarine lakes to climate change. These were primarily selected on their suitability and sensitivity to the selected climate change vectors, but also based on the availability of data across these systems.
- While only terrestrial climatic (e.g. temperature and rainfall) were assessed in detail as part of the climate change vulnerability assessment, the other key drivers of climate change, that changes in the oceanic circulation; ocean acidification; sea-level rise; and increased sea storminess were included in the mitigation and adaptation strategies for estuarine lakes, based on best available information.

1.4 Structure of this Report

This introductory chapter details the aims and objectives of the project. Chapter 2 provided a general overview of South Africa estuarine lakes extracted from the published literature and summarises characteristics patterns in key features and abiotic states, as well as an overview of the responses of key abiotic and biotic indicators. Chapter 3 details the approach and methods that were adopted in the development of Estuarine Lake Conceptual models that were needed to conduct the Climate Change Vulnerability Assessment, as well as the data availability and confidence. While Chapter 4 summarises key characteristics and the conceptual models developed for each lake system. Chapter 5 provides an overview of the overall sensitivity of abiotic and biotic components across estuarine lakes and distil key findings. Finally, Chapter 7 provides conclusions and recommendations on future refinements of the climate changes assessment methods, as well as key considerations for the development of the climate change adaptation strategy.

2. BACKGROUND

2.1 Study area

Thirteen estuarine lakes systems occur in four biogeographical regions along South Africa's coast, namely Verlorenvlei, Zeekoevlei, Klein, Bot/Kleinmond, Heuningnes, Touw/Wilderness, Swartvlei, uMhlathuze, St Lucia, uMgobezeleni and Kosi (Figure 2.1) (Van Niekerk et al. 2019). These lake systems mostly formed as a result of sea-level changes between the late Pleistocene and Holocene (Whitfield, et al. 2017), some stemming from drowned river valleys (e.g. Swartvlei) and others from marine flooding (e.g. Wilderness) (Whitfield et al. 2017).

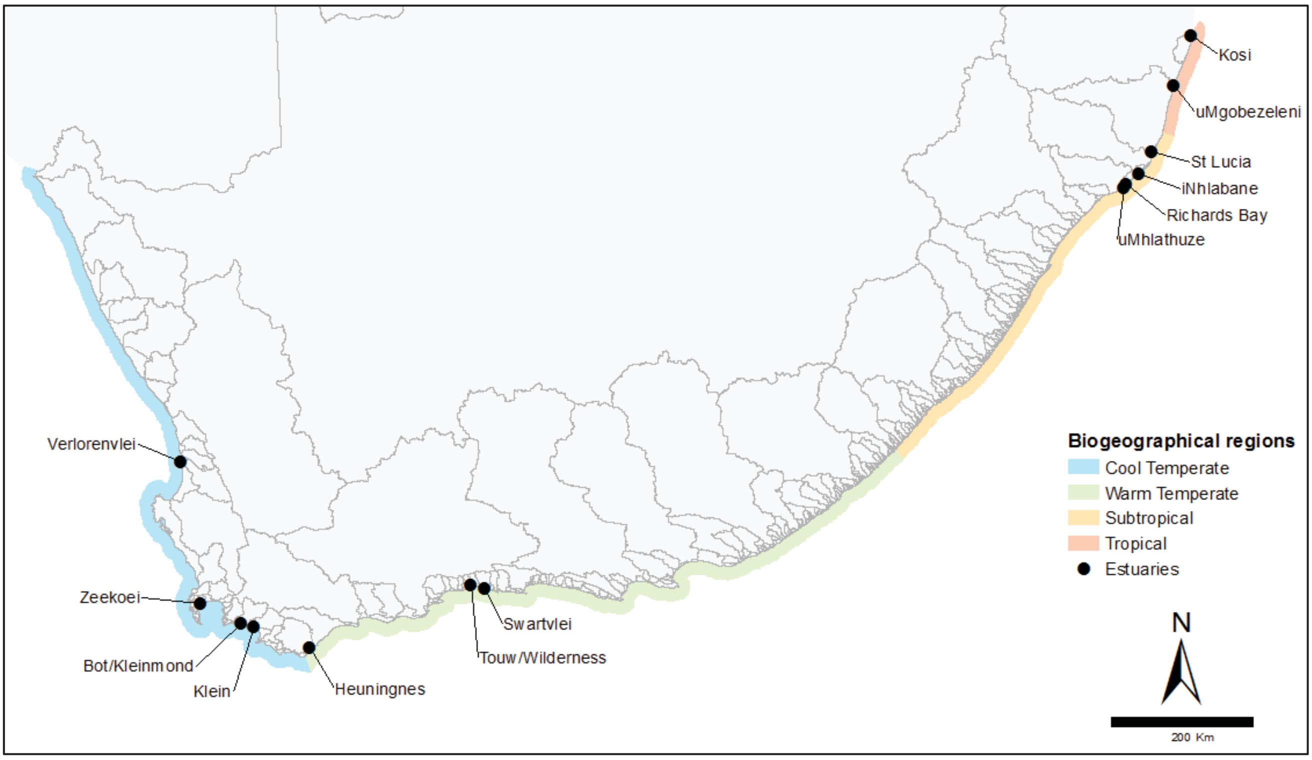


Figure 2.1: Location of South Africa's Estuarine Lakes

Estuarine lake connectivity range from near-permanently open (e.g. Kosi), through systems that are open on annual time scales (e.g. Swartvlei) (Russell and Randall 2017), to predominantly closed (e.g. Bot/Kleinmond and St Lucia). The extent and duration of marine connectivity influence the salinity regime in these lake systems, which can range from fresh to hypersaline. As a result of restricted connectivity to the sea and low tidal amplitudes (15 to 20 cm) wind plays a more prevalent role than tides in mixing processes (Van Niekerk et al. 2019). The low flushing rate and intermittent connection to the sea make South Africa's estuarine lakes vulnerable to catchment and development pressures and contribute to more than 84% of estuarine lake habitat already being in a poor condition from catchment and development pressures (Van Niekerk, et al. 2019). This reduces their ability to provide key ecosystem services such as flood regulation, nutrient cycling, nursery habitat, and has compromised recreational and tourism benefits derived from these systems. Catchment development is increasing, resulting in reduced inflow (either surface or groundwater) into many lakes, with Kosi being a good example.

2.2 Existing Anthropogenic Pressures on Estuarine Lakes

Of note is that estuarine habitats are already significantly degraded through other global pressures such as freshwater reduction, habitat destruction, nutrient pollution, and overexploitation of living resources, which affects related ecosystem services (e.g. nursery function).

South Africa's estuarine lakes are already subject to extensive anthropogenic pressures that go beyond the influence of climate change. Also, such impacts are likely to reduce the capacity of estuaries to buffer the effects of change. The key pressures acting on each of the country's estuarine lake systems are indicated in Table 2.3 as per Van Niekerk et al. (2019).

Table 2.1: Key anthropogenic pressures on South Africa's Estuarine Lakes

SYSTEM	PRESSURE																
	Overall Pressure Level	Reduced base flows	Reduced floods	Reduced groundwater input	Poor water Quality: Stormwater / floodplain drainage	Poor water quality: River inflow	Poor water quality: WWTW	Reduced connectivity/ hydrodynamic functioning	Artificial mouth management/breaching	Loss/degraded riparian areas/ wetlands	Alien vegetation	Grazing (sheep, cattle, goats)	Mangrove harvesting	Recreational activities impacting birds	High fishing pressure/ bait collection	Alien or translocated fish	Mining
Verlorenvlei	H	●		●		Agric		●	●	●		●			●*	●	
Zeekoevlei	VH	●			Urban	Urban	●	●	●		●			●		●	
Bot/Kleinmond	M	●				Agric	●		●		●			●	●	●	
Klein	M	●			Urban	Agric	●		●		●			●	●*	●	
Heuningnes	H	●			Agric	Agric		●	●	●	●	●		●	●	●	
Touw/ Wilderness	M	●						●	●		●			●	●	●	
Swartvlei	L	●				Agric		●	●		●			●			
uMhlathuze	VH	●	●		Agric	Agric/ Urban		●	●	●	●		●	●	●*	●	●
iNhlabane	VH	●	●					●		●	●	●			●*		●
St Lucia/uMfolozi	H	●	●					●			●		●		●*		
uMgobezeleni	M			●	Agric/ Urban			●	●				●		●*		
Kosi	L	●		●							●		●		●*		

**Illegal gillnetting impacting nursery function & food security*

3. APPROACH AND METHODS

3.1 Selection of Climate Change Scenarios

An ensemble of high-resolution climate model simulations of present-day climate and projections of future climate change over South Africa has been performed as part of the "Green Book" project. Simulations were developed using a regional conformal-cubic atmospheric model (CCAM) developed by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) (McGregor 2005; McGregor and Dix 2001, 2008). Six simulations of the Coupled Model Intercomparison Project Phase Five (CMIP5) and Assessment Report Five (AR5) of the Intergovernmental Panel on Climate Change (IPCC), obtained for the emission scenarios described by Representative Concentration Pathways 4.5 and 8.5 (RCP 4.5 and 8.5) were first downscaled to 50 km resolution globally and then further to 8 km resolution for South Africa. The simulations span the period 1960-2100, with the period 1960 to 1990 representing the baseline, 2021-2050 (mid-future) and 2070-2099 (far-future). RCP4.5 is a high mitigation scenario, whilst RCP8.5 is a low mitigation scenario. For the period 2021-2050 (mid-future) relative to the baseline, under low mitigation (RCP8.5), temperature increases of 1 to 3°C may plausibly occur over the coastal regions. For RCP8.5 Far-future relative to baseline, temperature increases of 3-4°C, are plausible to occur over coastal regions, with some months projected as high as 5°C (Figure 1.3). Under RCP 4.5 temperature increases may still be significantly reduced, estimated between 1 and 2.5°C. Under RCP 8.5 Mid-future, rainfall is projected to increase over the central interior and east coast, while the western interior, north-eastern parts and the winter rainfall region of the southwestern Cape are projected to become generally drier. The projected changes in rainfall patterns under RCP 4.8 and RCP8.5 are very similar. For RCP8.5 Far-future, rainfall is projected to decrease over the central interior and east coast of South Africa.

Since measured inflow data into estuaries are typically not available due to sparse observation networks, rainfall-runoff models were used to simulate hydrological data. The advantage of applying these modelling techniques is that natural flow regimes and future regimes can be simulated to assist in determining the sensitivity of ecological responses to changes in flow. No new hydrological modelling was undertaken as part of this study, and available simulated data for Reference (i.e. before any anthropogenic or climate changes pressures) and Present (i.e. accounting for existing anthropogenic pressures, but not climate changes pressures) were sourced from the literature (CSIR 1981, 2009, DWAF 2003, 2004, Van Niekerk et al. 2005, DWA 2009a, b, DWS 2014, 2016, Anchor 2015, 2018, Taljaard et al. 2018). Given that the climate model ensemble outputs do not span the required >70-year simulation periods, available simulated monthly present inflows were scaled according to the predicted relative shifts in monthly rainfall for the catchments and directly onto the estuaries using a delta-change approach. These broad extrapolations were further moderated with the outputs of Cullis et al. (2015). For example, large floods are not transformed to the same degree as average only flows, so factors were applied to moderate the impact on inflows that only occur for 5 to 10% of the time in the simulated sequence.

3.2 Selection of Key Abiotic and Biotic Indicators

For this study, four abiotic indicators (water level, mouth state, salinity, and water quality [nutrients]), and three biotic indicators (microalgae, macrophytes and fish) were selected to assess the responses of estuarine lakes to climate change. These were primarily selected based on their suitability and sensitivity to the selected climate change vectors, but also based on the availability of data across these systems. Temperature was used as a driver of changes and not as an indicator. Table 3.1 provides a summary of the rationale for the selection of the indicators. *Microalgae* form the base of food chains in estuaries and were considered an important indicator from that perspective (Lemley et al. 2016). Lake systems support very valuable *macrophyte* habitats. Macrophyte habitats provide important ecosystem services such as filtering and bank stabilisation. They cycle nutrients by taking them up and releasing them again through decomposition processes. Salt marsh, mangrove, reed, and sedge wetlands protect the land from floods and sea storms, sequester carbon and serve as a source of raw materials for humans. Submerged aquatic vegetation provides critical habitat for fish and invertebrates, thus supporting a valuable ecosystem service in the form of the provision of nursery areas (Whitfield 1998, 2005). Estuarine habitats are extremely important for *fish* in southern Africa. The vast majority of coastal habitat in this region very exposed to the open ocean, so its estuaries are disproportionately important relative to other parts of the world, in that they constitute the bulk of the sheltered, shallow water inshore habitat in the region (Field and Griffiths 1991). There are at least 100 species that show a clear association with estuaries in South Africa (Whitfield 1998). The response of estuarine fish assemblages to environmental and ecological change makes them good indicators of anthropogenic stress (Whitfield and Wooldridge 1994; Whitfield 2005, Whitfield 2019).

Table 3.1: Summary of the rationale for the selection of abiotic and biotic indicators to the selected climate change vectors of change

INDICATOR	RATIONALE
Water level	An increase/decrease in rainfall and associated runoff will result in a related increase/decrease in lake water levels driven by catchment inputs and direct rainfall on the lake surface areas.
Mouth state	An increase/decrease in rainfall and associated runoff will result in a related impact on breaching frequencies and the duration of open mouth conditions. Mouth state is also a direct indicator of land-sea connectivity.
Salinity	Salinity responds to increase rainfall and runoff, as well as mouth state (frequency and duration of open and closed conditions). It is also a key indicator of biotic community composition and/or abundance.
Water quality (nutrients)	Although it was not expected for the selected vectors of climate change to necessarily have a direct influence on nutrients, enrichment is a major anthropogenic pollution pressure in many estuarine lakes (Taljaard et al. 2017; Adams et al. 2020). It was, therefore, important to include this indicator to account for the cumulative impacts of climate changes and nutrient enrichment.
Microalgae	Microalgae are a major food source for higher trophic levels in estuaries (e.g. zooplankton, fish). The dynamics of microalgae (especially phytoplankton) are largely influenced by nutrient availability and residence time (Lemley et al. 2016). The latter is influenced by, for example, mouth state which, in turn, is affected by shifts in river runoff. Temperature increases can also stimulate primary production in estuaries.
Macrophytes	Macrophyte habitats provide important ecosystem services. Mouth state is a key driver of tidal inundation/water levels and salinity. Water levels (e.g. flooding), in turn, is a key determinant of macrophyte habitats, with any changes in water level resulting in vegetation changes. Salinity also influences macrophyte habitats and may lead to die back under extreme conditions or change community composition. Increased temperature will increase primary production.
Fish	Estuarine fish assemblages are economically important and good stress indicators (Whitfield and Wooldridge 1994; Whitfield 2005, Whitfield 2019). Mouth state governs connectivity, recruitment, and community composition. Water levels fluctuations can lead to loss of critical habitats, e.g. intertidal area. Salinity is a primary driver of fish distribution in estuarine lakes. High temperatures decrease tolerance to environmental perturbation and may influence sex ratios.

3.3 Characterisation of Abiotic States and Conceptual Models

Estuarine lake systems will remain closed until their basins fill up to a level equal to the height of the sand berm across the mouth. Any additional water added to the estuary basin after this will cause the mouth breaching (if inflow exceeds the outflow from the estuary). The foremost assumption in the development of a water balance model is therefore that breaching will occur when the water level (WL) in the estuary basin equals or is greater than the height of the berm (B_c). This results in the algebraic inequality which states that a breach occurs if:

$$WL(t) \geq B_c(t)$$

The volume of water in an estuary at a particular time (*t)* can be described as the sum of the various volumes entering and/or leaving the system by different means, as well as the previous volume of water in the estuary (i.e. at time *t-1*). This approach, which accounts for the quantity of water in an estuary, is known as the Water Volume Balance (e.g. Smakhtin 2004).

Potentially flows entering an estuarine lake include: the inflow from the river, V_{inflow}; Precipitation directly onto the estuary's surface (V_{precip}); the volume of seawater entering the estuary over the berm through wave action ($V_{overwash}$); the volume of water entering through anthropogenic influences ($V_{artificial}$); and the volume of water directly entering through the ground (V_{ground}). Potentially outflows from the estuary include: Evaporation from the estuary's surface (V_{evap}); the volume of water that seeps through the berm from the estuary ($V_{seepage}$); the volume of water exiting through anthropogenic influences ($V_{artificial}$); and the volume of water exiting through the ground as seepage (V_{ground}). Figure 3.1 provides a graphic representation of the water volume balance in a closed estuary.

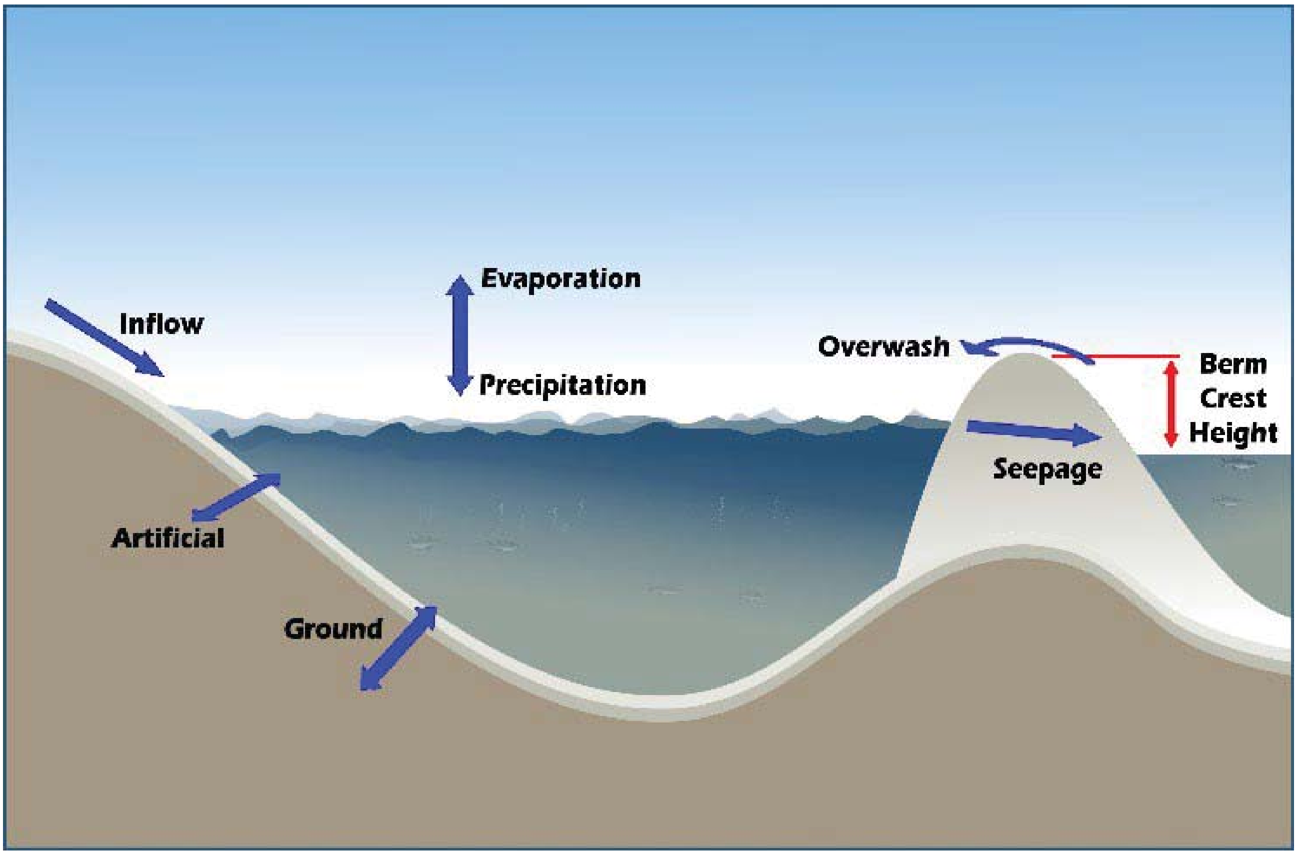


Figure 3.1: Schematic illustration of a water balance model for a closed estuary

The equation for the **Volume of water** in the estuary at time *t*, is thus given as:

$$V_t = V_{t-1} + V_{inflow} + V_{precip} + V_{evap} + V_{seepage} + V_{overwash} + V_{artificial} + V_{ground}$$

V_{inflow} is usually the dominant natural factor that causes the mouth to breach and in some studies mouth state and water levels can be directly attributed to flow (not require a water balance model). $V_{artificial}$ is normally not included in estuarine lake water balance calculation unless significant direct abstraction or discharges occur. Data on the quantity of water entering or leaving the estuary via the sub-surface flow (V_{ground}) are generally not readily available but should be included, if possible, in water balance calculation given the long periods of closure and extensive lake perimeter area. $V_{overwash}$ can also largely be ignored to simplify model development given the long periods of mouth closure (leading to a well-established berm) and extensive lake volumes. Evaporation can be calculated from the average surface area multiplied with the A-Pan Equivalent Potential Evaporation (mm) for the area within which the estuary occurs.

Water levels are the primary output data of the water balance model. The model both generates the current water level of the system and uses it as an input parameter for the following time step (e.g. month). In larger systems (e.g. St Lucia, Bot/Kleinmond and Swartvlei) where water levels fluctuate more slowly over time (i.e. measured at annual or seasonal time scales) water level data may need to be calculated and reported on independently from other variables such as mouth state. In more simplified applications of the model, water level estimates can be linked directly to river flow ranges through either measurement studies or area-volume relationships. Mouth State is generally inferred from water levels in complex water balance models, or directly generated in the case of more simplified versions of its application.

For example, the model may assume that an estuary mouth breaches once the water level inside the system exceeds the estimated berm level (e.g. 3.5 m mean sea level) and reset the water level to mean sea level. This, in turn, may activate a counter that aggregates the duration of open mouth conditions. Retention can be estimated based on the duration of mouth closure. The duration of mouth closure, in turn, can be determined through the aggregation of estimated months with continuous closed mouth conditions (e.g. mouth remained closed on average for 10 months at a time) or statistically calculated as the occurrence of closed mouth periods of a given period (e.g. mouth closed for 20% of the time over a 70-year period).

In the more simplified applications of the water balance model, water level and mouth state data are used to predict salinity based on measured data. For example, longitudinal salinity profiles are linked to open or closed mouth conditions and, in turn, used to predict changes in average salinity concentrations under certain hydrological or hydrodynamic conditions. The refined water balance model developed by (Lawrie and Stretch 2011a and 2011b) include a simplified salt budget model that assumes a fully mixed state.

Using the above information, together with the available understanding of South Africa's estuarine lake systems (Van Niekerk et al. 2022), cross-section (profile) conceptual models could be constructed for each of the estuarine lake systems from the generic seven open and five closed abiotic states, distinguished between dominant open-closed cycles, and drought and flood events (if persistent state). To allow for easy interpretation, lake depths and distance were also depicted to approximate scales.

These models provided the basis for the climate change sensitivity assessment, showing key physical characteristics (e.g. water levels and salinity) across various abiotic states typical to each estuarine lake, which provided a visual means of comparing complexities, but also identify typical patterns.

3.4 Ecosystem-based Method to Assess Climate Change Vulnerability

The Vulnerability Assessment, specifically focussed on terrestrial climatic and hydrological vectors associated with climate change, did not consider highly modified estuarine lake systems, such as uMhlathuze, impacted by port development, and Zeekoevlei and iNhlabane, which are impacted by weirs to the extent that they no longer function as estuarine lake systems. It also did not include St Lucia/uMfolozi system which has been the focus of a previous vulnerability assessment but was considered in the development of conceptual models to allow for a holistic view of major processes and responses across lakes.

3.4.1 Interpretation of abiotic responses

Based on the cross-section (profile) conceptual models, simple conceptual models were developed that indicated the average duration of the open-closed cycle (e.g. see the central circle in Figure 3.2a), while drought cycles (if present) and states are indicated by a smaller circle in the upper right-hand corner. To allow for easy comparison open abiotic states are indicated in blue, while closed states are shown in grey shades.

In addition, typical abiotic characteristics under present data conditions were also be summarised for each abiotic state focussing on water levels, salinity, temperature, and water quality as key distinguishing features.

3.4.1.1 Water levels

Available data and information were sourced to conceptualise typical water levels under the generic abiotic states for each of the estuarine lakes, graphically illustrated on the longitudinal conceptual models and captured in a detailed table provided with the models.

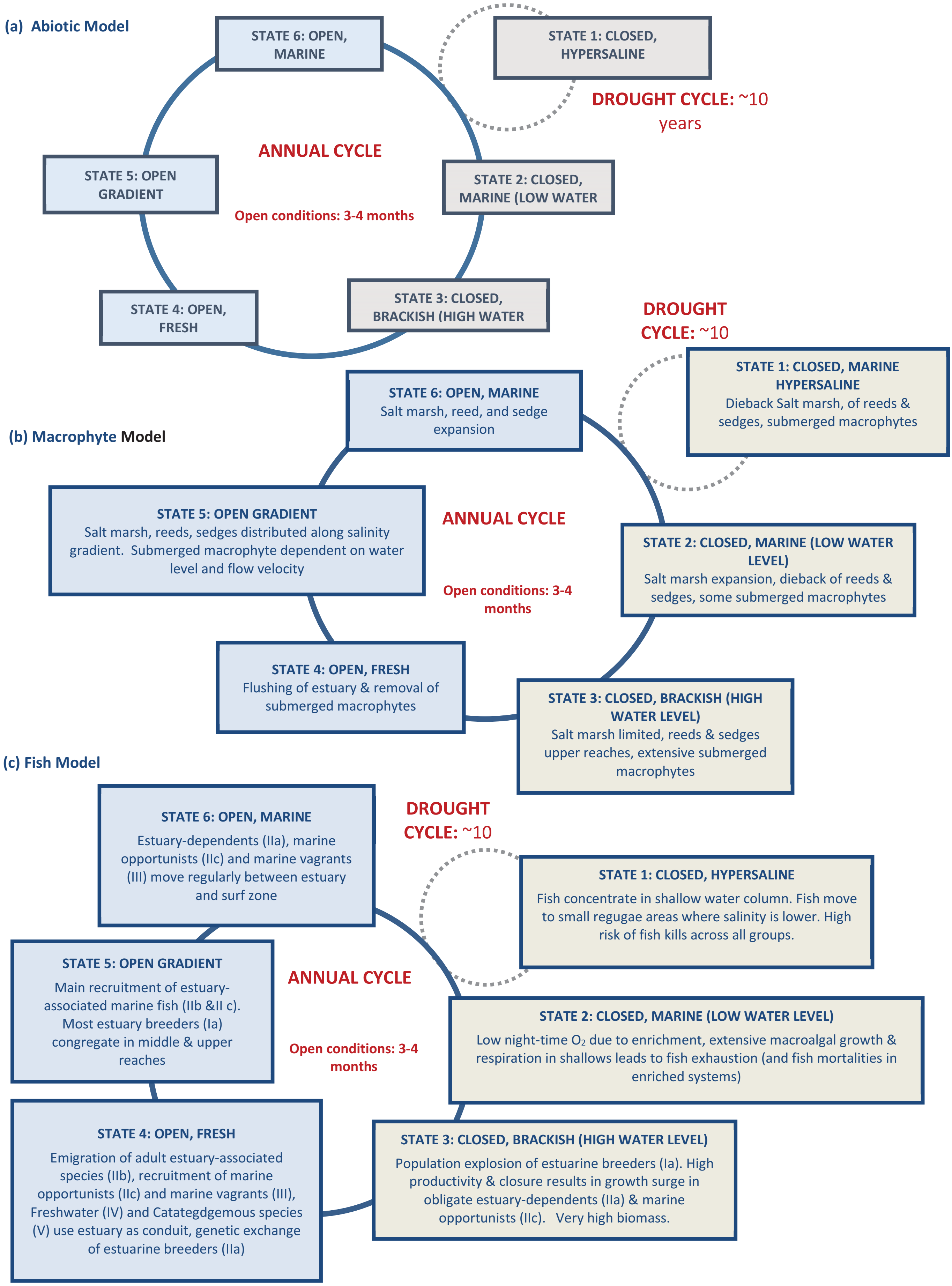
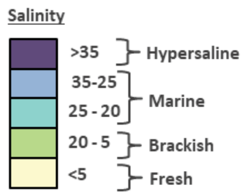


Figure 3.2: Example of (a) abiotic (a), (b) macrophyte and (c) fish (c) conceptual models for estuarine lakes

3.4.1.2 Salinity

Available data and information on salinity data was evaluated to conceptualise typical salinity ranges associated with the generic abiotic states in each of the estuarine lakes, using colour coding to distinguish between salinity ranges, as is illustrated in the diagram (observed salinity values are captured in a detailed table provided with the models for each system).



3.4.1.3 Temperature

The temperature ranges in the systems were mostly derived from available RDM studies usually showing strong seasonal temperature fluctuation, i.e. higher in summer than in winter. Temperature was included as it could be one of the physico-chemical parameters in estuarine lakes that will be directly influenced by climate change (e.g. global warming).

3.4.1.4 Water Quality

The official methods for determining ecological water requirements include an Estuarine Health Index (EHI) for assessing the present ecological condition of an estuary; a component of which is estuarine water quality (Turpie et al., 2012). In the water quality component of the EHI, the percentage similarity to the natural or reference condition of (i) the salinity distributions in the estuary (primarily influenced by changes in freshwater inflows) and, (ii) four other biogeochemical parameters, namely dissolved inorganic nutrients, dissolved oxygen, transparency, and toxic substances (primarily influenced by anthropogenic sources, such as polluted wastewater and contaminated runoff), are assessed and aggregated. In each case, for a given estuary water volume, the percentage similarity is determined using an adaptation of the Czekanowski's similarity index (Turpie et al. 2012). In South African estuaries, nutrients are the major driver of water quality status (Taljaard et al. 2017; Adams et al. 2020). Based on this, a water quality screening model has been developed as a rapid means of characterising water quality conditions (or state) in estuaries, using dissolved inorganic nitrogen (DIN) as a proxy. This nutrient was found to be the main driver of water quality modification in South African estuaries (Taljaard et al. 2017) (Table 3.2). Present conditions were mostly derived from available EWR studies conducted on these lakes system, where these were not available, data and expert opinion were used to derive such conditions.

Table 3.2: Water quality index applied in the estimation of water quality conditions under various abiotic states and scenarios, expressed as modification from reference (adapted from Taljaard et al. 2017)

% SIMILARITY TO NATURAL	EHI CATEGORY	SIMPLIFIED CATEGORY	ESTIMATED DIN CONCENTRATIO N RANGE	CORRESPONDING DESCRIPTION
100-91	A (1)	**Near-natural (NN)**	<u><</u>80	Near-natural conditions with no anthropogenic induced stress. Water quality, nutrient and organic loading relatively low, with acceptable oxygen/pH levels causing no marked stress on biota
90-76	B (2)		80-150	
75-61	C (3)	**Moderately Modified (MM)**	151-200	Moderate nutrient loading triggers moderate primary production, organic loading trigger some deterioration in oxygen/pH conditions potentially causing moderate stress in biota
60-41	D (4)	**Heavily Modified (HM)**	201-400	High nutrient loading triggers significant primary production, organic loading result in hypoxia and some pH variability potentially causing significant stress on biota
40-21	E (5)	**Sever/Critical Modified (SM)**	401-700	Very high nutrient loadings trigger nuisance primary production, organic loading result in hypoxia/anoxia with high pH variability potentially causing marked dysfunctionality in biota
< 20	F (6)		> 700	

3.4.2 Interpretation of biotic responses

3.4.2.1 Microalgae

Lemley et al. (2015) have proposed a classification system to rate eutrophic conditions in estuaries, which includes a section specifically directed at microalgae concentrations (Table 3.3). This classification was combined with the official EHI scoring approach applied in South Africa's estuaries (Turpie et al. 2012) to provide a simple desktop index to estimate microalgae condition, expressed as modification from reference (the official method includes microalgae score to be derived from species richness, biomass, and community composition, but do not provide a specific method). Present conditions were mostly derived from available EWR studies conducted on these lakes system, where these were not available, data and expert opinion were used to derive such conditions.

Table 3.3: Microalgae index applied in the estimation of microalgae conditions under various abiotic states and scenarios, expressed as modification from reference (adapted from Lemley et al. 2015; Turpie et al. 2015)

% SIMILARITY TO NATURAL	EHI CATEGORY	SIMPLIFIED CATEGORY	DESCRIPTION
100-91	A (1)	**Natural/ Near-natural (NN)**	Phytoplankton: < 5 µg/ℓ Benthic microalgae: < 50 mg/m² Harmful algae: Not present
90-76	B (2)		
75-61	C (3)	**Moderately Modified (MM)**	Phytoplankton: ≥ 5 but < 20 µg/ℓ Benthic microalgae: ≥ 50 but < 100 mg/m² Harmful algae: Possibly present
60-41	D (4)	**Heavily Modified (HM)**	Phytoplankton: ≥ 20 but < 60 µg/ℓ Benthic microalgae: ≥ 100 but < 150 mg/m² Harmful algae: Present
40-21	E (5)	**Severely/Critically Modified (SM)**	Phytoplankton: ≥ 60 µg/ℓ Benthic microalgae: ≥ 150 mg/m² Harmful algae: Abundantly present
< 20	F (6)		

3.4.2.2 Macrophytes

Present condition for macrophyte habitats was derived from available EWR studies. Where appropriate aerial photographs or Google earth images were available, these were also used to illustrate the distribution of macrophyte habitats. Present assessments also were refined by more detailed vegetation inundation modelling under different water level conditions, which focussed on the Klein, Bot and Verlorenvlei systems (e.g. Figure 3.2b).

To project modification in the macrophyte habitat within each of the estuarine lakes systems under future scenarios, optimal conditions for a range of abiotic parameters were estimated for various macrophyte habitats (Table 3.4). Projected change in these abiotic parameters was then used to derive the expected change in macrophyte habitat distribution, expressed as changes in the estuary habitat types namely salt marsh, reeds & sedges and submerged Macrophytes

Table 3.4: Optimal conditions for macrophyte habitats in estuarine lakes used to project responses to projected changes in abiotic conditions

HABITAT TYPE	WATER LEVEL (m above MSL)	WATER DEPTH (m)	SALINITY	TURBIDITY
Intertidal salt marsh – brackish	<1.3	-	<15	-
Intertidal salt marsh – saline	<1.3	-	15-40	-
Supratidal salt marsh	> 1.3	-	~	-
Mangroves		-	<40	Sediment can smother lenticels on air roots
Reeds & sedges	< 2		<20	-
Submerged macrophytes – *Zostera capensis*	Exposure: < 20 min		<40	5 to 15% of surface intensity or
Submerged macrophytes – *Ruppia cirrhosa*	Exposure: < 20 min		<55	> 0.2 m Secchi transparency
Submerged macrophytes – *Stuckenia pectinata*	Exposure: < 20 min		<20	same
Macroalgae	Exposure: < 20 min		<40	N/A

3.4.2.3 Fish

The most widely classification used for estuarine fish has been that of Whitfield (1994), although more recent refinements have been applied based on functional use categories more globally applicable (e.g. Elliot et al. 2007). For the purposes of building the fish conceptual models Whitfield's (2019) categorisation (Table 3.5) was used as a basis to classify fishes as:

- Estuarine resident: Species that complete their life cycles in South African estuaries (Whitfield's categories Ia and Ib)
- Estuarine dependent marine: Species that breed at sea with the juveniles depending on South African estuaries (Whitfield's categories IIa, IIb and Vb)
- Marine: Species which use South African estuaries opportunistically, but are not dependent upon these systems to complete their life cycles (Whitfield's categories IIc and III)
- Freshwater: Species that can (and mostly do) complete their life cycles in freshwater (Whitfield's category IV)
- Catadromous: anguillid eels, which use estuaries only as transit routes between the marine and freshwater environments (Whitfield's category Vb).

Table 3.5: Estuary-association Categories applied to fish conceptual models (modified from Whitfield 2019)

CATEGORIES	DESCRIPTION OF CATEGORIES
I	Estuarine species which breed in southern African estuaries. This category includes resident species that spawn only in estuaries, as well as species that also have marine or freshwater breeding populations.
II	Euryhaline marine species which usually breed at sea, with the juveniles showing varying degrees of association with southern African estuaries. Further subdivided into:
IIa	Juveniles dependent on estuaries as nursery areas.
IIb	Juveniles occur mainly in estuaries but are also common at sea.
IIc	Juveniles sometimes occur in estuaries but are more abundant at sea
III	Marine stragglers which occur in estuaries in very small numbers and are not dependent on these systems.
IV	Freshwater species whose penetration into estuaries is determined primarily by salinity tolerance. This category includes a species which may breed in both freshwater and estuarine systems. It also includes as some freshwater stragglers that are seldom recorded in estuaries.
V	Obligate catadromous species which use estuaries as transit routes between the marine and freshwater environments.

Fish species in categories I, II, and V as defined by Whitfield (1994 and 2019) are all wholly or largely dependent on estuaries for their survival and are hence the most important from an estuary conservation perspective. The degree of estuarine dependence varies intraspecifically and between assemblages in the different biogeographical regions (Lamberth 2008). Some such as silver kob *Argyrosomus inodorus* have no estuary association in the warm temperate bioregion but occur in all predominantly open west coast systems (Lamberth 2008). Similarly, the degree of estuary association shown by the Knysna sand goby *Psammogobius knysnaensis* appears to decline from east to west and, in the latter region, is mostly confined to the surf-zone. However, this *psammophyllic* species is more widely distributed within (sandier) systems on the west coast. Fish that breed in estuaries and/or estuary residents comprise 10%-28% of estuarine fish assemblages on the cool temperate west coast as opposed to 4%-18% for those on the Warm-temperate east coast or 25% for those in the south coast transition zone between the two biogeographical regions. Excluding these species, obligate estuary-dependent marine fish such as white steenbras *Lithognathus lithognathus* comprise only 11% of estuarine fish assemblages in the cool temperate region compared to 22% on the warm temperate east coast. This is most likely a function of the few estuaries and lower probability of recruitment success on the west coast. Including estuary residents, obligate and partially dependent species, up to 48% of cool temperate and 61% of warm temperate estuarine fish assemblages comprise species that have some degree of estuary association. Subtropical and tropical estuaries support the greatest diversity of fishes, with close to 160 species reported with some regularity (Whitfield 2019). Of these 24% are species that breed in estuaries, 53% are estuary-dependent marine fishes, 19% are marine stragglers and 5% are freshwater species that are tolerant of elevated salinities. Across systems, there is a high degree of heterogeneity in these percentages, driven primarily by estuarine category (temporarily open/closed estuaries vs permanently open systems).

There are of course also other ways of categorising, or grouping, components of estuarine fish assemblages. Feeding guilds are another common approach and in this respect, most South African species can be assigned to categories as being:

- Detritivores: Species that feed predominantly on detritus, deriving nutrition from bacteria on decaying vegetation and microphytobenthos

- Zooplanktivores: Species that feed on zooplankton, mostly small crustaceans
- Zoobenthivores: Species that feed on benthic invertebrates living on, or in the sediments
- Piscivores: Species that prey upon other fishes.

These categories are also not exhaustive and most estuarine fishes rely upon a variety of food sources. Many species feed across these categories, either opportunistically taking advantage of food and prey items that are easily available, or because of shifts in diet with ontogenetic development. In most species, ontogenetic changes involve shifts in diet from zooplankton to zoobenthos. These dietary shifts are extremely common and occur in size ranges of fishes that occupy estuaries. While not used as part of the classification systems, these feeding guilds will be used to express changes in the fish conceptual models. The response of fish to the generic abiotic states is also illustrated in conceptual models for each system (example presented in Figure 3.2c).

3.5 Integration of Assessment Results

To ensure alignment with existing estuarine health assessments conducted for South African estuaries (e.g. NBA 2018), the country's official Estuary Health Index (EHI), developed under the National Water Act (DWAF 2008; Turpie et al. 2012) was used to integrate assessment results in a compatible format. The index adopts an ecosystem-based approach that considers an array of abiotic (hydrology, hydrodynamics and mouth condition, sediment processes and water quality) and biotic (microalgae, macrophytes, invertebrates, fish, and birds) components. For this study, the abiotic components were simplified to three indicators, namely hydrology, hydrodynamics (mouth state and water level), and water quality (including salinity and nutrients), while the biotic indicators were simplified to three, namely microalgae, macrophytes and fish. For each of the abiotic and biotic components, the predicted state was estimated as a percentage (0-100%) of the natural state. Weighted averages for the abiotic and biotic indicators were then applied to attain a habitat and biotic health score, respectively. Finally, these habitat and biotic health scores were combined into a final health score, weighted equally (Figure 3.3).

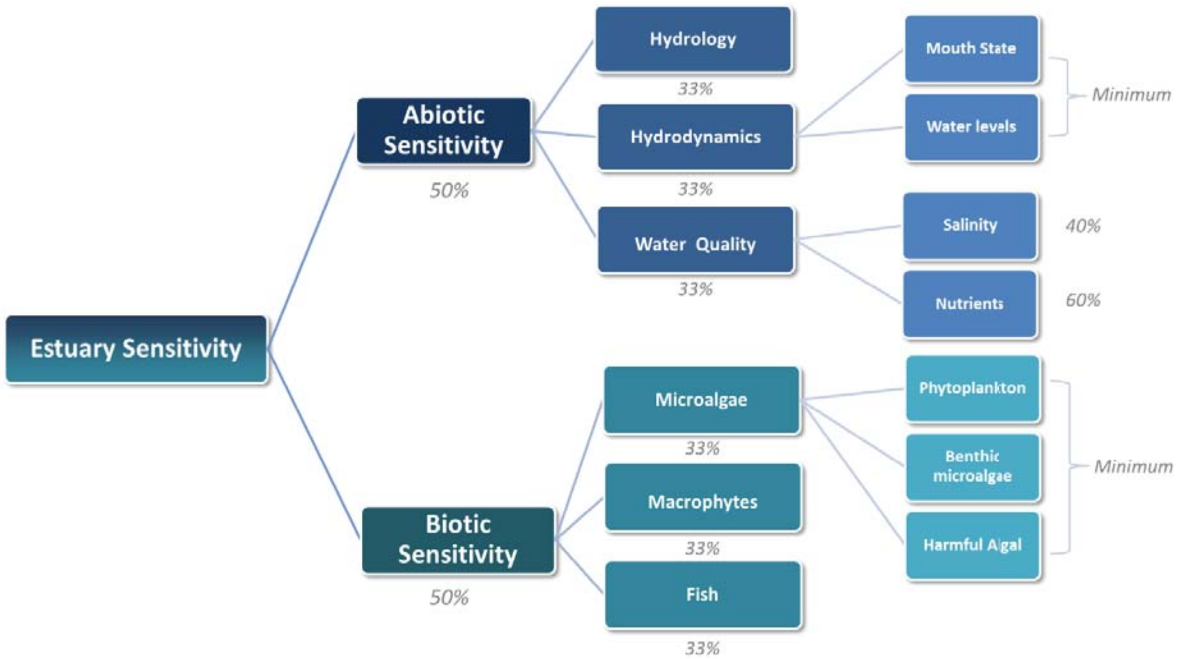


Figure 3.3: Abiotic and biotic components (and their relative weights) used to determine estuary sensitivity to Climate Change (modified from DWS 2008; Turpie et al. 2012)

As with the original index, these indicators were each categorised from natural (A) to critically modified (F) based on expected changes under each of the climate change scenarios (Table 3.6). Of note is that the A to F scale represents a continuum and that the boundaries between categories are conceptual points along the continuum as loss of estuarine functionality happens along a continuum (Van Niekerk et al. 2013). In estuaries, unlike the terrestrial environment, degradation or loss of habitat seldom means a complete loss of an estuary. 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. Generally, the physical conditions in estuaries are more dynamic when compared to other aquatic ecosystems, which means that severe degradation of an estuary often comprises 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 (Van Niekerk et al. 2013). In assessing and categorising shifts in estuary states, the term "trajectory of change" is used to define a directional change in the condition of abiotic and/or biotic components. A trajectory of change can be absent (close to natural or in a stable modified state), negative (moving away from reference conditions) or positive (moving back towards natural).

Table 3.6: Estuary health scoring system indicating the relationship between the six Ecological Categories and the loss of ecosystem condition and functionality (adapted from Van Niekerk et al. 2013)

Condition (% of natural)	≥91%	90-75	75 - 61	60 - 41	40-21	≤20
Ecological condition Category	A Natural	B Largely natural / few changes	C Moderately modified	D Largely modified	E Highly degraded	F Extremely degraded
Ecological State	NATURAL	NEAR NATURAL	MODERATE	HEAVILY	SEVERE/CRITICAL	
Functionality	Retain Process & Pattern (Representation)		Some loss of Process & Pattern	Significant loss of Process & Pattern	Little remaining Process & Pattern	

Category	Description
A	**Unmodified, 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	**Near 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	**Heavily modified**. A large shift natural processes and ecosystem functions and/or loss of habitat, biota have occurred.
E F	**Severely modified**. The loss of natural habitat, biota and basic ecosystem functions is extensive. **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.

This integration of assessment to determine the present state and each system's future sensitivity to climate-induced shifts in the abiotic and biotic processes was performed during a virtual workshop attended by a group of estuarine scientists using available information and their expertise on estuaries, including estuarine lakes.

3.6 Development of Adaptation and Mitigation Strategies

The development of the adaptation and mitigation strategies draws from several inputs, namely:

- Learning from the Climate Vulnerability Assessment;
- Review of international approaches;
- Incorporating existing national strategies (e.g. National Biodiversity Assessment, Blue Carbon Assessment);

- Proposed Mitigation and Adaptation Strategies for Estuarine Lakes; and
- Refinement through focus stakeholder workshop with estuarine managers.

3.7 Data Availability and Confidence

Data availability was not evenly distributed across the estuarine lakes evaluated in this study as is summarised in Table 3.7 (as extracted from the *Review of available literature*, Van Niekerk et al. 2022). The least studied estuarine lake system is the Klein Estuary, although little is also known on the Verlorenvlei and uMgobezeleni, especially how these would have functioned under more natural conditions.

Table 3.7: Summary of data availability on estuarine lake systems for this assessment (Low=L, Medium=M, High=H)

STUARY	HYDROLOGY	HYDRODYNAMICS	SALINITY	WATER QUALITY (NUTRIENTS)	MICROALGAE	MACROPHYTES	FISH
Verlorenvlei	L	L	M	L	L	L	M
Bot/Kleinmond	H	H	H	L	L	M	H
Klein	H	H	H	L	L	H	H
Heuningnes	H	H	H	L	L	H	H
Wilderness	H	H	H	H	L	M-H	H
Swartvlei	H	H	H	H	L	M-H	M-H
uMgobezeleni	L	L	L	L	L	L	L
Kosi	L	H	M	L	L	M	M-H

Table 3.8 summarises the overall confidence in the various aspects of the Climate Change Vulnerability Assessment.

Table 3.8: Summary of confidence in components of the vulnerability assessment (Low=L, Medium=M, High=H)

ESTUARY	CLIMATE MODEL RESULTS	WATER BALANCE MODEL	HYDROLOGY	HYDRODYNAMICS	SALINITY	WATER QUALITY (NUTRIENTS)	MICROALGAE	MACROPHYTES	FISH
Verlorenvlei	M-H		L	L	H	L-M	L	M	H
Bot/Kleinmond	M		L	M	M	M	L	M	H
Klein	M-H	Y	L	M	H	M	L	H	M
Heuningnes	M		L	M	M-H	M	L	H	H
Wilderness	M-H		L	M	H	H	M	M	M
Swartvlei	M-H	Y	L	M	H	L-M	L	M	M
uMgobezeleni	M-H		L	L	H	L	M	M	M
Kosi	M-H	Y	L	H	M-H	M	M	L	H

For the Bot/Kleinmond and Heuningnes systems, the climate ensemble model results (Deliverable 2) were out of sequence with regional trends, thus less confidence is attached to the outputs for those systems. Specifically, further clarity is required on the impact of local topography and marine conditions in the forcing of the climate models for these systems. Also, important to acknowledge was that the baseline climate model outputs do not reflect the intensity of droughts experienced at present in some systems. Further, the approach followed here may further have dampened some of this signal especially given the water-stressed nature of some of the catchments.

Detail water balance models (linked to abiotic states) were only available for a few estuarine lakes, namely Klein, Swartvlei and Kosi, that allowed for a more systematic form of assessment for these systems. However, it should be noted that the Kosi model was only for 17 years and did not include cyclone or drought events. In other systems connectivity was directly deducted from inflow patterns and abiotic conditions derived from the duration of the closed state. No models were available for Verlorenvlei and uMgobezeleni systems. Results were largely based on relative freshwater inflow patterns and therefore are of very low confidence. No direct rainfall-runoff coupling was undertaken in the modelling of the future climate change inflow scenarios to the estuaries. Therefore, while the approach followed here will provide information on the trajectory of change because of predicted climate change, it is at a relatively low level of confidence, especially when interpreted at monthly time scales.

Confidence in the hydrodynamics assessment, reflecting the change in the mouth state and associated water levels, varied between low to medium, depending on the availability of data and information. To accurately predict change in mouth state and water levels requires detailed information on berm heights, total inflows, seepage losses, evaporation losses, groundwater inputs, and coastal storms. In most cases, detailed information was not readily available and was derived from limited data and expert opinion. Confidence was especially low in some RCP4.5 mid and far-future scenarios which were relatively like the present state.

Overall confidence in salinity change was relatively high given that many of the lake systems have stable salinity regimes that show relatively little sensitivity to flow changes, except for the Bot/Kleinmond, Heuningnes and Kosi where data availability was insufficient to resolve complexity. Very little measured data was available on the water quality (using nutrient dynamics as proxy) for estuarine lake systems, except for the Touw/Wilderness and Swartvlei systems. Overall confidence in this component is therefore low.

Little information also was available on the microalgae component of most of the estuarine lake systems. Overall, the confidence was higher in the phytoplankton and benthic microalgae assessments than in the harmful algae evaluation, the latter mostly relying on field observations and anecdotal evidence. The macrophyte assessment relied on a combination of historical and recent maps and Google Earth which were generally available for all the lake systems, and as a result, confidence ranged between medium to high. From a fish perspective, shallow estuarine lake systems are very dynamic and go through event-scale fluctuations, and as a result fish communities in these goes through boom-and-bust cycles that are relatively resilient to change. On the other hand, the deeper systems are very stable, but once change is imposed, such change may be irreversible and represent a shift away from such stable states. Thus, overall confidence in the fish assessment of deeper systems was often lower as this aspect could not be addressed at a high level of confidence.

4. CONCEPTUAL MODELS OF ESTUARINE LAKES

4.1 Characterisation of Abiotic States in Estuarine Lake Systems

Estuarine lakes have unique system-specific characteristics relating to connectivity, morphological complexity, and salinity regimes (CSIR 1981, 2009, DWAF 2003, 2004, Van Niekerk et al. 2005, DWA 2009a, b, DWS 2014, 2016, Anchor 2015, 2018, Taljaard et al. 2018). Table 4.1 summarises the general characteristics of connectivity, morphological complexity, and salinity regimes in these systems. This insight is important in the development of conceptual models on the dynamics of lake systems, and to identify sub-categories within estuarine lake systems. Connectivity to the sea can occur via constricted inlet channels, fully functional estuaries, or in some cases, large estuarine lakes can be directly connected to the sea with no clearly defined channels (e.g. Klein).

From a temporal scale perspective, connectivity varies from permanently open to only open on near decadal scales. Estuarine lakes can comprise single basins, or they can occur as a series of linked lake systems (up to five), which can be linked through several meandering channels (e.g. Kosi has four connected lakes that are connected to the sea by a large shallow estuary). Across the country's estuarine lakes, average depth varies from 2 m to more than 30 m, with most lakes around 3 to 5 m. Most lake systems also have more than one river feeding them, while two systems are fed nearly exclusively by groundwater. Salinity regimes vary from 0 to 35, but most lakes are brackish to fresh, with some lakes showing a tendency to become hypersaline during dry periods.

This complexity is further compounded by the occurrence of a wide range of generic abiotic states that is observed in estuarine lake systems of South Africa. In total, seven open and five closed generic abiotic states were observed in the lakes systems that form part of this study. Table 4.2 provides a summary of typical abiotic conditions in each state focussing on mouth state, salinity regime and water levels as key distinguishing characteristics.

While there are individual lake differences in the states because of the interplay between bathymetry and freshwater input, some common features could nevertheless be grouped into the 12 states as listed in Table 3.2. Estuarine lakes can comprise single basins, or they can occur as a series of linked lake systems that are connected through several meandering channels. Kosi, for example, comprises four linked lakes that are connected to the sea by a large shallow estuary. Across the country's estuarine lakes, average depth varies from 2 m to more than 30 m, with most lakes typically 3 to 5 m deep. Most lake systems have more than one river feeding them, but two are fed nearly exclusively by groundwater. Salinity regimes vary from 0 to 35. Most lakes are brackish to fresh, but some show a tendency to become hypersaline during dry periods (Tables 3.1 and 3.2).

Table 4.1: Overview of connectivity, complexity and salinity regimes in South Africa's estuarine lakes under present conditions

ESTUARINE LAKE	CONNECTIVITY			MORPHOLOGICAL COMPLEXITY					SALINITY	
	# Mouths	Tidal exchange	Temporal scales	Inlet channel/ estuary	Lakes	Depth (m)	Connecting channels	Rivers	Inlet/ Estuary	Lakes
Verlorenvlei	1	Perched	1–4 yrs	Inlet channel	1	2.5 m (Max: 5)	-	1	0-110	Fresh
Zeekoevlei	1	Perched	Open (100%)	Canalised	2		2	2	0-100	Fresh
Bot/Kleinmond	2	Tidal/ Constricted	1-4 yrs	Estuary (Kleinmond)	1 (Bot)		1 (Rooisand)	2/1	0-35 (Kleinmond)	0–45 Bot
Klein	1	Tidal	1-2 yrs	-	1	3 (Max: 2)	-	2	-	0-40
Heuningnes	1	Tidal	Open (95%)	Estuary	1			2	0-45	0-6
Touw/Wilderness	1	Tidal	1-3 yrs	Estuary (Touw)	3 (Wilderness)	4-6 (Max:7)	3	1/2	0-35	0-20
Swartvlei	1	Tidal	1-4 yrs	Estuary	2	5 (Max: 17)		3 + Groundwater	0-35	5-12
St Lucia/uMfolozi	2 (during floods)	Tidal	1-10 yrs	Estuary (Narrows)/ Estuary	3	1/1 (Max: 3 /2)	1	5 / 2 + Groundwater	0-35	0-250
uMhlathuze	2	Tidal/Tidal	Open (100%)	-	2	1/12 (Max: 2/20)	2	2/3	- -	0-35 35
iNhlabane	1	Constricted	>1 yr	Estuary	1	2 (Max: 5)		1	0-35	0
uMgobezeleni	1	Constricted	Open (99%)	Inlet channel	2	3 (Max: 5)	2	Groundwater +2		Fresh
Kosi	1	Tidal	Open (99%)	Estuary	4+1 (Zilonde)	3 (Max: 31)	4	Groundwater + 3	0-35	0-20

Table 4.2: Description of generic abiotic states occurring in South Africa's estuarine lake systems

ESTUARY	OPEN ABIOTIC STATES							CLOSED ABIOTIC STATES					
	Fresh	Marine/ Fresh	Gradient	Marine/ Brackish	Marine	Marine/ Hypersaline	Hypersaline	Fresh	Brackish	Gradient	Marine/ Brackish	Marine	Hypersaline
Verlorenvlei	●							●	●				
Zeekoevlei	●												
Bot/Kleinmond					●			●	●			●	●
Klein	●		●		●				●			●	
Heuningnes	●		●		●		●		●				●
Touw/Wilderness	●		●					●	●		●		
Swartvlei	●		●						●	●		●	
St Lucia/uMfolozi					●	●	●	●		●			●
iNhlabane	●							●					
uMhlathuze			●		●								
uMgobezeleni	●							●					
Kosi	●	●	●	●							●		

	ABIOTIC STATE	STATE DESCRIPTION
OPEN	Fresh	Mouth is open and the system is (nearly) fresh throughout. Average water levels. Can have elevated water levels due to flooding for short periods.
	Marine/ Fresh	Mouth is open with limited salinity penetration in lower reaches (estuarine zone), while lakes are generally fresh. Average water levels.
	Gradient	Mouth is open and full salinity gradient is observed throughout the system. Average water levels.
	Marine/ Brackish	Mouth is open and salinity varies from marine (near mouth) to brackish. Average water levels.
	Marine	Mouth is open and a marine salinity regime is observed throughout the system. Average water levels.
	Marine/ Hypersaline	Mouth is open and the salinity regime varies from marine to hypersaline in parts of the system. Average to low water levels. Some parts of the system may become isolated.
	Hypersaline	Mouth is open and most of the lake system is hypersaline. Very low water levels.
CLOSED	Fresh	Mouth is closed and the system is nearly fresh throughout. High to very high-water levels.
	Brackish	Mouth is closed and the system is brackish throughout. High water levels.
	Gradient	The mouth is closed, and partial longitudinal salinity gradient is observed. High water levels.
	Marine/ Brackish	Mouth is closed and salinity regime varies from marine to brackish in parts of the system. Low water levels.
	Marine/ Hypersaline	Mouth is closed and salinity regime varies from marine to hypersaline in parts of the system. Very low water levels, some littoral habitats may be exposed, or parts of lakes isolated from larger system.

4.2 Conceptual models of Individual Systems

4.2.1 Verlorenvlei

Assessment Level
Desktop
Probability of Outcome
Likely (66 -100%)

The surface area of Verlorenvlei is estimated to be 198 000 ha (Figure 4.1) with an average water area depth between 2 and 3 metres with a maximum depth of 5 metres (Robertson 1980). A small channel of about 2.6 km connects the lake to the sea. The entire channel is very shallow (about 0.5 m deep), tending to inhibit free water exchange. During the dry summer months, the mouth is usually closed by a sandbar overlying a rocky sill and the channel may be reduced to a few series of stagnant saline pools. The bar is formed by wave action and a south-going longshore current in combination with frequent onshore winds. When good rains provide sufficient water, the lake and lower estuary fill and the bar is overtopped. The outflowing water scours the sandbar away thus permitting some tidal interaction. Verlorenvlei normally functions as a freshwater system as the mouth is perched and only allows occasional seawater inflow during high spring tides and stormy conditions at sea.

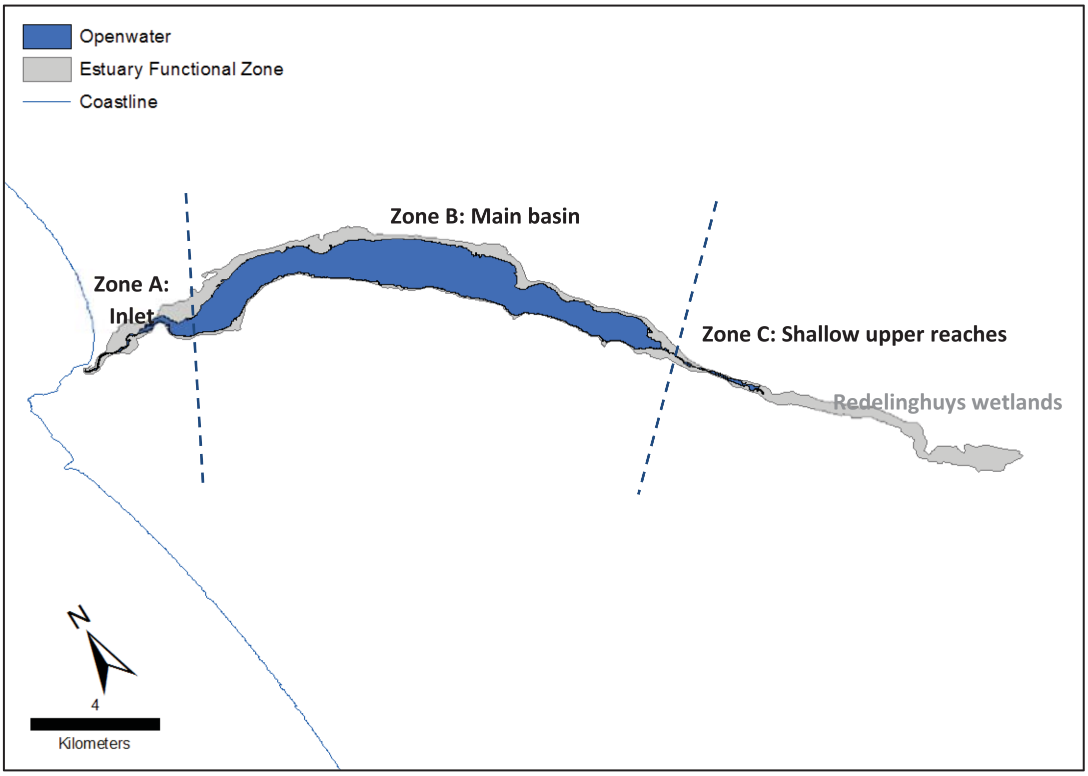


Figure 4.1: Verlorenvlei Estuarine Lake EFZ, openwater area and proposed zonation

The lake systems can be zoned into three homogeneous zones (Van Niekerk et al. 2009). A small inlet channel (~2.6 km) in the lower estuary connects the larger lake (or basin) to the sea (Zone A). The inlet channel is very shallow (about 0.5 m deep). The main basin (Zone B) has an average depth of between 2-3 m with a maximum depth of 5 m (Robertson 1980). The Verlorenvlei River feeds the system through a series of wetlands at Redelinghuys into a shallow upper reach (Zone C) that back floods under closed mouth conditions. The characteristic abiotic states (and associated distinctive temporal patterns) for the Verlorenvlei are illustrated conceptually in Figures 4.2 (see Table 4.2)

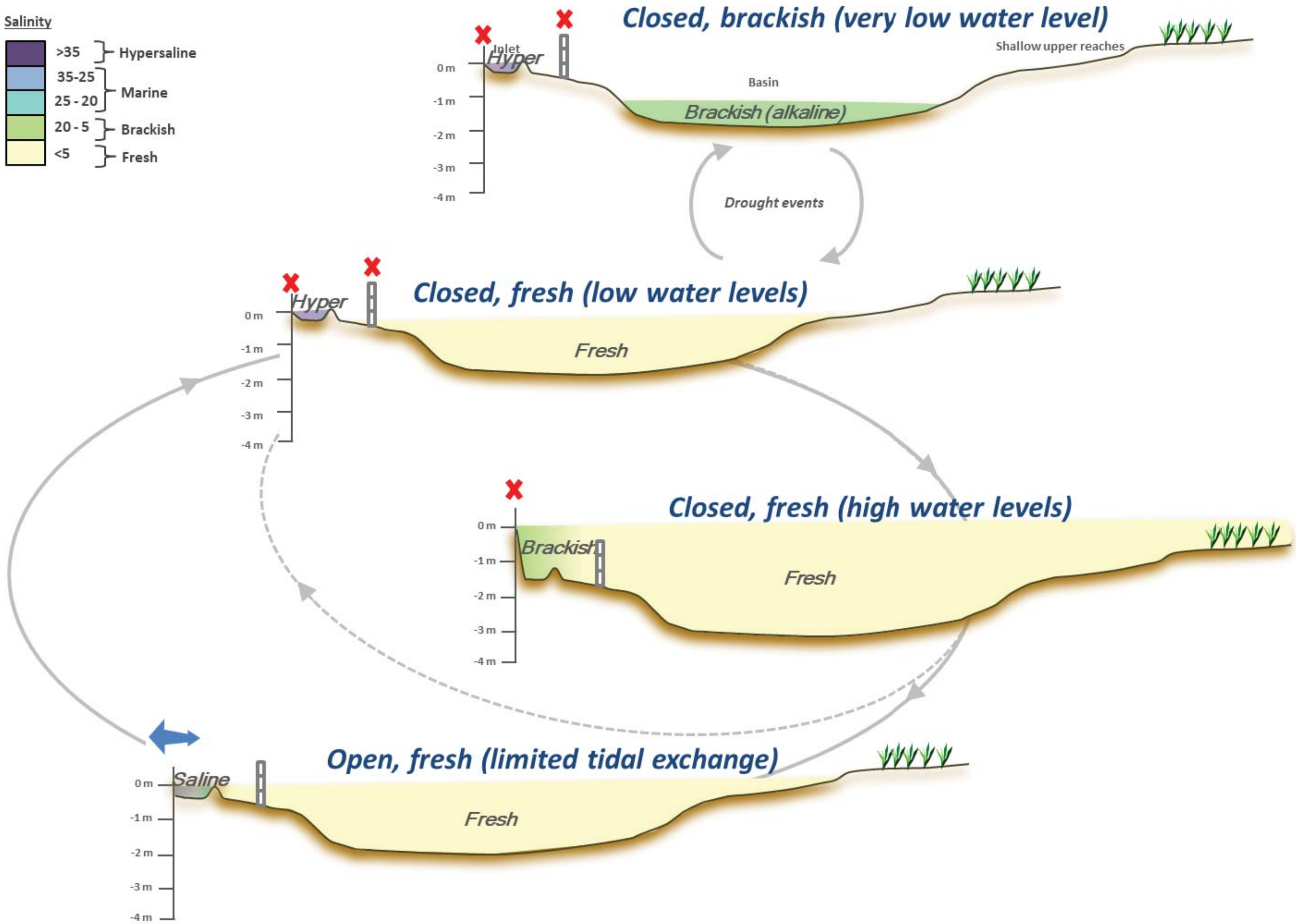


Figure 4.2: Verlorenvlei: Abiotic states

4.2.2 Zeekoevlei

Zeekoevlei is a U-shaped lake (Figure 4.3), divided into North and South basins. Its surface area is estimated at 2.56 km^2. Most freshwater inflow is into the North basin via two rivers, Big and Little Lotus, while the outflow to the sea is from the southwestern corner of the South basin through the Zeekoe Canal. The vlei is also fed by an extensive aquifer (Brown and Magoba 2009). Rondevlei, lying directly to the west, is considerably smaller than Zeekoevlei, covering an area of approximately 0.45 km^2. Its surface inflow is mainly from the road canals, and its outflow to the Zeekoe Canal is in the southeast corner. A natural link existed between the two vleis until 1943, at which time it was closed permanently and an outlet from Rondevlei was constructed to connect to the Zeekoevlei outlet canal (Brown and Magoba 2009).

At present, outflow from the vleis is concentrated in a narrow canal through the dune field at the mouth. The mouth of the canal is fixed by the Baden Powell Drive Road bridge. The system often partially dams up behind the 2 to 3 m high beach bar forming a shallow longshore 'lagoon'. Because of the high elevation, the 'lagoon' is usually perched and non-tidal. At times the meandering of the beach canal threatens road infrastructure, and the canal is straightened by the City of Cape Town, which significantly reduces the backwater area.

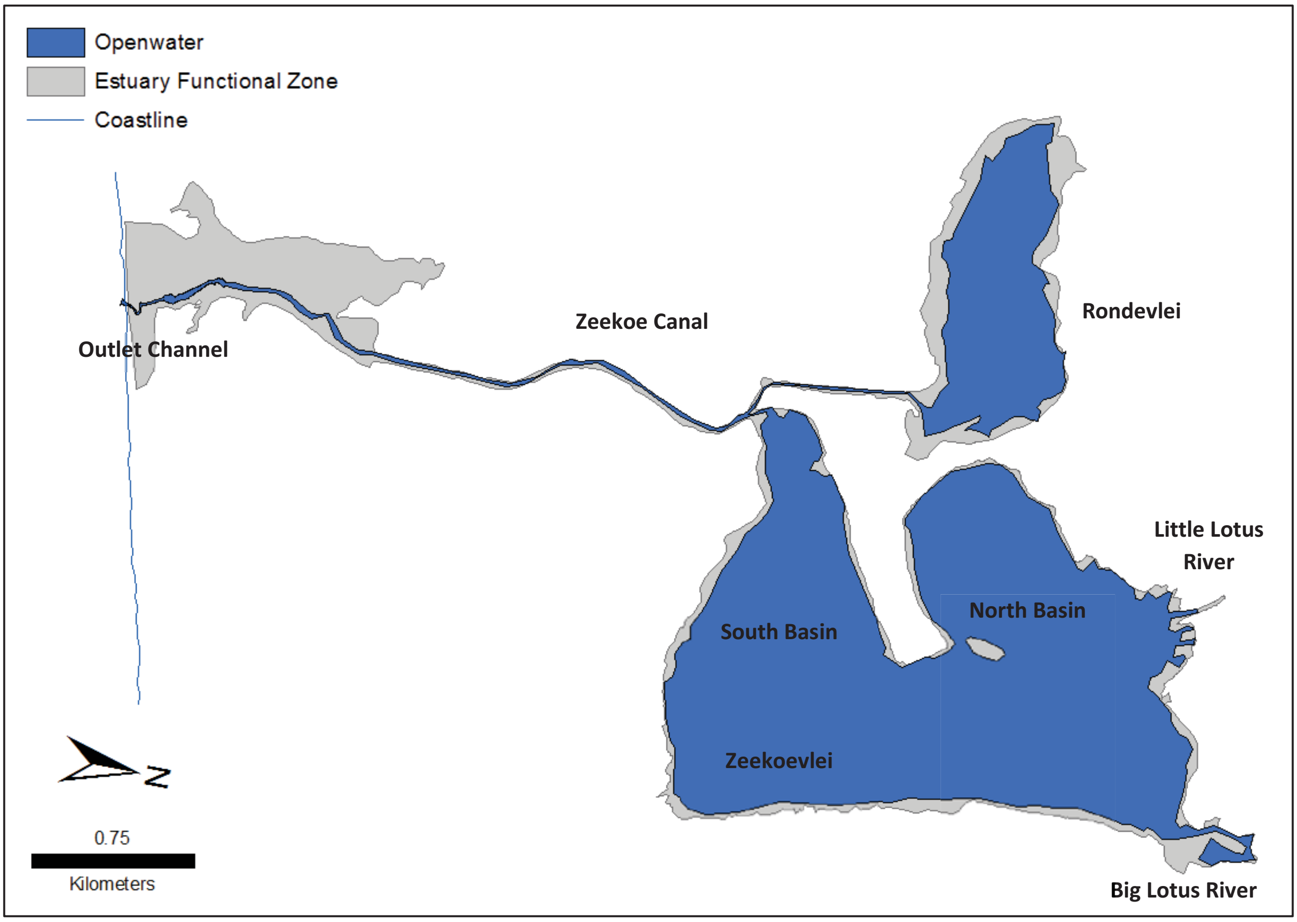


Figure 4.3: Zeekoevlei: EFZ and open water area

The Zeekoevlei and Rondevlei in their natural state would have functioned similarly to an estuarine lake taking a year or more to fill up and breaching once water levels were high enough to facilitate a cut-through of the coastal dune system. The resultant high outflow would have scoured a deep and wide outflow channel that could have remained open for 3 to 6 months at a time. After breaching saline water would have penetrated the system freely. The system would have been tidal during the open phase (possibly 10-20 cm on average). After a prolonged open period, mouth closure would have occurred that initially would be associated with low water level and even seasonally drying out of parts of the system. With persistent and increased inflows during the winter months, a period of elevated water levels would have followed. The mouth of the system would have migrated significantly from its present fix position. Old maps also show an outlet from Zeekoevlei to the sea, but this closed during the first quarter of the last century. In the past, water levels fluctuated greatly and in summer large marginal areas of the vlei became dry white sandflats. The water was brackish and formed a salt crust where it evaporated on the shore. Under present conditions, two weirs (at Rondevlei and Zeekoevlei) and the constricted channel obstruct flow and prevent natural fluctuations in water level. The Cape Flats Wastewater Treatment Works discharges effluent into the channel below the weir. The elevated inflows ensure that the mouth of the Zeekoevlei is now permanently open (Bickerton 1982).

The characteristic abiotic states (and associated distinctive temporal patterns) for Zeekoevlei are illustrated conceptually in Figures 4.4 (see Table 4.2)

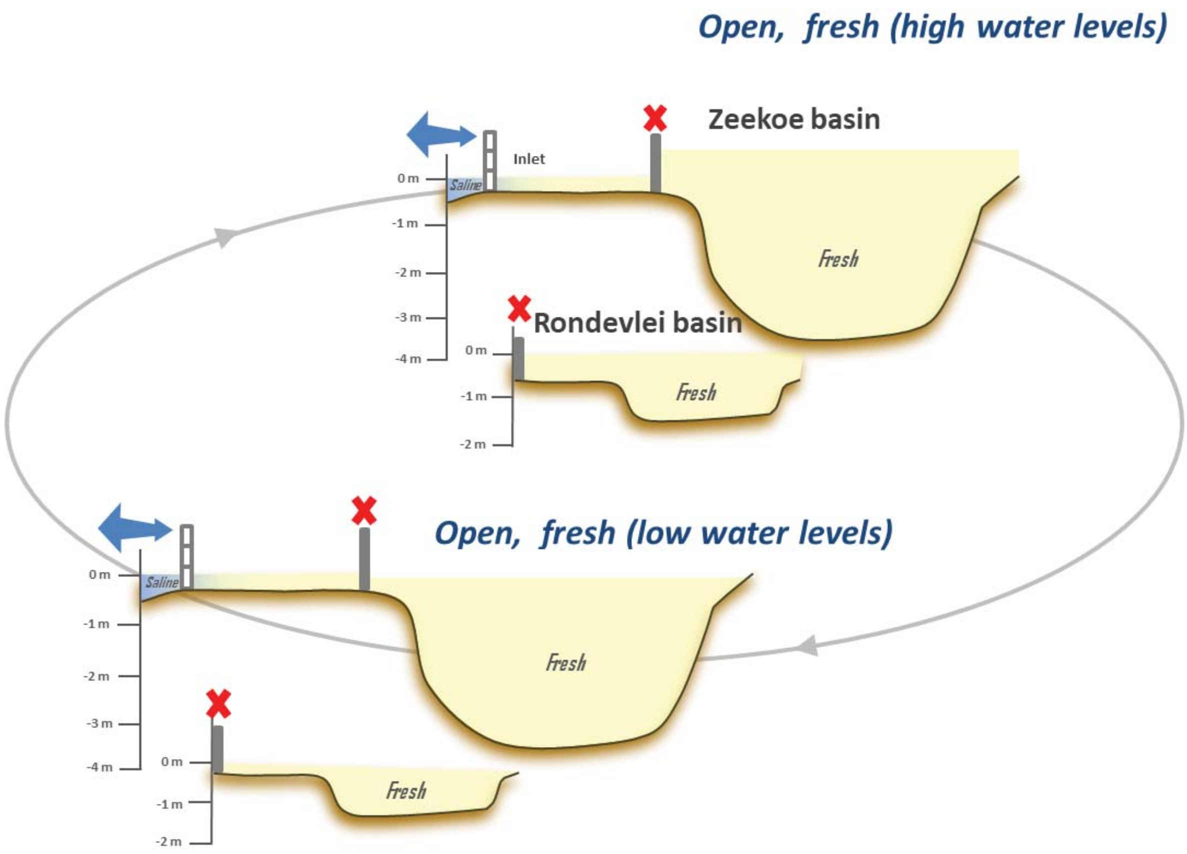


Figure 4.4: Zeekoevlei: Abiotic states

To reduce the amount of pollution entering the lake system during summer low-flow diversion weirs were constructed in the Lotus River catchment (Bickerton 1982). In 1997, a management scheme was initiated to improve water quality in Zeekoevlei that involved opening the sluice gates at the Zeekoevlei weir in late summer to draw down the water levels of the vlei. The previously solid weir was altered through the construction of six openings that permitted adjustment of water levels in the vlei, allowing for the release of up to 3 x10^{6}m^{3} from Zeekoevlei (~1.2 m drawdown). The first drawdown improved the functioning of the vlei through a reduction in the phytoplankton and improved light penetration. Drawdowns have taken place each year since then but the initial success in promoting a clear water phase has not been achieved again. The sluice gates on the weir were upgraded in 2007 so outflow mostly comprises contaminated bottom water.

4.2.3 Bot/Kleinmond

Assessment Level
Systematic
Probability of Outcome
Very Likely (90 -100%)

The Bot/Kleinmond system (Figure 4.5) is located on the south-western coast of South Africa some 110 km south-east of Cape Town (Koop 1982). The Bot and Bot/Kleinmond are connected via a natural overflow channel through the Lamloch swamps at a water level of 1.7 m MSL. When the joint system is breached at the Bot mouth, the Bot loses water at about 310 000 m^3 a day or approximately 0.11 m a week (Willis 1985). The Bot mouth is mostly closed (or 'blind') since it is cut off from the sea by a belt of coastal dunes. The valleys between the dunes are sufficiently low in some places to permit occasional overtopping by waves from the sea during exceptionally high tides.

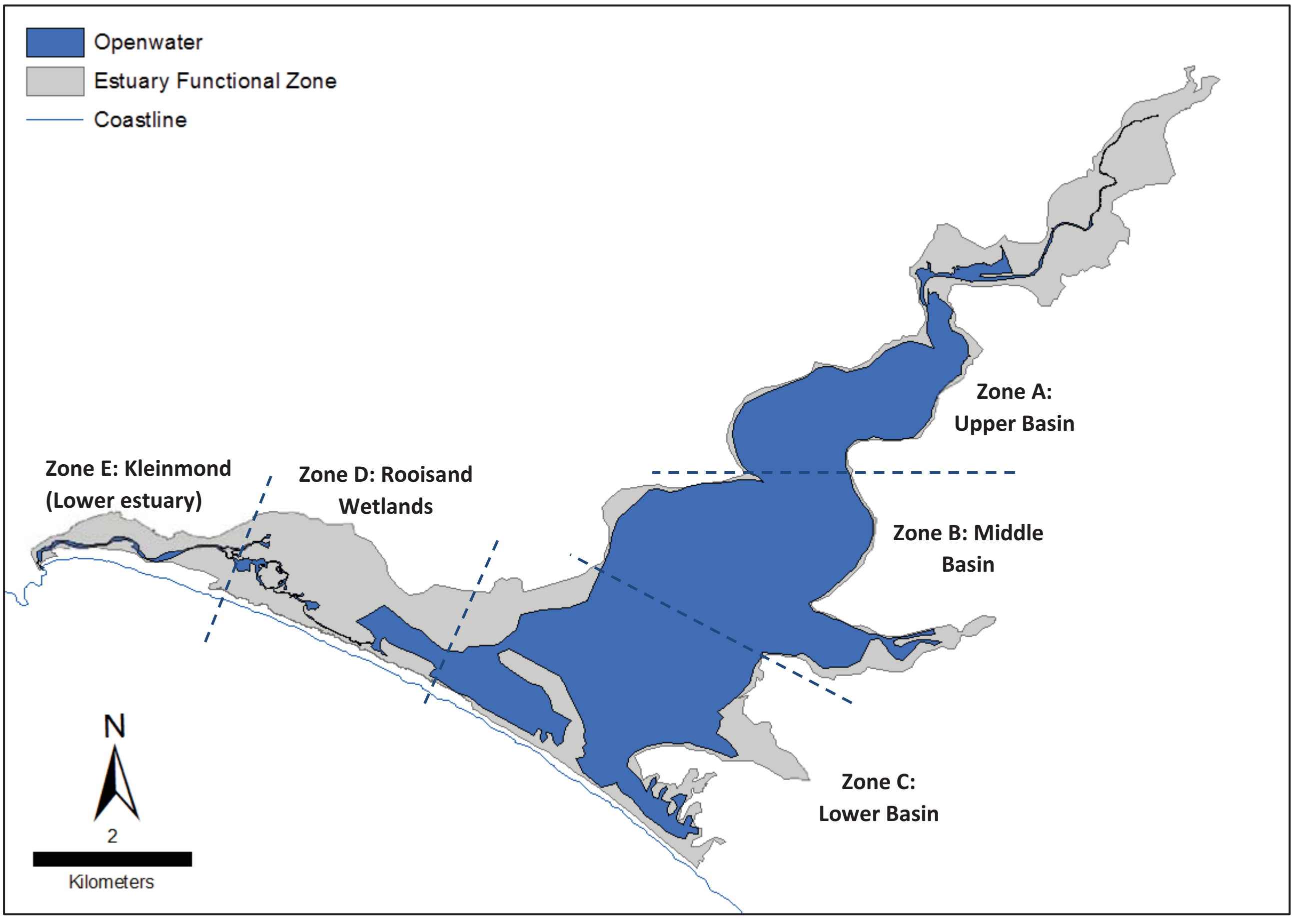


Figure 4.5: Bot/Kleinmond: EFZ, openwater area and zonation

The Bot/Kleinmond systems form a relatively shallow coastal lake, roughly 10 km long and a maximum width of about 2 km with a mean depth of -1.5 m MSL (Willis 1985). The Bot and Kleinmond are connected via a natural overflow channel through the Lamloch swamps at a water level of 1.7 m MSL. The system was sub-divided into five distinct zones using bathymetry (size and shape) and salinity distributions as indicators of more homogenous sections (Van Niekerk et al. 2010). The characteristic abiotic states (and associated distinctive temporal patterns) for the Bot/Kleinmond are illustrated conceptually in Figure 4.6 (see Table 4.2).

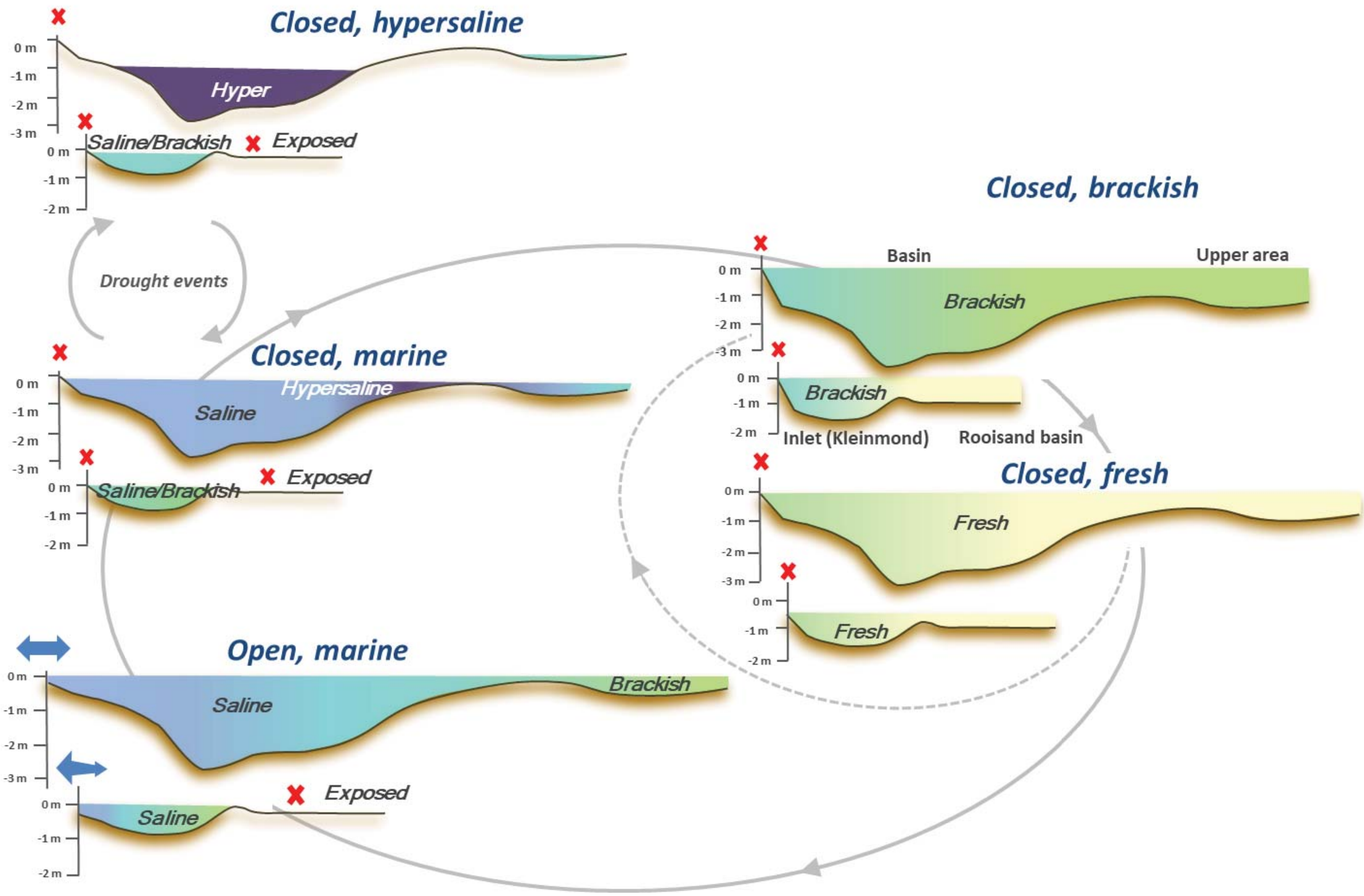


Figure 4.6: Bot/Kleinmond: Abiotic states

4.2.4 Klein

Assessment Level
Systematic
Probability of Outcome
Very Likely (90 -100%)

The Klein Estuarine Lake (Figure 4.7) is situated more or less midway between Cape Point and Cape Agulhas on the southwest coast within the Cool Temperate biogeographic region of South Africa. The system comprises a single connected lake (basin) directly linked to the sea. The main basin, is relative deep at about 4-6 m MSL, while the upper reaches and lower reaches of the basin, is shallower and more confined due to fluvial and marine sediment inputs respectively. The estuarine lake is mainly fed by the Klein River, with the much smaller Voëlgat River flowing into the main waterbody.

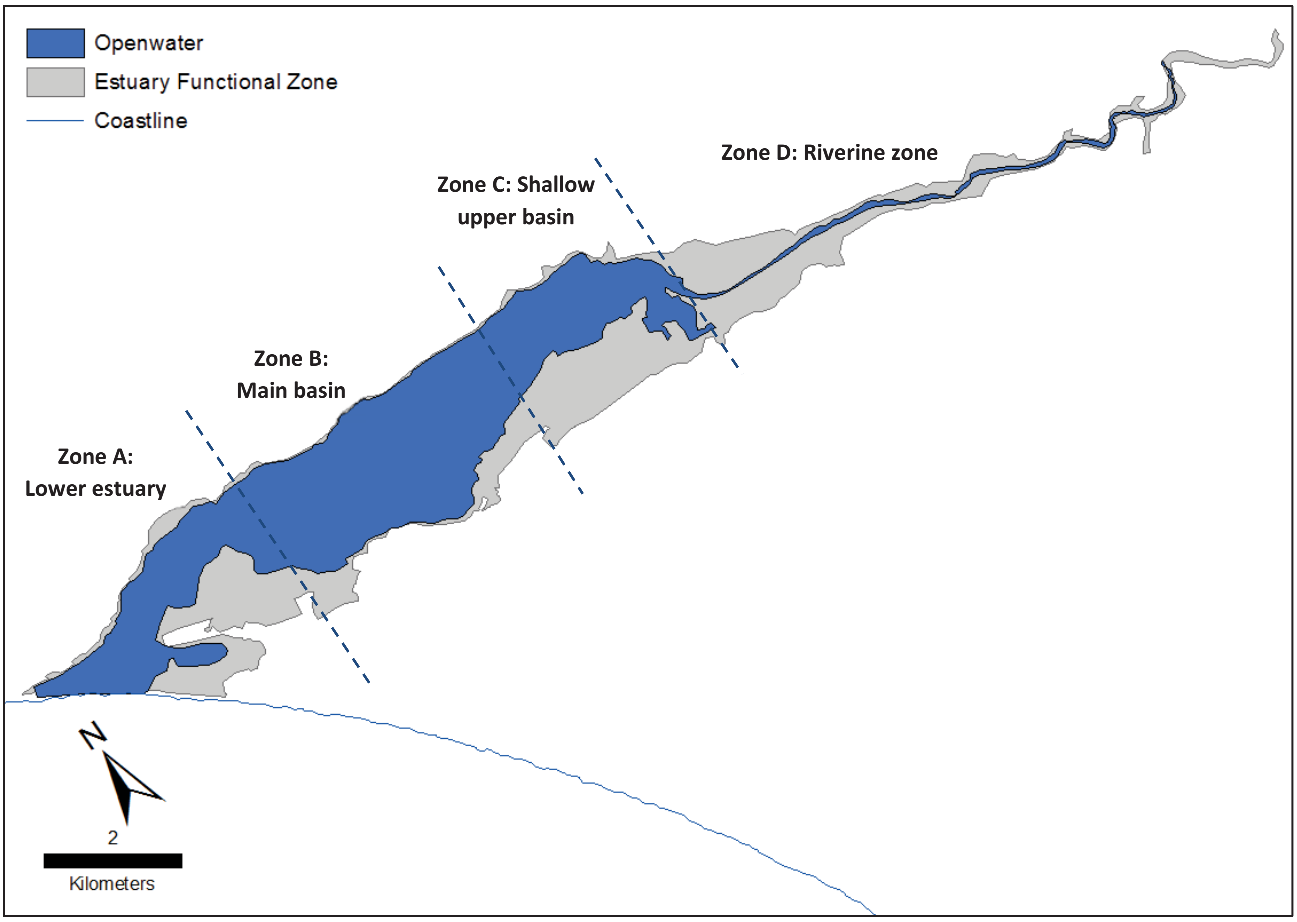


Figure 4.7: Klein: EFZ, openwater area and zonation

The Klein Estuarine Lake system comprises four relative homogenous zones (parts) that behave differently under different mouth states and associated water levels: a shallow lower reaches (A), a deeper main basin (B), shallow upper basin (C) the deeper riverine (D) section (Anchor 2015). The characteristic abiotic states (and associated distinctive temporal patterns) for the Klein are illustrated conceptually in Figures 4.8 (see Table 4.2).

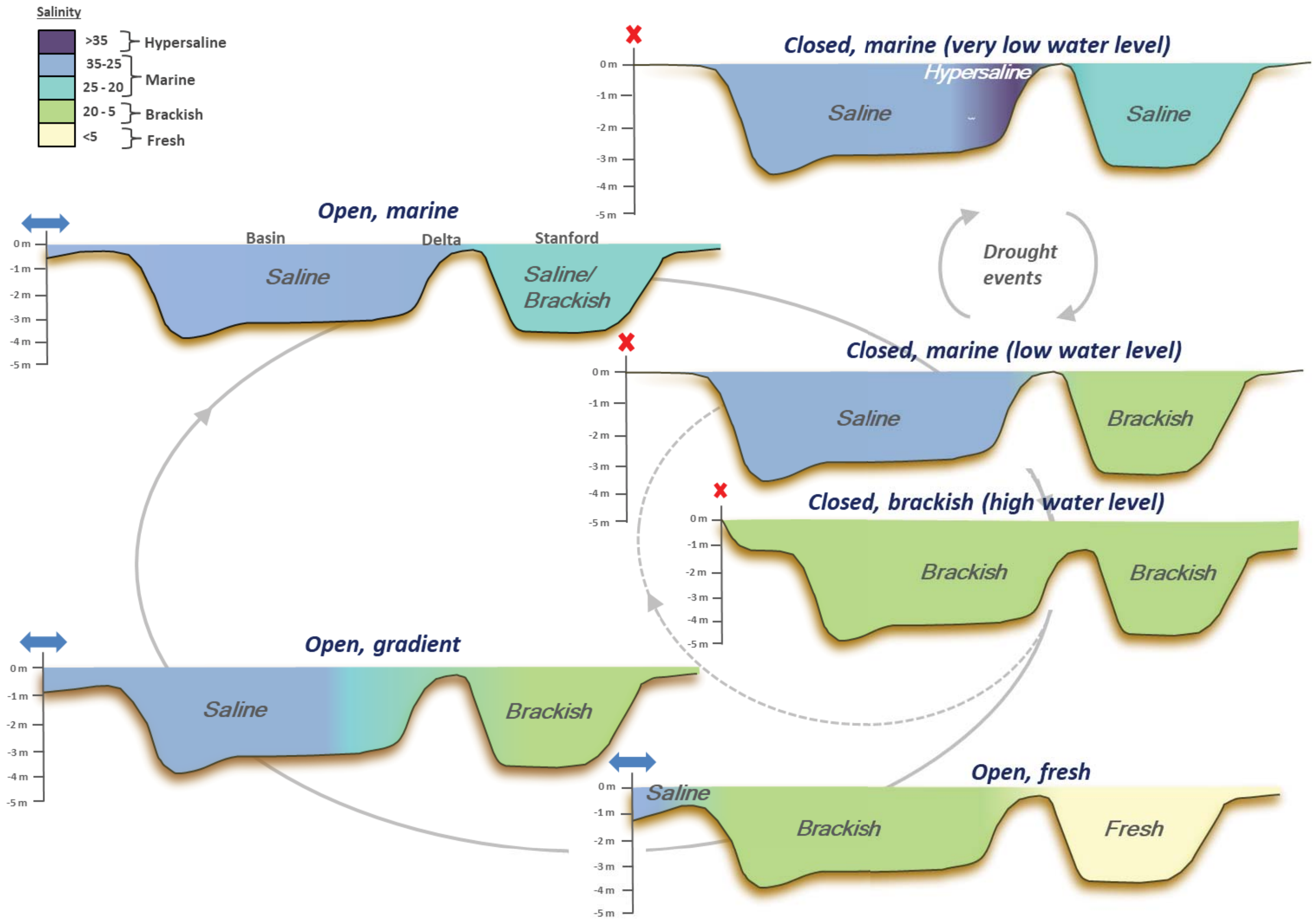


Figure 4.8: Klein: EFZ, openwater area and zonation

4.2.5 Heuningnes

Assessment Level
Desktop
Probability of Outcome
Likely (66 -100%)

The Heuningnes Estuarine Lake (Figure 4.9) system is located south of Bredasdorp and west of Arniston in the Overberg region of the Western Cape in South Africa. The catchment and lake system falls within the Agulhas Plain, an area that contains one of the largest lowland fynbos and Renosterveld habitats within the Cape Floral Region. Heuningnes Lake System is fed by two major tributaries, namely the Nuwejaars and Kars Rivers. The catchment of the Heuningnes has been given as 1 938 km² (Bickerton 1984).

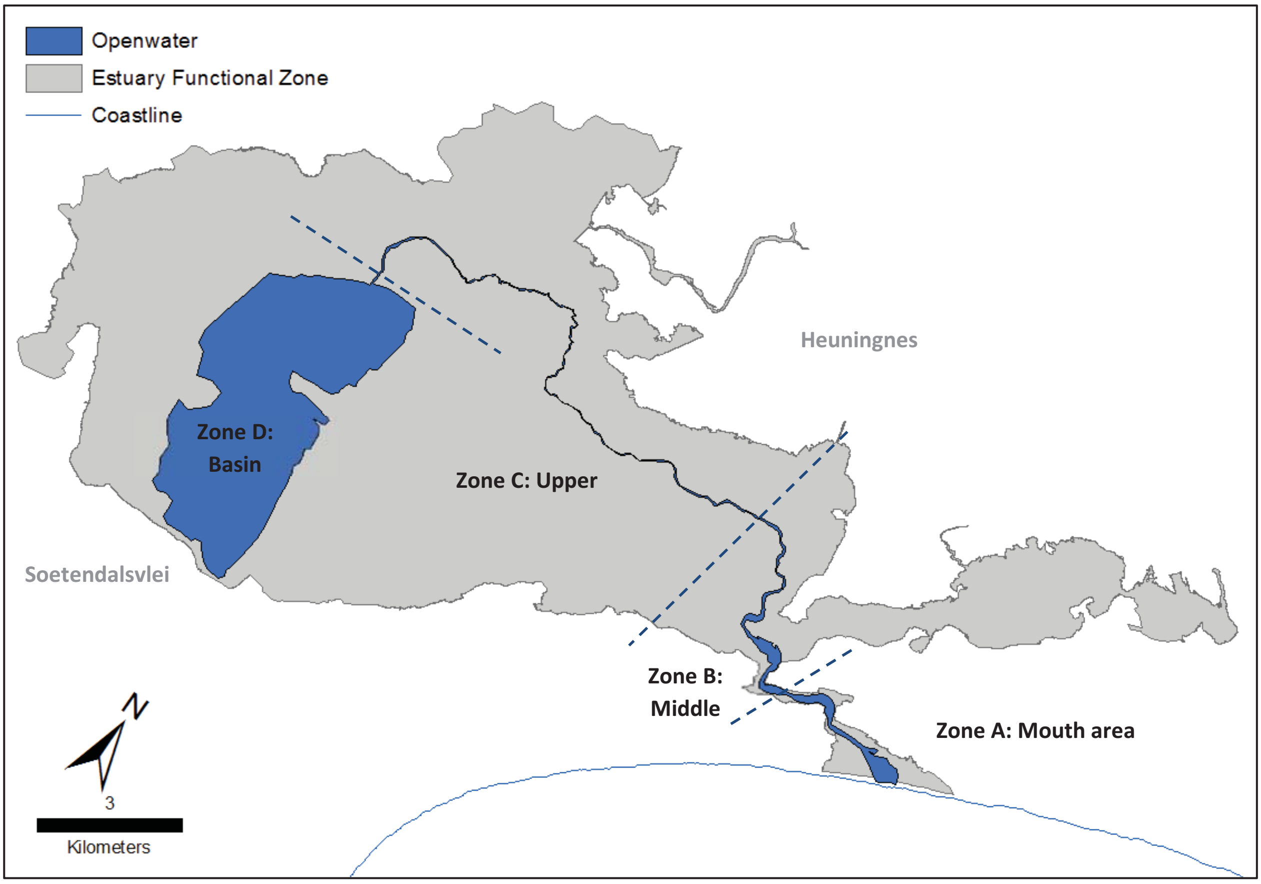


Figure 4.9: Heuningnes: EFZ, openwater area and zonation

The lower estuary is tidal to about 12 km upstream of the mouth, although most of the tidal influence is within the first 2 km. There are two major natural wetlands in the catchment, namely, Voëlvlei and Soetendalsvlei. Soetendalsvlei is within the EFZ of the lake system, and while not tidal, increases and decreases in water level occur depending on the mouth state of the system. Soetendalsvlei, comprising the lake area within this system, is approximately 8 km along its north/south axis and 3 km wide at the middle. The Heuningnes Estuarine Lake system can be divided into four zones (Figure 6.1) based on tidal exchange, bathymetry, and salinity regime (Anchor 2018). The tidal lower estuary (comprising Zone A: Mouth, Zone B: Middle; Zone C: Upper) and Zone D: Soetendalsvlei basin. The characteristic abiotic states (and associated distinctive temporal patterns) for the Heuningnes are illustrated conceptually in Figures 4.10 (see Table 4.2).

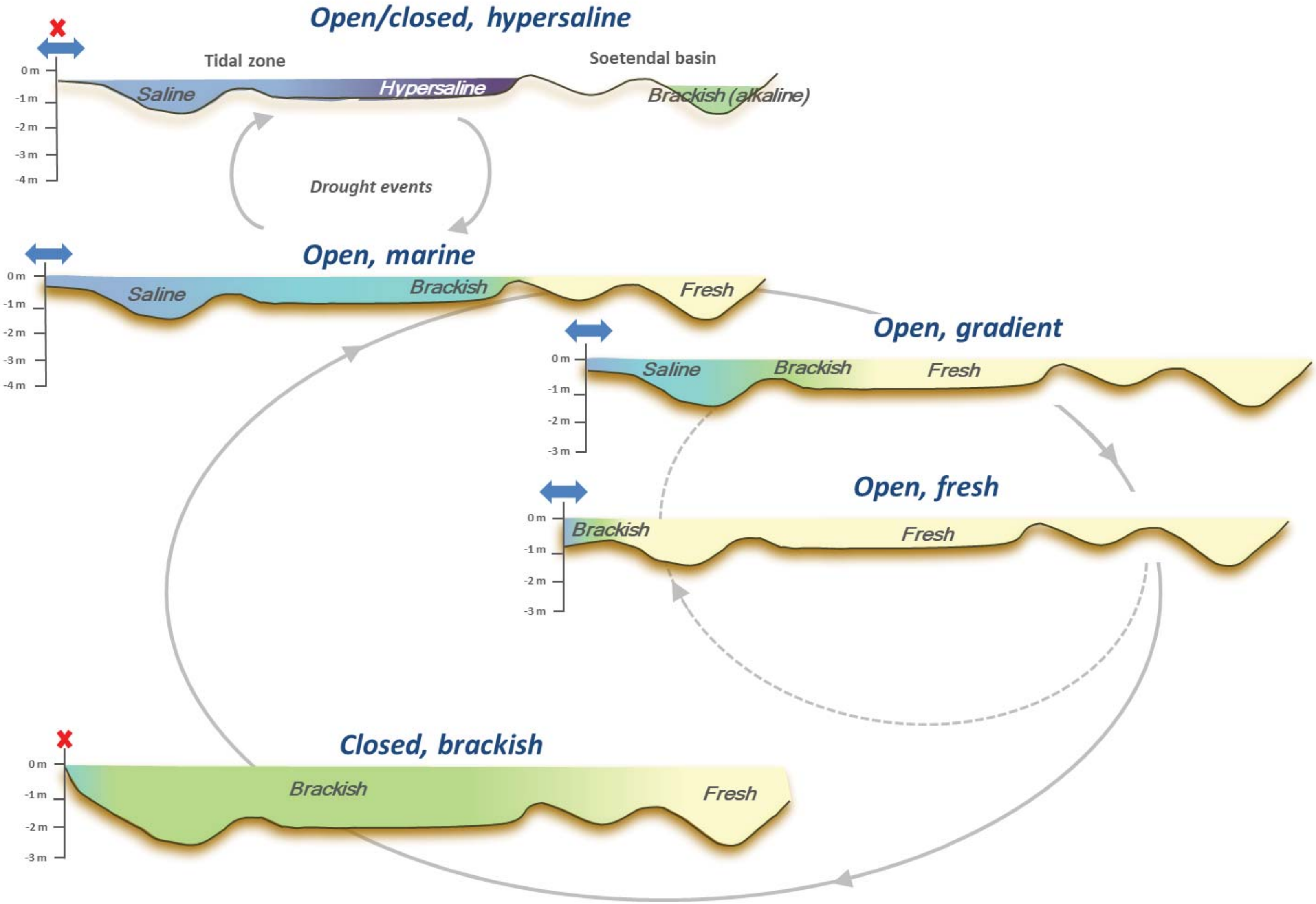


Figure 4.10: Heuningnes: Abiotic states

4.2.6 Touw/Wilderness

The Touw/Wilderness system (Figure 4.11) comprises a series of three coastal lakes (Eilandvlei, Langvlei and Rondevlei) interconnected by shallow channels and a temporarily open/closed tidal section (Touw). Although the Touw shows strong longitudinal gradients in physico-chemical characteristics, the Wilderness Lakes are more uniform. Variability in the Touw is seasonal whereas that in the lakes is more inter-annual (DWS 2014).

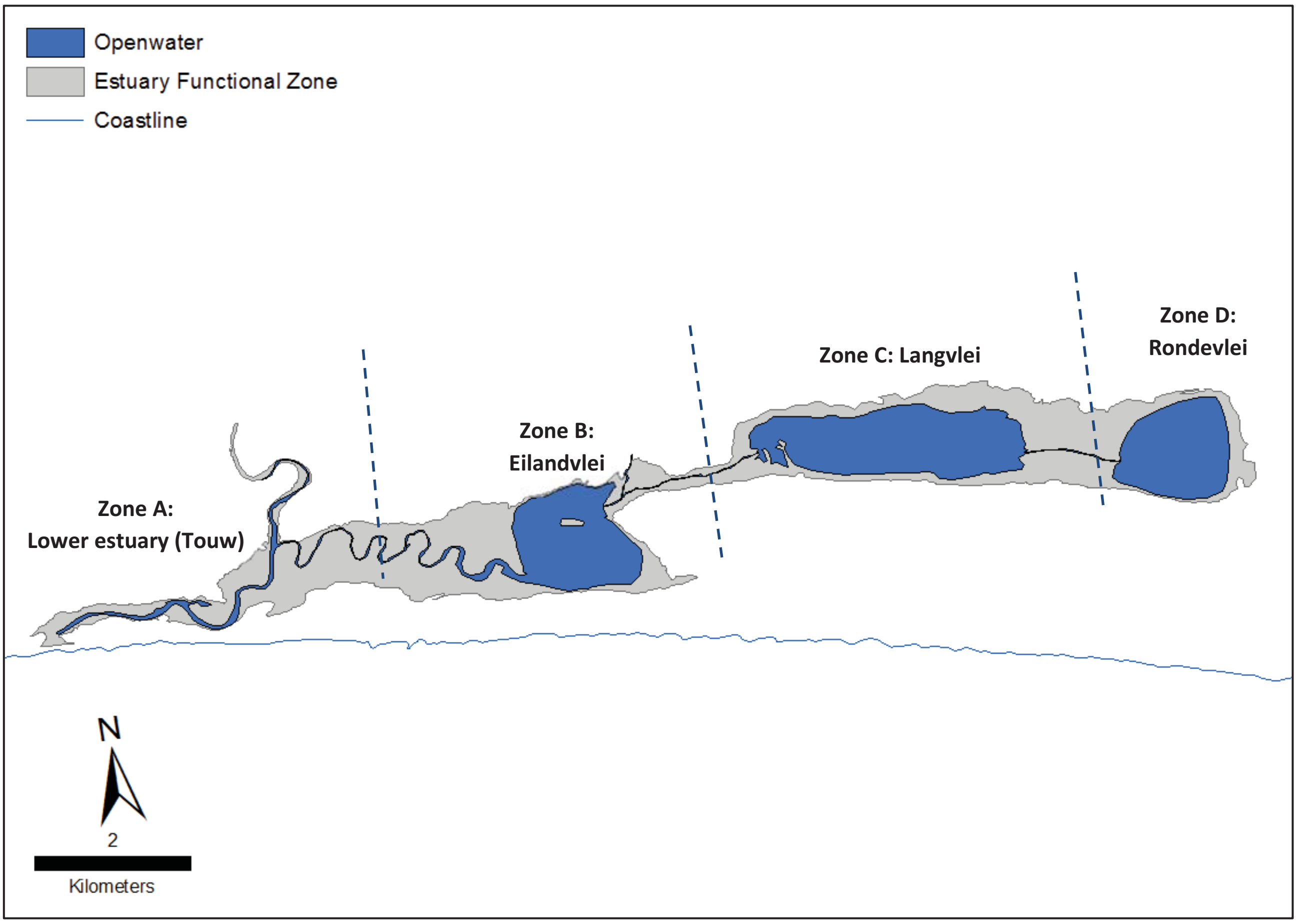


Figure 4.11: Touw/Wilderness: EFZ, openwater area and zonation

Under naturally occurring high lake levels there would have been a free connection between all the parts of the system when the mouth is closed (Fijen 1995). At present artificial breaching has reduced the lake levels by more than 1.5 m, resulting in loss of connectivity and dredging of link channels between the lakes to maintain connectivity. However, under drought conditions, Rondevlei can still be completely separated from Langvlei (Olds et al. 2016, Whitfield et al. 2017). The 2014 EWR study on the Touw/Wilderness System (DWS 2014) subdivided the system into Zone A: Touw (tidal section), Zone B: Eilandvlei, Zone C: Langvlei and Zone D: Rondevlei. The characteristic abiotic states (and associated distinctive temporal patterns) for the Touw/Wilderness are illustrated conceptually in Figures 4.12 (see Table 4.2).

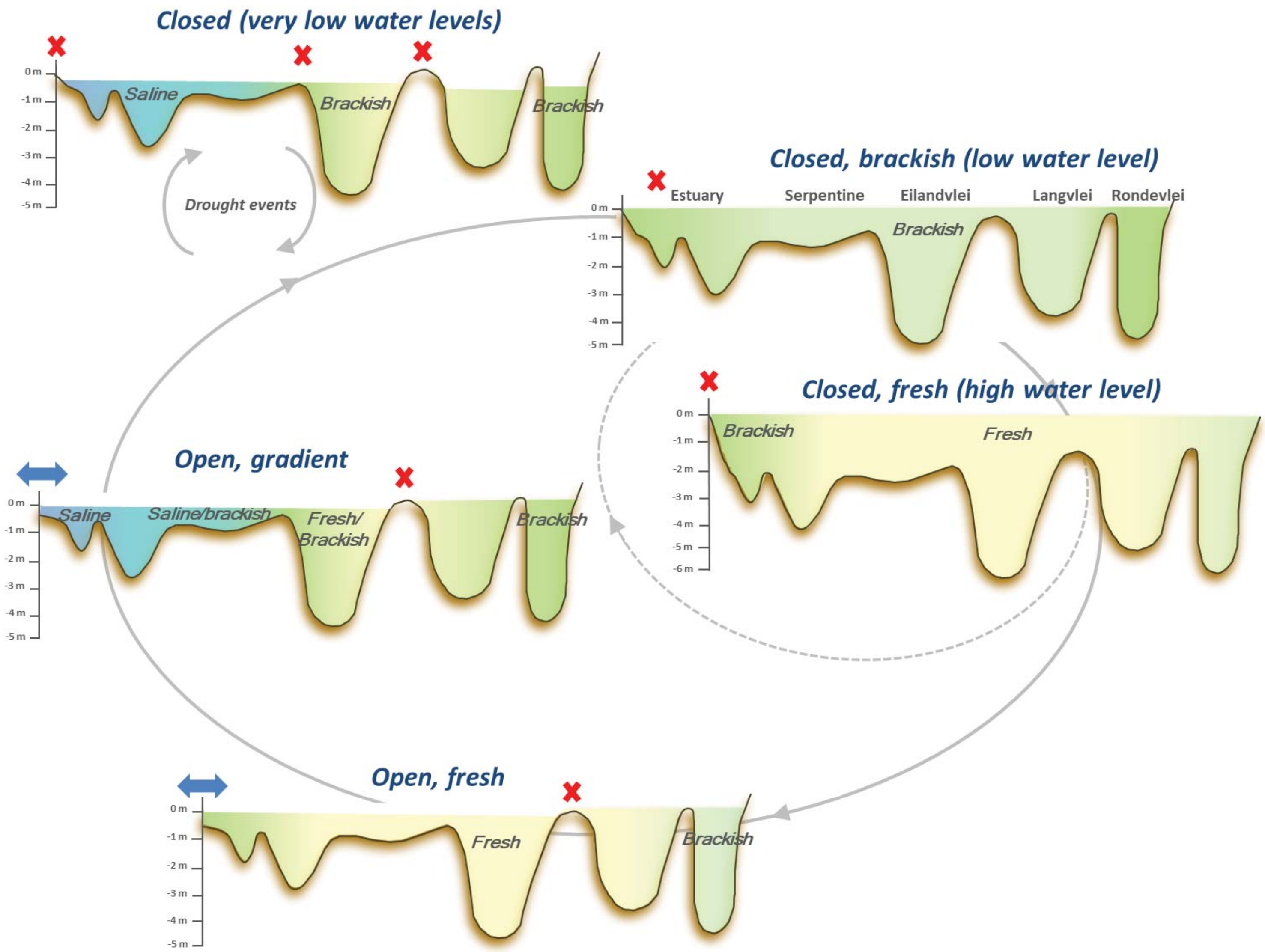


Figure 4.12: Touw/Wilderness: Abiotic states

4.2.7 Swartvlei

Assessment Level
Desktop
Probability of Outcome
Likely (66 -100%)

The Swartvlei Estuarine Lake (Figure 4.13) system is situated on the Cape south coast and is fed by three rivers that arise in the Outeniqua Mountain (Kok and Whitfield 1986). There are two connected but distinct parts of the system; the humic-stained upper reaches (Swartvlei) and the shallow sinuous lower estuary. The MAR to the systems was 83.4 million m^3 under Natural conditions, compared with 56.6 million m^3 under the present state (DWA 2009).

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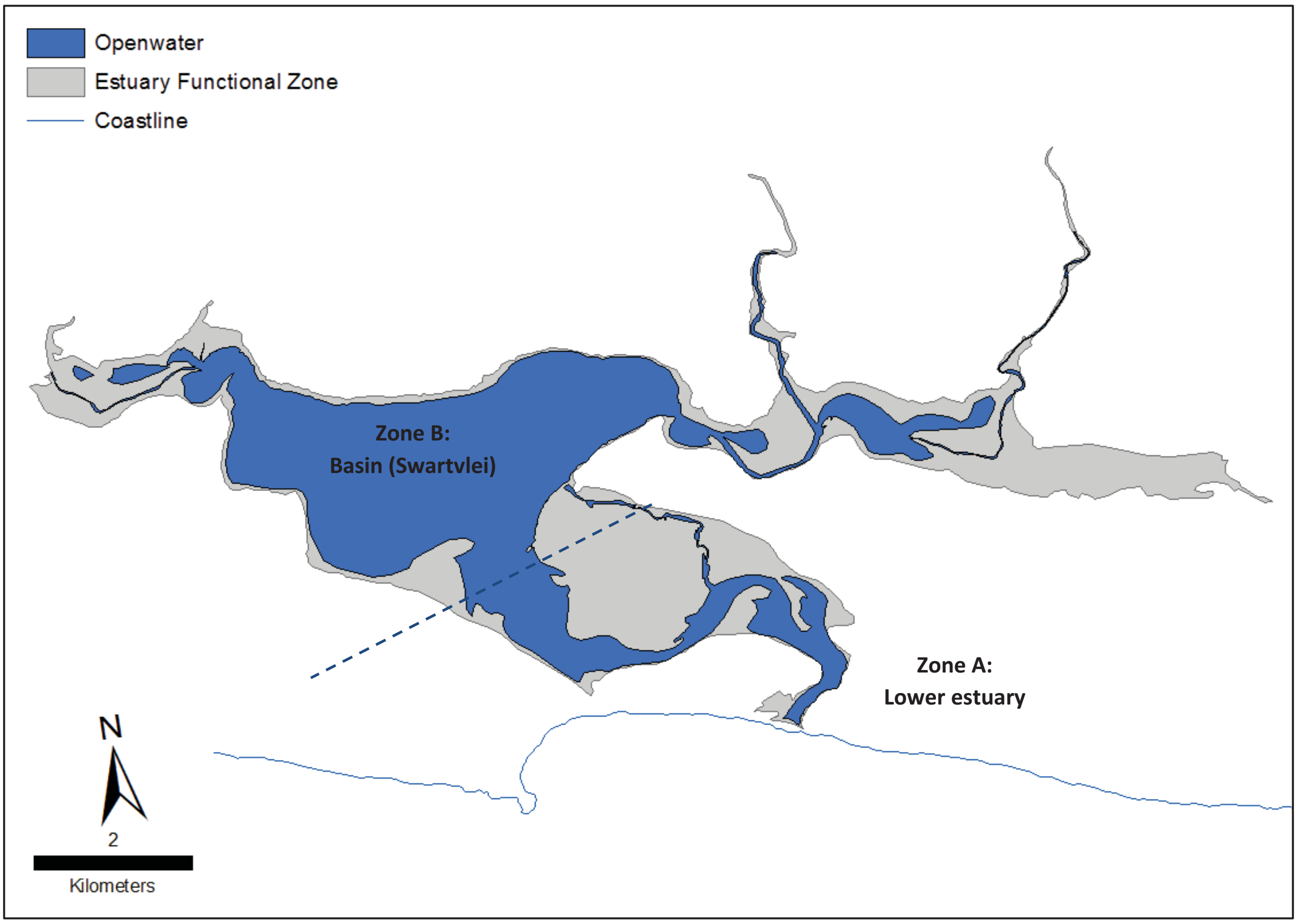

Figure 4.13: Swartvlei: EFZ, openwater area and zonation

Swartvlei has a mean depth of 5.5 m and a maximum depth of 16.7 m (Howard-Williams and Allanson 1981). The lake is 8.8 km^2 with a maximum depth of 16.7 m and a mean depth of 5.5 m. There is a wide littoral shelf, covered in sand, which slopes to a depth of 2 m, followed by a basin of 12 m deep of which the bottom is filled with mud (Whitfield et al. 1983). The lower estuary forms a 7.2 km long shallow channel that links the Swartvlei to the sea, has a maximum depth of 4 m and a water surface area of 2 km^2. The tidal lower estuary is a 7 km long channel extending from the rail bridge to the mouth and is shallow (maximum depth 4 m) with a narrow central channel bordered by intertidal sand flats of varying widths. The Swartvlei system comprises the lower estuary (Zone A) and the lake (Zone B) as defined in the EWR study (DWA 2009). The characteristic abiotic states (and associated distinctive temporal patterns) for the Bot/Kleinmond are illustrated conceptually in Figures 4.14 (see Table 4.2).

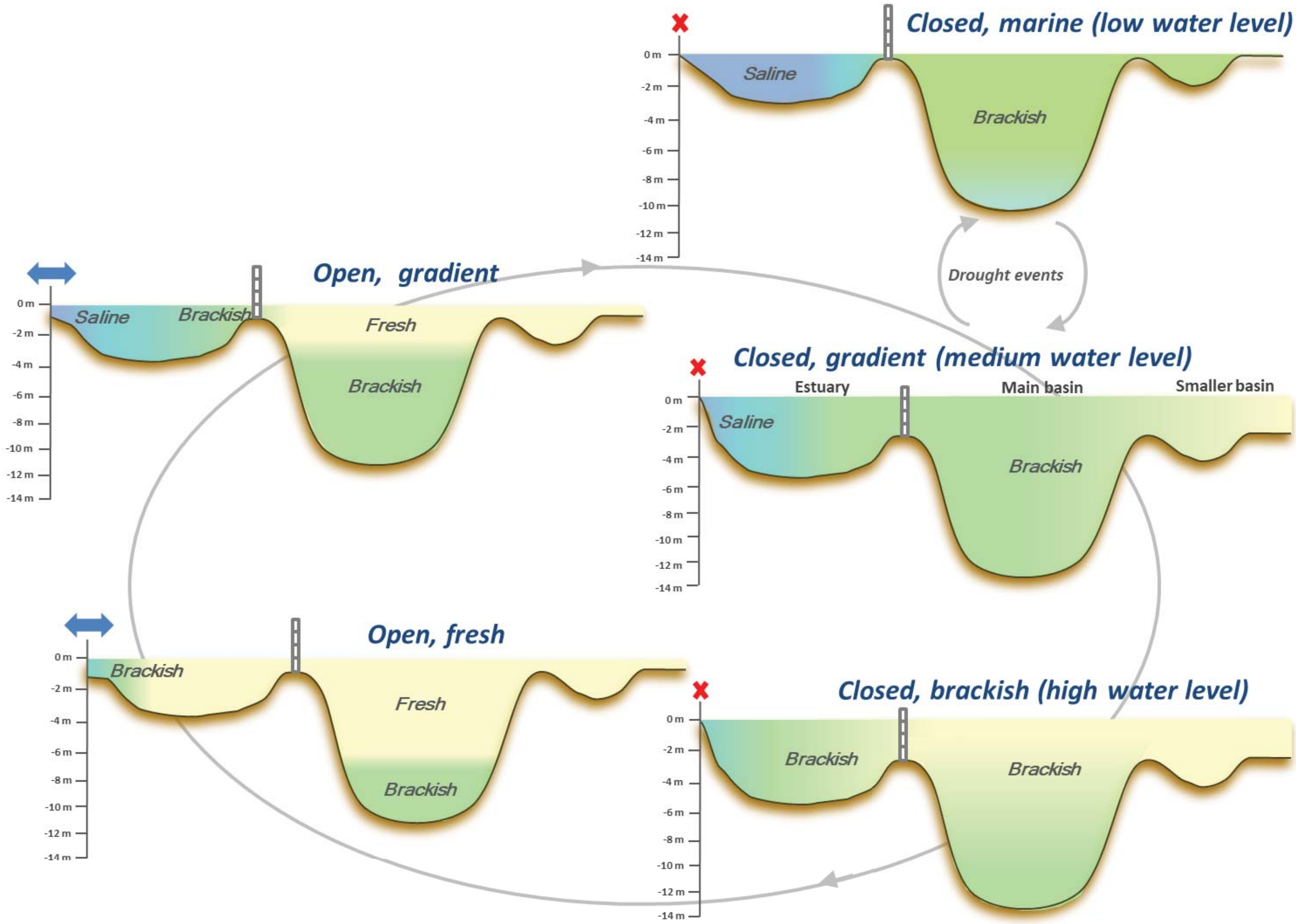

Figure 4.14: Swartvlei: Abiotic states

4.2.8 uMhlathuze

Pre-development, uMhlathuze Estuarine Lake was a large system covering some 3 100 ha comprising two main parts; a broad shallow lake '"Umhlatuzi Lake') and a narrow channel to the sea (Millard and Harrison 1954) (Figure 4.15). Present classification of South African estuaries would have categorised the system in this pre-development state as an estuarine lake (Weerts and Macka, 2019). The naturally narrow and shallow mouth constrained the tidal range in the lower estuarine channel to 0.5 m and 0.2 m across the lake. Salinities were marine (>30) in the channel and typically polyhaline (18-30) in the lake (Millard and Harrison, 1954). The low tidal range restricted mangrove distribution to the system's lower reaches and the eastern shore of the lake.

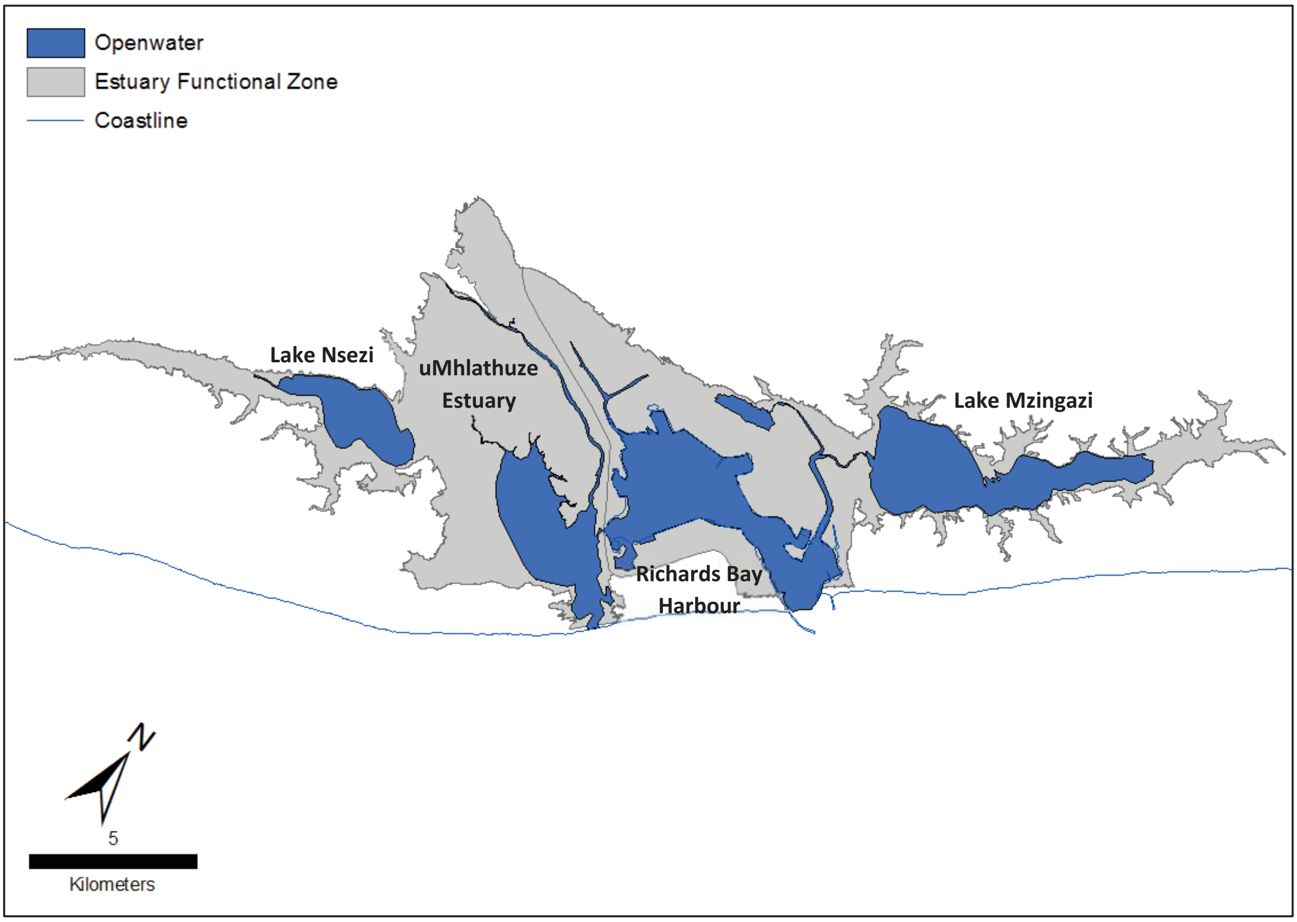

Figure 4.15: uMhlathuze: EFZ and openwater area

Three lakes, Nsezi, Cubhu and Mzingazi originally formed part of the uMhlatuze system (now disconnected). Of these Cubhu and Mzingazi could be categorised as being at least partly estuarine in character, up until the recent past at least. All three of these lakes are regulated at their outflows by weirs and maintain a surface elevation above sea level. Lake Nsezi is a drowned river valley with a surface area of 614 ha fed by the Nseleni River and augmented via an intrabasin water transfer from the uMhlathuze River. The characteristic abiotic states (and associated distinctive temporal patterns) for the Bot/Kleinmond are illustrated conceptually in Figures 2.17 (see Table 2.2).

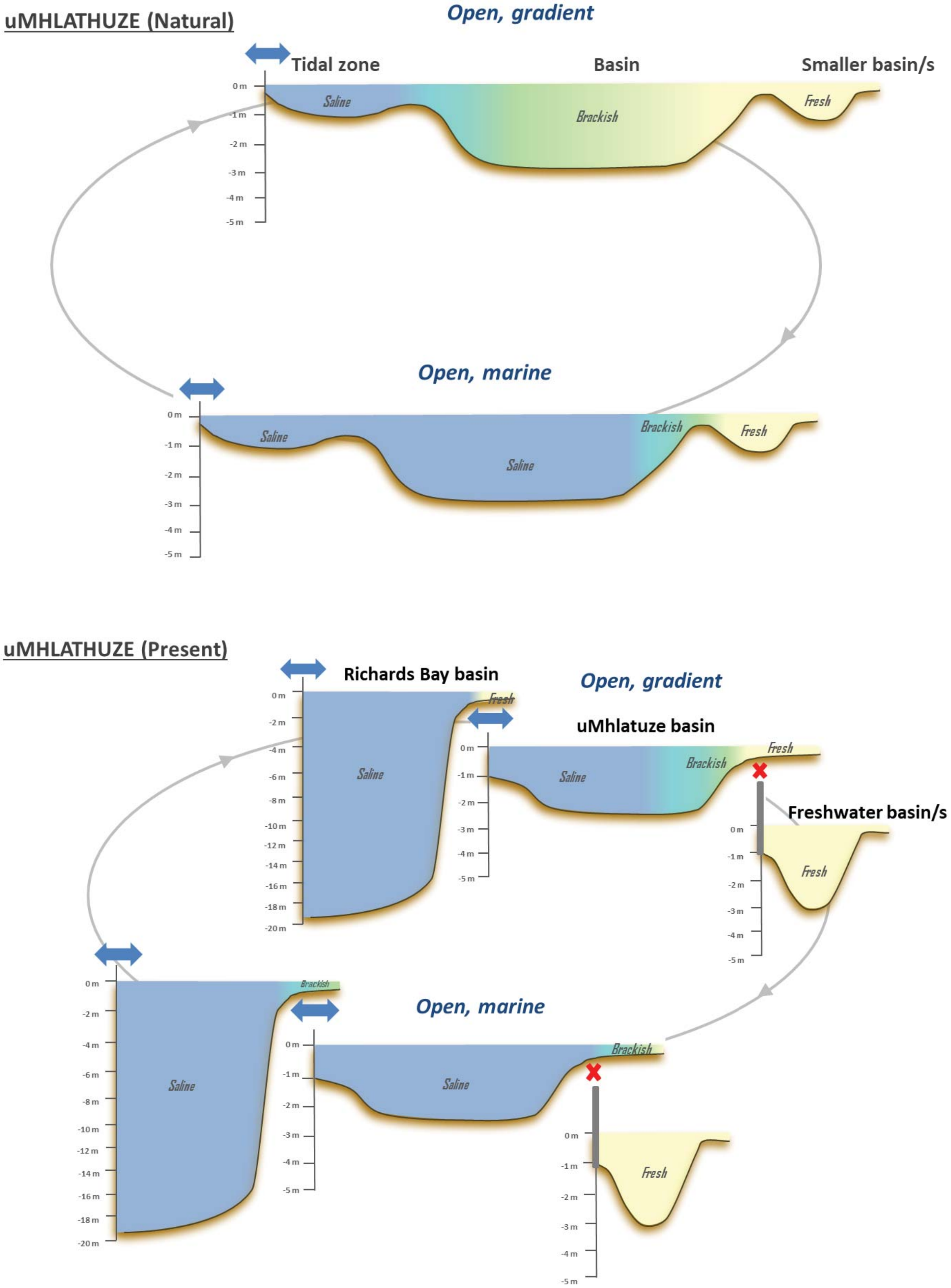

Figure 4.16: uMhlathuze: Abiotic states for Natural conditions (top) and Present (bottom)

4.2.9 iNhlabane

The iNhlabane Estuarine Lake system (Figure 4.17) historically comprised a freely connected lower estuary and lake system. The lake consisted of two basins with large areas of open water, mostly more than 1 m deep with a maximum depth of 5 m in the main basin. The larger upper lake was completely fresh, and the lower lake had some brackish characteristics (salinities recorded in the range of approximately 10). The lower estuary, a narrow channel some 4 km long, linked these lakes to the sea (Begg 1978).

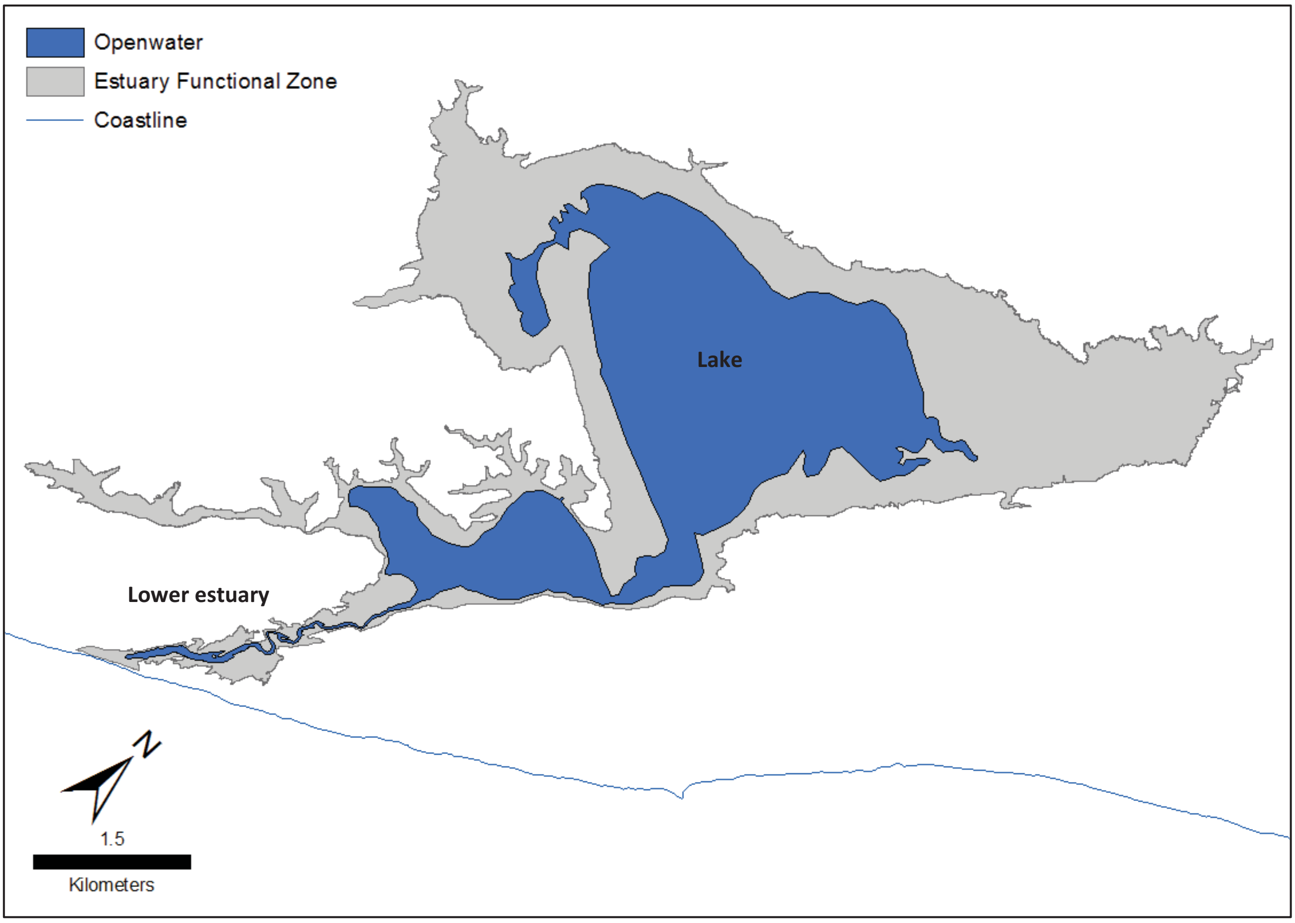

Figure 4.17: iNhlabane: EFZ and openwater area

The mouth of the system is situated on an open coastline and is directly exposed to wave action, without any protection. The beaches at the mouth are very steep, a feature that is also typical of this area and that is caused by the interaction of the local wave climate and the coarse sand particles on these beaches. An interesting situation can develop at the mouth at very small estuaries such as Nhlabane after the construction of the weir whereby a small outflow channel is maintained by a base flow of between 0.2 and 0.6 m^3/s. This outflow channel will then be in a perched position on the sand berm and tidal inflow will hardly occur, even at spring tides. However, such an outflow does allow limited immigration of juvenile fish and invertebrates to take place. Recruitment by wave overtopping has also been identified as a mechanism allowing immigration of estuarine fish into the system to occur, even during a period of mouth closure (Vivier and Cyrus 2001). The characteristic abiotic states (and associated distinctive temporal patterns) for the iNhlabane are illustrated conceptually in Figures 4.18 (see Table 4.2).

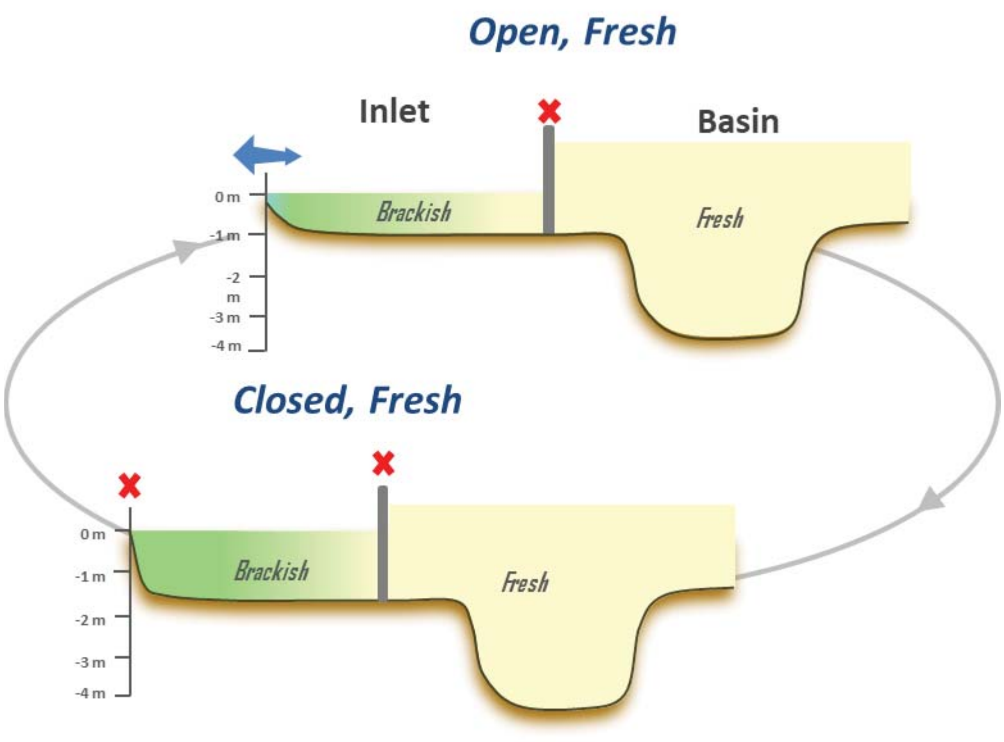

Figure 4.18: iNhlabane: Abiotic states

4.2.10 St Lucia/uMfolozi

St Lucia/uMfolozi Estuarine Lake system (Figure 4.19) is one of the most important estuarine systems in Africa. It is the largest estuary in South Africa with a water surface of > 300 km^2 and a shoreline of over 400 km. The lake complex comprises two distinctly different, but interconnected parts – the St Lucia system and the fluvially dominated uMfolozi system. The St. Lucia system is divided into False Bay, North Lake, South Lake and the Narrows. The system is shallow (the normal average depth is 0.90 m) (DWAF 2004).

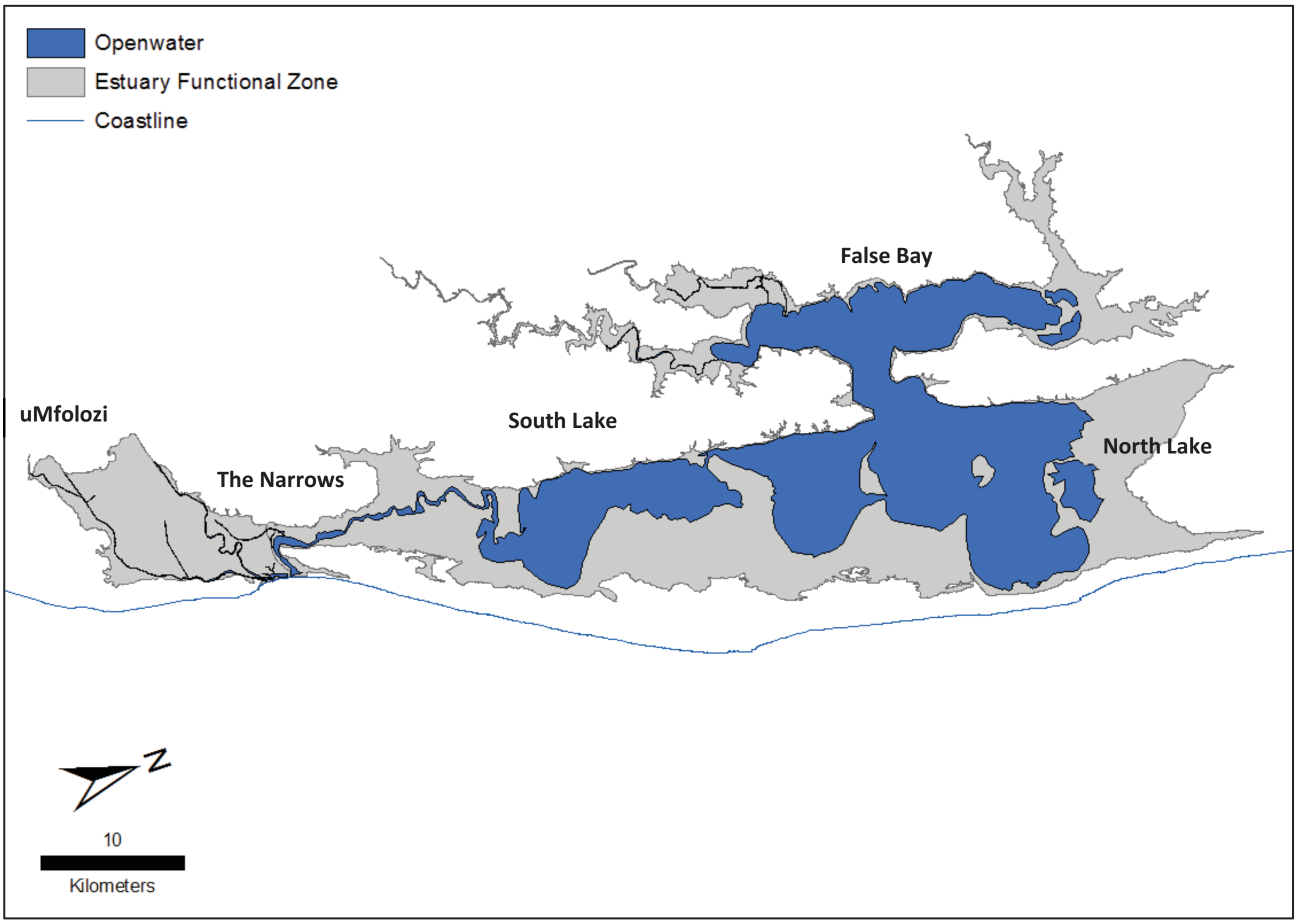

Figure 4.19: St Lucia/uMfolozi: EFZ and openwater area

Five rivers drain into St Lucia in order from north to south, the Mkuze, Mzinene, Hluhluwe, Nyalazi and Mpate Rivers. The uMfolozi and Msunduzi rivers enter the Indian Ocean together, south of the St. Lucia Mouth (Stretch and Maro 2013). The lake system is separated from the sea by large coastal dunes that flank its eastern bank (Taylor 2006). The Present MAR for the Mkuze, Mzinene, Nyalazi, Hluhluwe and Mpate rivers is 362.26 million m^3, which is 86% of the MAR under the Reference Condition (i.e. 417.89 million m^3). In addition, the influence of groundwater (23.14 million m^3), direct rainfall (273.25 million m^3), evaporation (-420 million m^3) and discharge to and from the sea also need to be considered to evaluate the consequences of changes in the surface runoff (DWAF 2004). The characteristic abiotic states (and associated distinctive temporal patterns) for St Lucia/uMfolozi are illustrated conceptually in Figures 4.20 (see Table 4.2).

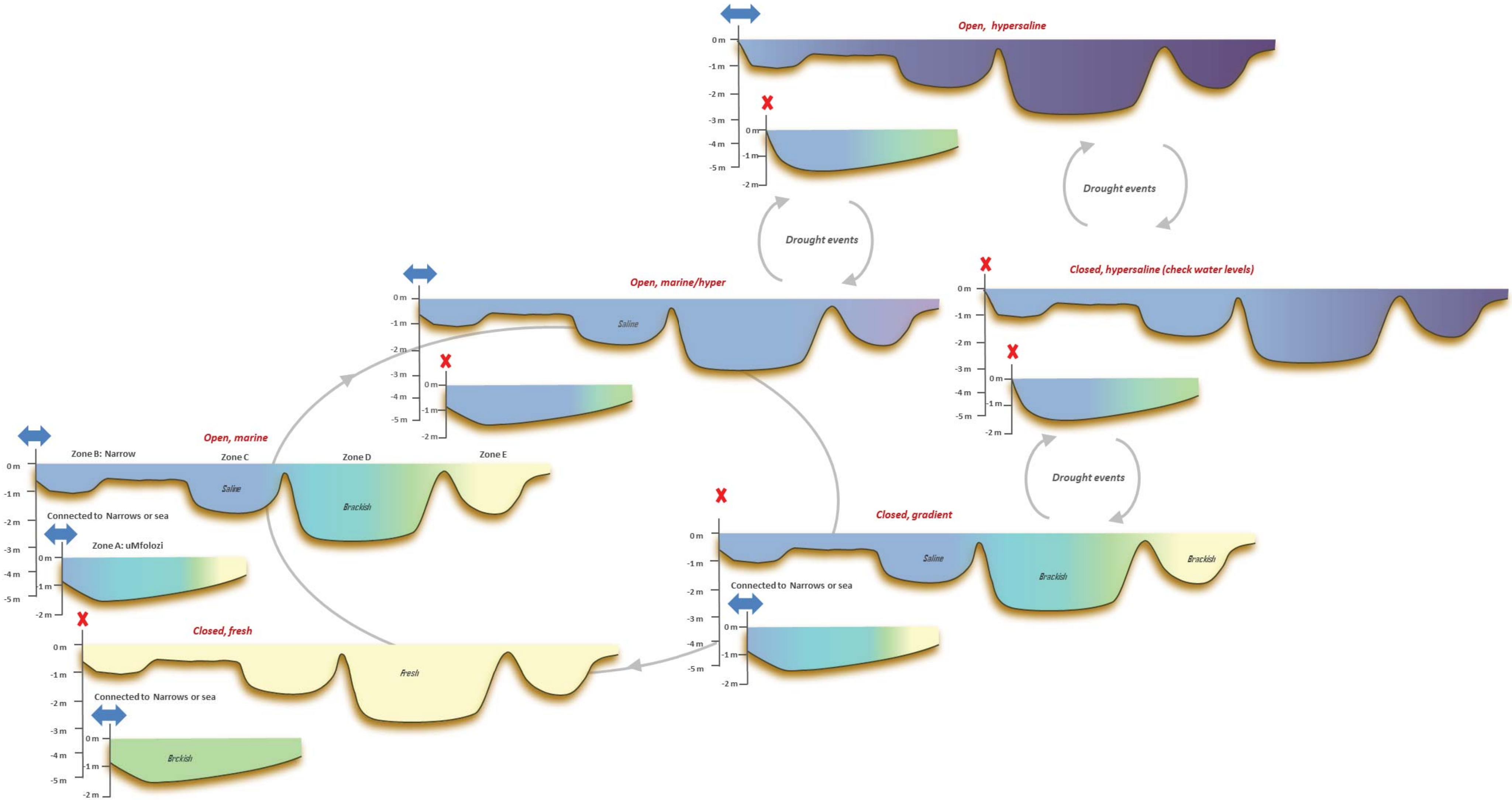

Figure 4.20: St Lucia/uMfolozi: Abiotic states

4.2.11 uMgobezeleni

Assessment Level
Desktop
Probability of Outcome
Likely (66 -100%)

The uMgobezeleni Estuarine Lake (Figure 4.21) is located on the east coast of South Africa, in an exclusively rain-fed catchment, i.e. there is no river water flowing into the catchment (Bate et al. 2016, 2018). The system receives water that drains out of the ground into two streams of approximately 6 km in length, rising from two separate lakes (Mgobezeleni and Shazibe).

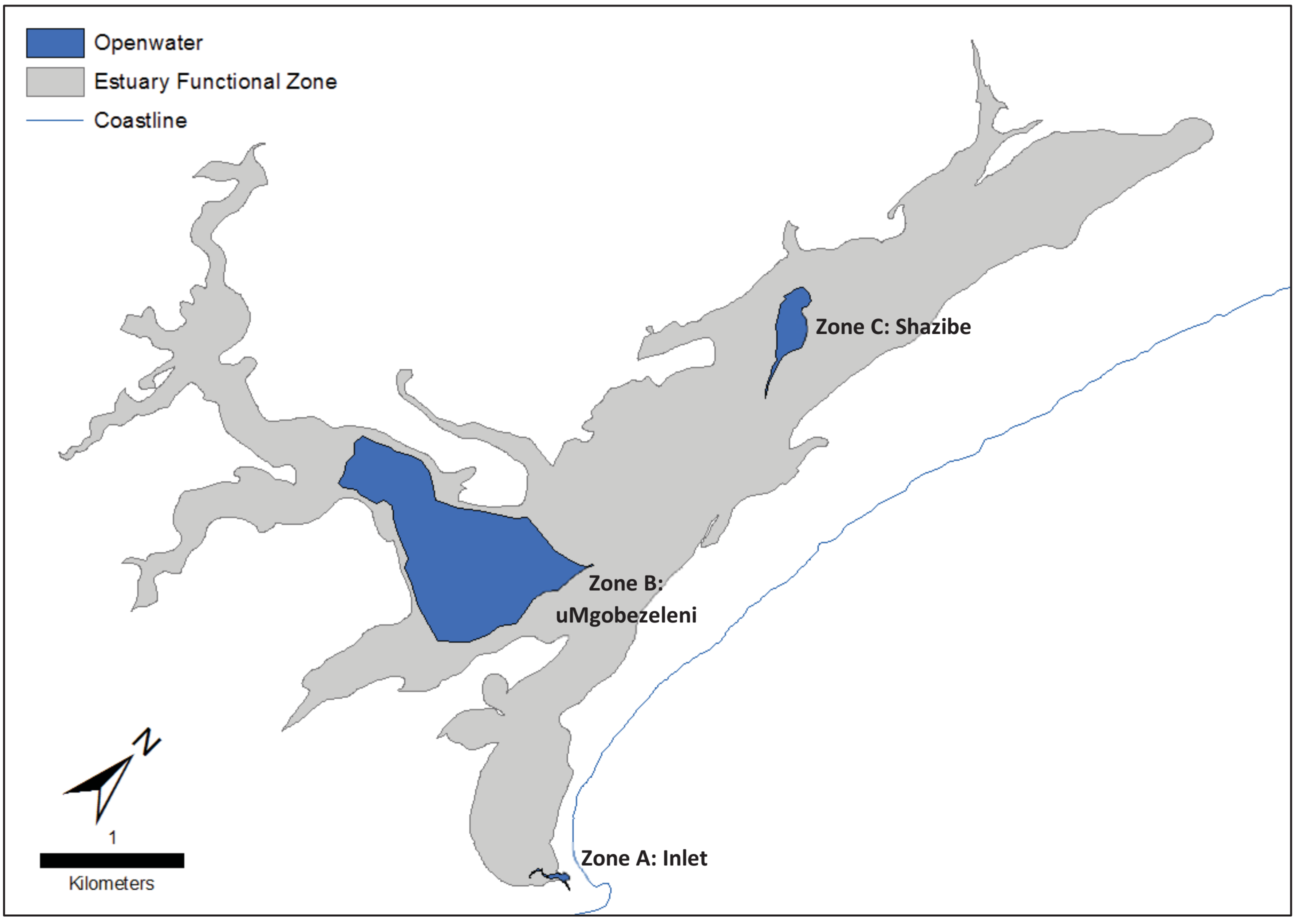

Figure 4.21: uMgobezeleni: EFZ, openwater area and zonation

The two lakes, uMgobezeleni (Zone B) and Shazibe (Zone C), are connected to the sea by a small inlet (Zone A) and buffer the flow variability of the groundwater feeder streams providing a very consistent inflow to the system. The appearance of the water, in pools, flowing into the swamp above the lower estuary is completely black. The system is perched and predominantly open. The system is mostly groundwater-fed and buffered from extreme water levels by the lakes. Because of a large tourist population, management is periodically required to breach the mouth artificially. The water in the lower estuary is black and oligotrophic and phytoplankton and phytomicrobenthic biomass are accordingly low (Bate et al. 2016, 2018). The characteristic abiotic states (and associated distinctive temporal patterns) for the uMgobezeleni are illustrated conceptually in Figures 4.22 (see Table 4.2).

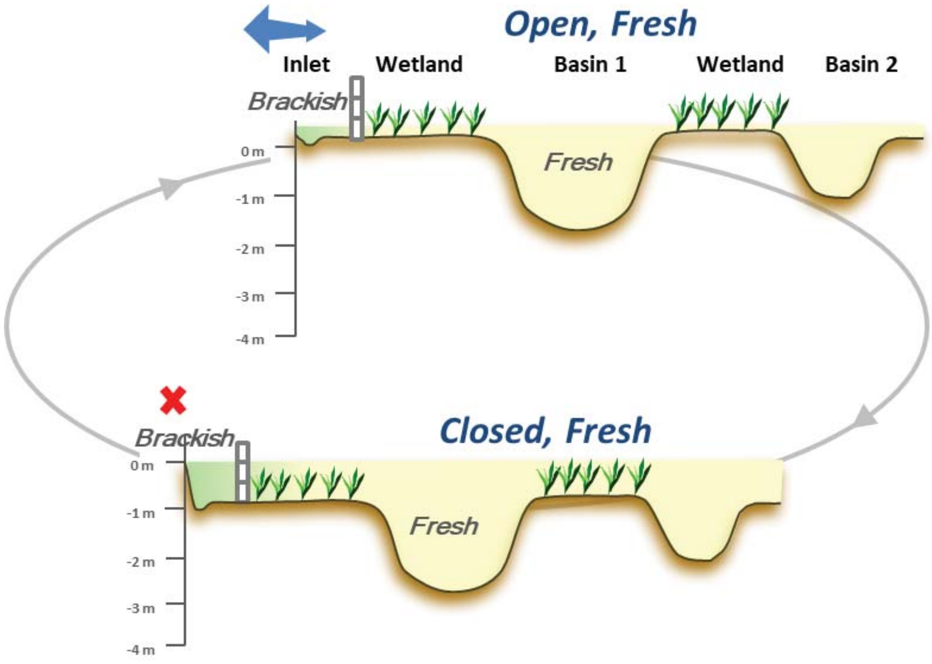

Figure 4.22: uMgobezeleni: Abiotic states

4.2.12 Kosi

The Kosi Bay Estuarine Lake system (Figure 4.23) is located on the east coast of South Africa, approximately 2 km south of the Mozambique border. The system is sited on the edge of the flat northern KwaZulu-Natal coastal plain, about 75 km from the Lebombo Mountain range.

Assessment Level
Systematic
Probability of Outcome
1 – 3: Very Likely (90 -100%) 4: Likely (66 -100%) 5: More likely than not (>50 – 100%)

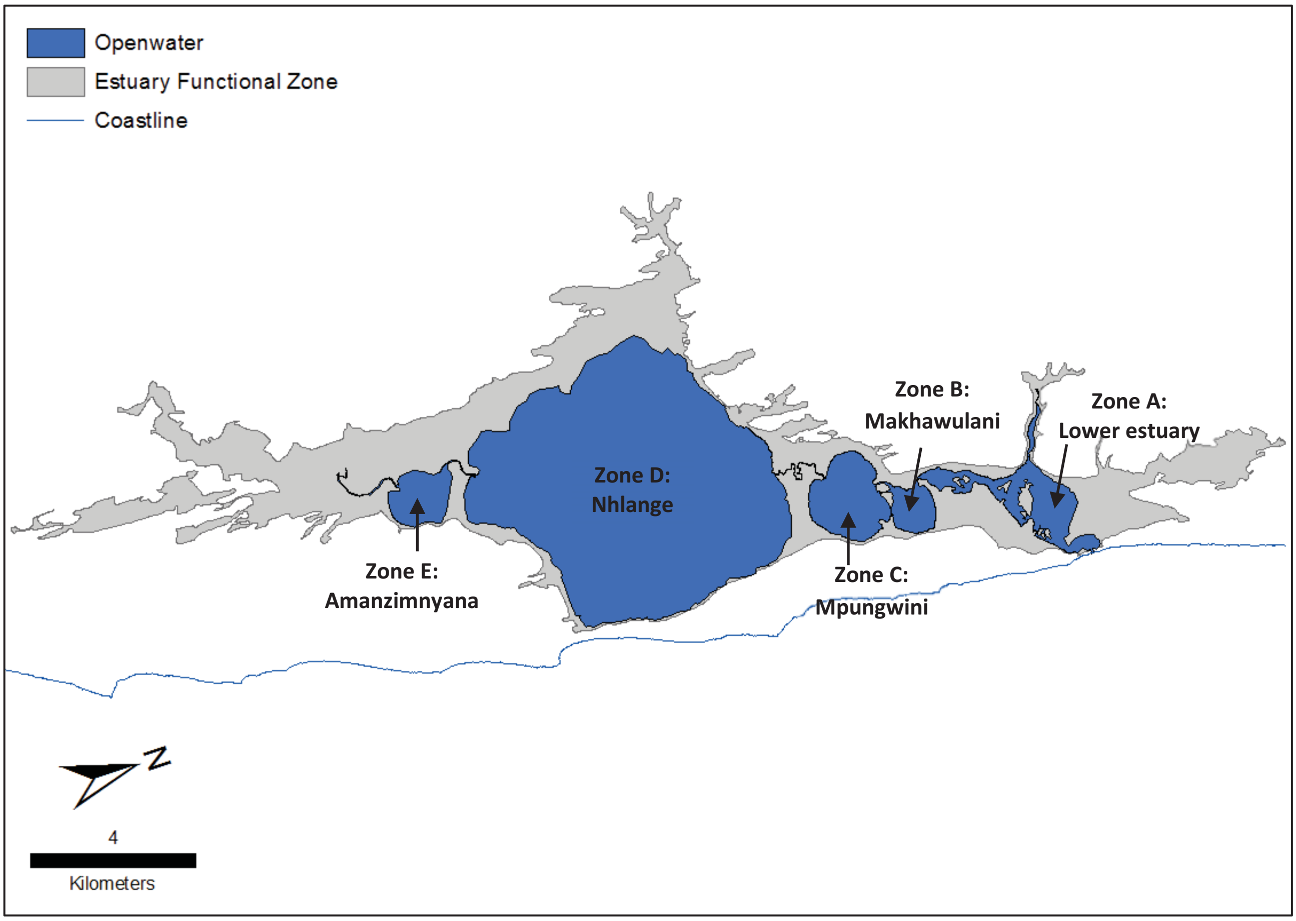

Figure 4.23: Kosi: EFZ, openwater area and zonation

The Kosi Estuarine Lake system comprises four interconnected channels and lakes that link with the sea through the lower (tidal) estuary. These lakes are separated from the sea by a high, vegetated barrier dune complex that reaches 130 m in height. A fifth freshwater lake (KuZilonde) lies directly north and is connected via outflow to the estuary. The estuary comprises a broad tidal flat that opens to the sea via a serpentine channel. Three rivers feed the system. The Kosi mouth is nearly always open and subjected to strong tidal movements, though at times the connection to the sea becomes tenuous. The mouth varies in size with every tide, particularly during the spring tides. Generally, it is between 20 to 50 m wide and about 3 m deep but can vary in width from 5 to 100 m (DWS 2016). Because of the tropical affinities of several species that occur in Kosi, the system has recently been included in a newly categorised tropical transition zone (Van Niekerk, et al. 2019). The characteristic abiotic states (and associated distinctive temporal patterns) for Kosi are illustrated conceptually in Figure 4.24 (see Table 4.2).

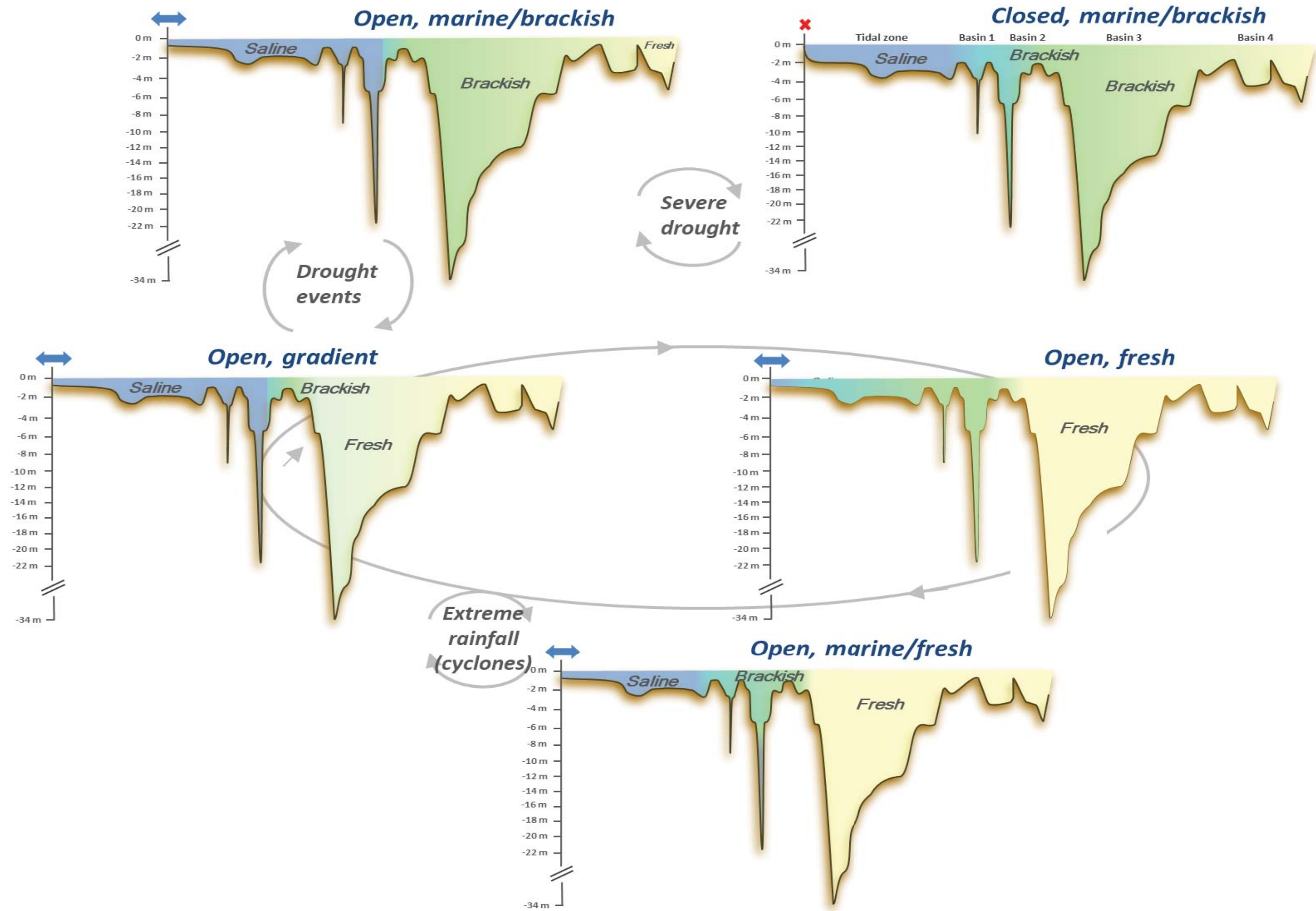

Figure 4.24: Kosi: Abiotic states

5. VULNERABILITY TO TERRESTRIAL VECTORS OF CLIMATE CHANGE

The detailed outcome of the terrestrial climate change vulnerability assessment for each of the selected estuarine lake systems are captured in an Appendix to this report (see Volume III). The overall results from this assessment are discussed in this Chapter.

5.1 Sensitivity of Selected Abiotic and Biotic Indicators

Evaluating the different indicator responses to climate change highlights some of the regional responses. Table 5.1 summarises the impacts climate may have on key abiotic and biotic processes in estuarine lakes.

Hydrology: Depending on the predicted degree of change in precipitation and in which part of the rainfall regime (low flow or high flow season) these changes occur runoff changes could be negligible (e.g. RCP 4.5 Mid-future) or severe (RCP 8.5 Far-future). The most change was projected for the cool temperate regions, with systems such as the Bot/Kleinmond showing a severe decline in indicator condition (~ 20%), i.e. from a B category to a C/D category. While lake systems in the warm temperate region (Heuningnes, Touw/Wilderness and Swartvlei) saw a smaller decline overall and even incremental improvement in hydrology under mid-future conditions. The least impacted were the tropical systems (Mgobozeleni and Kosi).

Mouth state: Most systems showed some sensitivity to changes in mouth state and marine connectivity, with most declining by half a category or a full category. Bot/Kleinmond and Klein in the warm temperate region showed the most sensitivity to this indicator.

Water levels: Lake level fluctuates annually and inter-annually as a natural response to local climate and rainfall events. These fluctuations are expected to amplify under climate change as rainfall reduces and abstraction for human consumption increases. An increase in temperature is likely to increase evaporation rates and decrease lake water levels during the closed phase due to high evaporative losses (and thus also decrease opportunities for open mouth conditions). This will be a problem particularly during drought conditions (e.g. Verlorenvlei, Bot). However, given the high variability in water level over long time scales, this indicator was the least sensitive to predicted climate change, with the Verlorenvlei system being the most likely to respond to future climate change conditions.

Salinity: Rising temperatures and evaporation rates may lead to hypersalinity developing in some lakes systems (e.g. Klein), or increase the duration and intensity of existing hypersalinity cycles, such as what has happened in St Lucia. However, in some systems, like the Bot/Kleinmond, it could lead to a freshening of the lake system under prolonged closed conditions due to seepage losses and outflow through Kleinmond. Overall, average salinity regimes shifted significantly over longer time scales with the Heuningnes and Bot/Kleinmond system showing the greatest sensitivity to future climate conditions (e.g. RCP 8.5 Far-future).

Water Quality (Nutrients): As expected, the water quality did not change much because of climatic conditions with less than a 5% change observed under most scenarios. No significant shifts in condition categories were observed.

Microalage responses: The dynamics of microalgae (especially phytoplankton) is largely influenced by nutrient availability and residence time (Lemley et al. 2016). During the open state, previously submerged sand and/or mud banks become exposed (weeks to years). The exposure of previously inundated sediments has a profound impact on the available microphytobenthic habitat within a lake system. Salinity drives distinct microalgae communities shifts in both phytoplankton and microphytobenthos. The relative contribution of either of these two communities in an estuarine lake system is dependent on the hydrodynamics (e.g. mouth state and freshwater inflow). Increases in temperature and nutrient loading can stimulate primary production, occasionally supporting high microalgal biomass. Vertical stratification in nutrient-rich estuarine lakes is likely to support flagellate-dominated phytoplankton communities (e.g. dinoflagellates, raphidophytes). Extended periods of low runoff and limited, or no, tidal exchange in a nutrient-rich system will accelerate the process of eutrophication, resulting in an organic-rich and oxygen-poor environment that can support a cyanobacterium dominated microalgal community. Phytoplankton was the most sensitive of the algae groups, with notable responses observed under the RCP 8.5 scenario for all systems, while benthic microalgae were the least responsive. Harmful algal blooms were a key concern in enriched systems, such as the Klein, Swartvlei, and Mgobozeleni; while the blooms in Kosi were largely attributed to a natural process but needs further investigation. The increased temperature was a major driver of change in this component under RCP 8.5 Far-future conditions.

Table 5.1: Summary of the Lake indicators to climate change scenarios (RCP 4.5 and RCP8.5)

ESTUARY	SCENARIO	Hydrology	Mouth State	Water levels	Salinity	Water Quality	Abiotic Sensitivity	Phytoplankton	Benthic Microalgae	Harmful Algal Blooms	Macrophytes	Fish (-Fishing impacts)	Biotic Sensitivity	Estuary Sensitivity
Verloren	Present	B/C	A/B	B/C	A	E	B/C	D	C	C/D	D	D/E	D	C
	1: RCP4.5Mid	C	B	C	A	E	B/C	D	C	C/D	D	E	D	C/D
	2: RCP4.5Far	C	B	C	A	E	B/C	D	C	C/D	D	E	D	C/D
	3: RCP8.5Mid	C	B/C	C	A	E	C	D	C	C/D	D	E	D	C/D
	4: RCP8.5Far	C/D	B/C	C	A	E	D	D/E	C/D	C/D	D	E	D/E	D
Bot/ Kleinmond	Present	B	B	A/B	A/B	D	B	B	A/B	A/B	B	B/C	B	B
	1: RCP4.5Mid	B/C	C/D	A/B	A	D	C	B/C	A/B	B	B	B/C	B	B/C
	2: RCP4.5Far	C	C/D	A/B	A	D	C	B/C	A/B	B	B	B/C	B	B/C
	3: RCP8.5Mid	C	D	A/B	A	D	C	B/C	A/B	B	B	B/C	B	C
	4: RCP8.5Far	C/D	C/D	A/B	A	D	D	B/C	A/B	B	B	C	B/C	C
Klein	Present	B/C	C	A	A/B	D/E	B/C	C	B/C	B/C	C	C	C	B/C
	1: RCP4.5Mid	B/C	C	A	A/B	D/E	B/C	C	B/C	B/C	C	C	C	C
	2: RCP4.5Far	B/C	B/C	A	A/B	D/E	B/C	C	B/C	B/C	C	C	C	C
	3: RCP8.5Mid	C	C/D	A	A/B	D/E	C	C	B/C	B/C	C	C/D	C	C
	4: RCP8.5Far	C	D	A	A/B	D/E	D	C/D	B/C	C	C/D	D	D	D
Heuningnes	Present	B	B	A/B	D/E	C	B/C	B	B/C	A	C/D	C/D	C	C
	1: RCP4.5Mid	B	B/C	B	D/E	C	B/C	B	B/C	A	C/D	C/D	C	C
	2: RCP4.5Far	B	B/C	B	E	C	B/C	B	B/C	A	C/D	C/D	C	C
	3: RCP8.5Mid	A/B	B/C	B	D/E	C	C	B	B/C	A	C/D	C/D	C	C
	4: RCP8.5Far	B/C	B/C	B	E	C	D	B/C	B/C	A/B	D	D	C/D	D
Touw/ Wilderness	Present	C	C/D	B	B	B	C	A/B	C/D	A/B	B/C	C	C	C
	1: RCP4.5Mid	A/B	C	B	B	B	B	A/B	C/D	A	B/C	C	C	B/C
	2: RCP4.5Far	B	C/D	B	B	B	C	A/B	C/D	A/B	B/C	C	C	C
	3: RCP8.5Mid	B/C	D	B	B	B	C	A/B	C/D	A/B	B/C	C/D	C	C
	4: RCP8.5Far	C	D	B	B	B	D	B	C/D	A/B	B/C	D	C/D	D
Swartvlei	Present	C	B	B	C	B	B/C	B/C	A/B	B	B/C	B/C	B/C	B/C
	1: RCP4.5Mid	C	B	B	C	B	B/C	B/C	B	B	B/C	B/C	B/C	B/C
	2: RCP4.5Far	C	B/C	B	C	B	C	B/C	A/B	A/B	C	C	C	C
	3: RCP8.5Mid	C	A	B	C	B	C	B/C	B	B	B/C	B	B/C	B/C
	4: RCP8.5Far	C/D	B	B	B/C	B	C/D	C	B	B/C	B/C	B/C	C	C
Mgoboze-leni	Present	A/B	A/B	A	A	B/C	A/B	B	A	C	B	C	C	B
	1: RCP4.5Mid	B	A/B	A	A	B/C	A/B	B	A	C	B	C	C	B
	2: RCP4.5Far	A	A	A	A	B/C	A	B	A	C	B	C	C	B
	3: RCP8.5Mid	B	A	A	A	B/C	B	B	A	C	B	C	C	B
	4: RCP8.5Far	A	B	A	A	B/C	B/C	C	A	C/D	B/C	C	C	C
Kosi	Present	A/B	A	A	A	A/B	A	B	B/C	A/B	A/B	A/B	B	A/B
	1: RCP4.5Mid	B	A	A	A	A/B	A	B	B/C	A/B	A/B	A/B	B	A/B
	2: RCP4.5Far	A	A	A	A	A/B	A	B	B/C	A/B	A/B	A/B	B	A/B
	3: RCP8.5Mid	A	A	A	A	A/B	A	B	B/C	A/B	A/B	B	B	A/B
	4: RCP8.5Far	A/B	A	A/B	A	A/B	B	B/C	C	B	C	B	C	B

Macrophyte responses: High water levels result in flooding of macrophyte habitats. Macroalgae and submerged macrophytes flourish in this state, while mangroves and swamp forest are sensitive to flooding, standing water and anoxic conditions and will not survive prolonged inundation (months). Lakeshores are ecotones (a transitional zone between terrestrial and aquatic habitats) characterized by fluctuations in water levels. Any rapid changes in water level will result in vegetation changes. Stable water levels can also cause an expansion of macrophytes such as reeds and sedges. Increased temperature will increase primary production. Open mouth states create intertidal habitat, with salt marsh species occurring along a tidal inundation gradient. Closed states promote the growth and proliferation of macroalgae. Prolonged mouth closure could result in the dieback of intertidal salt marsh species. A change in salinity will influence the macrophyte habitats, e.g. reeds and sedges grow better in brackish water whereas salt marsh and seagrass grow better in salinity close to seawater. Reeds and sedges are sensitive to increases in salinity but can survive if their roots and rhizomes are in salinity less than 20. However, if freshwater seepage is reduced then it may lead to die back. Freshwater inflow prevents hypersaline conditions in sediments of salt marshes. Hypersaline sediments caused by evaporation and infrequent flooding will result in dry bare patches in the supratidal areas. Macrophyte conditions decline between 3 and 10% under future climate conditions, but in most cases remain in the present condition category. Bot/Kleinmond and Klein were the most sensitive to change as a result of a change in mouth state and water levels.

Fish responses: Mouth state governs connectivity between estuarine lake habitats and the sea. Mouth closure prevents recruitment of marine spawned fish into the system and may also prevent movement (migration) of fishes during spawning periods. It also results in a loss of salinity gradients that govern fish (and prey and habitat) distributions. Under closed conditions intertidal area, already limited in most lakes, is lost, with implications for the productivity of intertidal habitats and trophic effects to the fish community. Increased open states, stimulating microphytobenthic production to the benefit of components of the fish assemblage (e.g. Mugilidae), but to the detriment of others either through direct loss of habitat (e.g. loss of shallow submerged vegetation such as *Zostera capensis* beds as preferred or even critical [i.e. pipefish, seahorses] habitat) and/or through trophic effects (e.g. loss of benthic invertebrate productivity, sand prawns). Salinity is a primary driver of fish distribution in estuarine lakes, either directly as different species have different salinity preferences, or indirectly, through affecting prey and habitat distribution. Most estuarine dependant fishes are tolerant of low rather than high salinity and several freshwater species can tolerate slight (or even marked) elevations in salinity. High temperatures decrease tolerance to hypoxia and low salinities and increase the risk of mass mortality. Sex ratios can be skewed in fish where sex determination is temperature related. Temperature increases tend to skew towards males. Consequently, climate change influences on temperature could have a profound impact on fish populations. Growth rates and gonadal development tend to decrease on either side of the optimal temperatures for individual species. Shallow marginal areas tend to be warmer than deeper channel areas and are thus favourable for metabolic processes. Juveniles and small adults also use shallow water as a predation refuge. Submerged aquatic macrophytes are also important for some estuarine resident species (e.g. pipefishes and seahorses, gobies and blennies). These habitats, in estuarine lakes, are typically shallow subtidal. Intertidal habitats are limited, but where they occur are important for estuarine dependant marine species. Deeper intertidal habitat is used as a refuge from predation. Very deep subtidal areas in estuarine lakes are likely to have quite distinct water quality characteristics, including low oxygen levels, that might preclude use by fishes. A decrease /increase in floods will have a related impact on the fluvially dependant nearshore marine habitats that rely on river inflow for salinity and turbidity fronts, nutrient input, sediment supply and detritus (organic matter). Changes in flood behaviour will also have an impact on migratory signals and fish recruitment to estuaries. Most systems reflected sensitivity to future climate change conditions (between 5 and 25%), with the biggest shift observed in the Klein reflecting the cumulative impact of climate change and nutrient enrichment. Systems such as the Touw/Wilderness and Swartvlei were also sensitive to the combination of changes in rainfall/runoff, mouth state, warmer conditions, and enrichment.

Droughts and floods: An increase in the future occurrence of drought conditions is very likely to decrease marine connectivity (less open mouth conditions) and/or decrease lake water levels. Drastically reduced lake levels are likely to isolate parts of the estuarine lake systems from each other (e.g. Rondevlei), thus impacting lake connectivity. Droughts are also likely to increase the likelihood of hypersalinity developing in some systems (e.g. Klein), or increase the duration and intensity of hypersalinity cycles (Heuningnes). However, in some systems, prolonged periods of closure may lead to freshening of the lake system such as the case of the Bot/Kleinmond system. An increase in floods will increase opportunities for mouth breaching – and vice versa – which, in turn, will change connectivity with the marine environment. Changes in flood regimes will also change the sediment equilibrium in lake systems. In many cases, lakes are sediment sinks and thus sensitive to increased sediment input. Larger floods may deposit more sediment. During a flood event, salinities can be fresh or nearly fresh. However, after flood events salinities tend to increase significantly due to increased tidal amplitude and related seawater intrusion. Thus, an increase in floods and related scouring of the mouth area can result in increased salinities after a flood event. Systems such as Swartvlei may thus experience an increase in the maximum salinity achieved during the open cycle if floods were to intensify. Low tide levels can be dramatically lower after a flood event, reducing subtidal habitat and causing dieback /desiccation of submerged vegetation that is now exposed. Thus, reduction in habitat can impact biota such as fish.

5.2 Overall Sensitivity of Estuarine Lakes

One of the key findings that emerged from the Estuarine Lake Vulnerability Assessment was that the maximum potential shift in estuarine state varied between 9% and 22% from present functionality under the RCP 4.5 and RCP 8.5 Climate scenarios (Figure 5.1).

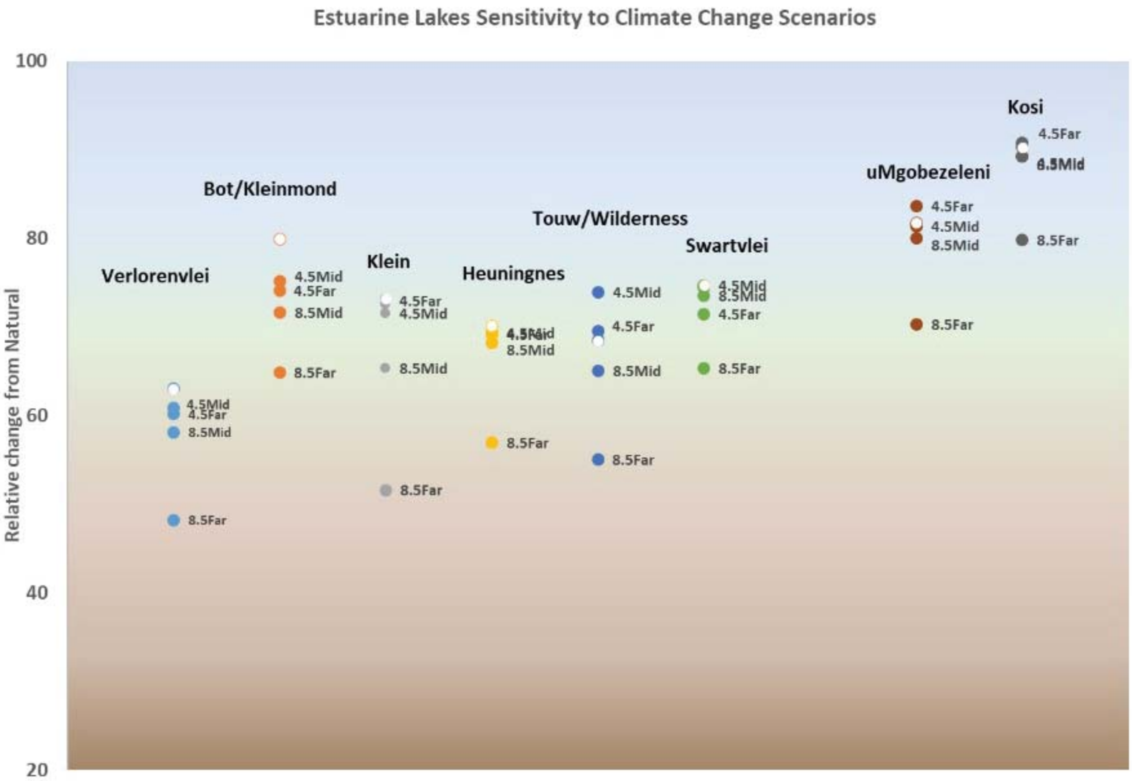

Figure 5.1: Relative sensitivity of the estuarine lakes of South Africa to RCP 4.5 and RCP 8.5 Climate Change Scenarios

In all cases, the maximum degree of change was induced by the RCP 8.5 Far-future Scenario. RCP 8.5 Far-future conditions were very likely to cause major impacts on estuarine connectivity and associated functioning, with related impacts on biotic productivity and composition. The responses to the RCP 4.5 scenarios were generally grouped around the present state, with some scenarios even representing a shift towards natural conditions because of increased freshwater input in the mid-future scenarios. In most cases, the estuarine lakes were somewhat buffered against slight shifts in connectivity, water levels or salinity regimes as they are generally weekly connected to the sea and subjected to long periods of closure.

5.3 Climate Change versus Anthropogenic Change

An important finding of the assessment was that in all systems assessed, except for Kosi, anthropogenic-induced change exceeded climate-induced shifts in estuary functioning (Figure 5.2), highlighting the degree of transformation the estuarine lakes have already experienced. In the case of Kosi (near-natural in its present state), the relative shifts were similar in magnitude.

Given that estuarine lakes are nutrient sinks that cannot be flushed by floods like other systems, the present water quality was a good predictor of future resilience, with enriched systems more likely to decline further in the condition under hotter and/or drier future conditions. For example, the Klein Estuarine Lake system that receives continuous wastewater input, is expected to become significantly more degraded under warmer climatic conditions. Increased mouth closure, lower water levels and warmer temperatures are *very likely* to drive an increase in harmful algal blooms and concomitant lower oxygen levels. Thus, it is v*ery likely* to increase the occurrence of fish kills in the system. In contrast, Kosi with near-natural water quality, mostly only responded to shifts in water levels and salinity regimes.

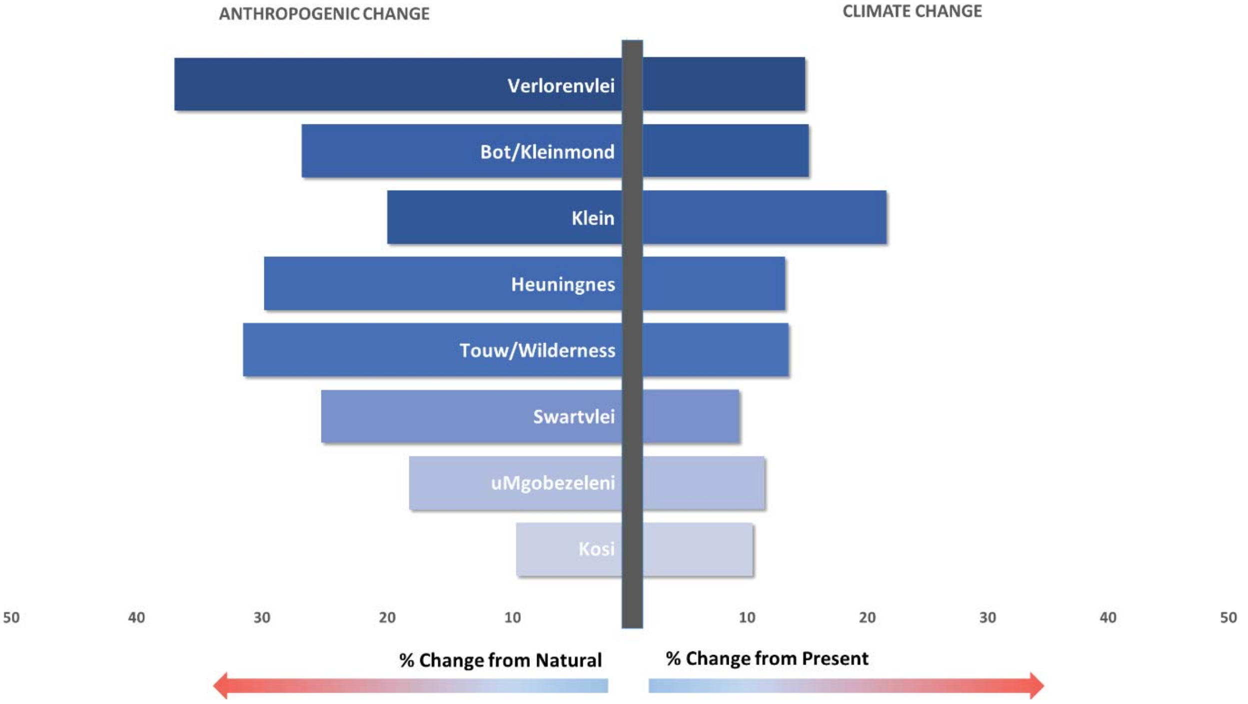

Figure 5.2: Graphic representation of the degree of anthropogenically-induced versus climate-induced change in the Estuarine Lakes of South Africa

Relatively shallow lake systems, such as Verlorenvlei, Bot/Kleinmond and Heuningnes tend to be more vulnerable to the impact of reduced flows and/or the impact of drought conditions. In this type of system, event-scale droughts tend to dry out a large part of the lake beds and surrounding estuarine vegetation. Depending on the degree of marine connectivity, this type of system may also develop extreme hypersalinity in some parts of the system. This effect could be further amplified if the system was already subjected to enrichment, with harmful algal blooms often associated with this type of conditions. In some systems like Verlorenvlei, blue-green algal blooms are associated with fish developing lesions during the breeding season. While in Botvlei and Soetendalsvlei (Heuningnes) drought conditions are associated with extensive reed die-off due to low water levels and hypersalinity.

6. PROPOSED CLIMATE CHANGE STRATEGIES

The impacts of climate change are far-reaching for both natural and human systems making it a collective global challenge that needs to be addressed using transdisciplinary approaches that deliver sustainably and socially just outcomes (Fam et al. 2017). Mitigation and adaptation of climate change are the two main societal response options for reducing these risks (Füssel 2007). Together, adjustments in procedures, strategies, and structures can be made as adaptation actions that will also mitigate the effects of climate change or allow for taking advantage of the economic opportunities that come with these approaches.

6.1 The rationale for Climate Change Strategies

6.1.1 Mitigation Strategies

Climate change mitigation is aimed at maintaining greenhouse gas (GHG) levels in the atmosphere at stable concentrations to avoid grave impacts on the climate system. Mitigation is formally defined as "human intervention to reduce the sources or enhance the sinks of greenhouse gases" (IPCC 2014). In comparison, climate change adaptation focuses on actions to face the consequences of climate change. Adaptation refers to changes in ecological, social, or economic systems because of existing or anticipated climatic stressors, as well as their ramifications or consequences (Schipper 2006).

Africa has contributed the least to global atmospheric GHG emissions, but the continent suffers from some of the worst Climate Change related consequences and has limited capacity to cope with climate change impacts. Notwithstanding, South Africa is one of the top 20 most carbon-intensive countries in the world (currently ranked number 13) (UNFCCC 2011, Klausbruckner et al. 2016) because of high dependence on industrial activities that rely on the burning of coal, crude oil and, natural gas (Arndt et al. 2013). As the largest CO_2 emitter in Africa, it is rated 27th in the Global Climate Risk Index. South Africa has therefore made international and national commitments towards GHG mitigation, and the government has stated that there is an urgent need to strengthen the resilience of our society and economy to climate change impacts and to develop and implement policies, measures, mechanisms, and infrastructure that protect the most vulnerable communities. One of these strategies involved 'Blue Carbon'.

6.1.2 Role of 'Blue Carbon' in Mitigation Strategies

The term "blue carbon" was coined in 2009 by a UNEP Rapid Response Assessment with the aim "to highlight the critical role of the oceans and ocean ecosystems in maintaining our climate and in assisting policy makers to mainstream an oceans agenda into national and international climate change initiatives" (Nelleman et al. 2009).

"Blue carbon ecosystems" -mangroves, salt marshes, and seagrasses (Nellemann et al. 2009), as the term suggests, contribute towards the role of the oceans within the global carbon (C) cycle. As in other vegetated ecosystems, atmospheric CO_2 is taken up during photosynthesis, and organic carbon is stored within in the soils/sediments, the living biomass of the plants both aboveground (leaves, stems, and branches) and belowground (roots), as well as in non-living biomass (leaf litter and dead wood) (McLeod et al. 2011, Howard et al. 2014. These habitats are unique in that the carbon that they sequester during photosynthesis is often moved from the short-term carbon cycle (10-100 years) to the long-term carbon cycle (1000 years) and is continuously buried as slowly decaying biomass (Barbier et al. 2011). Blue carbon habitats thus have a much higher projected sequestration potential than terrestrial habitats. In addition to 'blue carbon', South Africa also supports swamp forests, reeds and sedges which are generally seen as habitats that sequester 'teal carbon' referring to carbon captured in freshwater inland wetlands.

The explicit incorporation of blue carbon ecosystems into climate change policy has been recommended as a key climate protection strategy to maintain these habitats as carbon sinks and thus ensure their continued future contribution towards carbon sequestration. This is generally accomplished through national-level policies, as these are closely tied to the implementation of the Paris Agreement (United Nations 2015). However, there is also scope to integrate the benefits from blue carbon into provincial and local level policy – namely in the form of coastal/estuarine planning and management, as well as provincial climate mitigation policies (Wedding et al. 2021).

In South Africa, all blue carbon ecosystems are found within estuaries so the relevant policies and measures to reduce pressures are related to estuarine ecosystems in general, and not specifically to the mangroves, salt marshes and seagrasses. Policies focussed on environmental management include the Acts and Regulations that are related to the National Environmental Management Act (NEMA), as well as the Acts that aim to reduce negative impacts on ecosystems. Policies that are focussed on undertaking prevention and mitigation for natural disasters (which could be related to climate change threats) are also relevant to blue carbon ecosystems from a climate change adaptation and resilience perspective. Additionally, the planning policies can be leveraged for potential land-use change activities, such as spatial planning to resolve competing land-use interests.

The pressures that have been projected to increase greenhouse gas emissions from blue carbon ecosystems (land-use change/transformation, freshwater inflow/flow modification, water quality/eutrophication, and artificial breaching) were identified based on extensive research on the anthropogenic impacts on estuaries that have been occurring over several decades. It is also well-established that there is existing legislation to ensure freshwater inflow, maintain water quality, promote sustainable resource use, and control development within estuarine functional zones (Adams et al. 2020). In general, it is the implementation of these measures that is lacking, but in some cases, the legal instruments do fall short, such as for the appropriate (lower) standards for wastewater discharge (Adams et al. 2020). The current standards are insufficient to prevent downstream estuary eutrophication, the proliferation of harmful algal blooms, low oxygen events, and fish kills. The implementation of Ecological Reserves and Estuarine Management Plans is critical, and a National Estuary Restoration Programme is urgently needed to support the above (Van Niekerk et al. 2019, Adams et al. 2020).

6.1.3 Adaptation Strategies

Climate change adaptation is the 'adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities' (Sheaves et al. 2016). Climate change adaptation focuses on actions addressing the consequences of climate change. Adaptation refers to changes in ecological, social, or economic systems because of existing or anticipated climatic stressors, as well as their ramifications or consequences (Schipper 2006). Adaptation actions aim to reduce the vulnerability of ecosystems like estuaries to the impacts of climate change or to delay the negative consequences of climate change rather than the prevention of impacts.

Climate Change adaptation strategies (a set of planned adaptation actions that are developed using a formalised process) can be developed in response to observed climate impacts, or in anticipation of future climate conditions; they can be proactive, aimed at reducing exposure to future risks, or reactive, aimed at alleviating impacts that have occurred (Sheaves et al. 2016). Proactive adaptation generally requires a greater initial investment but is usually more effective at reducing future risk and cost. However, reactive strategies are important in dealing with risks that remain after the implementation of proactive adaptation, or due to unexpected or unavoidable impacts (Sheaves et al. 2016).

6.2 Proposed Mitigation Strategies

6.2.1 Conservation Strategy

Globally an important climate mitigation strategy is ensuring the protection of blue carbon/teal carbon habitats. South Africa has a strong policy and legislative framework with regard to estuary protection and management, and significant progress has been made with implementation across several sectors. However, specific actions aimed at resource and biodiversity protection are lagging, as reflected in the low protection levels of estuaries (<10% Well protected), with only some estuaries (37%) having limited overlap with protected areas. Therefore, urgent measures are required across the spectrum of responses to ensure a protected network of healthy and productive estuaries. In this context, Table 6.1 presents the proposed Preservation Strategy for Estuarine Lakes in South Africa, providing the overall strategy, target, propose actions, and potential mainstreaming tools.

Table 6.1: Recommended Conservation Strategy for Estuarine Lakes in South Africa

<table>
<tr><th colspan="4">OVERALL STRATEGY</th></tr>
<tr><td colspan="4">To use existing international and national processes and structures to protect all remaining blue and teal carbon habitats in the Estuary Functional Zone of estuarine lake systems (in agreement with the United Nations Framework Convention on Climate Change (UNFCCC) [Reduced Emissions from Deforestation and Degradation (REDD+) and Paris Agreement).</td></tr>
<tr><th colspan="4">RECOMMENDED TARGETS</th></tr>
<tr><td colspan="4">SHORT TERM (2035) TARGET FOR ESTUARY CONDITIONS:
- 100% Estuarine Lakes have Estuary Condition Score ≥ A or B, if not achievable then PES +1 category (e.g. PES D ➔C)

SHORT TERM (2035) TARGETS FOR BLUE CARBON HABITATS (REMAINING):
- 100% Mangroves
- 100% Supratidal and Intertidal salt marsh (different from 30% national target of remaining)
- 100% Submerged macrophytes

SHORT TERM (2035) TARGETS FOR TEAL CARBON HABITATS (REMAINING):
- 100% Swamp forest
- 50% Reeds and sedges (different from 30% national target of remaining)</td></tr>
<tr><th colspan="4">PROPOSED ACTIONS</th></tr>
<tr><th>Activity</th><th>WEM</th><th>WAM</th><th>Legislation</th></tr>
<tr><td>Following an ecosystem-based approach that conserves abiotic and biotic processes and ensure functional estuaries:</td><td></td><td></td><td rowspan="5">Biodiversity Act
Protected Areas Act</td></tr>
<tr><td>• Increase the protection through a combination of enhanced formal protection (e.g. parks) and initiating less formal approaches such as implementing OECMs at lower priority / smaller estuaries</td><td>●</td><td>●</td></tr>
<tr><td>• Identify and protect ecologically significant ("critical") areas such as nursery grounds, feeding grounds, and areas of high species diversity and abundance to ensure that supporting biotic processes and feed-back loops are retained.</td><td>●</td><td></td></tr>
<tr><td>• Connect land- and seascapes with corridors to conserve key biophysical processes and enable land-sea connectivity</td><td>●</td><td></td></tr>
<tr><td>• Regularly re-evaluate and adapt boundaries of protection areas/zones to make sure that critical processes are included as the spatial distribution of these areas change under future climate conditions</td><td>●</td><td></td></tr>
<tr><td>Identify and protect blue and teal carbon habitats:</td><td></td><td></td><td rowspan="7">Biodiversity Act
Protected Areas Act
ICM Act</td></tr>
<tr><td>• Develop a blue and teal carbon register (blue carbon register have been developed, teal carbon register needs to be developed).</td><td>●</td><td></td></tr>
<tr><td>• Set ambitious protection targets for blue and teal carbon habitats to ensure climate protection (see above).</td><td>●</td><td></td></tr>
<tr><td>• Conserve and protect key habitat types in multiple areas to spread risks associated with climate change.</td><td>●</td><td></td></tr>
<tr><td>• In developing Protected Areas/Protected Areas Expansion Plans actively plan for ‘accommodation space’ that allow coastal wetlands in protected environments to migrate inland (e.g. through setbacks, density restrictions, land purchases).</td><td></td><td>●</td></tr>
<tr><td>• Ensure 100% inclusion of blue and teal carbon habitats in the Critical Biodiversity Areas Map of South Africa.</td><td>●</td><td></td></tr>
<tr><td>• Apply the IUCN Red Listing of Ecosystems criteria to salt mash to determine their overall threat status and ensure increased legislative protection.</td><td>●</td><td></td></tr>
<tr><td>• Develop a blue and teal carbon monitoring programme and standardize indicators for carbon ecosystems monitoring and inclusion in reporting frameworks to Outlook, MINTECH Working Group 7: Oceans and Coast, SANBI National Biodiversity Assessment and Stats SA Natural Capital Accounting.</td><td>●</td><td></td><td rowspan="2">Carbon Tax Act</td></tr>
<tr><td>• Develop a mechanism by which blue carbon ecosystems can be used to generate carbon credits under South Africa’s Carbon Tax Act. The national demand for offsets has been estimated as 10 Mt CO2e.yr-1, but it is expected that the Carbon Tax could drive investments into GHG removal activities. Blue carbon ecosystems, therefore, represent an important opportunity to generate carbon credits in South Africa.</td><td></td><td>●</td></tr>
<tr><td>Clearly define land ownership within the EFZ area so that state-owned land can be proclaimed as protected, or to identify as areas suitable for stewardship. An assessment of land ownership found significant discrepancies between the SA Cadastral layer and estuarine habitats extent. These and other data gaps need to be resolved so that potential areas for protection can be identified.</td><td>●</td><td></td><td>ICM Act
Biodiversity Act</td></tr>
<tr><td>Develop a land acquisition programme – purchase coastal land that is damaged or prone to regular flooding and use it for protection of estuarine habitats (e.g. blue and teal carbon) and estuarine processes. Owners can exchange property in the floodplain for county-owned land outside of the floodplain.</td><td></td><td>●</td><td>ICM Act</td></tr>
<tr><td>Maintain Sediment Transport processes as they are critical to the management of sea level rise impacts. Assess regional-scale sediment process and develop a regional sediment management (RSM) plan. Such a plan should include the management of impacts by dam development, mining, dune stabilisation and harbour development.</td><td></td><td>●</td><td>ICM Act
NEMA</td></tr>
<tr><th colspan="4">POTENTIAL MAINSTREAMING TOOLS</th></tr>
<tr><td colspan="4">NBA National Estuarine Biodiversity Plan: The NBA 2011 developed a biodiversity plan for estuaries of South Africa by prioritising and establishing which should be assigned partial or full protected Area status (Van Niekerk & Turpie 2012). The National Estuary Biodiversity Plan provides the ‘lens’ through which all present, and future, estuarine resource allocations should be evaluated to ensure that national and international biodiversity targets are achieved. The plan is relevant to climate protection strategies as it had a 100% inclusion target for mangrove areas larger than 5 ha, and a 20% target for salt marsh, and seagrass habitats. It is strongly recommended that future updates of the National Biodiversity Plan up the overall targets for</td></tr>
</table>

inclusion of saltmarsh to 30% and prioritise estuaries that support large expanses of blue and teal carbon ecosystems and that above area targets be incorporated to support South Africa's climate mitigation strategies.
Ramsar Convention: The Convention on Wetlands, called the Ramsar Convention, is a global intergovernmental treaty that provides the framework for national action and international cooperation for the conservation and wise use of wetlands and their resources. Nine estuaries are listed Ramsar sites under the Ramsar Convection (Orange, Verlorenvlei, Langebaan, Bot/Kleinmond, Touw/Wilderness, Heuningnes, Kosi and St Lucia estuaries. Of the above-listed systems, three estuaries do not have formal protection. From a climate mitigation perspective, it is critically important that these systems be elevated to formally protected. Given the importance of Klein and Swartvlei estuarine lakes systems, consideration should be given to their inclusion as Ramsar sites. This will elevate their importance and ensure reporting of further decline at the global level (e.g. Ramsar SDGs).
Important Bird and Biodiversity Area: Important Bird and Biodiversity Areas (IBAs), as defined by BirdLife International, constitute a global network (with 112 sites in South Africa). IBAs are sites of global significance for bird conservation and are identified nationally through multi-stakeholder processes using globally standardised, quantitative, and scientifically agreed criteria. Nineteen estuaries form part of IBAs in South Africa.
Biodiversity stewardship programmes: Historically, the preferred mechanisms for creating protected areas in South Africa were by proclamation of state-owned land or purchase and proclamation by the state. More recently, biodiversity stewardship programmes have expanded, allowing for the proclamation of protected areas on privately owned land. This approach relies on the willingness of key landowners and is 70 to 400 times cheaper to establish and 4 to 17x cheaper to manage. Stewardship is particularly effective in multiple-use landscapes where biodiversity priority areas are embedded in a matrix of other land uses. It should be noted that biodiversity stewardship agreements are often confined to estuarine riparian areas and not the open water area. It is strongly recommended that there should be more engagement with biodiversity stewardship programmes to ensure that the EFZs of estuarine lakes are more represented in the protected area network in the future. Stewardship may also present an important opportunity to conserve saltmarsh in particular, as supratidal areas can be located within private land, e.g. Klein, Bot/Kleinmond and Verlorenvlei.
Critical Biodiversity Areas and Ecological Support Areas: The purpose of Critical Biodiversity Areas (CBAs) and Ecological Support Areas (ESAs) are to guide decision-making about where best to locate development and are designed for use by a range of sectors (e.g. land-use planning, mining and environmental authorisations) that impact on the use and management of natural resources. CBAs are areas required to meet biodiversity targets for ecosystems, species, and ecological processes. Ecological Support Areas (ESAs) play a vital role in supporting the ecological functioning of Critical Biodiversity Areas and Protected Areas and/or in delivering ecosystem services. Moving forward CBAs and ESAs should be designed across land- and seascapes. Some estuaries have been listed as CBAs under the Biodiversity Act due to their sensitivity and high productivity. This initial list needs to be expanded to include all key estuarine lake habitats as CBAs and transformed areas as ESAs.
Other effective area-based conservation measures (OECMs): This is a conservation designation for areas that are achieving the effective in situ conservation of biodiversity outside of protected areas. OECMs are a means of identifying and globally recognising biodiversity-rich areas, where protected area status is not an option. They present a means by which to report conservation estate to the World Database on OECMs (WD-OECMs), thereby contributing to South Africa's national and international area-based targets. OECM is a relatively new approach that was only formalised in 2018. BirdLife South Africa is piloting OECMs in the Western Cape. The project aims to identify, assess, and report on potential OECMs in the province. There is thus an opportunity to include a few high-value blue carbon sites and or important fish nurseries, e.g. Klein, Bot/Kleinmond and Verlorenvlei that support saltmarsh and/or seagrass for assessment as part of the pilot project.
IUCN Red List of Ecosystems (RLE): RLE is a tool to assess the conservation status of ecosystems and complements the IUCN Red List of Threatened Species. Assessments determine whether an ecosystem is not facing imminent risk of collapse, or whether it is vulnerable, endangered, or critically endangered by assessing losses in area, degradation, or other major changes.

6.2.2 Restoration Strategy

In March 2019, the United Nations (UN) General Assembly proclaimed 2021-2030 as 'the Decade on Ecosystem Restoration', to support and scale up efforts to prevent, halt and reverse the degradation of ecosystems worldwide and raise awareness of the importance of successful ecosystem restoration (UN General Assembly 2019). The UN Decade calls for strong commitments and efforts to restore 'at least 350 million hectares of degraded landscapes by 2030's recognising that 'there has never been a more urgent need to restore damaged ecosystems than now'. Restoration efforts would also contribute to achieving the UN Sustainable Development Goals, 2030 Agenda for Sustainable Development, and other targets set out by international conventions and agreements. However, restoration and/or rehabilitation of degraded or novel ecosystems (highly transformed estuaries) have not been systematically dealt with in South Africa. Table 6.2 presents the proposed Restoration Strategy for Estuarine Lakes in South Africa, presenting the overall strategy, target, propose actions, as well as potential mainstreaming tools.

Table 6.2: Recommended Restoration Strategy for Estuarine Lakes in South Africa

OVERALL STRATEGY			
To use existing international and national processes and structures to restore all disturbed blue and teal Carbon habitats in the Estuary Functional Zone of estuarine lake systems.			
TARGETS			
SHORT TERM TARGET (2035): 80% of disturbed land (gardens and agricultural) below the 2.5 m MSL contour should be restored **LONG-TERM TARGET (2050):** 100% of disturbed land (gardens and agricultural) below the 2.5 m MSL contour should be restored **SUPPORTING TARGETS (LINKED TO PROTECTION, FLOW MODIFICATION AND POLLUTION ADAPTATION STRATEGIES):** 100% Estuarine Lakes have Estuary Condition Score ≥ A or B, if not achievable then PES +1 category (e.g. PES D ➔C) 100% of Estuarine Lakes have Hydrology status ≥ C category (near-natural/moderately modified) or higher 100% of Estuarine Lakes have a Water quality status ≥ C category (moderately modified) or higher			
PROPOSED ACTIONS			
Activity	**WEM**	**WAM**	**Legislation**
Develop a national restoration programme for estuaries with clear restoration targets that are integrated into provincial and local coastal management programmes, blue and teal carbon habitats and water quality should be a key focus of such a restoration programme.		●	NWA, NEMBA,

• Conserve and restore the structural complexity and biodiversity of vegetation in salt marshes, seagrass, and mangroves of estuarine lakes. • Actively plan to allow estuaries and supporting coastal wetlands to migrate inland. • Restore habitat types in multiple areas to spread risks associated with climate change. • Restore fluvial and tidal flows/connectivity to ensure the rewetting of key habitats. • Restore water quality to allow for optimum recovery. • Restore/promote wetland accretion in sediment-starved catchments by introducing sediment.		● ● ● ● ●	ICM, Municipal Systems Act, SPLUMA, National Buildings Act
Develop adaptive stormwater management practices that attenuate stormwater peak inflows and fit retrospectively (e.g. remove impervious surface, replace undersized culverts, promote natural buffers, and detention wetlands) to reduce flood risk and provide water quality and ecological benefits.		●	Water Services Act Municipal Systems Act, National Buildings Act
Manage realignment/deliberately realign engineering structures affecting rivers, estuaries, and coastlines in 'working with nature' approach.		●	

POTENTIAL MAINSTREAMING TOOLS
National Estuary Restoration Programme: The NBA 2018 highlighted a pressing need for a National Estuary Restoration Programme to halt and reverse the on-going decline in estuary condition. Such a programme would focus on degraded and novel systems, with an emphasis on the larger systems of high biodiversity importance and the socially important urban systems. National-scale deterioration in water quality and quantity threatens estuarine species and habitat diversity. Impacts include loss of seagrass habitat due to macroalgal blooms (Klein), alien invasive aquatic plants (Bot/Kleinmond) and persistent microalgal blooms from agricultural return flow (Verlorenvlei). Improvement in water quality of the most cost-effective restoration measure for aquatic systems such as estuaries. Transdisciplinary approaches to aquatic ecosystem restoration are important, i.e. a socio-ecological systems approach to restoration through action research should be adopted. There are opportunities to implement a circular, regenerative economic approach to restoring estuary health with a focus on water quality management. Reducing nutrient inputs whilst culturing a harvestable resource as a restoration activity would significantly improve estuary health in South Africa. This provides for the opportunity to develop a 'National Restoration Programme' for estuaries.
MINTECH Working Group 7 (WG7): Oceans and Coast & Inland fisheries: Provides the ideal mechanism to facilitate and coordinate a national roll-out of a National Estuaries Restoration programme.
Extended Public Works Programmes: "Working for wetlands" have funding available to work in estuaries. The benefit is that "Working with Wetlands" are working towards an approval process that will ensure that restoration activities do not have to do an EIA to restore wetlands. If restoration were to occur under a separate arm of government, it will require a full EIA. Thus, there are significant benefits to implementing estuary restoration through these exiting processes. DFFE are in the process of formally linking the Estuaries Realm to this ongoing programme. There is some "red tape" that needs addressing as there is a disjunct between 'Oceans and Coast' and 'Biodiversity and Conservation', but DFFE is working on alignment within the different sections. DFFE: Oceans and Coast is currently engaging around the Orange Estuary with the process. "Working for the Coast" needs to become involved in priority systems. Estuarine lakes need to be put forward as such a group of priorities.
Traditional Authorities: Traditional authorities play an important role in land management in South Africa, especially in KZN where a large extent of estuarine lake habitat occurs within their areas of jurisdiction. They have an important role to play in restoration and can make a valuable contribution to the restoration agenda. It is thus very important to engage with them early in the process and develop an approach that is relevant to land management in these areas.
Action research required of ongoing restoration programme: The St Lucia Lake system, is undergoing a restoration effort to restore estuarine connectivity and functionality. The Swartkops Estuary is the focus of a saltpan restoration effort. Lessons learned from these, and other restoration processes will inform future management and restoration efforts of estuaries across the country.
DFFE Ramsar Compliance Initiatives: DFFE is currently investigating compliance and restoration at Ramsar sites. All activities are evaluated (e.g. development, pollution and water use) and non-compliance is mapped. For example, at Verlorenvlei bad farming practices, sumps, mining activities and illegal harvesting activities were first mapped and then assessed and investigated. Non-compliance are then addressed to restore the condition.

6.3 Proposed Adaptation Strategies

6.3.1 Land-use Change & Instream Infrastructure Development

Table 6.3 presents the proposed Adaptation Strategy for Estuarine Lakes in South Africa pertaining to land-use change and instream infrastructure development, presenting the overall strategy, targets, recommended actions (indicating where possible, showing With Existing Measure (WEM)/With Additional Measures (WAM)), as well as potential mainstreaming tools.

Table 6.3: Recommended Adaptation Strategies for Estuarine Lakes in South Africa: Land-use and Instream Infrastructure

OVERALL STRATEGY
Commit to active retreat below the 2.5 m MSL to allow natural processes to re-establish critical habitats under future climate conditions. Discourage all developments and future land-use change below the 5 m MSL contour. Return disturbed land to natural process to allow for wetland accretion (accommodation space).
TARGETS
SHORT TERM TARGET (2035): 100% of land below the 2.5 m MSL contour should be targeted for a managed retreat 100% of agricultural land below 2.5 m MSL contour should be allowed to return to natural cover, only light opportunistic uses allowed (e.g. grazing, harvesting of mangroves, reeds, and sedges). 100% of high-value infrastructure below the 2.5 m MSL contour raised/protected against flooding 100% of critical access routes below the 2.5 m MSL contour replanned/rerouted 100% of estuarine lakes have Estuary Management Plans No mining within the EFZ No hard infrastructure within the EFZ (with exception of bridge supports) Developed a strategy and engaged with traditional authorities on the risk climate change pose to their coastal land and the need to retreat in low-lying coastal areas.

LONG TERM TARGET (2050):
100% of land below the 5 m MSL contour should be targeted for a managed retreat
100% of agricultural land below 5 m MSL contour should be allowed to return to natural cover, only light opportunistic uses allowed (e.g. grazing, harvesting of mangroves, reeds and sedges).
100% of high-value infrastructure below the 5 m MSL contour raised/protected against flooding
100% of critical access routes below the 5 m MSL contour replanned/rerouted
100% of estuarine lakes have Estuary Management Plans
No mining within the EFZ
No hard infrastructure within the EFZ (with exception of bridge supports)

SUPPORTING TARGETS (LINKED TO PROTECTION AND RESTORATION MITIGATION STRATEGIES):
100% Estuarine Lakes have Estuary Condition Score ≥ A or B, if not achievable then PES +1 category (e.g. PES D → C)
100% of disturbed land (gardens and agricultural) below the 2.5 m MSL contour should be restored (2050)

RELEVANT VECTORS OF CLIMATE CHANGE

Increase in droughts and floods, sea level rise & increase storminess

KEY ACTIVITIES THAT REDUCE/CONTROL THE IMPACT OF LAND-USE CHANGE AND INSTREAM INFRASTRUCTURE DEVELOPMENT

Activity	WEM	WAM	Legislation
Incorporate consideration of climate change impacts (including sea level rise) into all planning for new infrastructure (e.g. homes, businesses, sewage systems) • Expand the planning horizons of land use planning to incorporate longer climate predictions, e.g. 2100. • Retreat from, and abandonment of, coastal land predicted to regularly flood. • Encourage land-use planning practises that allow upslope and upstream migration of critical estuarine habitats with sea-level rise. • Actively prevent 'coastal squeeze' through the development of conservative setback lines/coastal management lines and protection of the EFZ from land-use change and development. • Develop a land-exchange programme to reclaim 'accommodation space' (private land regularly inundated by flooding) to ensure the persistence of key habitats under rising sea level conditions.	 ● ● ● ●	 ●	ICM, NEMBA
Protect/restore natural wetting process and avoid escalated erosion of estuarine habitat (and adjacent coastal land) which improve resilience to increase flooding and storminess under future climate conditions • Remove shoreline hardening structures such as seawalls, levees, dikes, and other engineered structures to allow for shoreline migration and replace shoreline armouring with living shorelines – through beach nourishment, planting vegetation, etc. • Prohibit 'hard' shore protection to prevent upstream and downstream erosion of estuarine habitats. • Assess and remove hard protection and/or barriers to tidal and riverine flow that inhibit the natural process that reduces floodplain inundation.	 ● ● ●		NEMA (EIA), ICM
Develop overarching policies/strategies and reporting mechanisms that will ensure the persistence of blue and teal carbon ecosystems and avoid future losses and maintain CO_2 sinks, focussing on land use practices as well as other anthropogenic activities that cause degradation. • Actively incorporate blue/teal carbon habitat protection into the approval processes and planning of infrastructure (e.g. transportation planning, sewer utilities). Include protection requirements in the municipal Integrated Development Plans and the location of blue/teal carbon habitat in municipal Spatial development frameworks. • Avoid clearing and avoid soil disturbance within the Estuarine Functional Zone (EFZ). Re-evaluate/revoke consent for biomass clearing and/or soil disturbance activities within the EFZ (for agriculture or other developments) • Avoid infilling of estuarine floodplains and channels to ensure that natural wetting and drying processes remain intact. Even short-term disturbances (e.g. temporary road crossing or infilling by mining) can lead to long-term consequences because of disruption to carbon sequestration processes. Avoidance is best practice in these sensitive habitats. • Elevate all land use change and soil disturbance within the EFZ in the NEMA EIA Regulations (2014) to Listing notice 1, i.e. Regulations currently list the clearing/infilling of estuarine habitat within EFZ in Listing Notice 3. • Encourage the wise use of blue carbon ecosystems and protect / monitor against destructive uses, e.g. overgrazing by sheep and goats, excessive browsing by cattle of mangroves, harvesting of mangroves. • Restore blue and teal carbon habitats to enhance carbon sequestration in degraded areas. • Highlight the importance of carbon ecosystems in the development of Estuary Management Plans under National Estuarine Management Protocol (2021) and formally include them in future updates of the DFFE Guidelines for the Development and Implementation of Estuarine Management.	 ● ● ● ● ● ●	 ●	NEMA (EIA), ICM, NEMBA
Avoid all mining-related activities (sand mining, diamond mining, mineral mining, salt works) within a 1 km buffer of the EFZ given the largely irreversible, long-term impacts on blue and teal carbon systems. In addition to disturbance to soils and the water table, mining also poses a significant risk of smothering by dust of blue carbon ecosystems, e.g. the ongoing impact of mining dust. Conduct a "Mining SEA" for South Africa's estuaries to determine the impact on estuarine processes (including sediment budgets)	●		Minerals Act NEMA (EIA)
Develop strategies to manage the impact of boating (e.g. zonation and limiting engine size) on channel stability and to prevent marsh erosion (and oil pollution). Including the development and construction of instream infrastructure such as jetties and slipways that impact ecosystem function and associated blue and teal carbon ecosystems. Actively remove old jetties that reduce water flow and tidal exchange.	●		ICM

POTENTIAL MAINSTREAMING TOOLS

NEMA EIA Regulations: Various activities listed in the NEMA Environmental Impact Assessment ('EIA') Regulations have a bearing on activities within the coastal zone and require environmental authorisation before they can proceed. The EIA Regulations are especially pertinent to estuaries as many estuaries are situated within rapidly expanding development nodes along the South African coast and are under tremendous development pressure. Depending on the activity and/or applicant, DFFE, DMRE or the provincial competent authority will be responsible for assessing applications for environmental authorisation. In terms of GNR 327 (Listing Notice 1) a Basic Assessment must be conducted; and in terms of GNR 325 (Listing Notice 2) an EIA must be conducted. GNR 324 (Listing Notice 3) identifies activities in sensitive areas (including the estuarine functional zone limited to the 5

m topographical contour) that also require environmental authorisation before they may proceed. Particularly in KwaZulu-Natal there is the realisation that the current EFZ delineation is inadequate and that a new EFZ area must be legislated before even more estuarine habitat is compromised. All land use change and soil disturbance within the EFZ should be elevated to Listing notice 1 to ensure future climate resilience.
Estuary Management Plans: The ICM Act (2008) provides for integrated coastal and estuarine management. A key supporting measure was the promulgation of the National Estuarine Management Protocol (NEMP) and the roll-out of the Estuary Management Planning (EMP) framework and the provision of resources, both human and funding, to sustain this effort. Conservation bodies such as SANParks and CapeNature have also embraced the process as a legislative measure for community engagement, integrative planning and cooperative governance. It is envisaged that all estuarine lakes should have Estuary Management Plans that are nested in Coastal Management Programmes, Protected Areas Plans and local Integrated Development Plans (IDPs) to ensure wise use of estuary resources. Estuary Zonation plans (for all areas within the EFZ) should also be incorporated into the Spatial Development Frameworks (SDFs) of local or district municipalities to guide sustainable development and use. The relevant municipality needs to develop an environmental overlay that reflects the estuarine lakes as areas of high conservation value as well as providing migratory corridors to a range of species. It is recommended that blue and teal carbon ecosystems be highlighted in these overlays as areas of high conservation and societal value and development in these zones be curtailed.
Agricultural guidelines to mitigate the impact of agriculture on estuaries: The Conservation of Agricultural Resources Act (CARA) does not explicitly support estuary management as evidenced by agriculture being one of the main sectors responsible for land use change in EFZs. Guidelines need to be developed on how to mitigate the impact of agriculture on estuaries given their sensitivity to agriculture focussing on: agricultural return flow, drainage structures within the EFZ, spaying of herbicides and pesticides, grazing of salt marsh, browsing of mangroves, burning of reeds, livestock stock and dairy farming impacts and the need for buffer zones, and crops and fields within the EFZ. The latter can result in pressure to artificially breach estuary mouths, if agricultural land becomes backflooded.
'Mining Strategic Environmental Assessment (SEA) for South Africa's estuaries: Spatial planning, monitoring and management of mining operations is essential to make optimum use of mineral resources and to avoid/mitigate the worst impacts and not compromise South Africa's natural and associate cultural heritage. No mining activities should occur within the EFZ of estuaries, especially estuarine lake systems. Sand, mineral and diamond mining have severe impacts on estuaries and are largely unregulated with a significant amount of illegal activity not being adequately addressed. Given the irreversibility of the impact of mining and the substantial threat it poses to estuarine ecosystems, a sector-specific engagement is urgently needed to ensure ongoing estuarine functionality, productivity and a sustainable flow of benefits (e.g. coastal protection) to local coastal communities. A strategic assessment of the spatial extent and associated impacts of mining on estuaries (especially the estuarine lakes) and the coast is urgently needed Also required is a national scale 'estuary and coastal sediment budget analysis' guiding the sustainable rate of sand extraction from the different systems.
Engage with Traditional Authorities: Traditional authorities play an important role in land management in South Africa, especially in KZN where a large extent of estuarine lake habitat (below 2.5 m MSL) falls within their ambit. A social-ecological system's approach (not only an ecosystems-based approach) needs to be developed that communicate the implication of future climate conditions in a transparent manner and how to implement adaptation strategies in the face of ongoing sea level rise.

6.3.2 Flow Modification

Table 6.4 presents the proposed Adaptation Strategy for Estuarine Lakes in South Africa pertaining to flow modification, presenting the overall strategy, targets, recommended actions (indicating where possible With Existing Measure (WEM)/With Additional Measures (WAM)), as well as potential mainstreaming tools.

Table 6.4: Recommended Adaptation Strategies for Estuarine Lakes in South Africa: Flow Modification

OVERALL STRATEGY			
Protect /restore freshwater inflows to the estuarine lakes of South Africa to ensure their future resilience to shifts in rainfall/runoff cycles and extreme droughts.			
TARGETS			
SHORT TERM TARGET (2035): 100% of estuarine lakes have Hydrology status ≥ B/C category (near-natural/moderately modified) or higher 100% of estuarine lakes have Hydrodynamic status ≥ B category (representative of near-natural open-close cycles) or higher, except for St Lucia 100% of estuarine lakes have drought flow allocation No obstruction to estuary-catchment connectivity in river-estuary ecotone 100% of estuarine lakes have Water Quality status ≥ C Category (moderately modified) or higher (to ensure adequate low /drought flows are allocated in high retention polluted systems)			
RELEVANT VECTORS OF CLIMATE CHANGE			
Increase in droughts and floods, sea level rise, increase storminess			
ACTIVITIES THAT MITIGATION FLOW			
Activity	WEM	WAM	Legislation
Protect/reinstate freshwater inputs to estuarine lakes (especially system < B/C Category):			NWA
• Determine the freshwater flow allocations ('Reserves') that ensure the maintenance of critical estuarine processes (e.g. land-sea connectivity) and habitats (e.g. blue and teal carbon habitats) through medium to high confidence environmental flow assessments (not only desktop assessments).	●		
• Explicit 'drought' flow allocations should be made to estuaries high biodiversity value and that support blue and teal carbon habitats and these need to be adhered to, e.g. at present Groot Berg Estuary has such an allocation but water was not released during the drought.	●		
• Explicitly incorporate the requirements of blue and teal carbon habitats in the Resource Quality Objectives (RQOs) developed as part of the DWS Water Resource Classification process to ensure contribution climate mitigation strategies. Investigate opportunities to retrospectively adjust flow RQOs to protect critical blue and teal carbon habitats.	●		
• The clearing of invasive alien plants in the catchments of estuaries should be encouraged to restore critical baseflows.	●		
• Manage water demand (through water reuse, recycling, rainwater harvesting, desalination, etc.)	●		
• Control the proliferation of illegal small farm dams that cumulatively can remove all mean annual run-off and freshwater inflow to estuaries.	●		
• Strengthen compliance efforts (e.g. compulsory licensing) to reduce the impact of illegal freshwater abstraction in or above estuaries.	●		

Protect/restore groundwater to estuarine lakes: • Over-abstraction and lowering of the groundwater table near estuaries should be prevented. Detailed investigations should be undertaken where such activities are licensed to ensure no impact on estuaries. The management of groundwater tables is of critical importance in the maintenance of water levels in estuarine lakes. • Incorporate the licensing of current/new plantations in the environmental flow allocation process and institute buffers zones around plantations to limit the impact on base flows – no commercial forest plantations should be allowed within a 2 km buffer of estuaries to protect the groundwater table. Manage escapees from commercial plantations. • No mining (including sand mining) should be allowed within the EFZ given the high risk of disturbance to the groundwater table and obstruction to flow. All mining within a 5 km radius of an estuary should be supported by a detailed EIA that evaluates and mitigates the impacts to freshwater input (including the groundwater table).	● ● ●		NWA
Reinstate fluvial and tidal connectivity: • Remove barriers that limit tidal exchange within the EFZ, including weirs and causeways. • Remove/redesign transport infrastructure that impedes tidal exchange, e.g. old railways and bridges.	● ●		NEMA, ICM, NWA
Invest in effective compliance monitoring and regular auditing of water resource use.	●		NWA
Invest in long-term monitoring programmes that can inform streamflow management strategies and country-level indicators.	●		NWA
POTENTIAL MAINSTREAMING TOOLS			
Classification/ ecological water requirements (EWRs)/Resource Quality Objectives (RQOs): Estuarine lakes should be priorities by the Department of Water and Sanitation (DWS) / Catchment Management Authorities (CMAs) for future interventions. The water resource 'Classification' process and the associated 'setting of RQOs' is one of the critical tools that can be used to ensure future persistence and/or protection of estuarine lakes system and associated blue/teal carbon ecosystems. However, 'Classification' seems to view existing water resource use as sacrosanct, while other forms of resource use, e.g. fishing or pollution, are treated as negotiables. To reach a truly balanced distribution of estuarine benefits even existing lawful uses may need to be redistributed through compulsory licensing mechanisms, e.g. returning some baseflows to maintain critical ecosystem services (e.g. carbon sequestration). Unfortunately, there is an ongoing decline in estuary condition as in the recently gazetted RQOs for the Breede-Gouritz Water Management Area critically important estuaries (Klein, Bot/Kleinmond and Heuningnes) supporting a wide array of blue carbon ecosystems were gazetted at lower than recommended conditions, with ripple effects to related estuarine management plans and conservation strategies. The determination and implementation of estuarine environmental flow requirements are critical for 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 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 thus requiring higher flows to offset impacts.			

6.3.3 Pollution

Table 6.5 presents the **recommended** Adaptation Strateg**ies** for Estuarine Lakes in South Africa pertaining to pollution, presenting the overall strategy, targets, recommended actions (indicating where possible With Existing Measure (WEM)/With Additional Measures (WAM)), as well as potential mainstreaming tools.

Table 6.5: Recommended Adaptation Strategies for Estuarine Lakes in South Africa: Pollution

OVERALL STRATEGY			
Improve the overall water quality of estuarine lake systems to enhance resilience to future warmer and drier conditions. Remove all wastewater inputs to estuarine lakes.			
TARGETS			
SHORT TERM TARGET (2035): 100% of estuarine lakes have a water quality status ≥ C category (moderately modified) or higher No harmful algal blooms in estuarine lakes No fish kills in estuarine lakes (due to low oxygen quality) No wastewater discharges into or in river just upstream of estuarine lakes No accumulation of Persistent Organic Pollutants (POPs) in estuarine lakes (and to the sea – DDT has been detected in the shells of turtle eggs at iSimangaliso)			
RELEVANT VECTORS OF CLIMATE CHANGE			
Changes in rainfall/runoff, increase in droughts and floods, increased temperature, ocean acidification			
ACTIVITIES THAT MITIGATE POLLUTION			
Activity	**WEM**	**WAM**	**Legislation**
Control/reduce the impact of wastewater discharges on estuarine lakes: • Reduce and improve water quality from existing wastewater treatment works, with the intent of recycling or reusing effluent in the long term (in-line with current national policies). Estuarine lakes are nutrient sinks it is thus critical that all wastewater discharges be removed from these systems. • Prohibit the development of new wastewater treatment works that would discharge into estuarine lakes/estuaries (in line with current national policies). • In the process of phasing out WWTWs to estuarine lakes, develop strict permit conditions (more strict than General/Special Standards that do not limit nutrient input to the required level) and invest in artificial wetlands as treatment in the interim.	● ● ●		NWA, ICM
Control/reduce the impact of agricultural runoff on estuarine lakes:			CARA, NWA

• Develop agriculture best practice guidelines and generate awareness of the impact of over fertilisation on wetlands and estuaries. Develop industry standards that will support this. • No direct agriculture drainage of estuarine floodplains should be allowed. This practice both enhances nutrient input and dries out remaining blue and teal carbon ecosystems and soils. • Control and discourage the use of herbicide and pesticide inputs in and around estuaries. Given the high retention of these environments, applications often have long-lasting and unintended consequences, e.g. oxygen depletion due to accumulated organic matter, accumulation of toxic substances in edible fish. • Develop Catchment-to-Coast plans for estuaries that support important blue/teal carbon ecosystems to ensure an integrated management approach	● ● ● ●		
Control/reduce the impact of stormwater runoff on estuarine lakes: • Stormwater should be captured and treated onsite where possible using soft engineering approaches (e.g. in new residential developments). The use of Sustainable Urban Drainage Systems (SUDS), bio-retention, stormwater tree trenches, blue roofs and underground storage systems should be encouraged. • Develop adaptive stormwater management practices that attenuate stormwater peak inflows (e.g. remove the impervious surface, replace undersized culverts, promote natural buffers, and detention wetlands to reduce flood risk and provide water quality and ecological benefits). • Developing stormwater model legislation/ordinance/by-laws that require the use of green infrastructure. These can help local municipalities/metros incorporate climate change projections or green infrastructure incentives into local practices. Including the adoption of more stringent stormwater policies and requirements for developers to manage water onsite to the maximum extent feasible. • Provide training for municipal staff on green infrastructure and offer incentives for developers/engineers to use green infrastructure designs, rather than relying on pipe-based systems. • Require developers to make decisions informed by future climate, and local governments to incorporate climate change into decision-making processes.	● ● ● ● ●		NWA, ICM, Municipal Systems Act, SPLUMA, National Buildings Act
Permitting systems should constrain locations for landfills, hazardous waste dumps, mine tailings, and toxic chemical facilities in or near estuaries.	●		Waste Act
POTENTIAL MAINSTREAMING TOOLS			
Wastewater control measures: Nutrient pollution, which reduced water quality and promotes eutrophication, mainly originates from wastewater disposal, agricultural return flows and stormwater runoff. Of high concern, is the rapid escalation of pressures associated with municipal wastewater (sewage) disposal and sewage spills, especially in the urban centres. Even if the treatment plants can treat effluent to legal standards (e.g. General Standards), the volumes of effluent are simply too large to remain within the assimilative capacity of the systems. This highlights the urgent need to implement reuse and recycling strategies. Any discharge of effluent that originates from land into an estuary requires general authorisation or a coastal waters discharge permit. The development of infrastructure related to effluent discharges may also trigger listed activities under the NEMA EIA Regulations. New regulations on coastal waters discharges emphasise that no new wastewater discharges will be allowed into estuaries (DEA 2019).			
Stormwater control measures: Contaminated runoff contains an array of pollutants posing a serious threat to ecosystems, including toxic substances (such as metals, petroleum hydrocarbons and persistent organic pollutants). However, unlike point sources (e.g. WWTW discharges) these diffuse sources of pollution are extremely difficult to identify, regulate or control at end-of-pipe; and potential management actions should rather focus on identifying interventions at the source. Management of urban stormwater resides with local authorities typically manage this through the use of by-laws. Estuaries are being overwhelmed by contaminated stormwater runoff resulting from rapid urbanisation along banks and adjacent catchments. Traditional approaches to managing pollution sources require urgent re-thinking. More stringent and technologically innovative municipal guidelines are needed to address this growing pressure. Poor legal compliance and lack of enforcement contribute significantly to deteriorating water quality in estuaries.			

6.3.4 Overexploitation of living resources

Table 6.6 presents the recommended Adaptation Strategy for Estuarine Lakes in South Africa pertaining to over-exploitation, presenting the overall strategy, targets, recommended actions (indicating where possible, With Existing Measure (WEM)/With Additional Measures (WAM)), as well as potential mainstreaming tools. It needs to be understood that, unlike the ocean where habitats and species aggregations are spatially distributed along the entire coast, the relatively small estuarine space can be easily and intensively targeted (or "mined") by fishers leading to a high risk of stock depletion due to intensive fishing pressure.

Table 6.6: Recommended Adaptation Strategies for Estuarine Lakes in South Africa: Overfishing

OVERALL STRATEGY
Reduce fishing pressure to ensure a self-maintaining population that is resilient to future climate conditions. Reduce pollution pressure to increase resilience to droughts and periods of low connectivity to the sea.
TARGETS
SHORT TERM TARGET (2035): 100% of estuarine lakes have Fish status ≥ B/C category (near-natural/moderately modified) or higher No commercial fishery be allowed in estuarine lakes Control/reduce the impact of traditional fish traps (Kosi) (escalated over last 20 years) – no increase in area/effort from 2000, no gear changes, no lining of traps with gillnet or other plastic material, all traps face up-stream. No netting (seine or gill nets) be allowed in estuaries (except for cast netting) No obstruction to estuary-catchment connectivity in river-estuary ecotone No fishing at night (to allow breeding stock some recovery) No fish kills in estuarine lakes (due to low oxygen quality) More than 60% of fishing effort is monitored and reported 2 (or more) compliance personnel dedicated to each estuarine lake

SUPPORTING TARGETS (LINKED TO PROTECTION, FLOW MODIFICATION AND POLLUTION ADAPTATION STRATEGIES):			
100% Estuarine Lakes have Estuary Condition Score ≥ A or B, if not achievable then PES +1 category (e.g. PES D ➔C) 100% of estuarine lakes have Hydrology status ≥ B/C category (near-natural/moderately modified) or higher 100% of estuarine lakes have Water quality status ≥ C category (moderately modified) or higher No harmful algal blooms in estuarine lakes			
RELEVANT VECTORS OF CLIMATE CHANGE			
Change in rainfall/runoff patterns, increase in droughts and floods, increased temperature, sea level rise, increased storminess, ocean acidification			
ACTIVITIES MANAGEMENT ALLEVIATE THE IMPACTS OF OVEREXPLOITATION OF LIVING RESOURCES			
Activity	**WEM**	**WAM**	**Legislation**
Increase formal protection of estuarine living resources, e.g. through the establishment of Marine Protected Areas, closed area zonation, IUCN Red listing of Threatened Species.	●		LMRA
Institute catch/gear control measures to ensure sustainable fishing levels, e.g. catch limits, size/slot limits, closed periods (spawning seasons, night ban on fishing)	●		LMRA
Invest in effective compliance measures, e.g. remote tracking systems, human resources	●		LMRA
Develop estuarine resource monitoring programmes that can feed into management strategies and country-level indicators	●		LMRA
Invest in strategic restoration programmes to restore estuarine productivity and functionality	●		LMRA
Create public awareness of the risk over-exploitation poses to estuary function and societal benefits	●		LMRA
Control/reduce fishing effort levels in Kosi by implementing an existing fisheries management plan for the Kosi Fish traps, e.g. traps must face up-stream, not down-stream; no increase in the efficiency of the traps.	●		LMRA
POTENTIAL MAINSTREAMING TOOLS			
Fisheries management measures: Over the last 10 years, high fishing pressure has resulted in some estuarine-dependent fish species showing no signs of stock recovery, with some experiencing further decline to critical levels (<1% of pristine) and at risk of population extirpation. Total extinction of endemic species is becoming a real possibility. In response to this, and the fact that more than 50% of large reproductive adults are caught at night, a ban on night fishing was introduced at the Breede Estuary. This measure is proving so successful that the approach will be rolled out to all other estuaries in the country over the next few years. Estuarine lakes need to be prioritised for this measure. Similarly, a prohibition on targeting and catching sharks and rays in the Breede Estuary has shown promise in controlling trophy fishing for these species. It is suggested that either a ban or catch-and-release of these, should also be rolled out countrywide. No commercial fishing is allowed in estuaries with the exception being the Olifants and Langebaan estuaries. Except for the traditional Kosi trap fishery and bait harvesters in the Knysna and Swartkops estuaries, small-scale fishers in all systems are not allowed to sell their estuarine catch. The key priority is the implementation of the prohibition on fishing at night in all estuaries and the implementation of more stringent bag and slot limits (minimum and maximum sizes) for priority species – Dusky Kob, Dusky Steenbras, Spotted Grunter, Leervis and Elf. Consideration should be given to testing rotational time/area closures in pilot estuaries. Regularly stock assessments of the aforementioned species are also required.			
Increase compliance management with a focus on illegal gill netting: Escalating gill net poaching is responsible for at least half the catch in South Africa's important estuary fish nursery areas. This has resulted in recruitment and growth overfishing and the collapse of the six most economically and socially important species in estuaries and the sea. The most severely impacted are small scale coastal fisheries. There needs to be a coordinated campaign to eradicate this destructive fishing method. This includes national government support (financial and logistical) to provincial management authorities. There is much scope for the improvement and resourcing of fisheries compliance monitoring and enforcement efforts.			
Estuary Management Plans and aligned processes: Multiple interventions are required to avoid further decline in fish health. These include reduction in fishing effort, protection of freshwater inflow, restoration of water quality, and avoidance of mining, infrastructure development and crops in the EFZ.			

6.3.5 Artificial breaching

Table 6.7 presents the proposed Adaptation Strategy for Estuarine Lakes in South Africa pertaining to artificial breaching, presenting the overall strategy, targets, recommended actions (indicating where possible With Existing Measure (WEM)/With Additional Measures (WAM)), as well as potential mainstreaming tools.

Table 6.7: Recommended Adaptation Strategies for Estuarine Lakes in South Africa: Artificial breaching

OVERALL STRATEGY
Short term (2035): Survey and evaluate all hard infrastructure within the EFZ to determine flooding risk of low-lying infrastructure and re-evaluate the need for artificial breaching. Development Mouth Management Plans nested within the objectives of relevant Estuary Management Plans. Where artificial breaching is deemed needed, develop a Maintenance Management Plan to achieve the highest possible breaching level and guide breaching practices. **LONG-TERM (2050):** Commit to active retreat below the 5 m MSL to allow natural processes to re-establish critical habitats under future climate conditions. Discourage all developments and future land-use change below the 5 m MSL contour. Return agricultural land to natural process to allow for wetland accretion (accommodation space).
TARGETS
SHORT-TERM TARGET (2035): Legal definition of estuaries is changed In ICM Act and Water Act to incorporate the entire EFZ (all estuarine processes) 100% of all hard infrastructure mapped and surveyed to MSL to determine flooding risk 100% of estuarine lakes have Estuary Management Plans/Protected Areas Plans 100% of relevant estuarine lakes have a Mouth Management Plan/Protected Areas Plan to decide on the appropriateness of breaching, and an approved Maintenance Management Plan to guide breaching where relevant 100% of land below the 2.5 m MSL contour should be targeted for active retreat. 100% of agricultural land below 2.5 MSL contour should be allowed to return to natural cover, only light opportunistic uses allowed (e.g. grazing, harvesting of mangroves, reeds and sedges). 100% of critical access routes below the 2.5 MSL contour re-planned/rerouted 100% of high-value infrastructure below the 2.5 MSL contour raised/protected against flooding **LONG-TERM TARGET (2050):**

Activity	WEM	WAM	Legislation
100% of land below the 5 m MSL contour should be targeted for active retreat. 100% of agricultural land below 5 MSL contour should be allowed to return to natural cover, only light opportunistic uses allowed (e.g. grazing, harvesting of mangroves, reeds and sedges). 100% of critical access routes below the 5 MSL contour re-planned/rerouted 100% of high-value infrastructure below the 5 MSL contour raised/protected against flooding			
RELEVANT VECTORS OF CLIMATE CHANGE			
Increase flooding, sea level rise, increase storminess			
ACTIVITIES MANAGEMENT ALLEVIATE THE IMPACTS OF ARTIFICIAL BREACHING			
Activity	**WEM**	**WAM**	**Legislation**
National develop a plan for a "managed retreat" under rising sea levels, focussing on all land use in estuaries below the 2.5 m MSL level as a priority.			ICM
Ensure that a conservative flood line assessment is in place that highlights the impact of 1:100 year flood events under future climate conditions (e.g. sea-level rise, increase wave energy and increase flooding) and incorporate in the municipal Integrated Development Plan and local estuary management plans.	●		ICM
Prohibit the development of new infrastructure within the EFZ of estuaries that would require artificial breaching, mouth stabilization, or inlet diversion in the future.	●		ICM
Develop a National Artificial Breaching Protocol for estuaries (informed by approaches already developed for the Western Cape and KwaZulu-Natal provinces).	●		ICM
Develop a comprehensive Estuary Management Plan (under the ICM Act) for all estuaries subjected to artificial breaching, this should include a detailed 'Mouth Management Plan' that stipulates the motivation for breaching and a pre-approved 'Maintenance Management Plan' (under the Environmental Impact Assessment (EIA) regulations) that details the criteria for and approaches to a breaching. • Re-evaluate the need to artificially breach estuaries (e.g. to prevent inundation of legally erected properties is a valid reason, while inundation of farmland is legally not seen as valid (high court finding St Lucia and Klein estuaries). • Investigate options to remove poorly planned, low-lying infrastructure and access roads (e.g. public ablution facilities too close to an estuary, farm roads through EFZ). This has the added benefit that it supports an active retreat policy in the face of sea-level rise. • Investigate possibilities of raising or protecting build infrastructure and access roads where the retreat is not an option. • Approve Maintenance Management Plan are enforced	● ● ● ● ●		NEMA, ICM
• Engage with National and Provincial Disaster Risk agencies to highlight the risk poor breaching practices pose to estuarine/ carbon ecosystems and develop a strategy to mitigate the impact of premature breaching.	●		
• Develop a land acquisition programme – purchase coastal land that is damaged or prone to regular flooding and use it for the protection of estuarine habitats (e.g. blue and teal carbon) and processes. Owners can exchange property in the floodplain for county-owned land outside of the floodplain.		●	ICM Act
POTENTIAL MAINSTREAMING TOOLS			
Legal definition of an estuary: Estuary mouth manipulation is an outcome of South African coastal legislation not recognising back-flooding areas under closed conditions as being part of the estuary functional zone, i.e. 'estuary space' in the real world is not confined to below the highwater mark as defined in legislation. Consequently, inappropriate low-lying developments and land-use (e.g. urban infrastructure, golf courses or agricultural activities) within the flooding zones, and that regularly inundated under closed mouth conditions, are being protected at the cost of the natural environment. The updated EFZ delineation in parts of the country extends beyond the 5 m contour, this poses the risk of further estuarine habitat being compromised as the EIA regulations define the EFZ as up to the 5 m contour. This conflicting definition needs to be urgently resolved to fit the ecological boundary. It is of critical importance that the legal definition of an estuary in South Africa be adjusted in the ICM and National Water Acts to include back-flooding areas and incorporate the EFZ. A more inclusive legal definition will restore and protect estuarine processes.			
Mouth Management Plans and Maintenance Management Plans: In the Western Cape, the development of estuary 'Mouth Management Plans' have become the norm for estuaries under artificial breaching pressure, and once an agreement has been reached on the need for regular breaching, a 'Maintenance Management Plan' is developed under NEMA for formal approval by the provincial authority. The actual breaching activity by the relevant management authority, which includes the digging of a breaching channel, is then governed by the pre-approved Maintenance Management Plan. It is recommended that this proactive management approach be adapted and adopted at a national level. Mouth Management Plans should urgently be developed for all systems that are under artificial breaching pressure, or require regular breaching, to assess if breaching is a necessity (investigate socio-economic imperative for breaching) and if so, how to do it with the least amount of ecological impact to ensure the benefits derived from estuaries, e.g. nursery function, are equitably distributed to all users, not just riparian owners.			
Estuary Flood Lines/Set back lines/Management lines: Precautionary principles need to be applied in the development of estuary setback and management lines to ensure that future development does not take place in low lying areas which will necessitate artificial breaching of the estuary mouth as a flood risk mitigation measure.			

6.3.6 Biological invasions

Biological invasions represent a major threat to biodiversity and estuary functioning (Whitfield et al. 2021). Many species have been transported by humans (either accidentally or intentionally) to areas where they are not naturally present, and on reaching such areas, some species, due to lack of natural predators or competitors, have become invasive and have spread across natural ecosystems, threatening indigenous species and habitats and reducing the ability of ecosystems to deliver vital services. Aquatic invasive plants result in a loss of ecosystem services, e.g. decreasing species diversity, forming a homogenous habitat, and disrupting aquatic food webs (Adams et al. 2019). Thus, biological invasions often have direct negative impacts on the wellbeing of many people, and in particular, threaten rural livelihoods.

6.3.6.1 Invasive alien plants

Table 6.8 presents the proposed Adaptation Strategy for Estuarine Lakes in South Africa pertaining to invasive alien plants, presenting the overall strategy, targets, recommended actions (indicating where possible With Existing Measure (WEM)/With Additional Measures (WAM)), as well as potential mainstreaming tools.

Table 6.8: Recommended Adaptation Strategies for Estuarine Lakes in South Africa: Invasive alien plants

OVERALL STRATEGY			
Manage/eradicate invasive alien plant species in estuaries and their associated catchments. Prevent the introduction of new species through agriculture or aquaculture. Introduce nutrient control strategies to control growth.			
TARGETS			
SHORT-TERM (2035) 0% spread of invasive species to new systems Developed protocols/procedures for early detection, risk assessment and management Managed risk of introduction from aquarium/ pet trade **SUPPORTING TARGET (LINKED TO POLLUTION ADAPTATION STRATEGIES):** 100% of estuarine lakes have a water quality status ≥ C category (moderately modified) or higher			
RELEVANT VECTORS OF CLIMATE CHANGE			
Changes in rainfall/runoff (droughts and floods), sea level rise			
ACTIVITIES MANAGEMENT ALLEVIATE THE IMPACTS OF OVEREXPLOITATION OF LIVING RESOURCES			
Activity	**WEM**	**WAM**	**Legislation**
Develop protocols/procedures for early detection, risk assessment, and management of invasive alien plant species: • Develop protocols for monitoring the spread of invasive alien plant species in estuaries • Develop control programmes using a range of methods (biocontrol agents, manual, mechanical or herbicide control). NOTE: Chemical control most often NOT the solution (e.g. unintended consequences associated organic load, developing anoxia and fish kills, persistent organic pollutants (POPs) accumulation) in estuarine lakes as they are 'sinks' • Develop long-term catchment clearing programmes (e.g. in collaboration with Working for Water / Wetlands in South Africa)	● ● ●		CARA Agricultural Pests Act
Aquarium trade and aquaculture introduction pathways need to be controlled through permitting system(s) and detailed EIA studies.	●		LMRA, NEMBA
Institute nutrient management strategies (wastewater and agricultural return flow) to control growth	●		NWA, CARA, ICM
Create public awareness among civil society and researchers of the risk invasive species pose to estuaries and the need to clean gear and boats		●	ICM
Invest in research alien invasive programmes: • Identify and evaluate the full suite of invasive species occurring in estuaries – marine, estuarine, and freshwater. • Develop an understanding of the spread of alien invasive plants in South African estuaries.		● ●	CARA, NEMBA
POTENTIAL MAINSTREAMING TOOLS			
Conservation of Agricultural Resources Act (CARA): Regulations under CARA were promulgated to govern the management of certain (listed) invasive plant species ('weeds'), while the Agricultural Pests Act (Act 36 of 1983) provides for measures to combat agricultural pests and prevent their introduction. The International Convention for the Control and Management of Ship's Ballast Water and Sediments imposes obligations to prevent, minimise, and ultimately eliminate the transfer of harmful aquatic organisms and pathogens through the control and management of ship's ballast water and sediments.			
Biodiversity Act: In 2014, a set of regulations was promulgated under the Biodiversity Act, by which the management of biological invasions is to be governed. These regulations govern the import of new alien species, place existing alien species into several categories and specify how these species are to be controlled or managed. The Act also gives effect to ratified international agreements relating to biodiversity binding on the Republic, including the Convention on Biological Diversity (CBD) that requires the prevention, control or eradicate of 'alien species which threaten ecosystems, habitats or species'.			
Working for Water' and 'Working for Wetlands': Exotic aquatic macrophytes are generally found in the fresher upper reaches of estuaries. Low freshwater input and nutrient enrichment promote their growth, with Water Hyacinth, Eichhornia crassipes the worst aquatic weeds. Currently, control programmes utilise a range of methods (biocontrol agents, manual, mechanical or herbicide control), but will be only successful if nutrient management strategies are also implemented. Moreover, clear protocols and procedures are needed on the most environmentally effective clearing methods which could be pursued for particular species and in particular systems. Long-term eradication from estuaries will only be possible if supported by catchment clearing programmes such as the 'Working for Water' and 'Working for Wetlands' natural resource management programmes to prevent re-infestation after floods.			
SANBI Invasive Species Programme: Early detection is key to the eradication of invasive species. A good example of this is the complete eradication by 2018 of Smooth cordgrass *Spartina alterniflora* from the Groot Brak Estuary (first observed in 2004 by local residents). SANBI Invasive Species Programme oversaw the process. Progress was enhanced by enthusiastic and supportive local stakeholders, organized in the form of the local residents' association and Groot Brak Estuary management forum highlighting the role local communities can play in early detection and eradication.			

6.3.6.2 Alien invasive or extralimital fish and invertebrates

Table 6.9 presents the proposed Adaptation Strategy for Estuarine Lakes in South Africa pertaining to alien invasive or extralimital fish and invertebrates, presenting the overall strategy, targets, recommended actions (indicating where possible With Existing Measure (WEM)/With Additional Measures (WAM)), as well as potential mainstreaming tools.

Table 6.9: Recommended Adaptation Strategy for Estuarine Lakes in South Africa: Alien invasive or extralimital fish

OVERALL STRATEGY			
Manage/eradicate invasive species in estuaries and/or associated catchments feeding into estuaries. Prevent the introduction of new species through agriculture or aquaculture.			
TARGETS			
SHORT-TERM (2035): 0% spread of invasive species to new systems No new species recorded in estuaries (no more than 22 species nationally) No invasive species allowed in aquaculture ventures near estuarine lakes Managed the risk of introduction from aquarium/pet trade Developed protocols/procedures for early detection, risk assessment and management **SUPPORTING TARGET (LINKED TO POLLUTION ADAPTATION STRATEGY):** 100% of estuarine lakes have a water quality status ≥ C category (moderately modified) or higher			
RECOMMEDED ACTIONS			
Activity	**WEM**	**WAM**	**Legislation**
Develop protocols/procedures for early detection, risk assessment, and management of invasive alien fish and invertebrate species. • Develop protocols for monitoring the spread of invasive alien species in estuaries and conduct a census of all invasive species in estuarine lakes (but also the rest of the country as estuaries are connected) • Manage and eradicate invasive species in the catchments feeding into estuarine lakes • Prevent the establishment of aquaculture facilities near estuarine lake systems	 ● ● ●		NEMBA, LMRA
Aquarium trade and aquaculture introduction pathways need to be controlled through permitting system(s) and detailed EIA studies.	●		LMRA, NEMBA
Investigate the option of a controlled fishery to remove larger aliens/translocated fish.	●		LMRA
Create public awareness among civil society and researchers of the risk invasive species pose to estuaries and the need to clean gear and boats.	●		NEMBA
Invest in the research of invasive alien fish and invertebrate species to develop an understanding of the risk they pose to estuarine functionality and ecosystem services.	●		LMRA, CARA NEMBA
Prevent the discharge of ballast water in ports (especially those in or near estuaries).	●	●	Maritime Safety Authority Act
RELEVANT VECTORS OF CLIMATE CHANGE			
Change in rainfall/runoff patterns (droughts and floods), increased temperatures.			
POTENTIAL MAINSTREAMING TOOLS			
Convention on International Trade in Endangered Species (CITES)/Threatened or protected species (TOPS): Overall very little has been done about managing freshwater aquatic and estuarine invasive faunal species. Managing invasive fish without harming other indigenous biota is often not possible, and there are conflicting opinions about the need for, and the type of interventions. Management objectives range from the extirpation of alien fish from water bodies where possible; the prevention of spread to uninvaded areas; and the early detection of new incursions. Monitoring of Convention on International Trade in Endangered Species (CITES) of Wild Fauna and Flora exports, uptake of export quotas, and implementation of non-detriment findings is also required, as is the monitoring of conservation status and utilisation of species listed under the threatened or protected species (TOPS) regulations to determine if the regulations are effective.			
Control of entry points: Pathway-based control measures focus on reducing the risk of introducing damaging species. For example, organisms can be introduced by ships through several pathways (as stowaways in ballast water, in cargo containers, on the hull of the ship, or in the luggage of crew or passengers). In South Africa, intentional introductions are currently managed through a permitting system. For air traffic, inspections are currently only carried out at O.R. Tambo International Airport, where permit compliance is checked, illegal imports are intercepted, and the luggage of tourists and cargo is searched. For shipping, the Marine Draft Ballast Water Bill aims to reduce the risk of the unintentional introduction of alien marine species through the release of ship ballast water. Other control measures focus on potential agricultural pests (e.g. phytosanitary inspections at border posts) or threats to human health (e.g. spraying the interior of aircraft to eradicate insect disease vectors). The DALRRD regulates and monitors the importation of agricultural goods. Departments such as DALRRD and SARS-Customs are present at other ports of entry and sometimes identify instances of non-compliance and alert DFFE biosecurity.			
Maritime Safety Authority Act: The Act requires that all ballast water to be exchanged deep sea before entering the territorial waters of the Republic of South Africa as per the vessel's Ballast Water Management Plan.			

7. CONCLUSIONS AND RECOMMENDATIONS

7.1 Key messages

The following key messages are relevant to the development of a Climate Change Mitigation and Adaptation Strategy for Estuarine Lakes:

- South Africa has strong legislative measures ("good tools in the toolbox") to support the roll-out of climate change mitigation and adaptation strategies for estuarine lakes, but these need to be "sharpened" and their efficacy increased (e.g. implementation and compliance). Specifically, there is an **urgent need to increase efforts towards estuary protection** to ensure ongoing contribution to South Africa's climate mitigation efforts, especially for systems supporting extensive blue and teal carbon habitats.
- **Adaptation strategies need to be developed within a broad, holistic socio-ecological systems context, across land- and seascapes** – where there are many competing interests to be considered. The impacts of Climate Change need to be superimposed on the wide array of existing stressors and need to consider the multiple ways in which actions may impact other facets of the socio-ecological system at different temporal and spatial scales (Sheaves et al. 2016**). Key to this is generating awareness and protecting the complex natural cycles (i.e. drought-flood/open-closed) that occur in estuarine lakes at decadal temporal scale.**
- **The maximum public benefit accrues from the maintenance and restoration of resilient ecosystems that provide healthy human living environments**. This, in turn, supports the ecosystems and biodiversity that underpin robust and productive fisheries. This is best achieved by focussing on long-term transformative outcomes at a whole-of-system scale that provides ongoing benefits by enhancing resilience and reducing vulnerability into the future (Sheaves et al. 2016).
- Opportunities need to be investigated to "**retrofit" current approved resource uses to accommodate future climate change requirements** to ensure the protection of estuaries moving forward (e.g. drought flow allocations in DWS Classification).
- **'Managed Retreat'** should be actively encouraged to allow estuarine processes (and associated blue and teal carbon habitats) to re-establish under a changing climate. The passive "do nothing/wait and see" approaches will have immense ecological impacts with cascading implications for critical ecosystem services such as carbon sequestration and nursery function.

7.2 Improvements for Future Climate Change Assessments

The following is recommended based on the experience gained through this study:

- The development of the abiotic and biotic conceptual models for estuarine lakes as an explicit step in the vulnerability assessment method allowed for the identification of commonalities and differences across the lake systems and assisted with bridging data gaps and extrapolating findings. The assessment approach developed was **sufficiently sensitive to detect climate-induced shifts** in estuary function and productivity. It is thus recommended that **similar conceptual models be further developed for other types of estuaries**, e.g. Estuarine Bays, Fluvially dominate estuaries, Predominantly open). The generic identification of abiotic states and associated conceptual models also have wider application in flow requirement studies and estuary condition assessment.
- More effort should be made to **develop coupled rainfall-runoff yield models specifically geared to better resolve climate change projections on river flows**. Given the high degree of flow modification many estuary catchments are already subjected to, it is inappropriate to merely superimpose climate change impacts on natural flow regimes, as the impact of climate change must be reflected in conjunction with present levels of resource use (i.e. exploitation). Given the importance of **evaporation** in the development of water balance models for large water bodies such as the estuarine lakes, ongoing efforts in this regard should be supported. **Groundwater** is

often ignored in these assessments, but under hotter future climates, this relative stable freshwater input may change and needs to be considered as it plays a key role in maintaining lake levels especially during droughts.

- The impact of droughts is of special concern, but still not well understood. **Therefore, more effort should be made to develop modelling capability to improve our ability to explicitly predict the occurrence and duration of droughts** (some broad measures were included in this estuarine lake study). It is also recommended that all estuary conceptual models in future explicitly develop a 'drought state' (even if only based on theoretical understanding and/or extrapolated from similar systems). This will assist with developing a more informed understanding of the future impact and risk associated with severe droughts on estuaries.
- The **impact of increasing temperatures** on primary producers (e.g. algae and macrophytes) is not well understood and thus poorly coupled to predictions of change, especially under the RCP 8.5 far-future scenarios. Thus, resulting in a low confidence assessment. It is therefore recommended that more research be undertaken to inform predictions on primary production responses, as well as on the impact of elevated temperatures on estuarine fish and the protection deeper water refugia offer in the face of rising temperatures.
- As most of the tools utilised in this Estuarine Lake Vulnerability Assessment have been set up with ease re-evaluation in mind, e.g. estimating a change in mouth state, water quality and microalgae conditions. Should more detailed runoff, evaporation rates, or groundwater input datasets become available it is **recommended that the predicted abiotic state shifts be re-evaluated**, and if need be, the vulnerability assessment workshop repeated.
- The concomitant impact of **sea level rise** was not included in this estuarine vulnerability assessment. It is recommended that where detailed topographical (e.g. LiDAR) information is available more **systematic evaluation be undertaken of the impact of sea level rise on key estuarine habitats such as mangroves and salt marsh**, similar as to what was done in the Knysna Estuary (Raw et al. 2020).

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