

# Deterioration in the water quality of an urbanised estuary with recommendations for improvement

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## ABSTRACT

Water quality characteristics of the heavily urbanised and industrialised Swartkops River and Estuary in the Eastern Cape have been the focus of several studies since the 1970s. Overloaded and poorly maintained wastewater treatment works (WWTWs), polluted stormwater runoff and solid waste have all contributed to the deterioration in the water quality of the river and estuary. The objective of this study was to determine the current water quality status of the Swartkops Estuary, by investigating spatial and temporal variability in physico-chemical parameters and phytoplankton biomass and where possible relate this to historical water quality data. The present study found evidence suggesting that water is not flushed as efficiently from the upper reaches of the estuary as was previously recorded. Reduced vertical mixing results in strong stratification and persistent eutrophic conditions with phytoplankton blooms ( $> 20 \mu\text{g chl } a\text{-L}^{-1}$ ), extending from the middle reaches to the tidal head of the estuary. The Motherwell Canal was and still is a major source of nitrogen (particularly ammonium) to the estuary, but the Swartkops River is the primary source of phosphorus with excessive inputs from the cumulative effect of three WWTWs upstream. An analysis of historical water quality data in the Swartkops Estuary (1995 to 2013) shows that all recorded dissolved inorganic phosphorus measurements were classified as hypertrophic ( $> 0.1 \text{ mg P}\cdot\text{L}^{-1}$ ), whereas 41% of dissolved inorganic nitrogen measurements were either mesotrophic or eutrophic. If nutrient removal methods at the three WWTWs were improved and urban runoff into the Motherwell Canal better managed, it is likely that persistent phytoplankton blooms and health risks associated with eutrophication could be reduced.

**Keywords:** Swartkops Estuary, nutrients, salinity, eutrophication, microalgae

## INTRODUCTION

A threat facing many developing countries is the improper management of waste generated through various anthropogenic activities, combined with old and inadequate infrastructure, unskilled wastewater plant operators and financial constraints (WRC, 2013). Furthermore, urbanisation leads to increased stormwater volumes running off paved areas. Consequently, runoff that would previously have infiltrated the soil discharges directly into aquatic ecosystems, potentially harming the water quality and ecosystem health status more rapidly than diffuse sources (US EPA, 2003). Poor or inadequate stormwater management systems have also led to stormwater infiltrating the sewer system resulting in pump station overflows and overloading of sewage treatment plants not designed to cope with these loads.

All these issues are relevant to the urbanised Swartkops Estuary (33.8604° S, 25.6221° E) in the Eastern Cape, where land use activities have measurably changed the water quality and health of the system (Enviro-Fish Africa, 2011; Lemley et al., 2017). The estuary, located 15 km north of the Port Elizabeth Central Business District, opens into Algoa Bay in the Indian Ocean. The estuary is 16.4 km long and the total length of the river is 155 km from the mouth to its origin (Baird et al., 1986). Swartkops is a nationally important estuary as it is one of the few systems that remain permanently open to the sea. The river and estuary meander through a highly urbanised and industrialised region of the Nelson Mandela Bay Municipality (NMBM). Anthropogenic activities affecting

the estuary include wastewater treatment works (WWTW), salt pans, sand/clay mining, brickworks, tanneries, the motor industry, wool industry, extractive/beneficiation processes as well as marshalling railway yards and depots (Baird et al., 1986). In the 60 years from 1939 to 1998, industrial and residential developments removed 35 ha of supratidal salt marsh, leaving only 5 ha (Colloty et al., 2000). The deterioration in water quality has affected recreation, for example the relocation of the Redhouse River Mile swimming event elsewhere, because of high faecal coliform bacteria counts in the water. Furthermore, a number of sites above the tidal limit are used for cultural ceremonies by traditional healers, but the water quality is now so poor that participants mentioned during an informal interview that they cannot drink from the river during their cleansing ceremonies and depend on tap water carried to the sites.

Thus, the Swartkops Estuary is largely modified, with a Present Ecological State (PES) of Category D. A Recommended Ecological Category (REC) of a C is expected of this estuary (Van Niekerk et al., 2014) because of its national conservation importance. The estuary is ranked 11<sup>th</sup> out of over 280 estuaries nationwide, mainly as a result of its size, habitats and biodiversity (Turpie et al., 2002). Improvement to a C category can only be achieved through appropriate management interventions which require an understanding of the key drivers. Past studies have been of too short a duration to gather the long-term datasets needed for assessing historical patterns of change within the estuary. Our study in 2012–2013 measured water quality parameters to provide an assessment of the status of the estuary and to identify management actions and recommend monitoring requirements. River, sea and estuary sites were sampled as well as points of entry into the estuary (Chatty River, Markman Canal and Motherwell

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Canal) to identify pollutant inputs. New data were important because outdated water quality information had been used in the Swartkops Integrated Environmental Management Plan (Enviro-Fish Africa, 2011).

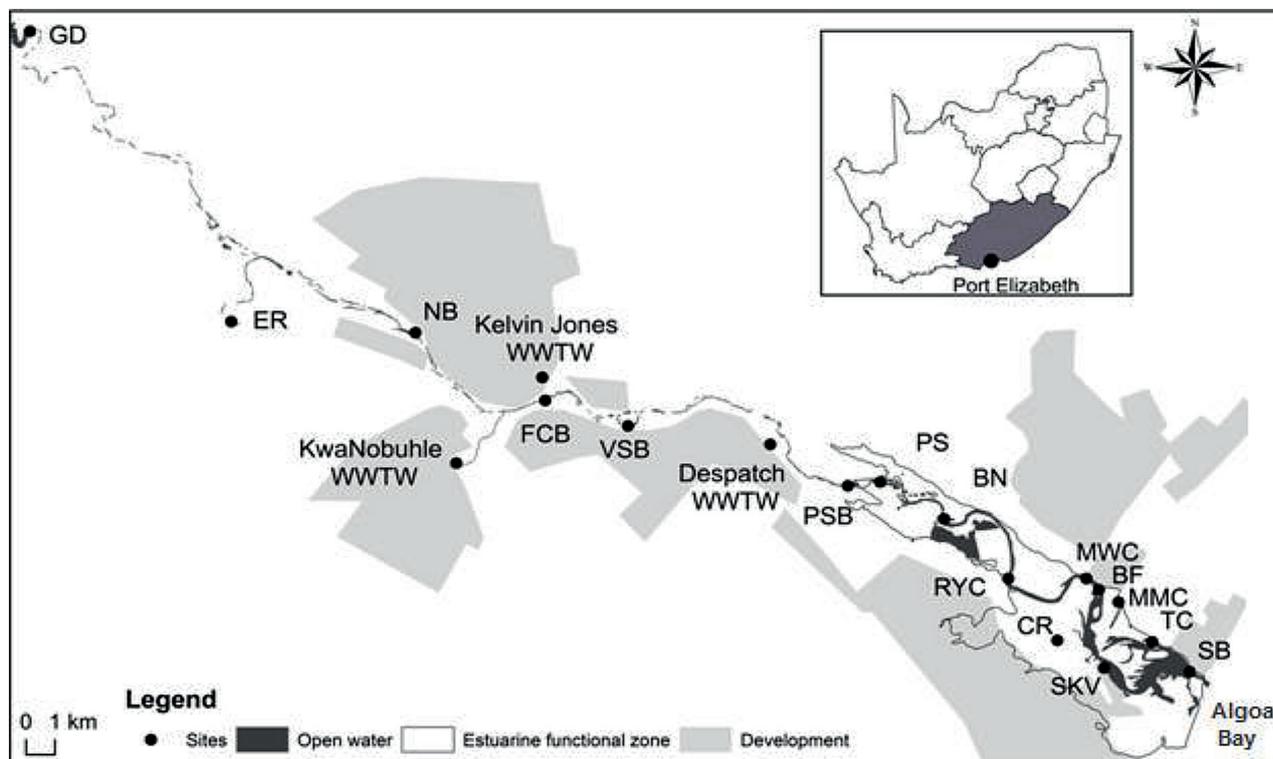
Bacterial measurements showed high *Escherichia coli* and enterococci levels, especially in the summer months, rendering the estuary unsafe for recreation. Faecal bacteria, originating from the Motherwell Canal, contaminated the middle reaches of the estuary, whereas the Swartkops River has intermediate effects because bacteria die off between the point of release from the WWTWs and the riverine reaches and the tidal limit of the estuary. Trace metal data for the water column suggested that copper, zinc, iron and cadmium concentrations have increased by at least 90% in the estuary, at the tidal limit of the estuary and in the Markman and Motherwell canals (Pretorius, 2015). Other recent studies have shown that macrophytes (*Phragmites australis*, *Typha capensis* and *Spartina maritima*) and sediments from the Markman and Motherwell canals had significantly higher concentrations of lead and zinc than those measured in the main channel of the estuary (Phillips et al., 2015). Biomagnification has resulted in high concentrations of arsenic, lead, mercury and cadmium in the juvenile stages of popular angling fishes, exceeding international food quality guidelines (Nel et al., 2015). These results show the necessity for management interventions with the main objective being to protect the estuary's ecological, recreational and economic functions.

## MATERIALS AND METHODS

### Sampling sites

River, estuary and point source sites were measured, as well as the sea. Nineteen sites, which form part of the long-term monitoring stations of the South African Department of Water and Sanitation (DWS), were selected for spatial and temporal analyses of water quality data (Fig. 1 and Table A1). Water samples were collected at 3 point-sources into the estuary, namely Chatty River, Markman Canal and Motherwell Canal, and then assessed for their impact on 7 sites within the estuary, namely Settlers Bridge, Tippers Creek, Swartkops Village, Brickfields, Redhouse Yacht Club, Bar None and Perseverance.

The Chatty River (CR) flows through the highly populated townships of Zwide, Veeplaas, New Brighton, Bethelsdorp and Missionvale, from where the river receives polluted stormwater runoff and the discharge of raw sewage and litter. The Markman Canal (MMC) enters the Swartkops Estuary approximately 6.1 km from the estuary mouth. An industrial area is located on its northern bank from where numerous stormwater drains discharge effluent into the canal. The canal passes through a small peri-urban village before entering the Swartkops Estuary near a road bridge. The quality of the water in the canal is also affected by two sewage pump stations that regularly malfunction and divert untreated domestic sewage and industrial wastewater into the canal (Rump, 2012). The Motherwell Township is located along the length of the 4.2 km long Motherwell Canal (MWC) that is serviced by a network of 14 stormwater drains that transport litter, debris and raw



**Figure 1**

Sampling sites within the Swartkops River catchment showing the river, estuary and point source sites as well as the location of the WWTWs. Flow direction: Groendal (GD) to estuary mouth at Settlers Bridge (SB). Remaining site names: Settlers Bridge (SB), Swartkops Village (SKV), Tippers Creek (TC), Markman Canal (MMC), Brickfields (BF), Motherwell Canal (MWC), Chatty River (CR), Redhouse Yacht Club (RYC), Bar None (BN), Perseverance (PS), Perseverance Bridge (PSB), Van Schalkwyk Bridge (VSB), Frans Claassen Bridge (FCB), Nivens Bridge (NB), and Elands River (ER)

sewage into the canal. During moderate and high flows, litter and human waste are carried to the estuary via the canal. Even during dry weather, a steady flow of polluted water is observed in the canal. Although litter traps are located at regular intervals in the canal they are frequently full or subject to vandalism. Illegal dumping takes place in this canal as well as in the canals of the Uitenhage area upstream. February 2010 marked the opening of the innovative Motherwell Canal Artificial Wetland System (SRK Consulting (Pty) Ltd, 2011). The wetland was designed to divert and filter 20% of polluted urban runoff from the stormwater canal through a series of ponds prior to release into the estuary.

Perseverance (PS), at the tidal head of the estuary, is characterised by shallow waters. It is downstream of Deranco Blocks, manufacturers of pre-cast concrete products, and the Perseverance and Karoo Ochse abattoirs. An abandoned gravel quarry is located close to the site. Free-floating invasive aquatic plants occur from the tidal limit to the lower reaches of the Bar None area of the estuary. Dominant species were *Eichhornia crassipes* (water hyacinth), *Azolla filiculoides* (water fern) and *Salvinia molesta* (Kariba weed). Pulses in river flow transport these floating macrophytes into the estuary. However, they cannot survive the saline estuary conditions.

The Perseverance Bridge (PSB) is situated approximately 2.6 km downstream of the Despatch WWTW and is positioned alongside a gravel quarry. The Van Schalkwyk Bridge (VSB) is located within the residential area of Despatch and downstream of the Kelvin Jones WWTW. The Frans Claasen Bridge (FCB) is located downstream of the Brak River confluence, near the Volkswagen manufacturing plant. The KwaNobuhle WWTW discharges via maturation ponds into the Brak River, which also collects stormwater runoff from surrounding townships (MacKay, 1994). The Nivens Bridge (NB) is situated approximately 300 m downstream from where the Kat Canal joins the river, carrying stormwater from Rosedale and McNaughton Townships. The Swartkops River flow is gauged by DWS Weir M1H012 at this site, and historical data from this site were used in this study. Approximately 56% of the treated sewage from the three WWTWs enters the river, contributing about 50% of the flow in the Swartkops Estuary (DWA, 1999).

### Flow, rainfall, tides

Sampling dates, river inflow, rainfall and tidal conditions are shown in Table A2. Swartkops River flow data were obtained from DWS and mean rainfall for the area was collated from the South African Weather Service daily data recorded at a rain gauge in Uitenhage (33.7140°S, 25.4350°E). The ecological health of estuaries is strongly influenced by the quality and quantity of freshwater inflow, so flow gauging closer to the head of an estuary would better quantify inflow. The nearest flow gauge is the abovementioned weir at Nivens Bridge, nearly 10 km from the head of the estuary. There is little correlation between measured flow and variables in the Swartkops Estuary, as a result of urban wastewater and runoff entering the river downstream of Nivens Bridge via tributaries, stormwater canals and the three WWTWs.

This study used river flow data to investigate the relationship between flow and inorganic nutrient levels of the river. Historical nutrient data recorded at Nivens Bridge by the DWS during the period 1995 to 2013 were related to river inflow data, also recorded at Nivens Bridge. Data were obtained from DWS (DWA, 2012). In addition to this, nutrient

loads from WWTWs were assessed in terms of daily nutrient loads ( $\text{kgd}^{-1}$ ) discharged from each sewage plant, including the minimum and maximum ranges recorded from 2009 to 2013, and thereafter related to nutrient concentrations recorded in the river and estuary. Historical water quality data for the WWTWs were obtained from the DWS.

### Sampling and analyses

Historical data on physico-chemical parameters were collated from Emmerson (1985), Scharler et al. (1997), DWA (1999) and SRK Consulting (Pty) Ltd (2011). Subsequently, the river and estuary were sampled in September and November 2012, February, May and August 2013, to understand the spatial and temporal characteristics of the system and to identify sources of nutrients and other inputs to the estuary. Temperature ( $^{\circ}\text{C}$ ), salinity and dissolved oxygen ( $\text{DO}$ ,  $\text{mg}\cdot\text{L}^{-1}$ ) were measured in situ at each estuarine and point-source site at 0.5 m depth intervals until the bottom was reached, using a 650 MDS YSI Multiprobe. Water samples for nutrient and phytoplankton analyses were collected from the surface and bottom at sites using a weighted pop-bottle where depth exceeded 0.5 m. Samples were kept frozen until analyses commenced at the Nelson Mandela University. Water column chlorophyll *a* was determined as an indicator of phytoplankton biomass using the spectrophotometric methods of Nusch (1980) and Hilmer (1990). Phytoplankton chlorophyll *a* concentration that exceeds  $20 \mu\text{g chl } a\cdot\text{L}^{-1}$  is used as a threshold of potential concern in this study, indicating the presence of a phytoplankton bloom (Snow, 2016). Ammonium ( $\text{NH}_4^+\text{-N}$ ) and soluble reactive phosphorus (SRP-P) were measured using standard spectrophotometric methods (Parsons et al., 1984). Oxidised nitrogen ( $\text{NOx-N}$ ;  $\text{NO}_2^- + \text{NO}_3^-$ ) was determined using the reduced copper-cadmium method (Bate and Heelas, 1975). Dissolved inorganic nitrogen (DIN; oxidised nitrogen and ammonium) and dissolved inorganic phosphorus (DIP; soluble reactive phosphorus) were expressed as  $\text{mg N}\cdot\text{L}^{-1}$  and  $\text{mg P}\cdot\text{L}^{-1}$ , respectively, for comparison with river and historical data.

To determine the suitability of the water for a particular use, the water quality parameters were compared against the target water quality ranges (TWQR) in the South African Water Quality Guidelines (DWA, 1996). These TWQRs provide thresholds of potential concern that are suitable for the management of the Swartkops River and Estuary. Additionally, the pelagic component (i.e.  $\text{DO}$ , DIN, DIP and phytoplankton biomass) of a recently proposed estuarine eutrophic condition index (Lemley et al., 2015) was applied to assess the state of the Swartkops Estuary on each sampling occasion. Finally, historical nutrient data for the freshwater site located in the Swartkops River (i.e. Nivens Bridge) were used to determine the frequency distributions of DIN and DIP concentrations, and presented as the percentage of values representing the various trophic levels, as described by DWA (1996), throughout the monitoring period.

### Statistical analysis

Water quality data from the different sites were collated and analysed for spatial and temporal trends. Data were tested for normality using the Kolmogorov-Smirnov test for normality. If the test result was negative, then a Johnson Transformation was performed to normalise the data. Levene's test for homogeneity of variance, with a confidence interval of 95%, was used to test the equality of variance across variables. Analysis of variance

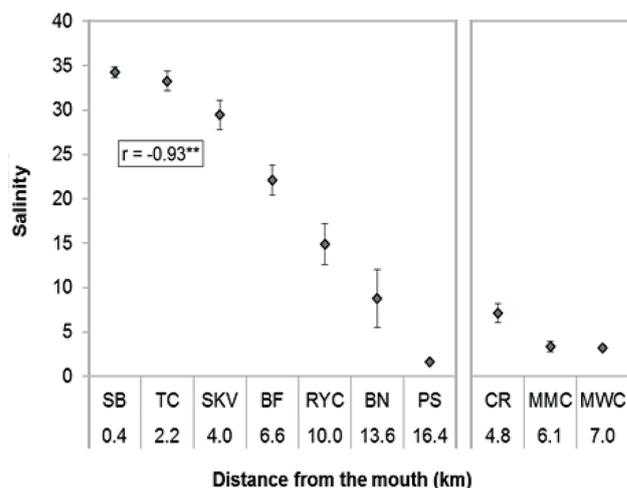
(ANOVA) was used to test the null hypothesis ( $H_0$ ) that there were no significant differences between estuary sampling sessions, sites and depths. Spearman rank correlation was used to determine relationships between all physico-chemical parameters. To assess the association of the different variables with the sampled sites, Simple Correspondence Analysis was conducted. These analyses were conducted using the Minitab Version 16 statistical package (Minitab Inc., PA).

## RESULTS

In 2012/2013 the salinity distribution in the estuary was typical of a permanently open estuary that receives a consistent base flow of river water; strong longitudinal salinity gradient from near-marine salinity at the mouth of the estuary (Settlers Bridge) to fresh at the head of the estuary (Perseverance). The salinity ranged from 35.5 at the mouth to 1.2 at the tidal limit, with marine intrusion occurring 13.6 km upstream (Fig. 2). The highest average salinities in the estuary were measured in August and May 2013 and the lowest in November 2012. The vertical salinity gradient, the difference in salinity between surface and bottom water, never exceeded 10 at any site. There were significant differences between estuary main channel sites and point sources which were fresher ( $F = 38.31$ ;  $p < 0.05$ ;  $n = 50$ ). However, these inputs from the Motherwell and Markman canals and the Chatty River to the middle reaches of the estuary were not large enough to cause localised decreases in water column salinity. Surface and bottom differences in salinity were greater (0–7.9) than previously reported (1–2) (Emmerson, 1985; Scharler et al., 1997).

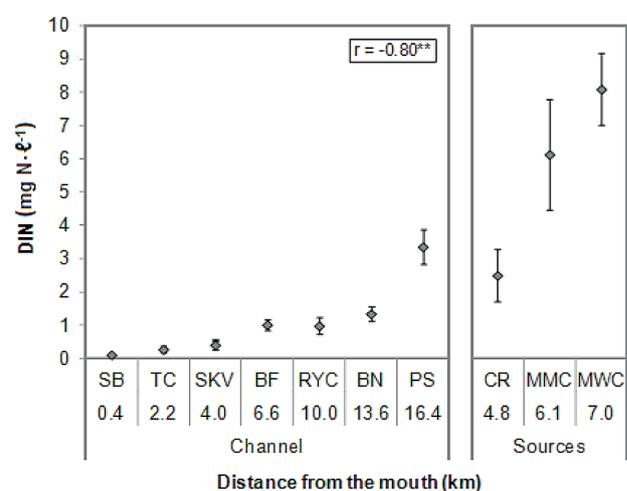
The lowest mean monthly temperature for the estuary water was recorded in August ( $14.4 \pm 0.20^\circ\text{C}$ ) and the highest in February 2013 ( $25.2 \pm 0.54^\circ\text{C}$ ). There was significant spatial ( $F = 3.17$ ;  $p < 0.05$ ;  $n = 35$ ) and temporal ( $F = 115.03$ ;  $p < 0.05$ ;  $n = 35$ ) variability, with an inverse relationship with salinity ( $r = -0.39$ ;  $n = 60$ ;  $p < 0.05$ ). Dissolved oxygen (DO) concentrations ranged from  $1.3$  to  $18.2 \text{ mg}\cdot\text{L}^{-1}$  ( $7.2 \pm 0.43 \text{ mg}\cdot\text{L}^{-1}$ ;  $n = 60$ ), with notable vertical patterns. The supersaturated DO conditions ( $18.2 \text{ mg}\cdot\text{L}^{-1}$ ) were recorded in the middle of a dense phytoplankton bloom. Mean DO levels were highest in November 2012 ( $9.4 \pm 1.26 \text{ mg}\cdot\text{L}^{-1}$ ) and lowest in May 2013 ( $5.4 \pm 0.57 \text{ mg}\cdot\text{L}^{-1}$ ), and were generally elevated between Redhouse Yacht Club and Perseverance but were lower at Tippers Creek. Hypoxic conditions ( $\text{DO} < 3.0 \text{ mg}\cdot\text{L}^{-1}$ ) were observed in February 2013 at Brickfields ( $2.7 \text{ mg}\cdot\text{L}^{-1}$ ) and Bar None ( $1.3 \text{ mg}\cdot\text{L}^{-1}$ ), and in May 2013 at Bar None ( $1.9 \text{ mg}\cdot\text{L}^{-1}$ ). Historically the water in the Swartkops Estuary has been well oxygenated with very few instances of hypoxic conditions being measured in bottom water.

There were temporal and spatial variations in DIN concentrations, with a persistent longitudinal gradient ( $r = 0.81$ ;  $p < 0.05$ ;  $n = 59$ ) from the mouth to the tidal limit at Perseverance (Fig. 3). Average surface DIN concentrations ranged from  $0.11 \text{ mg}\cdot\text{N}\cdot\text{L}^{-1}$  at Settlers Bridge to  $3.35 \text{ mg}\cdot\text{N}\cdot\text{L}^{-1}$  at Perseverance. Concentrations were highest in the Motherwell Canal ( $8.09 \pm 1.09 \text{ mg}\cdot\text{N}\cdot\text{L}^{-1}$ ), followed by the Markman Canal ( $6.13 \pm 1.67 \text{ mg}\cdot\text{N}\cdot\text{L}^{-1}$ ), Perseverance ( $3.35 \pm 0.53 \text{ mg}\cdot\text{N}\cdot\text{L}^{-1}$ ) and Chatty River ( $2.50 \pm 0.79 \text{ mg}\cdot\text{N}\cdot\text{L}^{-1}$ ). Water quality was generally mesotrophic or eutrophic (Table 1),  $0.5$ – $10 \text{ mg}\cdot\text{N}\cdot\text{L}^{-1}$ , from the middle to upper reaches of the estuary (i.e. from Brickfields to Perseverance), although in September 2012 and May 2013, DIN levels downstream of Brickfields also exceeded DIN guidelines.



**Figure 2**

Salinity regime of the estuary channel and at points of entry into the estuary (mean  $\pm$  SE; 'r' refers to linear regression with distance from the mouth; \*\*  $p < 0.05$ )



**Figure 3**

Dissolved inorganic nitrogen (DIN;  $\text{mg}\cdot\text{N}\cdot\text{L}^{-1}$ ) recorded within the estuary channel and at points of entry into the estuary (mean  $\pm$  SE; 'r' refers to linear correlation with salinity; \*\* indicate  $p < 0.05$ ).

	DIN ( $\text{mg}\cdot\text{N}\cdot\text{L}^{-1}$ )	DIP ( $\text{mg}\cdot\text{P}\cdot\text{L}^{-1}$ )	Dissolved Oxygen ( $\text{mg}\cdot\text{L}^{-1}$ )	Phytoplankton Biomass ( $\mu\text{g}\cdot\text{chl}\cdot\text{a}\cdot\text{L}^{-1}$ )
Sept '12	Poor	Poor	Good	Poor
Nov '12	Fair	Poor	Good	Very poor
Feb '13	Fair	Poor	Fair	Very poor
May '13	Poor	Poor	Fair	Poor
Aug '13	Fair	Poor	Good	Fair
Overall	Poor	Poor	Fair	Very poor

Time	SB	SKV	BF	RYC	BN	PS	CR
<b>DIN (mg·L<sup>-1</sup>)</b>							
1993–1994 <sup>a</sup>	0.3	–	0.3	–	0.3	0.4	–
1997–2001 <sup>b</sup>	0.2	0.3	2.2	0.3	0.3	–	2.5
2012–2013	0.1	0.4	1.0	1.0	1.3	2.6	2.5
<b>DIP (mg·L<sup>-1</sup>)</b>							
1979–1981 <sup>c</sup>	0.3	0.6	1.1	1.6	–	–	–
1997–2001 <sup>b</sup>	0.1	0.4	0.2	0.6	–	–	–
2012–2013	0.1	0.2	0.4	0.4	–	–	–
<b>Chlorophyll <i>a</i> (µg·L<sup>-1</sup>)</b>							
1993–1994 <sup>a</sup>	4.1	–	–	–	8.6	22.3	–
1999 <sup>d</sup>	22.5	–	–	–	20.6	23.7	–
2012–2013	2.9	–	–	–	71.6	89.0	–

Sources of historical data: <sup>a</sup>Scharler et al. (1997), <sup>b</sup>DWAF, <sup>c</sup>Emmerson (1985) and <sup>d</sup>Binning (1999). Site names: Settlers Bridge (SB), Swartkops Village (SKV), Brickfields (BF), Redhouse Yacht Club (RYC), Bar None (BN), Perseverance (PS), Chatty River (CR).

Past studies have indicated that soluble reactive phosphorus (SRP), also referred to as dissolved inorganic phosphorus (DIP), increased in concentration from the mouth to the upper reaches (Table 2). During the present study, the average concentrations ranged from 0.06 mg P·L<sup>-1</sup> at Settlers Bridge to 1.25 mg P·L<sup>-1</sup> at Perseverance (Fig. 4). DIP increased significantly ( $r = 0.89$ ;  $p < 0.05$ ) with distance from the mouth. Average concentrations in the Chatty River (0.40 mg P·L<sup>-1</sup>), Markman (0.14 mg P·L<sup>-1</sup>) and Motherwell canals (0.19 mg P·L<sup>-1</sup>) indicate the Swartkops River to be the primary source of SRP to the estuary. Historical data as well as that from this study (Table 1) show that all mean DIP levels measured along the longitudinal axis of the estuary from the lower to the upper reaches of the estuary were characteristic of eutrophic conditions;  $> 0.1$  mg P·L<sup>-1</sup> (Lemley et al., 2015).

To identify the source of inorganic nutrients in the Swartkops Estuary, DIN (Fig. 5) and DIP (Fig. 6) loads discharged from WWTWs, calculated according to Lemley et al. (2014), between 2009 and 2013 were examined and related to concentrations measured in the river and estuary. DIN concentrations increased steadily from the mouth of the estuary to the tidal limit. DIN ranges at the fresh river sites were higher than those recorded within the estuary. The results indicated that DIN was elevated at sites near WWTWs. The highest DIN concentrations were measured at Van Schalkwyk Bridge, which is located downstream of the Kelvin Jones WWTW discharge site. Using the median DIN concentrations measured from 2009 to 2013, the estimated daily load for each of the WWTWs ranged from 35.5 to 170.0 kg N·d<sup>-1</sup>. The highest median daily load was discharged from the KwaNobuhle WWTW (170.0 kg N·d<sup>-1</sup>; 16.0–622.4 kg N·d<sup>-1</sup>), followed by Kelvin Jones (152.6 kg N·d<sup>-1</sup>; 28.5–1 167.9 kg N·d<sup>-1</sup>) and then Despatch (35.5 kg N·d<sup>-1</sup>; 7.4–81.1 kg N·d<sup>-1</sup>).

At the freshwater monitoring sites DIP ranges were highest at the Van Schalkwyk Bridge followed by Perseverance Bridge and Elands River. Furthermore, data showed that the daily DIP load determined for each of the WWTWs ranged from 13.4 to 128.6 kg P·d<sup>-1</sup> and that the

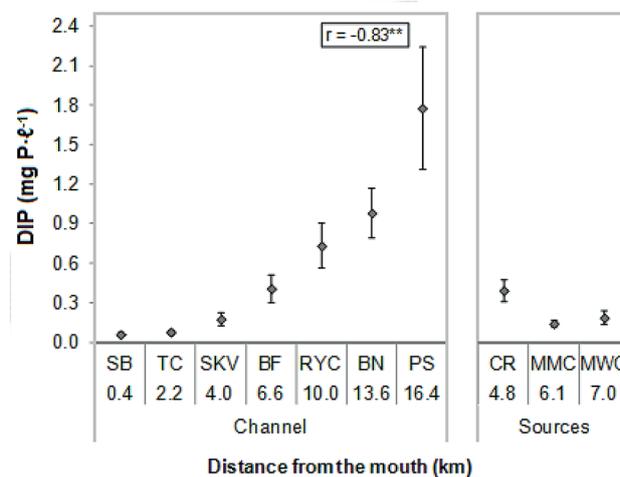


Figure 4

Dissolved inorganic phosphorus (DIP; mg P·L<sup>-1</sup>) recorded within the estuary channel and at points of entry into the estuary (mean  $\pm$  SE; 'r' refers to linear correlation with salinity; \*\* indicate  $p < 0.05$ ).

highest median daily load was discharged from the Kelvin Jones WWTW (128.6 kg P·d<sup>-1</sup>; 9–826.1 kg P·d<sup>-1</sup>), followed by KwaNobuhle (46.4; 6.6–130.5 kg P·d<sup>-1</sup>), and then Despatch (13.4 kg P·d<sup>-1</sup>; 0.2–53.2 kg P·d<sup>-1</sup>).

Historical data (Fig. 7) recorded by the Department of Water Affairs at Nivens Bridge from 1995 to 2013 showed that 47% of the 343 DIN measurements were classified as oligotrophic ( $< 0.5$  kg N·d<sup>-1</sup>), 39% mesotrophic (0.5–2.5 kg N·d<sup>-1</sup>), 14% eutrophic (2.5–10 kg N·d<sup>-1</sup>) and 0.6% hypertrophic ( $> 10$  kg N·d<sup>-1</sup>). None of the 357 DIP measurements were oligotrophic ( $< 0.005$  kg P·d<sup>-1</sup>), 30% were mesotrophic (0.005–0.025 kg P·d<sup>-1</sup>), 45% were eutrophic (0.025–0.1 kg P·d<sup>-1</sup>), and 25% were hypertrophic ( $> 0.1$  kg P·d<sup>-1</sup>).

There were no apparent effects of tidal stage and flow regime on chlorophyll *a* in the estuary, since the highest concentrations were recorded on a neap flood tide and also on a spring ebb

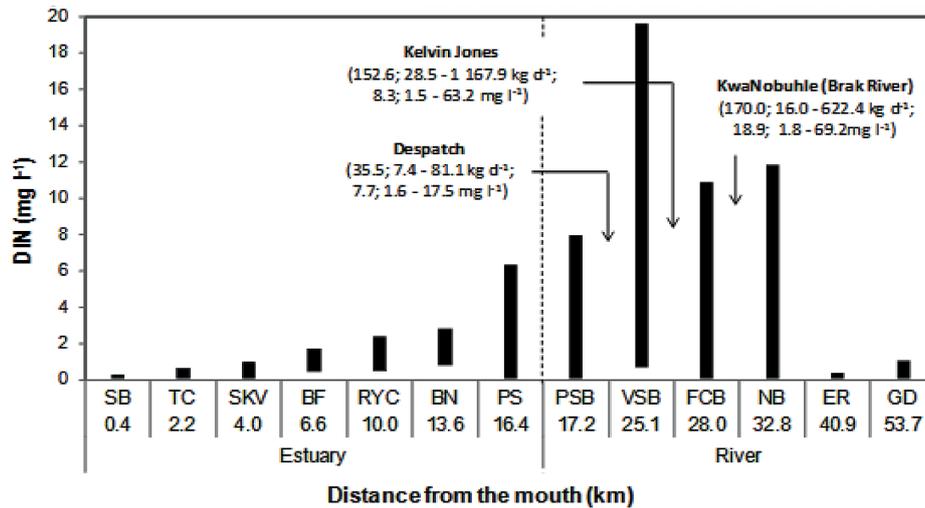


Figure 5

Bars showing the minimum and maximum concentrations of dissolved inorganic nitrogen (DIN) measured in the Swartkops River and estuary, with the loads and concentrations in discharges from wastewater treatment works entering at the points shown; 2009 to 2013. DIN is expressed as median and range of load and concentration. (Data for WWTWs obtained from DWA, 2013.)

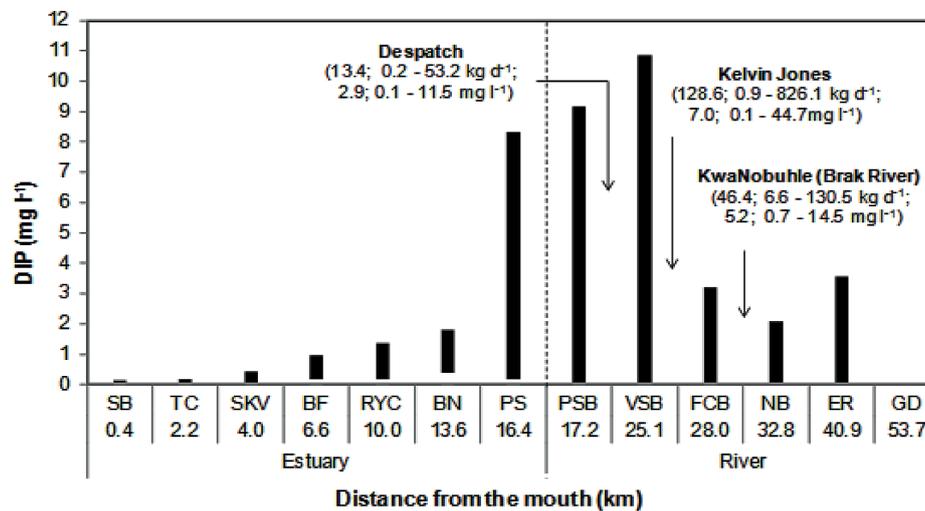


Figure 6

Bars showing the minimum and maximum concentrations of dissolved inorganic phosphorus (DIP) measured in the Swartkops River and estuary, with the loads and concentrations in discharges from wastewater treatment works entering at the points shown; 2009 to 2013. DIP is expressed as median and range of load and concentration. (Data for WWTWs obtained from DWA, 2013.)

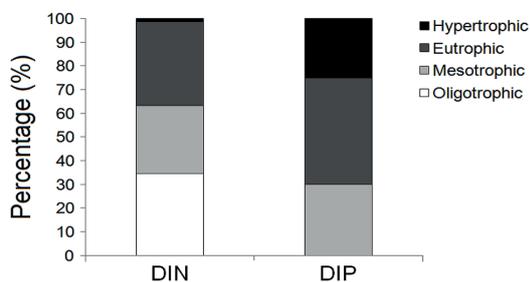
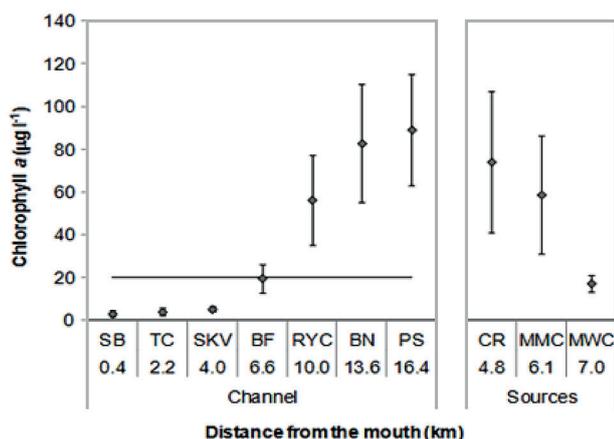


Figure 7

Frequency distributions of dissolved inorganic nitrogen (DIN;  $n = 343$ ) and dissolved inorganic phosphorus (DIP;  $n = 357$ ) trophic states in the Swartkops River (Nivens Bridge). Trophic states: DIN ( $\text{mg N}\cdot\text{L}^{-1}$ ) < 0.5 is oligotrophic, 0.5–2.5 is mesotrophic, 2.5–10 is eutrophic, > 10 is hypertrophic; DIP ( $\text{mg P}\cdot\text{L}^{-1}$ ) < 0.005 is oligotrophic, 0.005–0.025 is mesotrophic, 0.025–0.1 is eutrophic, > 0.1 is hypertrophic (DWAF, 1996)

tide, with flow discharges of 2.14 and 0.50  $\text{m}^3\cdot\text{s}^{-1}$ , respectively. Phytoplankton chlorophyll *a* increased with distance from the mouth of the estuary in 2012–2013 (Fig. 8). Average chlorophyll *a* was  $31.8 \pm 6.56 \mu\text{g chl } a\cdot\text{L}^{-1}$ , ranging from 0 to 248.7  $\mu\text{g chl } a\cdot\text{L}^{-1}$ . Chlorophyll *a* levels were highest in November 2012 ( $58.3 \pm 25.23 \mu\text{g chl } a\cdot\text{L}^{-1}$ ) on a neap tide, and lowest in August 2013 ( $9.2 \pm 4.10 \mu\text{g chl } a\cdot\text{L}^{-1}$ ), also on a neap tide.

For the point-source sites the highest mean chlorophyll *a* concentration was measured in the river inflow water at Perseverance and the lowest concentrations were measured at the mouth of the estuary. The present study has shown that the high nutrient concentrations are consistently supporting a phytoplankton biomass of bloom concentrations (> 20  $\mu\text{g chl } a\cdot\text{L}^{-1}$ ) from the middle to upper reaches of the estuary. Chlorophyll *a* concentration showed a positive correlation with DIN ( $r = 0.57$ ;  $p < 0.05$ ) and DIP ( $r = 0.67$ ;  $p < 0.05$ ), and a negative correlation with salinity ( $r = -0.83$ ;  $p < 0.05$ ;  $n = 60$ ).



**Figure 8**

Average chlorophyll *a* concentrations ( $\mu\text{g chl } a\cdot\text{L}^{-1}$ ) in the Swartkops Estuary and at points of entry into the estuary (SB/sea, Settlers Bridge; CR, Chatty River; MMC, Markman Canal; MWC, Motherwell Canal; River, Swartkops River) (mean  $\pm$  SE). The horizontal line represents the  $20 \mu\text{g chl } a\cdot\text{L}^{-1}$  chlorophyll *a* concentration; phytoplankton bloom.

## DISCUSSION

This study investigated the spatial and temporal variability of physico-chemical parameters and phytoplankton biomass of the Swartkops Estuary and compared these data with past studies. The results show deterioration of water quality in this urbanised estuary, and an ecosystem under long-term stress from anthropogenic inputs. Evidence suggests that water is not flushed as efficiently from the upper estuary as was previously the case, and that the natural hydrology of the estuary has been modified. There is reduced vertical mixing and stratification occurs with a persistent salt wedge structure in the estuary. A possible cause is the increase in low-salinity water from the WWTWs. The discharge exceeds design capacity at the Kelvin Jones, Despatch and KwaNobuhle WWTWs ( $75 \text{ ML}\cdot\text{d}^{-1}$ ,  $77 \text{ ML}\cdot\text{d}^{-1}$  and  $79 \text{ ML}\cdot\text{d}^{-1}$  respectively; DWA, 2009). Increased stratification, water retention and high nutrient loads favour phytoplankton blooms (Lemley et al., 2015), thus encouraging eutrophic conditions that are now persistent in the estuary.

Eutrophication is 'the enrichment of water by nutrients causing an accelerated growth of algae and higher forms of plant life to produce an undesirable disturbance to the balance of organisms present in the water and to the quality of the water concerned' (OSPAR, 2003 p. 28). It is accompanied by increased phytoplankton biomass, changes in community composition, de-oxygenation of the water column and the possible proliferation of harmful or toxic species (Officer and Ryther, 1980; Smayda, 1990). The latter requires further investigation in the Swartkops Estuary. However, the propensity for reduced dissolved oxygen concentrations (i.e. hypoxia) in the middle to upper reaches of the Swartkops Estuary is thus further evidence of eutrophication. Furthermore, strong longitudinal gradients of nutrients exist, with DIN and DIP concentrations increasing with distance from the estuary mouth. Such distribution profiles are indicative of anthropogenic nutrient loading from the catchment as the primary nutrient source. These findings were consistent with those of De Villiers and Thiart (2007), where a pronounced increase in DIN and DIP in the Swartkops River was reported, leading the authors to describing it as one of the most threatened freshwater systems in South Africa.

The middle to upper reaches of the estuary are persistently eutrophic, with blooms of phytoplankton (using chlorophyll *a* as an index of biomass of  $> 20 \mu\text{g chl } a\cdot\text{L}^{-1}$ ) occurring in response to nutrient input. Elevated concentrations of inorganic nutrients caused high phytoplankton biomass; ranging from 0 to  $248 \mu\text{g chl } a\cdot\text{L}^{-1}$  ( $31.8 \pm 6.56 \mu\text{g chl } a\cdot\text{L}^{-1}$ ). This is consistent with findings of several authors who have shown that nutrients enhance phytoplankton and algal production in general (Fong et al., 1993; Anderson et al., 2002; Borja et al., 2012). This is particularly true of estuaries subject to daily WWTW inputs, as observed by Thomas et al. (2005) in two South African temporarily open/closed estuaries. The nutrient-driven 'bloom-decay' cycle of algae will result in increased DO production during the growth phase of phytoplankton blooms and a decline during the decay phase (Biswas et al., 2009; O'Boyle et al., 2016; Lemley et al., 2018). This was consistent with findings for the Swartkops Estuary, where hypoxic conditions were recorded in the upper reaches of the estuary on two occasions.

The eutrophication of estuaries caused by human-induced nutrient enrichment is a global environmental concern because of the ecological and economic value of these ecosystems (Cloern et al., 2016). Eutrophication in South Africa appears to be increasing with persistent phytoplankton blooms being reported in a number of other estuaries (Snow et al., 2000; Kotsedi et al., 2012; Kaselowski and Adams, 2013; Lemley et al., 2018). By applying the pelagic component of a eutrophic condition index, proposed by Lemley et al. (2015), the eutrophic condition of the Swartkops Estuary could be assessed (Table 1). Except for dissolved oxygen levels, all the parameters (DIN, DIP and phytoplankton biomass) were classified as being in an overall 'Poor' or 'Very Poor' state, thus indicating the eutrophic or hypertrophic nature of the system. With regards to dissolved oxygen, localised hypoxic conditions were frequently measured in bottom waters in the upper reaches of the estuary. However, the eutrophic condition index rated the entire estuary as 'Good' or 'Fair'. This is most likely because surface waters were supersaturated with oxygen produced by blooms of phytoplankton at the time of sampling and the lower reaches of the estuary were well oxygenated via tidal flushing. The temporal scale at which in-situ estuary monitoring was undertaken in this study is appropriate for achieving a reliable assessment of eutrophic condition using this method. With regards to effective management, this further emphasises the value of continuous monitoring.

Water quality data (1995 to 2013) for the river showed that 52% of DIN measurements were classified as either mesotrophic or eutrophic and all DIP measurements exceeded the guideline value of  $0.05 \text{ mg P}\cdot\text{L}^{-1}$  (DWA, 1996). WWTWs within the Swartkops catchment are a major source of nutrients, which have promoted the growth of water hyacinth (*Eichhornia crassipes*) and other invasive aquatic plants in the river between Uitenhage and Perseverance. High levels of DIP in the river are attributed to the sewage discharges from KwaNobuhle, Uitenhage and Despatch, which are major residential and industrial areas. The released effluent is poorly monitored for acceptable nutrient levels and has been shown to exceed standards (DWA, 2009), which results in the transport of high loads of nutrients into the estuary. Another concern is the possible future occurrence of harmful algal bloom (HAB) species in the estuary which would likely cause further ecological changes and influence human health. The toxic dinoflagellate, *Lingulodinium polyedra*, was recorded in Algoa Bay and the Swartkops Estuary when it formed extensive red tides in the summer of 2013/2014. Although in this instance

the HAB was allochthonous in nature, not proliferating from within the estuary, the possibility of future autochthonous HABs is a concern because they pose a health risk and are difficult/expensive to control.

In addition to nutrient inputs from the WWTWs, nutrient inputs from the Motherwell and Markman canals and the Chatty River are also significant. The Motherwell Canal has been a major source of nitrogen (generally in the form of ammonium) to the estuary, while the Swartkops River is the primary source of phosphorus to the estuary because of the upstream WWTWs. The DIN:DIP ratio averaged  $56.8 \pm 14.8$  ( $\pm$  SE) in the Motherwell Canal for the study period, compared to  $2.3 \pm 0.4$  measured near the head of the estuary at Perseverance. Elevated nutrient concentrations were observed during both high and low flow conditions so cannot be linked to freshwater input from the Swartkops River alone. This is consistent with findings from previous studies which showed that these canals contributed nutrients to the estuary (Hilmer, 1984; Emmerson, 1985; MacKay, 1993; Scharler et al., 1997). Furthermore, DIN concentrations recorded in both canals were higher than all other sites measured.

These results provide valuable information for management of the Swartkops catchment and estuary. Given the economic, ecological and recreational importance of the Swartkops River and estuary, Van Niekerk et al. (2014) envisaged a recommended ecological category of 'C' for the estuary. However, the current results show that estuary health will continue to deteriorate if a 'business as usual'

scenario continues. Changes in the estuary and catchment have caused an extensive loss of natural habitat, biota and ecosystem functioning. Management interventions are needed to improve estuary health so that the system can continue to provide important ecosystem services (Table 3). This can be done through better management of sewage systems; use of artificial wetlands prior to wastewater discharge, reduction in the use and discharge of phosphates, and improvement of stormwater systems so that they do not divert into sewers. The pilot artificial wetland that was constructed to divert and filter 20% of the run-off from the Motherwell Canal is operational but requires continual maintenance, such as cutting back the wetland plants in order to maintain optimum functionality.

## CONCLUSION

Continuous data are important for understanding changes in water quality in estuaries. Ideally water quality monitoring should be aligned with the objectives of simple mass balance models, or more complex ecosystem modelling. A mass balance approach will identify the sources, sinks and export of variables (N, P and heavy metals). From the results, predictions can be made to help managers take the most cost-effective action. A numerical model can be used for investigating mitigation scenarios, to improve conditions in the system (i.e. how much do we need to reduce waste loading to meet environmental objectives; Prof. S Taljaard, pers. comm.

**TABLE 3**  
**Monitoring for restoring the health of the Swartkops Estuary**

Issues	Monitoring objective
No measured inflow to estuary	Freshwater inflow recorded continuously at head of estuary, e.g., by installation of flow gauge.
Eutrophication of the river and estuary	System variables (pH, oxygen, salinity, turbidity, TSS nutrients) measured in river inflow. Measurement of water quality variables at 7 sites in the estuary to ensure that normal ecological processes are maintained. Microalgal biomass and community composition measured at same sites.
Elevated stormwater and effluent inputs	Measurement of volume of stormwater and effluent flowing into Motherwell Canal, Markman Canal, Chatty River, Swartkops Village and from Pond 6 of the Road and Transport depot. Measurement of flow into estuary. Measurement of effluent quality at end of pipe before entering estuary.
Contamination by toxins (trace metals and organic compounds)	Measurements of trace metals (Cr, Pb, Zn, Mn, Sr, Cu) in sediments along length of the estuary. Focus on sheltered depositional areas where sediments are fine and have high organic content. Focus on source sites, i.e. Perseverance, Motherwell Canal, Markman Canal, Chatty River and Tippers Creek. Measure biotissues every 3–5 years to assess metal accumulation.
Faecal pollution – a threat to recreational use and health	Measure faecal bacteria in river inflow, at source sites (Motherwell, Markman, Chatty), at 7 sites along the length of the estuary and in the adjacent sea.
Illegal dumping and littering (solid waste)	Monitor extent of litter and frequency of dumping. Check that litter traps are clean and functional. Check that municipal garbage removal is adequate. Intensive clean-up operations needed during peak season, after high winds and rainfall events. Monitor volume of litter collected by the number of standard garbage bags filled to see if enforcement officers and education and awareness programmes are successful.

2015). A comprehensive Department of Water and Sanitation (DWS) ecological water requirement study is needed for the Swartkops Estuary so that Water Resource Quality Objectives can be identified. The detailed water quality data for 2012/2013 reported here have contributed to the required assessment by illustrating the persistently eutrophic condition in which the Swartkops Estuary currently resides. A comprehensive Reserve study can only proceed once there are flow data available for river inflow to the estuary at Perseverance. For this reason, a flow gauge must be installed. This could be a low-flow weir with a fishway and could also be used as a DWS water quality monitoring site.

Improved wastewater treatment at the three WWTWs and management of urban runoff into the Motherwell Canal are likely to reduce the intensity and frequency of phytoplankton blooms and the health risks. When the Nelson Mandela Bay Municipality finishes implementing the applicable management plans, such as the Water Services Development Plan, the Water Management Systems Plan, Sewer Management Systems, Water Master Plan and the Sewer Master plan, we expect a measurable reduction in the pollution of the Swartkops Estuary. Furthermore, a healthy estuary state can only be attained and maintained if management decisions are based on up-to-date, reliable and quantitative data. For this reason, a long-term monitoring programme is necessary to continuously evaluate the effectiveness of management actions in improving the health of the estuary.

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APPENDIX

Description	Site name	Latitude (°S)	Longitude (°E)	Distance from mouth (km)
Estuary	Settlers Bridge (SB)	33.8619	25.6271	0.4
	Tippers Creek (TC)	33.8536	25.6155	2.2
	Swartkops Village (SKV)	33.8606	25.6005	4.0
	Brickfields (BF)	33.8400	25.5989	6.6
	Redhouse Yacht Club (RYC)	33.8366	25.5708	10.0
	Bar None (BN)	33.8214	25.5509	13.6
	Perseverance (PS)	33.8111	25.5312	16.4
Point sources	Chatty River (CR)	33.8536	25.5856	4.8
	Markman Canal (MMC)	33.8433	25.6048	6.1
	Motherwell Canal (MWC)	33.8366	25.5950	7.0
River	Perseverance Bridge (PSB)	33.8121	25.5214	17.2
	Van Schalkwyk Bridge (VSB)	33.7964	25.4527	25.1
	Frans Claasen Bridge (FCB)	33.7892	25.4269	28.0
	Nivens Bridge (NB)	33.7711	25.3867	32.8
	Elands River (ER)	33.7675	25.3295	40.9
	Groendal Dam (GD)	33.6900	25.2667	53.7
WWTWs	Despatch WWTW	33.8006	25.4969	19.8
	Kelvin Jones WWTW	33.7831	25.4261	27.5
	KwaNobuhle WWTW	33.8058	25.3994	29.7

Sampling date	<sup>2</sup> Mean daily discharge (m <sup>3</sup> ·s <sup>-1</sup> )	Rainfall: 24 h prior to sampling [ $< 10$ days] (mm)		<sup>1</sup> Tide
		Uitenhage	Bluewater Bay	
18/09/2012*	1.37 [1.36]	1.2 [6.8]	2.2 [5.8]	High: 04H41 (1.94 m) Low: 10H42 (0.15 m)
20/11/2012 (neap tide)	2.14 [8.86]	0 [3.4]	0 [12.8]	High: 08H33 (1:56 m) Low: 14H49 (0.80 m)
12/02/2013 (spring tide)	0.50 [0.33]	0 [31.8]	0 [29.8]	High: 04H56 (2.08 m) Low: 11H01 (0.29 m)
21/05/2013 (flood tide)	0.31 [0.30]	0	0.2 [1.2]	Low: 06H51 (0.58 m) High: 12H53 (1.51 m)
14/08/2013 (neap tide)	0.22 [0.21]	0 [1.4]	0.2 [4.4]	Low: 01H54 (0.61 m) High: 08H11 (1.41 m)

Note: Spring tide on 17/09/2012

Source: <sup>1</sup>[www.kwathabeng.co.za/tides/](http://www.kwathabeng.co.za/tides/)

<sup>2</sup> Mean daily discharge calculated using monthly mean