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Research paper

Health assessment and restoration options for the degraded Swartkops Estuary, South Africa

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The Global Biodiversity Framework and UN Decade of Ecosystem Restoration have focused attention on the need for health assessments and restoration options for estuaries. This study focused on the Swartkops Estuary because of its biodiversity and socio-economic importance that are threatened by pressures from surrounding development and human activities. The 'Present Ecological State' (PES) was assessed using an estuarine health index to determine the health score of the estuary compared to historical reference conditions, using both abiotic and biotic indices. Results showed that nutrient-rich freshwater from upstream wastewater treatment works and stormwater canals has increased freshwater inflow to the estuary by 41% compared to natural, leading to eutrophication and persistent harmful algal blooms. Development and disturbance have transformed the estuary functional zone, impacting on macrophyte and bird abundances. Invertebrate bait organisms and linefish species are overexploited. As a result, the health of the Swartkops Estuary has continued its downward trajectory from 53% of its natural state in 2015 to 47% at present. This study is the first to identify potential remediation measures aimed at improving the current ecological health of the estuary. These include the removal of wastewater inputs and the restoration of salt marsh habitat, which would improve the ecological status from a largely modified to moderately modified condition. This study highlights how difficult it is to restore an estuary once deteriorated, while emphasising the need for an implemented estuary management plan with well-defined management, conservation, and restoration goals.

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INTRODUCTION

Degradation of aquatic ecosystems, such as rivers and estuaries, is escalating following the intensification of anthropogenic activities (Feio et al., 2021). As a result of this, coastal systems are experiencing extensive deterioration in ecosystem health and their ability to maintain productivity and associated ecosystem services is compromised (Elko et al., 2022; Van Niekerk et al., 2022). Drivers of this degradation include urban and industrial development, agriculture, aquaculture, tourism, forestry, coastal erosion, overexploitation and climate change pressures such as sea-level rise (Beaumont et al., 2014; Van Niekerk et al., 2022). This is of concern as estuaries are ecologically important habitats that sustain and support unique biodiversity and provide humans with important services, including water purification, climate regulation, erosion control and habitat provision, and cultural benefits (Barbier et al., 2011).

The rehabilitation of rivers and estuaries is a global challenge and one that must be overcome if we aim to achieve global sustainability and water security. Indeed, the goals of the United Nations Agenda 2030 for sustainable development clearly state the necessity to decrease pollution, guarantee access to safe drinking water for all, and protect freshwater aquatic ecosystems and biodiversity (Kirschke et al., 2020; Feio et al., 2021). Target 2 of the 2030 Kunming-Montreal Global Biodiversity Framework (GBF) aims to expand conservation and restoration to 30% by 2030 (CBD 2022). The UN Decade on Ecological Restoration (2021 to 2030; United Nations General Assembly, 2021) calls for immediate action. Management interventions in the form of ecosystem restoration are often undertaken to improve the aesthetics of urban environments, implement ecological flow requirements as per existing legislation, prevent flooding of adjacent lands, or facilitate invertebrate and fish passage across barriers (Weerts et al., 2014; Van Niekerk et al., 2022). Regardless of the motives for restoration projects, it is important that ecosystem monitoring takes place to inform future actions (Ebberts et al., 2017; Adams et al., 2020). Successful estuarine restoration is complex and difficult, with monitoring to some type of 'conclusion' state important for costs and benefits to be defined (Elliott et al., 2016). A socio-ecological systems framework is recommended to guide estuary restoration (Adams et al., 2021; 2023). This study aims to inform estuary restoration in South Africa as few studies have addressed this topic.

In South Africa, researchers work across the science–policy–practice continuum, providing science-based solutions in support of ecosystem restoration through the National Water Act (NWA) (RSA, 1998b), National Environmental Management: Integrated Coastal Management Act (ICMA) (RSA, 2008), and Marine Living Resources Act (MLRA) (RSA, 1998a). The NWA requires that 'Ecological Reserves' and 'Resource Quality Objectives' be set for all water resources, including estuaries, through a process of 'Water Resource Classification' (Dollar et al., 2010) before water is distributed to other users, except for basic human needs and international commitments. In addition, the NWA requires the formation of 'catchment management agencies' (CMAs) to decentralise water resource management and allow all stakeholders to participate in this management within 9 'water management areas' (RSA, 1998b). The Estuarine Management Protocol (DEA, 2015), promulgated under the ICMA, was written in collaboration with estuarine scientists and offers a framework of standards and best practices for addressing the integrated management of estuaries, including the development and implementation of comprehensive 'estuarine management plans' (EMPs) for each estuary in the country (Adams et al., 2020). In addition, the MLRA requires management and monitoring of living resource use in the ocean and estuaries. Research and case studies are therefore needed to ensure implementation of this legislation and to provide the tools for comprehensive restoration planning (Simenstad et al., 2006; Claassens et al., 2022).

The Swartkops Estuary is nationally important due to its large size, diversity of habitats, and the high level of biodiversity it supports. Nationally important intertidal salt marshes as well as the endangered seagrass *Zostera capensis* are found in the estuary. The estuary is also of great social importance supporting recreational fishing, boating, water sports, and religious ceremonies (Adams and Riddin, 2020). It has been a well-studied estuary since the 1980s due to its urban location and proximity to Nelson Mandela University, formerly the University of Port Elizabeth (Olisah and Adams, 2021). This provides a rich source of available knowledge to inform a 'Present Ecological State' (PES) assessment of the Swartkops Estuary. The importance of the estuary and need for socio-ecological interventions to protect the services it provides have been recognised for decades (Heydorn and Grindley, 1986; DWAF, 1999a; Adams et al., 2019; Hartmann, 2021), yet the implementation of recommendations has been poor. The Swartkops River catchment falls within the Mzimvubu-Tsitsikamma Water Management Area and, up until March 2023, was managed by the Mzimvubu-Tsitsikamma proto-CMA led by the Eastern Cape Province Department of Water and Sanitation (DWS) (Meissner et al., 2017). The implementation of catchment-level restoration plans, in conjunction with the Swartkops Estuary Management Plan (EMP), is key to improving the health of the estuary and society (Adams et al., 2023). Some restoration activities have been attempted in the Swartkops Estuary, such as the construction of a pilot artificial wetland associated with the Motherwell Canal (Lemley et al., 2022; Fig. 1), implementation of a 'sustainable urban drainage system' on the Markman Canal (Mmachaka et al., 2023), and controlled collection and sale of bait organisms. However, the continued degradation of water quality (e.g., hypoxia, harmful algal blooms (HABs)) in the estuary (Lemley et al., 2023) highlights the limited success of these activities, partly due to poor control and enforcement by the responsible authorities (Lemley et al., 2022).

In the 2011 National Biodiversity Assessment, the health of the Swartkops Estuary was examined for the first time (Van Niekerk and Turpie, 2012; Van Niekerk et al. 2013). The PES of the estuary was assessed as a Category C (moderately modified) with a 'Recommended Ecological Category' (REC) of B (largely natural with few changes). In 2015, Van Niekerk et al. (2015) updated the earlier results applying the Estuarine Health Index (EHI), a standardised metric used to determine the condition of an estuary (Turpie et al., 2012), and the PES of the Swartkops Estuary declined to a D (largely-modified) with the REC re-defined as a C. The ecological health of the estuary had to be improved so that the system could continue providing ecosystem services (Adams and Riddin, 2020). It was concluded that the improvement of the estuary to a Category C could only be achieved with appropriate management interventions, based on a sound understanding of the main drivers and pressures impacting the estuary. As such, the aim of this study was to provide an updated PES of the Swartkops Estuary using the EHI and, for the first time, to use this process to identify possible restoration activities. Understanding the PES provides the point of departure for developing any management objectives related to estuary restoration. Lastly, restoration activities are provided to ensure the future health of one of South Africa's most important estuaries. This study provides a new standardised approach for future assessments of restoration scenarios and informs the protection and restoration objectives of the Global Biodiversity Framework.

METHODS

Study site description and available information

The Swartkops Estuary is located along the coast of the Nelson Mandela Bay Municipality in the Eastern Cape Province of South Africa (NMBM, 2023; Fig. 1). The Swartkops River catchment drains an area of approximately 1 390 km^2 (Baird et al., 1986). The river and estuary are 155 km and 16.4 km long, respectively, and both fall within the warm temperate biogeographic region of South Africa. The estuary is highly urbanised, with most development and residential areas located within a 15 km radius of the 'Estuarine Functional Zone' (Baird et al., 1986). The EFZ is that area occurring below the 5 m above mean sea level contour line. The Swartkops Estuary has a mean annual precipitation of 636 mm, with a natural mean annual runoff (MAR) of 56.9 x 10^6 m^3 (Reddering and Esterhuysen, 1981). The driest months are in summer, with the catchment receiving most of its rainfall in October with a smaller peak in April. Low baseflows and small floods of 40 to 80 x 10^6 m^3 distinguish the flow pattern in the basin. The largest recorded floods (120 to 160 × 10^6 m^3) occurred in 1879, 1912, 1914, 1971, 1979, and 1981 (Baird et al., 1986; DWAF, 1994; Adams et al., 2023). Floods of these magnitudes change estuary channel migration and sediment distribution (Esterhuysen and Rust, 1987). Nyawo (2017) found that water from the Swartkops River and neighbouring Coega aquifer contributed to the Swartkops aquifer, making the aquifer vulnerable to Swartkops River pollution. Despite the importance of groundwater dynamics in the Swartkops Estuary, little is known about the influence and contribution of this water resource to the system.

The main residential areas surrounding the estuary are Redhouse Village, Amsterdamhoek, the Aloes community and Swartkops Village. Various developments have obstructed freshwater flow to the estuary from the river catchment, which include 5 causeways below Groendal Dam that act as weirs and reduce baseflow. The Wylde and railway bridges at Swartkops Village obstruct floodwaters, and saltpans at Redhouse hold back floodwaters, with restricted erosion resulting in downstream sand deposition (Adams et al., 2023). Lastly, the Settlers Bridge on the N2 national highway restricts flow to the northern bank at the estuary mouth and prevents lateral migration of the channel (Adams and Riddin, 2020).

Water quality in the lower reaches of the estuary is influenced by tidal flushing and turbulent mixing. In the upper reaches, however, longitudinal mixing and dispersion are limited by the Wylde Bridge. The Swartkops Estuary has an estimated residence time of 10 to 14 days for the region upstream of Bar None saltpan,

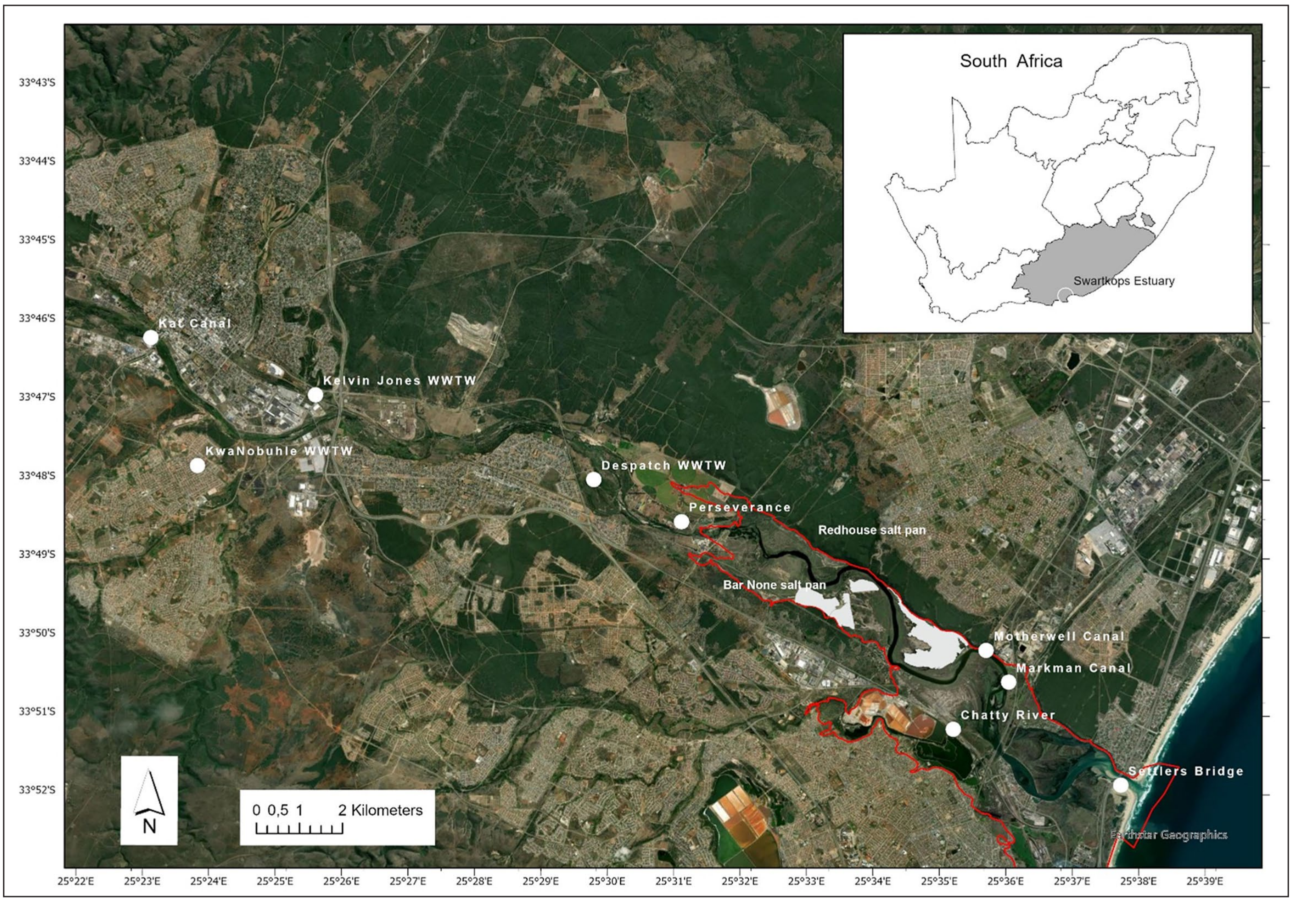


Figure 1. Swartkops Estuary study site map indicating key locations mentioned in the text

and localised trapping of water may also occur in the estuary. As such, pollutants discharged into some regions of the estuary are likely to persist for extended periods (MacKay, 1994; Adams and Riddin, 2020). The estuary receives a significant volume of effluent from three wastewater treatment works (WWTWs) (i.e., Despatch, KwaNobuhle, and Kelvin Jones) that discharge into the Swartkops River just upstream of the estuary (DWAF, 1999a; Lemley et al., 2019; Lemley et al., 2023; Fig. A1, Appendix). The estuary is also subject to consistent discharges from untreated stormwater drainage systems (domestic and industrial), including the Motherwell Canal (Fig. 1; Fig. A2, Appendix), Markman Canal, Kat Canal, and Chatty River. These WWTWs and stormwater discharges have contributed to excessive eutrophication of the estuary, causing HABs and fish kills (Bornman et al., 2016; Adams, 2020; Lemley et al., 2023).

Organophosphate pesticides (OPPs) pose a threat to aquatic organisms in the Swartkops Estuary, potentially causing certain abnormalities (Olisah et al., 2022). The seagrass, *Zostera capensis*, is capable of accumulating OPPs and transporting these from the roots to their leaves (Olisah et al., 2021). A recent study by Olisah et al. (2023) found that fishes in the Swartkops Estuary are contaminated by OPPs, but at concentrations that are unlikely to have any human health consequences. However, the presence of antibiotic-resistant bacteria, antibiotic-resistant genes and carcinogens in the Swartkops Estuary pose a health risk to humans (Olisah et al., 2019; Chibwe et al., 2023; 2024). Kalinski et al. (2024) showed that Swartkops Estuary dissolved organic matter (DOM) composition was strongly impacted by features annotated as urban pollutants including pharmaceuticals such as antiretrovirals. Further research is needed to understand the influence of these pollutants on estuarine biota. It is important that pollutant loads be managed and natural habitats, such as seagrass beds, be restored to mitigate the social-ecological effects of water pollution.

In addition, the estuary experiences high fishing pressure because of its proximity to urban, suburban, and informal settlements, with an estimated total catch of 47 t per annum (Van Niekerk et al., 2022). Residents from nearby townships and informal settlements make a living by subsistence fishing and supplying bait (invertebrates) to recreational anglers. Illegal fishing, unpermitted bait collection, linefishing and gillnetting are responsible for 20% of the annual catch and increasing. Lack of monitoring of the fishery at the Swartkops Estuary has led to uncontrolled bait collection (Fielding, 2021; Simon et al., 2021). Alien vegetation is also a growing threat to the estuary's biodiversity as some of these invasive species, such as water hyacinth (*Pontederia crassipes*), enter a stage of exponential growth in the river/upper estuary and choke waterways (Zengeya et al., 2020; Lakane et al., 2024). Similarly, there are 5 introduced freshwater fish species in the upper reaches, and poor water quality has facilitated the proliferation of invasive alien Pacific oyster *Crassostrea gigas* throughout the estuary (Ellender et al., 2011; Keightley et al., 2015). This and other available information were used to assess the PES of the Swartkops Estuary.

Study approach

The PES of the Swartkops Estuary was assessed using the EHI that considers 4 abiotic drivers and 5 biotic responses, addressing the characteristics and functioning of each component, their inter-relationships, and distinguishing between flow and non-flow-related pressures and associated impacts (Turpie et al., 2012; Van Niekerk et al., 2022) (Fig. 2 adapted from DWAF, 1999a). For the abiotic drivers, the components studied included hydrology, water quality, hydrodynamics (which includes mouth condition), and physical habitat alteration. In terms of the biotic components, microalgae, macrophytes, invertebrates, fishes and birds were assessed (Van Niekerk et al., 2022).

For each abiotic and biotic component, the change in condition was estimated as a percentage (0–100%) of the natural state (120 years ago, i.e., predevelopment conditions), based on the Bray-Curtis dissimilarity index (Bray and Curtis, 1957). The macrophytes are used as an example to show how the detailed scoring is completed for the biotic components of the EHI. Scores were weighted (25% for each abiotic and 20% for each biotic component) and aggregated (50:50) to provide an overall score that reflected the present health of the system as a percentage of that under natural conditions (Van Niekerk et al., 2015; Fig. 2). Individual scores were then aggregated into an overall EHI score using a scale of A to F (Fig. 2). Further details on the approach and scoring method applied are described in Van Niekerk et al. (2013; 2019a; b) and can be found in the environmental water requirement report (Swartkops EWR Report, 2021).

The assessment of the PES was undertaken at an estuarine specialist workshop comprising a multi-disciplinary team including both abiotic and biotic expertise with specific knowledge on the Swartkops system. Restoration activities were also identified to improve ecological health. Confidence levels for the data used in the study applied the scoring criteria presented in Fig. 2. A literature evaluation of all recent research undertaken within the Swartkops Estuary was completed, and existing datasets were evaluated to quantitatively detect any changes over time (Table 1) to inform the estuary health assessment.

A key driver in the evaluation of estuary health is understanding the past and present freshwater inflow (hydrology), as it is the modification of freshwater flow regimes that affects estuarine productivity and functioning (Van Niekerk et al., 2013; Stein et al., 2021). Monthly hydrological flows over a 90-year period were simulated using a Pitman monthly flow hydrological model (Water Resources of South Africa, 2012: WR2012, 2021). These were generated for the reference (or natural) conditions, the present state, as well as for a range of future scenarios. These simulated data sets were then used to provide monthly flow percentile distribution summaries that highlight occurrences of low flows, drought and flood events. The hydrodynamics of the predominantly open Swartkops Estuary considered changes to the estuary mouth state (closed, constricted, open, or wide open), flood inundation of the floodplain, tidal range, circulation processes, and salinity structure (well-mixed or stratified) by comparing field observations conducted prior to the construction of the Settlers Bridge at the estuary mouth to present. Water quality parameters applied in the EHI and for which reliable data were readily available included salinity, dissolved oxygen, Secchi depth (alternative to total suspended solids), inorganic nutrients (dissolved inorganic nitrogen (DIN) and phosphorus (DIP)), and toxic substances (metals and selected persistent organic pollutants (POP)) (Table 1).

The changes in hydrology, water quality, hydrodynamics, and physical habitat from natural to present were then used to score the present state for the abiotic components. A comparison of the abiotic and biotic scores between the 2015 and current assessment are presented. Available literature and data were used to determine the present species richness, abundance, and community composition of each of the 5 biotic components, with the lowest scoring of these 3 indices being used as the health score of that component (Fig. 2). Past aerial images dating back to the 1930s were used to determine the extent of natural habitat and vegetation lost in the EFZ to development and land transformation. Aerial imagery was obtained from the Chief Directorate: National Geo-spatial Information (2021). Heads up digitizing was completed for the earliest imagery (1930s to present 2015). The recent images are orthorectified and have a 50 cm resolution; these were used as the basemaps to digitize present and past habitat extent. Recent Google Earth imagery was used to assess habitat changes.

Flow scenarios

Five alternative future flow scenarios, two worst case and three restoration options, were considered to predict possible future conditions of the Swartkops Estuary using the EHI. The scenarios were as follows:

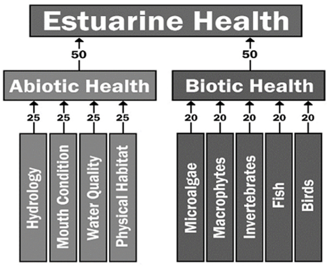
- **Scenario 1**: Future climate change scenario with more intense freshwater flooding. Baseflow remains similar to present due to input from the WWTWs. Floods will increase in volume and intensity, resulting in an increase of stormwater to the estuary.
- **Scenario 2**: Increase in wastewater input to the estuary as reflected by a growing population and increased numbers of people predicted for the year 2050. This adds baseflow and nutrients to the estuary resulting in further water quality deterioration. This scenario is a worst-case scenario where sewage spills and low maintenance of the WWTWs are expected, and no recycling or nutrient reduction occurs.
- **Scenario 3 (water quality restoration)**: Improvement in water quality by removing the volume of wastewater from the upstream Kelvin Jones WWTW (approximately 75% of the total present WWTW input). All other pressures remain the same as the present state so that water quality restoration can be understood and quantified.
- **Scenario 4 (water quality restoration)**: Full water quality restoration scenario – although unlikely – where all influence from upstream WWTW inputs is removed from the estuary. Some of this could be achieved through artificial wetlands and effluent recycling. Nutrient-rich baseflow input is reduced, improving eutrophic conditions. All other pressures remain as present so that water quality restoration can be understood and quantified.
- **Scenario 5 (habitat restoration)**: Habitat restoration scenario where 10% of the supratidal habitat is restored through re-wetting the Cerebos salt marsh areas and some riparian zone improvement by removing alien plants. All water quality pressures remain the same as present so that habitat restoration can be understood and quantified.

RESULTS AND DISCUSSION

Present Ecological State: abiotic components

Hydrology

Persistent input of nutrient-rich freshwater from 3 upstream WWTWs and stormwater drainage systems has increased the MAR to the Swartkops Estuary, increasing baseflows by 4 to 8 times (Table 2). Under the reference condition, river inflow of less than 0.3 $m^3 \cdot s^{-1}$ occurred for 55% of the time, but the increase in river flow means that flows of less than 0.3 $m^3 \cdot s^{-1}$ seldom occur (99% change from natural). The dams in the catchment of the Swartkops system are relatively small and thus have little effect (15%) on both smaller floods (1:5 to 1:10 years) and major floods (1:50 years). The current MAR into the Swartkops Estuary is 80.3 x 10^6 m^3, which represents a 41% increase from the natural MAR of 56.9 x 10^6 m^3. The hydrological assessment had medium to low confidence due to the lack of a flow gauge at the head of the estuary to provide more accurate data (Tables A1 and A2, Appendix). The Swartkops River is well known for the occurrence of major floods. Historical studies estimate that the maximum flow into the estuary during a 1:100-year flood was approximately 2 500 $m^3 \cdot s^{-1}$ (CSIR, 1987; Hughes, 1987). Urbanisation has been shown to create higher surface runoff, higher river discharge rates, and quicker times for floods to reach their peak (Feng et al., 2021). A key uncertainty is the hardened surfaces due to urbanisation and influence on flow.



EHI score	PES category	General description
91 – 100	A	Unmodified, natural
76 – 90	B	Largely natural with few modifications
61 – 75	C	Moderately modified
41 – 60	D	Largely modified
21 – 40	E	Highly degraded
0 – 20	F	Extremely degraded

Confidence level	Situation	Certainty (%)
Very low (VL)	No data available for the estuary or similar estuaries	< 40%
Low (L)	Limited data available	40 – 60%
Medium (M)	Reasonable data available	60 – 80%
High (H)	Good data available	> 80%

Figure 2. Components of the weighting for the calculation of the Estuarine Health Index (adapted from DWAF, 1999a), the resulting scores and categories, and the confidence levels (adapted from Turpie at al., 2012)

Table 1. Published studies and available data used to assess changes in abiotic and biotic characteristics of the Swartkops Estuary

Component	Description of data/info	Reference
Hydrology	Flow data from river and estuary	DWAF, 1994; DWAF, 1999b; Van Niekerk et al., 2012; this study
Hydrodynamics	Water residence time, mouth condition and flushing	MacKay, 1994
Physical habitat	Salt marsh area	Adams, 2020; Adams et al., 2021
	Vegetation and habitat disruption	Bornman et al., 2016
	Habitat condition	Scharler and Baird, 2003; Pretorius, 2015; Lemley et al., 2017; Snow, 2008; Adams et al., 2019
Water quality	Nutrients, salinity, turbidity, dissolved oxygen, pH	Scharler and Baird, 2003; Adams et al., 2014; Pretorius, 2015; Lemley et al., 2017; 2019; 2022; Wasserman et al., 2022a ; 2022b; Kalinksi et al., 2024
	Metals and inorganic pollutants	Binning and Baird 2001; Nel et al. 2015; 2020a; 2020b; 2023; Van Aswegen et al. 2019; Ndhlovu et al. 2024a
	Persistent organic pollutants	Olisah et al., 2020; Olisah et al., 2024
	Blue carbon	Human et al., 2022; Wasserman et al., 2023
	Eutrophic state	Lemley et al., 2017, 2023
Microalgae	Harmful algal blooms	Lemley et al., 2019, 2023
Macrophytes	Distribution of macrophyte species	Adams, 2016; Lakane et al., 2024
	Extent/area cover	Colloty et al., 2000; Adams and Riddin, 2020
	Salt marsh area	Adams, 2020; Van Niekerk and Turpie, 2012
Invertebrates	Macroinvertebrates and bait species	McLachlan and Grindley, 1974; Wooldridge and Melville-Smith, 1979; Hanekom et al., 1988; Perissinotto and Wooldridge, 1989; Keightley et al., 2015.; Odume et al., 2012, Fielding, 2021; Ndhlovu et al., 2024b
Fishes	Larval fish assessment	Melville-Smith and Baird, 1980; Beckley, 1985; Strydom, 2003; Strydom et al., 2003; Kisten et al., 2015, 2020
	Juvenile fish assessment	Beckley, 1983; Edworthy and Strydom, 2016; Nel et al., 2018; Nodo et al., 2023, 2024; Mkhize et al., 2025
	Ecosystem productivity	Scharler et al., 1997
	Adult fish assemblages	Marais and Baird, 1980; Marais, 1982; Pradervand and Baird, 2002; Whitfield and Smith, 2024
Birds	Bird distribution	Martin and Baird, 1987
	Recent bird data	P Martin raw data (unpublished: Martin, 2021)
	Waterbird abundance	Coordinated Waterbird Counts, 2021

Table 2. Summary of the change in low-flow conditions from the reference to present state

Percentile	Monthly flow ($m^3 \cdot s^{-1}$)		% Change
	Natural	Present	
30^{th}	0.13	0.66	498
20^{th}	0.10	0.61	604
10^{th}	0.07	0.58	807
% Similarity in low flows			17

Hydrodynamics and mouth condition

The Swartkops Estuary is permanently open to Algoa Bay, and the mouth has been stabilised by the construction of the Settlers N2 highway bridge, causing the buildup of sand and constriction of the mouth during extended periods of low river input. Low river input (<0.3 $m^3 \cdot s^{-1}$) during the natural state would have resulted in well-mixed marine conditions for 55% of the time. Elevated baseflows, mouth stabilisation, and the influence of bridges have led to the complete loss of the marine state and the tidal amplitude in the lower reaches of the estuary has increased from 0.5 m to between 1.0 m and 1.5 m. Confidence in this assessment is 'medium', as this was based on observations and measured data, supported by historical numerical modelling of circulation of the system (Table A1, Appendix).

Water quality

Available water quality data for the Swartkops Estuary are extensive (i.e., since 2012) and provide a good overview of changes occurring in the system (Table 1). The estuary is typically eutrophic from the middle to the upper reaches (Adams et al., 2019). There are clear trends in DIN and DIP concentrations, increasing upstream because of inputs from the three WWTWs and diffuse runoff from the Motherwell, Markman, Kat, and Chatty catchments. An approximate increase of 85% has been recorded for both DIN and DIP concentrations in the estuary. DIN concentrations exhibited a persistent longitudinal gradient, with average surface concentrations ranging from 0.11 $mg \cdot L^{-1}$ at Settlers Bridge to 3.35 $mg \cdot L^{-1}$ upstream at Perseverance (Adams and Riddin, 2020). The elevated inflow from WWTWs and stormwater runoff has caused the estuary to become slightly fresher, decreasing the overall salinity in the estuary by 7% on average. There has also been an increase in toxicants, mostly due to surrounding industrial activities.

The high nutrient concentrations result in eutrophication, where persistent phytoplankton blooms are recorded, especially in the middle to upper reaches of the estuary. Hypoxia and anoxia (i.e., dissolved oxygen < 2 $mg \cdot L^{-1}$) are frequently measured in the bottom water of these reaches, associated with the die-off and decay of phytoplankton blooms. In a recent study by Lemley et al. (2022), the Motherwell artificial wetland was deemed inefficient in reducing nutrient concentrations entering the estuary from the Motherwell Canal, thus making this an important additional source of pollution to the estuary. Essentially, the canal functions as a WWTW, which is problematic because the untreated inputs are characterised by high ammonium and DIP concentrations and represent a constant daily source of inorganic nutrients that influence the nearshore environment (Lemley et al., 2019). Confidence in this assessment is 'high' as it is based on measured data.

Physical habitat alteration

Analysis of past images dating back to the 1930s shows 882 ha loss of estuarine habitat to infrastructure, coupled with residential and industrial development (Adams and Riddin, 2020). Extensive supratidal habitat has been lost with only 50% similarity to natural. This loss is the result of development, which includes the construction of the Wylde and railway bridges at Swartkops Village, the extensive saltpans near to Redhouse Village (560 ha), and the Settlers Bridge at the mouth of the estuary. An additional 556 ha is disturbed habitat due to trampling, walkways, and urban encroachment. Confidence in this assessment is 'medium to low' as the assessment could improve if there was a recent bathymetric survey (Table A2, Appendix).

Present Ecological State: biotic components

Microalgae

The EHI considers the species richness, abundance, and community composition of phytoplankton and benthic microalgae (microphytobenthos) in the estuary. The strongest driver of change for microalgae is nutrient availability, with excess concentrations supporting the persistent, high-biomass phytoplankton blooms of HAB species recorded in the estuary (Adams et al., 2019; Lemley et al., 2023). *Heterosigma akashiwo* was documented as being responsible for numerous high-biomass HABs (> 100 μg Chl-$a \cdot L^{-1}$) particularly in the mid-to-upper estuary reaches, with two mass fish mortality events associated with these events (Lemley et al., 2023). Based on these field data there has been an estimated 61% increase in phytoplankton biomass in the middle to upper reaches of the estuary from baseline/natural conditions. Field data have shown that phytoplankton blooms facilitate drastic shifts in dissolved oxygen concentrations during the bloom-decay cycle, with supersaturated surface waters typical of the bloom phase and bottom-water hypoxia characterising the decay phase (Lemley et al., 2023). From published literature for other South African estuaries (Lemley and Adams, 2020; Lemley et al., 2021; Nunes et al., 2021; Nel et al., 2023), we expect that nutrient enrichment and reduced flow variability (e.g., less frequent flooding events, augmentation of baseflows) are likely to facilitate increased abundance and reduced diversity of benthic microalgal communities due to less sediment disturbance. Contrastingly, elevated turbidity, resulting from external sources (e.g., WWTWs, stormwater canals) and in-situ phytoplankton blooms (including HABs), can result in the increased shading of benthic microalgal communities in the mid-to upper reaches, reducing abundance and diversity of these microalgal communities. The microalgal assessment had a 'medium' confidence level (Tables A1 and A2, Appendix).

Macrophytes

Mapped data showed that intertidal and supratidal salt marsh areas have decreased by 64% in extent since the 1930s (Table 3). Development and industries are the major pressures causing the loss of habitat and decline of the floodplain vegetation and supratidal salt marsh area. Aerial photographs taken in 1939 indicated that large areas of intertidal salt marsh were already lost when the Swartkops and Redhouse Villages were developed. Post 1939, smaller areas of marsh were lost to the solar salt works, the power station, the Uitenhage Road and other roads and bridges. The upgrading of road interchanges in the Fish Water Flats region led to further removal of intertidal salt marsh (Colloty et al., 2000).

Elevated nutrient concentrations and more stable flow conditions have simultaneously supported the spread of invasive alien aquatic plants such as water hyacinth in the upper, fresher, estuary reaches (Lakane et al., 2024). The increase in river inflow, nutrients, turbidity, and water hyacinth has led to the loss of seagrass in the middle/upper reaches of the estuary (Adams et al., 2023). There has also possibly been some loss in reed and sedge habitat due to increased disturbance of the riparian zone. These mapped habitat changes informed the assessment of community composition (Table 4).

The health of the macrophytes was assessed in terms of species richness, abundance and community composition (Table 5). Change in species richness was measured as the loss in the average species richness expected during a sampling event, excluding species thought to not have occurred under reference conditions (Table 5). Abundance was measured as the change in area cover of macrophyte habitats. The following was used to measure abundance:

% similarity = 100 x present area cover / reference area cover

Intertidal salt marsh, supratidal salt marsh and floodplain area values were used to measure change in abundance (Table 3). In total these habitats covered 1865.93 ha but now cover 697.64 ha, with a 37% similarity compared to reference conditions. This represents habitat lost due to development, particularly establishment of salt

Table 3. Mapped habitat loss in the Swartkops Estuary due to development and disturbance. Reference condition is taken as that prior to any disturbance approximately 100 years ago.

Habitat	Reference area (ha)	2021 area (ha)	Area lost (ha) (% loss from baseline)
Developed	0	882.38	–
Disturbed	0	556.48	–
Beach	32.28	32.28	0
Open water	409.11	409.11	0
Reeds and sedges	21.8	21.8	0 (Not visible on image, possible loss due to riparian bank disturbance and increase in salinity)
Intertidal salt marsh	536.87	192.62	344.27 (64.2%)
Supratidal salt marsh	1 001.49	358.89	642.6 (64.2%)
Floodplain	373.31	146.13	227.18 (60.8%)
Sand and mudbanks	120.92	120.92	0
Submerged macrophytes	53.61	53.61	Variable in response to floods
Terrestrial plus ecotone	397.72	172.91	224.81 (56.5%)

Table 4. Area covered by macrophyte habitats and calculation of the similarity in community composition for the Swartkops Estuary

Macrophyte habitat	Reference area cover (ha)	Present area cover (ha) 2021	Minimum
Disturbed 2021 floodplain reference	556.48	0	
Developed 2021 floodplain reference	882.39	0	
Intertidal salt marsh	536.87	192.62	192.62
Supratidal salt marsh	1 001.49	358.89	358.89
Floodplain	327.57	146.13	146.13
Sum	3 304.8	697.64	697.64
% similarity	Sum min/(sum ref + present)/2 = 697.64/(3 304.8 + 697.64)/2	35% similar	

Table 5. Present macrophyte health score indicating how change was measured, the resultant score and the confidence assessment (M = medium, H = high)

Variable	Summary of change	Score	Confidence
a. Species richness	Species have mostly remained the same due to the presence of the large intertidal salt marsh in the lower reaches. Although disturbed, there is still supratidal and floodplain salt marsh present. However, some loss of ecotone species is expected. (Scoring approach: average species richness as a % of average species richness during the reference condition; only consider original species; 80% = 65).	65	M
b. Abundance	Large loss of salt marsh habitat (both floodplain, supratidal and intertidal) due to development and disturbance such as the saltpans and low-lying developments.	37	H
c. Community composition	Developed areas represent lost macrophyte habitats. Disturbed areas are characterised by invasives and have little similarity to the original communities. Invasive floating aquatics such as water fern and water hyacinth are abundant in the upper reaches in response to the elevated nutrients. Water hyacinth (floating macrophyte) has replaced the seagrass *Zostera capensis*.	35	H
Macrophyte health score: min (a to c)		35	H

pans that cover 551.2 ha. Invasive plants (terrestrial and aquatic) would not have been present in the reference condition but are now abundant in the areas quantified as 'disturbed'. In addition, there have been flow and water quality–related changes. Change in community composition was assessed using a similarity index which is based on estimates of the area cover of each macrophyte habitat in the reference and present state (Czekanowski's similarity index: $\sum(\min(ref,pres) / (\sum ref + \sum pres)/2)$ (Table 4). Disturbed and developed habitat were present as intact, mainly floodplain, vegetation in the reference condition. The overall macrophyte health score (Table 5) was the minimum score of 35 for community composition changes. The confidence in this assessment was 'high' as it was based on field studies and measured/mapped data.

Restoration of salt marsh and seagrass is important as this will increase the ability of the estuary to sequester carbon dioxide from the atmosphere, contribute to long-term carbon storage stocks, and mitigate the effects of climate change. It is estimated that salt marshes and seagrasses in South Africa store carbon at levels of 100–199 $Mg \cdot ha^{-1}$ and 45–144 $Mg \cdot ha^{-1}$, respectively (Raw et al., 2023). Coastal squeeze caused by rising sea levels and building encroachment is a significant danger to salt marsh habitats (Raw et al., 2021). Coastal squeeze will limit salt marsh expansion in response to sea level rise as there is little available space for inland migration (Adams et al., 2023).

Invertebrates

Invertebrates within an estuary can be subdivided into interstitial meiofauna (not typically considered in EHI assessments) and 4 prominent macrofaunal components based on dominant traits and drivers, namely: plankton, benthos, hyperbenthos, and intertidal. Each of these experience different pressures depending on their associated life history strategy and lifestyle. Sediment properties, especially granulometry and organic matter, are the primary structuring forces of benthic organisms (Teske and Wooldridge, 2003).

Additionally, the benthic and intertidal macrofauna are affected by anthropogenic pressures such as coastal squeeze, disturbance, and direct consumptive collections by recreational and subsistence user groups (Fielding, 2021). Consequently, populations of large benthic macrofauna species such as mudprawns (*Upogebia africana*) and cracker shrimps (*Alpheus lobidens*, i.e., benthic burrowers) have declined from bait-harvesting pressures. For example, using comparable sampling methods, the clearest decline has been in mud prawn abundance in the estuary, from 174 340 x 10^3 total estimated organisms in 1980 to 103 611 x 10^3 in 2008, and, most recently, 76 060 x 10^3 in 2020 (Fielding, 2021). This is a loss of over half of the stock of this ecologically and economically important bait species in 4 decades (Fielding, 2021). Similar declines are apparent for species such as giant mud crabs (*Scylla serrata*) that are collected for subsistence (Fielding, 2021). The most substantial change compared to the reference condition is a reduction in overall abundance of benthic macroinvertebrates, especially those used for bait (e.g., sand prawns, *Kraussillichirus kraussi*, mud prawns, and pencil bait, *Solen capensis*) and subsistence (e.g., giant mud crabs) (Fielding, 2021). This loss of abundance is exacerbated by the removal of intertidal habitat through development.

Significant changes to invertebrates are also related to increased nutrient loading, changes to primary producer groups, increased prevalence of alien or invasive taxa, and pollutant loading (Lemley et al., 2023; Ndhlovu et al., 2024b). Invasion of *Crassostrea gigas* (Pacific oyster) is facilitated by pollution and a decline in water quality (pH increase) as well as by bridges, pipes and other hard structures on which they settle. The increased prevalence of HABs in the Swartkops Estuary is likely to have negatively impacted the species richness, abundance, and community composition of the zooplankton and hyperbenthos components, particularly in the mesohaline zone (Smit et al., 2021; Smit et al., 2023). Changes in flood states and sediment supply appear to be temporary, causing minimal disturbances to this community (McLachlan and Grindley, 1974), while the fresher conditions brought on by elevated baseflows have shifted the overall community away from a marine-dominated invertebrate fauna. An understanding of how deterioration in water quality affects macroinvertebrate communities is crucial in their use as indicators of river and estuarine health. For example, Odume et al. (2012) investigated the impacts of water quality deterioration on Swartkops River macroinvertebrate communities. At downstream river sites, the abundances of families were skewed toward the most pollution-tolerant taxa (e.g., Chironomidae, Oligochaeta, Hirudinae) and the increased dominance of Chironomidae and Oligochaeta indicated depleted oxygen and increased nutrient levels (Odume et al., 2012). The confidence in this assessment was 'medium' since there is a good baseline of information across the various invertebrate assemblages, and at least one multi-decadal dataset exists as a reference point (Fielding, 2021).

Fishes

Over 75 species of bony and cartilaginous fishes have been identified in the Swartkops Estuary (Baird et al., 1986; Edworthy and Strydom, 2016; Nodo et al., 2023; 2024; Grundlingh, 2025). The estuary consists of a variety of habitat types with extensive eelgrass *Z. capensis* beds that make it an ideal nursery area for fishes (Beckley, 1983; Mkhize et al., 2025). The abundance and diversity of larval and juvenile stages of estuary resident and marine species increase in spring and summer (Strydom et al., 2003; Edworthy and Strydom, 2016; Nodo et al., 2023; Grundlingh, 2025). The estuary is also an important feeding area for adult marine estuarine-dependent fishes, such as *Argyrosomus japonicus* (dusky kob), *Pomadasys commersonnii* (spotted grunter), *Lithognathus lithognathus* (white steenbras), *Elops machnata* (ladyfish), *Rhabdosargus holubi* (Cape stumpnose), *Lichia amia* (leervis), and various species of marine opportunistic Mugilidae (mullet) that are used as live bait (Marais, 1982; Baird et al., 1996; Adams et al., 2023; Whitfield and Mann, 2023; Whitfield and Smith, 2024). In addition, Swartkops Estuary is an important system for recreational and small-scale fishing; however, catches have declined over time and the size of fishes caught has decreased (Marais and Baird, 1980; Pradervand and Baird, 2002; Whitfield and Mann, 2023; Whitfield and Smith, 2024).

The reference condition for the Swartkops Estuary would have consisted of a high abundance of fishes from all trophic levels. However, due to its proximity to heavily urbanised areas, very high fishing pressure (e.g., recreational and small-scale fishing, illegal gillnetting) has resulted in significant changes to fish abundance (estimated 60% loss) and community composition (estimated 40% change), all of which impact the nursery function and trophic structure of the system (Pradervand and Baird, 2002; Van Niekerk et al., 2022). Major changes have been observed in the sizes of species and therefore the age of species commonly targeted by anglers. This is evidenced by the sizes of *A. japonicus* and *L. lithognathus* being up to 4 times heavier in records by Fitzsimons (1915, cited in Heydorn and Grindley, 1986) compared with records by Marais and Baird (1980a, b) (see Whitfield and Mann, 2023). Recent findings also illustrate the knock-on effects of overfishing on fish reproduction, where larval fish densities have decreased for common angling species, indicative of smaller adult female sizes producing smaller and fewer eggs during spawning (Grundlingh, 2025). The HABs, driven by increased wastewater inflow, with the associated fluxes in dissolved oxygen in the middle to upper regions, cause the localized loss of fish abundance and shifts in community composition of fishes in the mesohaline reaches of the estuary. Low dissolved oxygen events (< 3 mg·L^{-1}) in the upper reaches resulted in declines in species richness (Nodo et al., 2023). Other impacts include habitat disturbance following bait collection, the prevalence of freshwater invasive alien fish species that potentially displace catadromous species, and the unknown impact of heavy metal, organic and inorganic contamination on fish reproductive biology. Confidence in this assessment is 'high' in terms of larval and juvenile stages of fishes but adult fishes are scientifically under-sampled in contemporary studies due to the harmful effects of using traditional gill nets on populations of fishes experiencing stock collapses. Changes in angler catches were used as an indicator of change in adult fish abundance and size. Adult fish data could improve with a contemporary study on angler fish catches for comparison with historical studies.

Birds

The Swartkops Estuary is a globally recognised 'Important Bird and Biodiversity Area' (IBA). The Swartkops Estuary and the Redhouse and Chatty saltpans are considered the most important estuarine and salt-flat habitats for waterbirds along the Eastern Cape Province's coast (Martin and Baird, 1987; BirdLife International, 2021). The estuary supports up to 20 000 birds, with over 3 000 of these being annual Palearctic migrant species (BirdLife International, 2021). Most of these birds are water- and wetland-associated birds (Adams and Riddin, 2020), including the African Oystercatcher (*Haematopus moquini*), Greater and Lesser Flamingos (*Phoenicopterus roseus* and *P. minor*), African Spoonbill (*Platalea alba*), several species of kingfishers, Roseate Terns (*Sterna dougallii*), as well as many other waders, waterfowl and piscivorous species (Adams et al., 2023). Disturbance and habitat modification have reduced the overall waterbird abundance (Andrade et al., 2018). It is likely that the establishment of the adjacent saltpans has compensated to some degree for this, making it possible for the waterbirds to breed, feed, and roost (Martin and Baird, 1987). However, decommissioning of the Chatty and Redhouse saltpans in recent years has minimised this compensation and therefore presents an opportunity for habitat restoration to enhance localised avifauna conservation (Wasserman et al., 2022a) and increase nutrient removal (Du Toit and Campbell, 2022).

Based on studies on the influence of freshwater, sediment and habitat on invertebrates and fish (Marais, 1982), it is concluded that elevated inflow of nutrient-rich freshwater, coarsening of intertidal sediments, loss of salt marsh habitat, disturbance, increase in reeds and sedges in the upper reaches of the estuary, decommissioning of saltpans, and reduced benthic invertebrate and fish biomasses have all impacted on bird species richness, abundance, and community composition. The impacts associated with elevated turbidity, heavy metals and organic pollutants are largely unknown. An estimated 40% loss in abundance has been attributed to disturbance and habitat modification. The Swartkops Estuary has one of the best long-term monitoring datasets in terms of waterbird counts, started in the 1980s thanks to initiatives led by Dr Martin (Martin and Baird, 1987) and continued through the CWAC (Coordinated Waterbird Count) project. Confidence in this scoring is therefore deemed to be 'medium to high', with the only major source of uncertainty being that many of the impacts on the system would have been pre-1980 and therefore before any systematic monitoring efforts occurred.

Changes in estuary health over time

The current study reviewed and collated current research findings and available new data on the Swartkops Estuary and determined the trajectory of change for abiotic and biotic features (Table 6). The individual present health scores for the abiotic and biotic components were used to determine the PES of the estuary using the EHI weightings as presented in Table 6. The EHI score for the Swartkops Estuary is 47, representing a 'largely modified' estuary with a PES Category D. The overall confidence in this score was 'medium to high', derived from confidence levels assigned to most of the abiotic and biotic components. The trajectory of change is towards a highly degraded Category E system. This is evident in the decrease in EHI score from 53 to 47. This is of great concern for estuary management because, according to the guidelines for determining the REC provided by DWAF (2008), the Swartkops Estuary should be 'largely natural' with few modifications (Category B). However, due to the extent of changes the estuary has undergone and the high degree of urbanisation, the best achievable state is that of a 'moderately modified' system (Category C). A review of restoration scenarios indicates that eliminating wastewater, regulating resource use of fish and bait, and restoring riparian habitat, particularly the Redhouse saltpan, may increase the likelihood of achieving a Category C.

Future flow scenarios

The responses of the five proposed future inflow scenarios were investigated for the different abiotic and biotic components and the two worst case scenarios did not change the estuary from being a 'largely modified' estuary (Category D) (Table 7). Similarly, the estuary remained in a 'largely modified' (Category D) condition under Scenario 3, which considered the removal of 75% of the wastewater input. The estuary condition only improved to a Category C/D (moderately/largely modified) when 100% of the wastewater input was removed in Scenario 4. This indicates the significant impact that the WWTW input has on the health of the estuary as well as the influence of other multiple pressures. Besides reducing WWTW input, habitat restoration will also be needed to improve the health of the Swartkops Estuary. There was a 4-point improvement in health score from the present state (score of 47) under Scenario 5 (score of 51). Therefore, if habitat restoration (Scenario 5) is implemented in conjunction with the complete removal of WWTW inputs (Scenario 4), the estuary health score could improve to 63 (an Ecological Category of C, representing a moderately modified estuary).

Restoration options

The decline in estuary health revealed by the health assessment confirms observations made by various scholars of a deteriorating state (Pretorius, 2015; Adams et al., 2019; Lemley et al., 2023). It is evident from this health assessment that restoration interventions on the Swartkops Estuary are urgently needed. For such interventions to be effective, cooperation from all stakeholders involved in the estuary will be key. The estuary is a complex social-ecological system and restoration efforts to improve estuary health should recognise this (Adams et al., 2023). Restoration ecology bridges the gap between application and supporting sciences, and rather than focusing primarily on ecological factors, it should include socio-ecological elements (Abelson et al., 2020; Adams et al., 2023).

From the scenarios tested, priority actions and additional restoration activities were considered for the Swartkops Estuary and are summarised in Tables 8 and 9. The poor health of the Swartkops Estuary is a result of multiple pressures that need to be addressed to improve its health. Effective water quality control measures are complicated, and it has been shown that the management of nutrients, particularly DIN and DIP, requires

Table 6. Health scores and Present Ecological State (PES) of the Swartkops Estuary determined using the Estuarine Health Index. PES scores from Van Niekerk et al. (2015) included for comparison as well as the motivation for the 2021 score.

Variable	Weight	Score (2015)	Score (2021)	Motivation for the 2021 score (changes from reference/natural)
Hydrology	25	38	44	Baseflow increased due to WWTW, stormwater/hardened surfaces, floods remain untransformed
Hydrodynamics and mouth condition	25	90	56	Loss of marine state in the estuary due to loss of low-flow conditions driven by increase in baseflow
Water quality	25	50	46	High nutrient concentrations and toxins
Physical habitat alteration	25	50	50	Subtidal, intertidal and supratidal habitat all disturbed by development
Habitat (abiotic) health score		**58**	**49**	
Microalgae	20	48	39	Increase in biomass and HABs in response to excessive nutrient input
Macrophytes	20	40	35	Loss of habitat from disturbance, development, invasive species
Invertebrates	20	40	50	Decrease in abundance due to disturbance and bait collecting
Fish	20	40	40	Fishing pressure and overexploitation decreased abundance as well as declines in response to HABs fuelled by wastewater
Birds	20	70	60	Disturbance and habitat modification have reduced bird abundance
Biotic health score		**48**	**45**	
Estuary health score (PES)		53	47	
Present Ecological State category		D	D	
Overall confidence				Medium/High

Table 7. EHI scores, corresponding 'Ecological Categories', and confidence levels under present and future inflow scenarios (confidence: L = low, M = medium, H = high)

Variable	Weight	Scenarios						Confidence
		Present	1	2	3	4	5	
Hydrology	25	44	33	42	50	54	45	M–L
Hydrodynamics	25	56	50	55	60	67	56	M
Water quality	25	46	45	44	60	70	46	H
Physical habitat	25	50	50	50	50	50	60	M–L
Habitat health score	**50**	**49**	**45**	**48**	**55**	**60**	**52**	**M**
Microalgae	20	39	37	27	60	63	39	M
Macrophytes	20	35	35	33	37	39	45	H
Invertebrates	20	50	50	45	55	60	55	M
Fish	20	40	50	35	55	60	45	M
Birds	20	60	55	55	65	70	72	M–H
Biotic health score	**50**	**45**	**46**	**39**	**54**	**58**	**51**	**M**
Estuary health score		**47**	**46**	**39**	**54**	**58**	**51**	**M**
Ecological Category		**D**	**D**	**D**	**D**	**C/D**	**D**	**M**

Table 8. Priority actions to improve estuary health from a PES category of 'largely modified' (D) to 'moderately modified' (C)

Action	Areas of focus and implementation
Remove all wastewater input to the estuary from the river	Recycle, artificial wetlands
Add water to the Redhouse saltpan	From Motherwell canal and estuary
Restore riparian habitat through removal of alien plants	In middle and upper estuary reaches
Reduce fishing pressure	Compliance monitoring and protected areas
Reduce bait collection	Compliance monitoring and protected areas

Table 9. Detailed restoration actions to improve estuary health from a PES category of 'largely modified' (D) to 'moderately modified' (C)

Variable	Restoration activity
Hydrology	Remove nutrient-rich baseflow that enters the estuary from WWTWs through recycling and reuse. Install a flow gauge/low-flow weir closer to the head of the estuary to better quantify freshwater inflow. Reduce stormwater input and polluted flows from Chatty River and Markman and Motherwell canals.
Water quality/ microalgae	Remove nutrient-rich baseflow that enters the estuary from WWTWs and restore hydrodynamic variability and the dominant marine state. Improve water quality by preventing inputs of urban run-off, raw sewage, and increased stormwater input. This would reduce nutrient, toxin, and bacterial inputs. Reduced nutrient input would prevent HABs and general eutrophication indicated by water hyacinth and other invasive floating macrophytes abundant in the upper estuary.
Physical habitat/ macrophytes	Restore abandoned dry saltpan habitats to encourage an increase in bird numbers. Motherwell Canal water can be used to rewet the Redhouse pans to promote macrophyte growth in the bare saltpan areas.
	Restore connectivity with the river by removing rubble and invasive aquatic macrophytes once water quality improves. Restore riparian vegetation where removed and disturbed. Remove alien invasive trees such as gums. Restore supratidal salt marsh lost due to development and disturbance (556 ha).
	Target salt marsh areas to restore blue carbon storage for possible trading and climate change mitigation. This includes the plants and sediment stocks.
Invertebrates	Control exploitation in terms of bait digging through protected areas. No spades to limit disturbance to seagrass. Prevent trampling of intertidal and supratidal salt marsh.
Fish	Introduce methods to prevent overfishing, such as a night ban on fishing. Increase protected areas as indicated in the EMP, including the river–estuary interface zone, and Tippers Creek. Water quality and habitat restoration will benefit fish. Implement the Marine Living Resources Act and compliance monitoring regarding bag limits and closed seasons.
	There are opportunities for compliance training through FishForce, Nelson Mandela University. Enhance larval and juvenile recruitment through habitat restoration and ecosystem engineering for concrete structures, particularly in the lower reaches.
Birds	Control movement of people and animals that disturb birds' feeding, nesting, and breeding. Implement protected bird areas as indicated in the EMP, particularly the gull nesting sites.
	There are opportunities for bird hides to encourage ecotourism, but personal safety currently threatens these activities. Walkways are an option, but the estuary is accessible on both banks, with numerous pathways.

a multi-sectoral approach (Maier et al., 2009). The Swartkops Estuary is a nationally important site for salt marsh restoration (Adams et al., 2021) and provides an array of important nursery habitats that must be protected through fishing and invertebrate bait collecting control and the implementation of no fishing zones where juveniles and pre-spawning adults are known to congregate (Table 9). There is a proposed fishery for the invasive alien Pacific oyster (*Crassostrea gigas*) that could provide opportunities for ecosystem restoration and contribute to livelihoods of small-scale fishers.

Recent approaches such as natural capital accounting and its official international framework, the System of Environmental-Economic Accounting (SEEA), have created a framework to account for nature's contributions to the economy and people (Taljaard et al., 2023). Local restoration efforts could be informed by the ecosystem accounting methods, which provide detailed information about the extent of abiotic habitats, the condition of the ecosystem assets, and the services they provide. Globally ecosystems accounting has largely focused on carbon accounting, fisheries/nursery function and tourism values as key ecosystem services (Dvarskas, 2019; Gomez Cardona et al., 2023). Taljaard et al. (2023) provides a local example of how blue carbon sequestration and recreational use can be incorporated into formal ecosystem accounting processes. Information from these accounts can help prioritise, monitor and report on restoration efforts in the Swartkops Estuary.

To restore the wetland function of an abandoned commercial saltpan at Swartkops Estuary, an opportunity was identified to fill it with nutrient-rich stormwater (Wasserman et al., 2022b). In 2018, a microcosm-based study was conducted to inform a planned restoration project that aimed to simultaneously address two issues: stormwater management and saltpan abandonment (Wasserman et al., 2022b). At the end of the study, the conditions in the experiment tanks resembled those typical of primary concentration pans in saltworks. The stormwater treatments that received freshwater extracted from the Motherwell Canal reached a brackish state and the estuary treatment (initial salinity of 23) became hypersaline. Both treatments hosted a diversity of primary producers, common in low salinity ponds of saltworks (Britton and Johnson, 1987; Davis, 2000; Wasserman et al., 2022b). A main conclusion of the study was that primary producers – particularly phytoplankton and macroalgae – at the Redhouse saltpan will quickly assimilate inorganic nutrients from the stormwater, thereby relieving the Swartkops Estuary from a significant source of anthropogenic nutrient pollution (Lemley et al., 2022; Wasserman et al., 2022b). The abandoned saltpans are currently being used to receive Motherwell Canal water and act as a large pollutant filter. Ongoing monitoring is necessary to investigate the removal of nutrients by the pans, changes in physico-chemical conditions and the ecological health of the system.

CONCLUSION

The use of the EHI as an estuary health assessment tool enabled the identification of drivers responsible for the deteriorating condition of the Swartkops Estuary. Similarly, the index helped identify remediation measures that can be implemented to improve the health of the estuary. These measures include:

- Removal of WWTW and stormwater drainage discharges into the estuary
- Restoration of salt marsh and seagrass habitats to mitigate the effects of climate change
- Conversion of the nearby defunct commercial saltpans into extensions of the existing artificial wetland to restore waterbird habitat and filter pollution
- Reducing the pressures of bait collection and overfishing

The findings of this study highlight that, over the past decade, management and conservation efforts have failed to prevent the continued deterioration of ecosystem health in the Swartkops Estuary. There is an urgency to revisit and change the current traditional estuary management process. A socio-ecological approach presents the opportunity to engage resource users and management holistically and pragmatically. This can be achieved through the implementation of existing legislative tools, which includes the determination of an 'Ecological Reserve' and 'Resource Quality Objectives' through the process of 'Water Resource Classification' as required by the NWA, and implementation of the EMP as required by the ICMA (Adams et al., 2020). Fortunately, the Swartkops EMP has recently been gazetted and rivers within the Mzimvubu-Tsitsikamma Water Management Area, into which the Swartkops River falls, are in the process of being classified and soon to be gazetted.

Lessons learned from the study are that long-term ecological data are needed for high-confidence assessments of estuary health. Monitoring of estuaries is inadequate and does not allow for effective conservation and management. This poses a threat to the ecological health and societal benefits of an estuary. Although the assessment of estuary health using the EHI is well established, this study showed how restoration and climate-change scenarios can be considered using a similar approach. This informs the management of impacted estuaries globally.

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AUTHOR CONTRIBUTIONS

All authors: Methodology of the study, data collection and fieldwork, sample/data analysis, interpretation of results, writing of the initial draft, interpretation of results, input to final draft.

JB Adams: Conceptualisation, research project management and funding.

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REFERENCES

ABELSON A, REED DC, EDGAR GJ, SMITH CS, KENDRICK GA, ORTH RJ, AIROLDI L, SILLIMAN B, BECK MW, KRAUSE G, SHASHAR N, STAMBLER N and NELSON P (2020) Challenges for restoration of coastal marine ecosystems in the Anthropocene. *Front. Mar. Sci.* 7 544105. https://doi.org/10.3389/fmars.2020.544105

ADAMS JB (2016) Distribution and status of *Zostera capensis* in South African estuaries – a review. *S. Afr. J. Bot.* **107** 63–73. https://doi.org/10.1016/j.sajb.2016.07.007

ADAMS JB (2020) Salt marsh at the tip of Africa: patterns, processes and changes in response to climate change. *Estuar. Coast. Shelf Sci.* **237** e106650. https://doi.org/10.1016/j.ecss.2020.106650

ADAMS JB and RIDDIN T (2020) State of knowledge: Conservation and management of the Swartkops Estuary. Benguela Current Convention Report September 2020. Institute for Coastal and Marine Research, Nelson Mandela University, Port Elizabeth. 44 pp.

ADAMS JB, SNOW GC and PRETORIUS L (2014) Assessment of the health of the Swartkops Estuary: Spatial and temporal variability in water quality characteristics. Report prepared for the Nelson Mandela Bay Municipality. Department of Botany, Institute for Coastal and Marine Research, Nelson Mandela Metropolitan University.

ADAMS JB, PRETORIUS L and SNOW GC (2019) Deterioration in the water quality of an urbanised estuary with recommendations for improvement. *Water SA* **45** 86–96. https://doi.org/10.4314/wsa.v45i1.10

ADAMS JB, WHITFIELD AK and VAN NIEKERK L (2020) A socio-ecological systems approach towards future research for the restoration, conservation and management of southern African estuaries. *Afr. J. Aquat. Sci.* **45** 231–241. https://doi.org/10.2989/16085914.2020.1751980

ADAMS JB, RAW JL, RIDDIN T, WASSERMAN J and VAN NIEKERK L (2021) Salt marsh restoration for the provision of multiple ecosystem services. *Diversity* **13** e680. https://doi.org/10.3390/d13120680

ADAMS JB, TSIPA V, HUMAN L, LAKANE CP, LEMLEY DA, MMACHAKA T, RIDDIN T, SNOW B, TALJAARD S, VAN NIEKERK L and WHITFIELD E (2023) Restoration of estuaries using a socio-ecological systems framework. WRC Report No. 3061/1/22. Water Research Commission, Pretoria. 90 pp.

ANDRADE R, BATEMAN HL, FRANKLIN J and ALLEN D (2018) Waterbird community composition, abundance, and diversity along an urban gradient. *Landscape Urban Plann.* **170** 103–111. https://doi.org/10.1016/j.landurbplan.2017.11.003

BAIRD D, HANEKOM NM and GRINDLEY JR (1986) Estuaries of the Cape: Part 2 Synopsis of available information on individual systems. Report No. 23 – Swartkops. CSIR Research Report No. 422. CSIR, Pretoria. 83 pp.

BAIRD D, MARAIS JFK and DANIEL C (1996) Exploitation and conservation of angling fish in two South African estuaries. *Aquat. Conserv. Mar. Freshwater Ecosyst.* **6** 319–330. https://doi.org/10.1002/(SICI)1099-0755(199612)6:4<319::AID-AQC201>3.0.CO;2-H

BARBIER BB, HACKER SD, KENNEDY C, KOCK EW, STIER AC and SILLIMAN BR (2011) The value of estuarine and coastal ecosystem services. *Ecol. Monogr. Ecol. Soc. Am.* **81** 169–193. https://doi.org/10.1890/10-1510.1

BEAUMONT NJ, JONES L, GARBUTT A, HANSOM JD and TOBERMANN M (2014) The value of carbon sequestration and storage in coastal habitats. *Estuar. Coast. Shelf Sci.* **137** 32–40. https://doi.org/10.1016/j.ecss.2013.11.022

BECKLEY LE (1983) The ichthyofauna associated with *Zostera capensis* Setchell in the Swartkops Estuary, South Africa. *S. Afr. J. Zool.* **18** 15–24. https://doi.org/10.1080/02541858.1983.11447809

BECKLEY LE (1985) Tidal exchange of ichthyoplankton in the Swartkops estuary mouth, South Africa. *S. Afr. J. Zool.* **20 (1)** 15–20. https://doi.org/10.1080/02541858.1985.11447906

BIRDLIFE INTERNATIONAL (2021) Important Bird Areas factsheet: Swartkops Estuary – Redhouse and Chatty Saltpans. URL: http://www.birdlife.org (Accessed 6 June 2021).

BINNING K and BAIRD D (2001) Survey of heavy metals in the sediments of the Swartkops River Estuary, Port Elizabeth South Africa. *Water SA* **27** 461–466. https://doi.org/10.4314/wsa.v27i4.4958

BORNMAN TG, SCHMIDT J, ADAMS JB, MFIKILI AN, FARRE RE and SMIT AJ (2016) Relative sea-level rise and the potential for subsidence of the Swartkops Estuary intertidal salt marshes, South Africa. *S. Afr. J. Bot.* **107** 91–100. https://doi.org/10.1016/j.sajb.2016.05.003

BRAY JR and CURTIS JT (1957) An ordination of the upland forest communities of Southern Wisconsin. *Ecol. Monogr.* **27** (4) 325–349. http://doi.org/10.2307/1942268. https://doi.org/10.2307/1942268

BRITTON RH and JOHNSON AR (1987) An ecological account of a Mediterranean salina: the Salin de Giraud, Camargue (S. France). *Biol. Conserv.* **42** 185–230. https://doi.org/10.1016/0006-3207(87)90133-9

CHIBWE M, ODUME ON and NNADOZIE CF (2023) Assessment of risk of exposure to *Campylobacter* species and their antibiotic-resistant genes from selected rivers in the Eastern Cape, South Africa. *Environ. Pollut.* **338** 122625. https://doi.org/10.1016/j.envpol.2023.122625

CHIBWE M, ODUME ON and NNADOZIE CF (2024) Spatiotemporal variations in the occurrence of *Campylobacter* species in the Bloukrans and Swartkops rivers, Eastern Cape, South Africa. *Heliyon* **10** (7) e28774. https://doi.org/10.1016/j.heliyon.2024.e28774

CLAASSENS L, DE VILLIERS N, ADAMS JB, WASSERMAN J and WHITFIELD AK (2022) Restoration of South African estuaries – successes, failures and the way forward. *Afr. J. Aquat. Sci.* **48** 1–18. https://doi.org/10.2989/16085914.2022.2115970

CBD (Convention on Biological Diversity) (2022) Nations adopt four goals, 23 targets for 2020 in landmark UN biodiversity agreement. CBD, Montreal, Canada. URL: https://www.cbd.int/article/cop15-cbd-press-release-final-19dec2022 (Accessed 9 March 2024).

CHIEF DIRECTORATE: NATIONAL GEO-SPATIAL INFORMATION (2021) URL: http://cdngiportal.co.za/cdngiportal/CDNGI.aspx?gpm=%7B0%7D (Accessed 20 March 2021).

COLLOTY BM, ADAMS JB and BATE GC (2000) The use of a botanical importance rating to assess changes in the flora of the Swartkops Estuary over time. *Water SA* **26** 171–180.

COORDINATED WATERBIRD COUNTS (2021) Coordinated Waterbird Counts (CWAC) dataset. URL: https://cwac.birdmap.africa/ (Accessed 20 January 2021).

CSIR (1987) Basic physical geography/hydro data for "estuaries" of the south-eastern Cape (CSE 1-59). NRIO Data Report D 8703. CSIR, Stellenbosch.

DEA (Department of Environmental Affairs, South Africa) (2015) National Estuarine Management Protocol: Guidelines for the development and implementation of estuarine management plans in terms of the national estuarine management protocol. DEA, Cape Town. 68 pp.

DWAF (Department of Water Affairs and Forestry, South Africa) (2008) Resource Directed Measures for Protection of Water Resources: Methodologies for the determination of ecological water requirements for estuaries. Version 2. DWAF, Pretoria.

DWAF (Department of Water Affairs and Forestry, South Africa) (1994) *Algoa Water Resources System Analysis*. Report No.'s PM 000/00/0193 to PM 000/001293. Prepared by Ninham Shand Consulting Engineers.

DWAF (Department of Water Affairs and Forestry, South Africa) (1999a) Zwartkops River water resources management plan: a situation assessment and development of a catchment water resources management plan. DWAF Report No. N/M100/REQ/0896. Department of Water Affairs and Forestry, Pretoria.

DWAF (Department of Water Affairs and Forestry, South Africa) (1999b) Establishment of the Water Management Areas and their Boundaries as a Component of the National Water Resource Strategy in Terms of Section 5(1) of the National Water Act (Act No. 36 of 1998). *Government Gazette* 1 October 1999 No. 20491. Government Printer, Pretoria.

DWS (Department of Water and Sanitation, South Africa) (2016) Development of Procedures to Operationalise Resource Directed Measures. Estuaries and Marine tool analysis and standardisation report. Report no. RDM/WE/00/CON/ORDM/0716. Prepared by CSIR for Rivers for Africa.

DAVIS J (2000) Structure, function, and management of the biological system for seasonal solar saltworks. *Glob. Nest* **2** 217–226. https://doi.org/10.30955/gnj.000175

DOLLAR ESJ, NICOLSON C, BROWN C, TURPIE J, JOUBERT A, TURTON A, GROBLER DF, PIENAAR H, EWART-SMITH J and MANYAKA MS (2010) Development of the South African Water Resource Classification System (WRCS): A tool towards the sustainable, equitable and efficient use of water resources in a developing country. *Water Polic.* **12** 479–499. https://doi.org/10.2166/wp.2009.213

DU TOIT SR and CAMPBELL EE (2022) An analysis of the performance of an artificial wetland for nutrient removal in solar saltworks. *S. Afr. J. Bot.* **68** 451–456. https://doi.org/10.1016/S0254-6299(15)30373-2

DVARSKAS A (2019) Experimental ecosystem accounting for coastal and marine areas: A pilot application of the SEEA-EEA in Long Island coastal bays. *Mar. Polic.* **100** 141–151. https://doi.org/10.1016/j.marpol.2018.11.017

EBBERTS BD, ZELINSKY BD, KARNEZIS JP, STUDEBAKER CA, LOPEZ-JOHNSTON S, CREASON AM, KRASNOW L, JOHNSON GE and THOM RM (2017) Estuary ecosystem restoration: implementing and institutionalizing adaptive management. *Restoration Ecol.* **26** 360–369. https://doi.org/10.1111/rec.12562

EDWORTHY C and STRYDOM N (2016) Habitat partitioning by juvenile fishes in a temperate estuarine nursery, South Africa. *Sci. Mar.* **80** 151–161. https://doi.org/10.3989/scimar.04333.01B

ELKO N, FOSTER D, KLEINHEINZ G, RAUBENHEIMER B, BRANDER S, KINZELMAN J, KRITZER JP, MUNROE D, STORLAZZI C, SUTULA M and co-authors (2022) Human and ecosystem health in coastal systems. *Shore and Beach* **90** 64–91. https://doi.org/10.34237/1009018

ELLENDER BR, WEYL OLF and SWARTZ ER (2011) Invasion of a headwater stream by non-native fishes in the Swartkops River system, South Africa. *Afr. Zool.* **46** (1) 39–46. https://doi.org/10.1080/15627020.2011.11407477

ELLIOTT M, MANDER L, MAZIK K, SIMENSTAD C, VALESINI F, WHITFIELD A and WOLANSKI E (2016) Ecoengineering with ecohydrology: successes and failures in estuarine restoration. *Estuar. Coast. Shelf Sci* **176** 12–35. https://doi.org/10.1016/j.ecss.2016.04.003

ESTERHUYSEN K and RUST IC (1987) Channel migration in the lower Swartkops Estuary. *S.-Afr. Tydskr. Weten.* **83** 521–525.

FENG B, ZHANG Y and BOURKE R (2021) Urbanization impacts on flood risks based on urban growth data and coupled flood models. *Nat. Hazards* **106** 613–627. https://doi.org/10.1007/s11069-020-04480-0

FEIO MJ, HUGHES RM, CALLISTO M, NICHOLS SJ, ODUME ON, QUINTELLA BR, KUEMMERLEN M, AGUIAR FC, ALMEIDA SF, ALONSO-EGUÍALIS P and ARIMORO FO (2021) The biological assessment and rehabilitation of the world's rivers: An overview. *Water* **13** 371. https://doi.org/10.3390/w13030371

FIELDING PJ (2021) Stock assessment of bait organisms in the Swartkops Estuary, Eastern Cape. Comparison of bait organism stock 1980, 2008, 2013, 2020. Prepared for: Zwartkops Conservancy.

FITZSIMONS FW (1915) Zwartkops River investigations (records of fish nettings). Manuscript records forming basis of the 1918 publication by JDF Gilchrist. 80 pp.

GOMEZ CARDONA CJ, MORENO JY, CONTERAS A, SANCHEZ-NUÑEZ DA, ARCINIEGAS MORENO N, GUERRERO D, VILORIA MAESTRE EA and LOPEZ NAVARRO J (2023) Accounting of marine and coastal ecosystems at the Ramsar Site, Estuarine Delta System of the Magdalena River, Ciénaga Grande de Santa Marta, Colombia. *One Ecosyst.* **8** e98852. https://doi.org/10.3897/oneeco.8.e98852

GRUNDLINGH PL (2025) Ingress of early-stage fishes into the Swartkops Estuary, South Africa: comparing present with past assemblages. MSc thesis, Nelson Mandela University.

HANEKOM N, BAIRD D and ERASMUS T (1988) A quantitative study to assess standing biomasses of macrobenthos in soft substrata of the Swartkops Estuary, South Africa. *S. Afr. J. Mar. Sci.* **6** (1) 163–174. https://doi.org/10.2989/025776188784480500

HARTMANN NR (2021) Social-ecological systems approaches to integrated estuarine governance: The Swartkops Estuary. PhD thesis, Nelson Mandela University. 207 pp.

HEYDORN AEF and GRINDLEY JR (1986) Estuaries of the Cape, Report No. 23: Swartkops. Report 422. Council for Scientific and Industrial Research, Pretoria. 82 pp.

HUGHES DA (1987) Swartkops flood hydrograph study: Report at the end of Phase II. Special report No. 3/87, Hydrological Research Unit, Rhodes University, Grahamstown.

HUMAN LR, ELS J, WASSERMAN J and ADAMS JB (2022) Blue carbon and nutrient stocks in salt marsh and seagrass from an urban African estuary. *Sci. Total Environ.* **842** e156955. https://doi.org/10.1016/j.scitotenv.2022.156955

KALINSKI JC-J, NOUNDOU XS, PETRAS D, MATCHER GF, POLYZOIS A, ARON A, GENTRY E, BORNMAN TG, ADAMS JB, and DORRINGTON RA (2024) Urban and agricultural influences on the coastal dissolved organic matter pool in the Algoa Bay estuaries. *Chemosphere* **355** 141782. https://doi.org/10.1016/j.chemosphere.2024.141782

MEISSNER R, STUART-HILL SI and NAKHOODA Z (2017) The establishment of catchment management agencies in South Africa with reference to the *Flussgebietsgemeinschaft Elbe*: Some practical considerations. In: Karar E (ed.) *Freshwater Governance for the 21st Century.* Springer, Heidelberg.

KISTEN Y, PATTRICK P, STRYDOM NA and PERISSINOTTO R (2015) Dynamics of recruitment of larval and juvenile Cape Stumpnose *Rhabdosargus holubi* (Teleostei: Sparidae) into the Swartkops and Sundays Estuaries, South Africa. *Afr. J. Mar. Sci.* **37** (1) 1–10. https://doi.org/10.2989/1814232X.2014.998708

KISTEN Y, EDWORTHY C and STRYDOM NA (2020) Fine-scale habitat use by larval fishes in the Swartkops Estuary, South Africa. *Environ. Biol. Fishes* **103** 125–136. https://doi.org/10.1007/s10641-019-00939-7

KIRSCHKE S, AVELLÁN T, BÄRLUND I, BOGARDI JJ, CARVALHO L, CHAPMAN D, DICKENS CWS, IRVINE K, LEE SB, MEHNER T and WARNER S (2020) Capacity challenges in water quality monitoring: understanding the role of human development. *Environ. Monit. Assess.* **192** 298. https://doi.org/10.1007/s10661-020-8224-3

KEIGHTLEY J, VON DER HEYDEN S and JACKSON S (2015) Introduced Pacific oysters *Crassostrea gigas* in South Africa: demographic change, genetic diversity and body condition. *Afr. J. Mar. Sci.* **37** (1) 89–98. https://doi.org/10.2989/1814232X.2015.1020874

LAKANE CP, ADAMS JB and LEMLEY DA (2024) Drivers of seasonal water hyacinth dynamics in permanently eutrophic estuaries waters. *Biol. Invasions* **26** 2831–2849. https://doi.org/10.1007/s10530-024-03347-w

LEMLEY DA and ADAMS JB (2020) Physico-chemical and microalgal gradients change rapidly in response to mouth closure in a predominantly open estuary. *Afr. J. Aquat. Sci.* **45** 11–21. https://doi.org/10.2989/16085914.2019.1661826

LEMLEY DA, ADAMS JB and STRYDOM NA (2017) Testing the efficacy of an estuarine eutrophic condition index: Does it account for shifts in flow conditions? *Ecol. Indicators* **74** 357–370. https://doi.org/10.1016/j.ecolind.2016.11.034

LEMLEY DA, ADAMS JB, BORNMAN TG, CAMPBELL EE and DEYZEL SHP (2019) Land-derived inorganic nutrient loading to coastal waters and the potential implications for nearshore plankton dynamics. *Continental Shelf Res.* **174** 1–11. https://doi.org/10.1016/j.csr.2019.01.003

LEMLEY DA, HUMAN LRD, RISHWORTH GM, WHITFIELD E and ADAMS JB (2023) Managing the seemingly unmanageable: Water quality and phytoplankton dynamics in a heavily urbanised low-inflow estuary. *Estuar. Coasts* **46** 2007–2022. https://doi.org/10.1007/s12237-022-01128-z

LEMLEY DA, LAKANE CP, TALJAARD S and ADAMS JB (2022) Inorganic nutrient removal efficiency of a constructed wetland before discharging into an urban eutrophic estuary. *Mar. Pollut. Bull.* **179** 113727. https://doi.org/10.1016/j.marpolbul.2022.113727

LEMLEY DA, LAMBERTH SJ, MANUEL W, NUNES M, RISHWORTH GM, VAN NIEKERK L and ADAMS JB (2021) Effective management of closed hypereutrophic estuaries requires catchment-scale interventions. *Front. Mar. Sci.* **8** 688933. https://doi.org/10.3389/fmars.2021.688933

MACKAY HM (1994) Management of water quality in an urban estuary. PhD thesis, Department of Oceanography, University of Port Elizabeth.

MARAIS JFK and BAIRD D (1980a) Seasonal abundance, distribution and catch per unit effort of fishes in the Swartkops Estuary. *S. Afr. J. Zool.* **15** 66–71. https://doi.org/10.1080/02541858.1980.11447688

MARAIS JFK (1982) The effects of river flooding on the fish populations of two eastern Cape Estuaries. *S. Afr. J. Zool.* **17** 96–104. https://doi.org/10.1080/02541858.1982.11447788

MARAIS JFK and BAIRD D (1980) Analyses of anglers' catch data from the Swartkops Estuary. *S. Afr. J. Zool.* **15** 61–65. https://doi.org/10.1080/02541858.1980.11447687

MARTIN AP and BAIRD D (1987) Seasonal abundance and distribution of birds on the Swartkops Estuary, Port Elizabeth. *Ostrich* **58** 122–134. https://doi.org/10.1080/00306525.1987.9633685

MCLACHLAN A and GRINDLEY JR (1974) Distribution of macrobenthic fauna on soft substrata in the Swartkops Estuary, with observations on the effects of floods. *Afr. Zool.* **9** 211–233. https://doi.org/10.1080/00445096.1974.11448527

MAIER G, NIMMO-SMITH RJ, GLEGG GA, TAPPIN AD and WORSFOLD PJ (2009) Estuarine eutrophication in the UK: current incidence and future trends. *Aquat. Conserv. Mar. Freshwater Ecosyst.* **19** 43–56. https://doi.org/10.1002/aqc.982

MELVILLE-SMITH R and BAIRD D (1980) Abundance, distribution and species composition of fish larvae in the Swartkops Estuary. *S. Afr. J. Zool.* **15** (2) 72–78. https://doi.org/10.1080/02541858.1980.11447689

MKHIZE T, ADAMS JB, PARKER-NANCE S, JAMES N (2025) Habitat use by juvenile fish in macroalgae and seagrass beds in a temperate seascape. *Estuar. Coast. Shelf Sci.* **319** 109258. https://doi.org/10.1016/j.ecss.2025.109258

MMACHAKA T, NEL MA, SNOW B and ADAMS JB (2023) Reduction in pollution load to an urban estuary using a sustainable drainage system treatment train. *Mar. Pollut. Bull.* **194B** 115378. https://doi.org/10.1016/j.marpolbul.2023.115378

NDHLOVU A, ADAMS JB, NEL M, NEWMAN B, RISHWORTH GM and HUMAN RD (2024a) A review of metal pollution in a transformed, urban South African Estuary. *Reg. Stud. Mar. Sci.* **76** 2024. https://doi.org/10.1016/j.rsma.2024.103588

NDHLOVU A, ADAMS JB, LEMLEY DA, NHLEKO J and RISHWORTH GM (2024b) Benthic macrofauna communities reflect eutrophic condition in a low-inflow estuary. *Reg. Stud. Mar. Sci.* **70** 103351. https://doi.org/10.1016/j.rsma.2023.103351

NEL L, STRYDOM NA and BOUWMAN H (2015) Preliminary assessment of contaminants in the sediment and organisms of the Swartkops Estuary, South Africa. *Mar. Pollut. Bull.* **101** 878–885. https://doi.org/10.1016/j.marpolbul.2015.11.015

NEL L, STRYDOM NA and ADAMS JB (2018) Habitat partitioning in juvenile fishes associated with three vegetation types in selected warm temperate estuaries, South Africa. *Environ. Biol. Fishes* **101** 1137–1148. https://doi.org/10.1007/s10641-018-0762-y

NEL M, ADAMS JB, HUMAN LRD, NUNES M, VAN NIEKERK L and LEMLEY DA (2023) Ineffective artificial mouth-breaching practices and altered hydrology confound eutrophic symptoms in a temporarily closed estuary. *Mar. Freshwater Res.* **74** 1519–1535. https://doi.org/10.1071/MF23053

NEL MA, ADAMS JB, RUBIDGE G and HUMAN LRD (2020a) Heavy metal compartmentalization in salt marsh and seagrass of the urbanized Swartkops estuary, South Africa. *Mar. Pollut. Bull.* **192** 115007. https://doi.org/10.1016/j.marpolbul.2023.115007

NEL MA, RUBIDGE G, ADAMS JB and HUMAN LRD (2020b) Rhizosediments of *Salicornia tegetaria* indicate metal contamination in the intertidal estuary zone. *Front. Environ. Sci.* **8** e572730. https://doi.org/10.3389/fenvs.2020.572730

NMBM (Nelson Mandela Bay Municipality) (2023) Nelson Mandela Bay Municipality: About Nelson Mandela Bay. URL: www.nelsonmandelabay.gov.za (Accessed 14 February 2023).

NODO P, CHILDS A-R, PATTRICK P, LEMLEY DA and JAMES NC (2023) Response of demersal fishes to low oxygen events in two eutrophic estuaries. *Estuar. Coast. Shelf Sci.* **293** 108514. https://doi.org/10.1016/j.ecss.2023.108514

NODO P, CHILDS AR, PATTRICK P and JAMES NC (2024) Spatial patterns and environmental drivers of demersal fish assemblages in the Swartkops and Sundays estuarine to marine seascapes, South Africa. *Afr. J. Mar. Sci.* **46** 125–141. https://doi.org/10.2989/1814232X.2024.2368525

NUNES M, LEMLEY DA, MATCHER GF and ADAMS JB (2021) The influence of estuary eutrophication on the benthic diatom community: a molecular approach. *Afr. J. Mar. Sci.* **43** 171–186. https://doi.org/10.2989/1814232X.2021.1897039

NYAWO BL (2017) Groundwater and surface water interaction in the Uitenhage Artesian Basin, Eastern Cape, South Africa: Case study of the Swartkops and Coega aquifer. MSc Dissertation, University of the Witwatersrand. 127 pp.

ODUME ON, MULLER WJ, ARIMORO FO and PALMER CG (2012) The impact of water quality deterioration on macroinvertebrate communities in the Swartkops River, South Africa: a multimetric approach. *Afr. J. Aquat. Sci.* **37** 191–200. https://doi.org/10.2989/16085914.2012.670613

OLISAH C, ADENIJI AO, OKOH OO and OKOH AI (2019) Occurrence and risk evaluation of organochlorine contaminants in surface water along the course of Swartkops and Sundays River Estuaries, Eastern Cape Province, South Africa. *Environ. Geochem. Health* **41** 2777–2801. https://doi.org/10.1007/s10653-019-00336-0

OLISAH C, OKOH OO and OKOH AI (2020) Spatial, seasonal and ecological risk assessment of organohalogenated contaminants in sediments of Swartkops and Sundays estuaries, Eastern Cape Province, South Africa. *J. Soils Sediments* **20** 1046–1059. https://doi.org/10.1007/s11368-019-02487-0

OLISAH C and ADAMS JB (2021) Analysing 70 years of research output on South African estuaries using bibliometric indicators. *Estuar. Coast. Shelf Sci.* **252** 107285. https://doi.org/10.1016/j.ecss.2021.107285

OLISAH C, RUBIDGE G, HUMAN LRD and ADAMS JB (2021) Organophosphate pesticides sequestered in tissues of a seagrass species – *Zostera capensis* from a polluted watershed. *J. Environ. Manage.* **300** 113657. https://doi.org/10.1016/j.jenvman.2021.113657

OLISAH C, RUBIDGE G, HUMAN LRD and ADAMS JB (2022) Organophosphate pesticides in South African eutrophic estuaries: Spatial distribution, seasonal variation, and ecological risk assessment. *Environ. Pollut.* **306** 119446. https://doi.org/10.1016/j.envpol.2022.119446

OLISAH C, RUBIDGE G, HUMAN LRD and ADAMS JB (2023) Tissue distribution, dietary intake and human health risk assessment of organophosphate pesticides in common fish species from South African estuaries. *Mar. Pollut. Bull.* **186** 114466. https://doi.org/10.1016/j.marpolbul.2022.114466

OLISAH C, RUBIDGE G, HUMAN LRD and ADAMS JB (2024) Investigation of alkyl, aryl, and chlorinated OPFRs in sediments from estuarine systems: Seasonal variation, spatial distribution and ecological risks assessment. *Environ. Res.* **250** 118465. https://doi.org/10.1016/j.envres.2024.118465

PERISSINOTTO R and WOOLDRIDGE T (1989) Short-term thermal effects of a power-generating plant on zooplankton in the Swartkops Estuary, South Africa. *Mar. Ecol.* **10** 205–219. https://doi.org/10.1111/j.1439-0485.1989.tb00473.x

PRADERVAND P and BAIRD D (2002) Assessment of the recreational line fishery in selected Eastern Cape estuaries: trends in catches and effort. *S. Afr. J. Mar. Sci.* **24** 87–101. https://doi.org/10.2989/025776102784528592

PRETORIUS L (2015) Spatial and temporal variability in water quality characteristics of the Swartkops Estuary. MSc Dissertation, Department of Botany, Nelson Mandela Metropolitan University. 217 pp.

RAW JL, ADAMS JB, BORNMAN TG, RIDDIN T and VANDERKLIFT MA (2021) Vulnerability to sea-level rise and the potential for restoration to enhance blue carbon sequestration in salt marshes of an urban estuary. *Estuar. Coast. Shelf Sci.* **260** 107495. https://doi.org/10.1016/j.ecss.2021.107495

RAW JL, VAN NIEKERK L, CHAUKE O, MBATHA H, RIDDIN T and ADAMS JB (2023) Blue carbon sinks in South Africa and the need for restoration to enhance carbon sequestration. *Sci. Total Environ.* **859** 160142. https://doi.org/10.1016/j.scitotenv.2022.160142

REDDERING JSV and ESTERHUYSEN K (1981) The sedimentary ecology of the Swartkops Estuary. Rosie Report 1. Geology Department, University of Port Elizabeth. 89 pp.

MARTIN P (2021) Personal communication, 20 January 2021. P Martin, private consultant, Bluewater Bay, Gqeberha 6001, South Africa.

RSA (Republic of South Africa) (1998a) Marine Living Resources Water Act (Act No. 18 of 1998). *Government Gazette, South Africa* 395 (18930). Government Printer, Cape Town.

RSA (Republic of South Africa) (1998b) National Water Act (Act No. 36 of 1998). *Government Gazette* 398 (19182). Government Printer, Cape Town.

RSA (Republic of South Africa) (2008) National Environmental Management: Integrated Coastal Management Act (Act No. 24 of 2008). *Government Gazette* 524 (31884). Government Printer, Cape Town.

SCHARLER UM and BAIRD D (2003) The influence of catchment management on salinity, nutrient stoichiometry and phytoplankton biomass of Eastern Cape estuaries, South Africa. *Estuar. Coast. Shelf Sci.* **56** 735–748. https://doi.org/10.1016/S0272-7714(02)00293-7

SCHARLER UM, BAIRD D and WINTER PED (1997) Diversity and productivity of biotic communities in relation to freshwater inputs in three Eastern Cape estuaries. WRC Report No 463/1/98. Water Research Commission, Pretoria.

SIMENSTAD CH, REED D and FORD M (2006) When is restoration not? Incorporating landscape-scale processes to restore self-sustaining ecosystems in coastal wetland restoration. *Ecol. Eng.* **26** 27–39. https://doi.org/10.1016/j.ecoleng.2005.09.007

SIMON CA, MUTHUMBI AWN, KIHIA CM, SMITH KMS, CEDRAS RB, MAHATANTE PT, WANGONDU VW and KATIKIRO R (2021) A review of marine invertebrates used as fishing baits and the implications for national and regional management in the Western Indian Ocean. *Afr. Zool.* **56** 237–263. https://doi.org/10.1080/15627020.2021.2001370

SMIT T, CLEMMESEN C, LEMLEY DA, ADAMS JB, BORNMAN E and STRYDOM NA (2023) Body condition of larval roundherring, *Gilchristella aestuaria* (Family Clupeidae), in relation to harmful algal blooms in a warm-temperate estuary. *J. Plankton Res.* **45** 523–539. https://doi.org/10.1093/plankt/fbad013

SMIT T, LEMLEY DA, ADAMS JB and STRYDOM NA (2021) Preliminary insights on the fine-scale responses in larval *Gilchristella aestuaria* (Family Clupeidae) and dominant zooplankton to estuarine harmful algal blooms. *Estuar. Coast. Shelf Sci.* **249** 107072. https://doi.org/10.1016/j.ecss.2020.107072

SNOW GC (2008) Contributions to the use of microalgae in estuarine freshwater reserve determinations. PhD thesis, Department of Botany, Nelson Mandela Metropolitan University.

STEIN ED, GEE EM, ADAMS JB, IRVING K and VAN NIEKERK L (2021) Advancing the science of environmental flow management for protection of temporarily closed estuaries and coastal lagoons. *Water* **13** (5) 595. https://doi.org/10.3390/w13050595

STRYDOM NA (2003) An assessment of habitat use by larval fishes in a warm temperate estuarine creek using light traps. *Estuaries* **26** (5) 1310–1318. https://doi.org/10.1007/BF02803633

STRYDOM NA, WHITFIELD AK and WOOLDRIDGE TH (2003) The role of estuarine type in characterizing early stage fish assemblages in warm temperate estuaries, South Africa. *Afr. Zool.* **38** 29–43. https://doi.org/10.1080/15627020.2003.11657192

SWARTKOPS EWR REPORT (2021) Swartkops Environmental Water Requirement Master Report 2 July 2021. URL: https://livenmmuac-my.sharepoint.com/personal/algoabayproject_mandela_ac_za/_layouts/15/onedrive.aspx?id=%2Fpersonal%2Falgoabayproject%5Fmandela%5Fac%5Fza%2FDocuments%2FCMR%2FCMR%20documents%20%28for%20sharing%20link%20%2D%20DO%20NOT%20DELETE%20OR%20MOVE%29%2FProf%20Janine%20Adam%27s%2FSwartkops%20EWR%20report%5FMaster%5F2%20July2021%2Epdf&parent=%2Fpersonal%2Falgoabayproject%5Fmandela%5Fac%5Fza%2FDocuments%2FCMR%2FCMR%20documents%20%28for%20sharing%20link%20%2D%20DO%20NOT%20DELETE%20OR%20MOVE%29%2FProf%20Janine%20Adam%27s&ga=1&LOF=1 (Accessed 17 April 2025).

TALJAARD S, VAN NIEKERK L and ADAMS JB (2023) Advancing ecosystem accounting in estuaries: Swartkops Estuary case study. *S. Afr. J. Sci.* **119** 14303. https://doi.org/10.17159/sajs.2023/14303

TESKE PR and WOOLDRIDGE TH (2003) What limits the distribution of subtidal macrobenthos in permanently open and temporarily open/closed South African estuaries? Salinity vs. sediment particle size. *Estuar. Coast. Shelf Sci.* **57** 225–238. https://doi.org/10.1016/S0272-7714(02)00347-5

TURPIE JK, TALJAARD S, VAN NIEKERK L, ADAMS J, WOOLDRIDGE T, CYRUS D, CLARK B and FORBES N (2012) The Estuary Health Index: A standardised metric for use in estuary management and the determination of ecological water requirements. WRC Report No. 1930/1/12. 84 pp. Water Research Commission, Pretoria.

UNITED NATIONS GENERAL ASSEMBLY (2019) Resolution 73/284: United Nations Decade on Ecosystem Restoration (2021–2030). United Nations General Assembly, New York. URL: https://undocs.org/A/RES/73/284

VAN ASWEGEN JD, NEL L, STRYDOM NA, MINNAAR K, KYLINA H and BOUWMAN H (2019) Comparing the metallic elemental compositions of Kelp Gull *Larus dominicanus* eggs and eggshells from the Swartkops River Estuary, Port Elizabeth, South Africa. *Chemosphere* **221** 533–542. https://doi.org/10.1016/j.chemosphere.2019.01.013

VAN NIEKERK L and TURPIE JK (eds.) (2012) *National Biodiversity Assessment 2011: Technical Report. Volume 3: Estuary Component.* CSIR Report Number CSIR/NRE/ECOS/ER/2011/0045/B. Council for Scientific and Industrial Research, Stellenbosch. URL: http://bgis.sanbi.org/nba/project.asp

VAN NIEKERK L, ADAMS JB, BATE GC, FORBES AT, FORBES NT, HUIZINGA P, LAMBERTH SJ, MACKAY CF, PETERSEN C, TALJAARD S and co-authors (2013) Country-wide assessment of estuary health: An approach for integrating pressures and ecosystem response in a data limited environment, *Estuar. Coast. Shelf Sci.* **130** 239–251. https://doi.org/10.1016/j.ecss.2013.05.006

VAN NIEKERK L, TALJAARD S, ADAMS JB, FUNDISI D, HUIZINGA P, LAMBERTH SJ, MALLORY S, SNOW GC, TURPIE JK, WHITFIELD AK and WOOLDRIDGE TH (2015) Desktop provisional EcoClassification of the temperate estuaries of South Africa. WRC Report No. 2187/1/15. Water Research Commission, Pretoria.

VAN NIEKERK L, TALJAARD S and HUIZINGA P (2012) An evaluation of the ecological flow requirements of South Africa's estuaries from a hydrodynamics perspective. WRC Report No. KV 302/12. Water Research Commission, Pretoria. 76 pp.

VAN NIEKERK L, TALJAARD S, ADAMS JB, LAMBERTH SJ, HUIZINGA P, JANE JK and WOOLDRIDGE TH (2019a) An environmental flow determination method for integrating multiple scale ecohydrological and complex ecosystem processes in estuaries. *Sci. Total Environ.* **656** 482–494. https://doi.org/10.1016/j.scitotenv.2018.11.276

VAN NIEKERK L, ADAMS JB, DAVID AG, TALJAARD S, WEERTS SP, LOUW D, COLIN T and ROOYEN P (2019b) Assessing and planning future estuarine resource use: A scenario-based regional-scale freshwater allocation approach. *Sci. Total Environ.* **657** 1000–1013. https://doi.org/10.1016/j.scitotenv.2018.12.033

VAN NIEKERK L, TALJAARD S, LAMBERTH SJ, ADAMS JB, WEERTS SP and MACKAY CF (2022) Disaggregation and assessment of estuarine pressures at the country-level to better inform management and resource protection – the South African experience. *Afr. J. Aquat. Sci.* **47** 1–22. https://doi.org/10.2989/16085914.2022.2041388

WASSERMAN J, ADAMS JB and LEMLEY DA (2022a) Investigating the potential for saltpan restoration for the provision of multiple ecosystem services. *Afr. J. Aquat. Sci.* **47** 436–446. https://doi.org/10.2989/16085914.2022.2067823

WASSERMAN J, LEMLEY DA and ADAMS JB (2022b) Saltpan primary producer and inorganic nutrient dynamics in response to inundation with nutrient-rich source waters. *J. Exp. Mar. Biol. Ecol.* **551** e51723. https://doi.org/10.1016/j.jembe.2022.151723

WASSERMAN J, HUMAN LRD and ADAMS JB (2023) Blue carbon stocks in southern Africa's endangered seagrass *Zostera capensis*. *Estuar. Coast. Shelf Sci.* **284** 108296. https://doi.org/10.1016/j.ecss.2023.108296

WR2012 (2021) URL: https://waterresourceswr2012.co.za (Accessed 20 March 2021).

WEERTS SP, MACKAY CF, and CYRUS DP (2014) The potential for a fish ladder to mitigate against the loss of marine-estuarine-freshwater connectivity in a subtropical coastal lake. *Water SA* **40** 27–30. https://doi.org/10.4314/wsa.v40i1.4

WHITFIELD AK and MANN BQ (2023) The changing status of important marine fishery species in selected South African estuaries. *Afr. J. Mar. Sci.* **45** 235–248. https://doi.org/10.2989/1814232X.2023.2274899

WHITFIELD AK and SMITH MKS (2024) Future of the IUCN Endangered white steenbras *Lithognathus lithognathus* (Sparidae) – a tale of two estuaries. *Afr. J. Mar. Sci.* **46** 155–167. https://doi.org/10.2989/1814232X.2024.2378714

WOOLDRIDGE T and MELVILLE-SMITH R (1979) Copepod succession in two South African estuaries. *J. Plankton Res.* **1** (4) 329–341. https://doi.org/10.1093/plankt/1.4.329

ZENGEYA TA, KUMSCHICK S, WEYL OL and VAN WILGEN BW (2020) An evaluation of the impacts of alien species on biodiversity in South Africa using different assessment methods. In: Van Wilgen BW, Measey J, Richardson DM, Wilson JR and Zengeya TA (eds) *Biological Invasions in South Africa*. Invading Nature: Springer Series in Invasion Ecology 14. Springer Open. 487–512. https://doi.org/10.1007/978-3-030-32394-3_17

APPENDIX

Figure A1. Top left: pipe from Motherwell artificial wetland entering the Swartkops Estuary. Top right: intertidal salt marsh. Bottom left: The seagrass *Zostera capensis* and lower intertidal salt marsh. Bottom right: mosaic of salt marsh species in a disturbed area.

Figure A2. Polluted Motherwell canal and artificial wetland, taken at Swartkops Estuary in 2019

Table A1. Data used for the abiotic and biotic components in the assessment of the Present Ecological State of the Swartkops Estuary. Confidence is shown as low (L), medium (M) or high (H). Table A2 highlights the data needed for a high confidence assessment.

	Confidence (H, M, L)	Measured data	Spatial data	Published literature	Modelled data	Extrapolated data
Hydrology	M–L	✓			✓	
Hydrodynamics	M	✓		✓	✓	
Water quality	H	✓	✓	✓	✓	
Physical habitat	M–L		✓	✓		✓
Microalgae	M	✓	✓	✓		
Macrophytes	H	✓	✓	✓		
Invertebrates	M	✓		✓		
Fish	M	✓	✓	✓		
Birds	M–H	✓		✓		

Table A2. Monitoring actions and data requirements for a high confidence assessment of Swartkops Estuary Present Ecological State

Component	Monitoring action and data requirements	Temporal scale (frequency and timing)	Spatial scale (No. of stations)
Hydrodynamics	Record water levels at the mouth (Settlers Bridge).	Continuous	Near the mouth of the estuary
	Measure freshwater inflow into the estuary at Perseverance to capture baseflow and floods.	Continuous	Head of estuary (Perseverance)
Sediment dynamics	Lidar survey, bathymetric surveys, sediment grab samples at invertebrate and heavy metal sites.	3–5 years	Entire estuary
Water quality	Conductivity, temperature, suspended solids, pH, inorganic nutrients (N, P and Si) and organic content (TP and Kjeldahl N) measurements in river inflow.	Monthly, continuous	Near head of estuary (Perseverance)
	Longitudinal in-situ salinity and temperature pH, DO, turbidity profiles (SAEON ongoing long-term monitoring – seasonal) together with inorganic nutrients (and organic nutrients) and suspended solid analysis for minimum surface and bottom sites.	Seasonally	Entire estuary (10 stations)
	Measure pesticides/herbicides and metal accumulation in sediments and fish (particularly edible species) at depositional sites (muddy areas).	Every 3–6 years, if results show contamination	Entire estuary
Microalgae	Relative abundance (i.e., cells·mL^{-1}) of phytoplankton groups and presence of HAB-forming taxa (e.g., *Heterosigma akashiwo* and dinoflagellates). Chlorophyll-a measurements taken with depth.	Seasonally	Along length of estuary; minimum 6 stations
Macrophytes	Groundtruthed maps to update the vegetation map and check area covered, particularly the seagrass (*Zostera capensis*) beds. Assess extent of invasive species within the 5 m contour line and extent of IAAPs in the upper reaches. Measure macrophyte and sediment characteristics along transects in the main salt marsh areas for changes in response to sea level rise.	Summer survey every 3 years	Entire estuary for mapping
Invertebrates	Consider zooplankton and hyperbenthos measurements. Assess key bait species (e.g. prawns) and intertidal invertebrate (e.g. crab) abundance.	Every 2 years, mid-summer	Three sites
Fish	Record species and abundance of fish based on seine net sampling. Sampling with a small beam trawl for channel fish should also be considered. Sample REI zone to understand effect of HABs. Contemporary study on angler fish catches needed for comparison with historical studies.	Twice annually	Entire estuary (10 stations)
Birds	Undertake counts of all non-passerine water birds, identified to species level. Continue these CWAC counts in zones as done by Dr Paul Martin for the past 40 years. Include upstream sites to document changes in response to restoration activities.	Annual winter and summer surveys	Entire estuary