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Baseline

Reduction in pollution load to an urban estuary using a sustainable drainage system treatment train

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ABSTRACT

Rapid urbanisation and industrialisation have placed increased pressure on the ecosystem health of urban estuaries. Sustainable drainage systems (SuDS) are globally accepted practices for managing the water quality of stormwater and effluent discharged into urban systems. The Swartkops Estuary in South Africa is a heavily urbanized estuary that has a long history of pollution, specifically trace metal contamination, originating from industrial sources and urban wastewater. Using a novel SuDS treatment train, the physical characteristics (total suspended solids), macronutrients (orthophosphates, nitrate, ammonium), trace metals (As, Cd, Hg, Fe, Pb, Cu), and *E. coli* concentrations were measured monthly for one year, both before and after the treatment train. The treatment train consisted of five interconnected 500 L plastic tanks for sedimentation, filtration (sand and stone), biodegradation and floating wetlands. Results indicate that the SuDS treatment train provided an efficient method in reducing the pollution load to this urban estuary, by reducing macronutrient concentrations by 76 %, trace elements concentrations by 74 % and faecal bacteria counts (*E. coli*) by 80 %.

Africa has gone through accelerated urbanisation and industrialisation in the last five decades, which has led to a growing population of the urban poor and the mushrooming of informal settlements in cities (Kellagher et al., 2007; Sulla and Zikhali, 2018). The expanding population presents a formidable challenge to city planning and development, as current wastewater systems and resources have been exceeded in their intended capacity. Pressure on the local water systems (i.e., rivers and estuaries) rapidly follows, as more pollutants are discharged into the system. Urban regulators are confronted with the difficult task of balancing social-economic development imperatives with those of environmental sustainability. Empirical evidence suggests that in the face of dwindling financial resources, social-economic developmental agendas such as job creation, provision of housing and health facilities often take precedence over ecological goals of maintaining and improving urban river health (Cullis et al., 2019; Starkl et al., 2022). The trajectories of urbanisation and industrialisation on natural resources are complex in water resource management (Kellagher et al., 2007; Cullis et al., 2019). Yet allowing stormwater discharge into urban estuaries to go unchecked, can create fertile grounds for disease transmission, and compromise the health and livelihoods of those who rely on its ecosystem services (Cullis et al., 2019).

Sustainable drainage systems (SuDS) are nature-inspired stormwater treatment technologies that are used worldwide in urban environments to mitigate pollution to natural systems (e.g., Kirby, 2005; Wong et al., 2006; McGrane, 2016; Oral et al., 2020). Sustainable management practices and increasingly water-sensitive urban design strategies are being implemented to help create areas that mimic “pre-development” dynamics. Nature can be mimicked at various levels applicable to a design problem, such as at the natural form (e.g., structure), processes (e.g., sedimentation, filtration, adsorption), and ecosystem level (e.g., natural wetland systems). SuDS are site specific, but their designs can be implemented and related to any location, e.g., swales, artificial wetlands, ponds, sediment traps and infiltration systems (Jurries, 2003). SuDS treatment trains can be the preferred alternative to centralised wastewater treatment systems in rural or small communities (Wood et al., 2016).

Pollutants such as trace metals, organometallic compounds, fossil fuels, lubricating oils, gear oils and greases are common contaminants in industrial effluent and stormwater runoff (Brown and Peake, 2006; Olisah et al., 2020). These pollutants affect the water quality and

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subsequent ecosystem health, which can have negative impacts throughout the food chain, including humans (Nel et al., 2015; van Aswegen et al., 2019; van Niekerk et al., 2020; Haghnazar et al., 2023). During storms, pollutants from industry are usually carried by runoff into receiving waters. Surface runoff releases and washes pollutants and deposits them into the channel beds and floodplains of receiving water bodies, such as estuaries (Olisah et al., 2020). The pollutants can either be in dissolved form or adsorbed into sediment and suspended solids (Zhang et al., 2001; Du Laing et al., 2009; Li et al., 2013). Stormwater pulses can cause scouring of the channel, which can remobilise and transport the contaminants further into receiving water bodies. Macronutrients (e.g., nitrogen and phosphorus) can change form and degrade naturally in the environment, however metals cannot be degraded over time, but bioaccumulate, causing toxicity through the food chain (Olguín and Sánchez-Galván, 2012; Omubo-pepple, 2015). SuDS can mimic the natural ecosystems by filtering contaminated water through unsaturated soil media, which then adsorbs and retains the pollutants (Armitage et al., 2014). Wetland plants are natural filters and can accumulate metals and incorporate macronutrients into their tissues (Phillips et al., 2015; Bonanno et al., 2018; Lemley et al., 2022). Artificial wetlands are effective SuDS that can be integrated into natural systems and used to remove pollutants (including metals) in an ecosystem (Knox et al., 2008; Tara et al., 2019; Tuttolomondo et al., 2020).

The objective of this research was to design and test a SuDS treatment train over a period of a year, to improve the water quality discharged from the Markman stormwater canal, a tributary which transports effluent to the Swartkops Estuary, a nationally important estuary on the south east coast of South Africa. The Swartkops Estuary is a permanently open system and the mouth opens into Algoa Bay, past the north-eastern edge of Gqeberha (previously Port Elizabeth). Its main catchment is situated in the Great Winterhoek Mountains and feeds into the Elands River and Swartkops River, both connected to the estuary. The Swartkops Estuary is highly developed and contains formal settlements, informal settlements, and various industries, which release wastewater into the estuary. Approximately 6.1 km from the mouth, the Markman Canal enters the estuary (Fig. 1). On the canal's northern side, there is the Markman industrial area, and several stormwater drains, which discharge wastewater into the canal. The Coega industrial area includes tanneries, freight and container transportation facilities, foundries, manufacturers (polystyrene, phenolic, rigid polyurethane foam, pallets), metal recyclers, materials testing laboratories, an abattoir, and automotive repair facilities. Hazardous waste disposal sites, a sewerage pre-treatment plant and informal settlements are also located in the lower reaches of the Markman industrial zone. Before entering the Swartkops Estuary the Markman canal traverses through the Aloes Settlement, a small peri-urban village. Two sewerage pump stations (The Aloes and Studebaker) release treated wastewater into the Markman Canal.

The Markman Canal is not reinforced and is covered with natural vegetation on its banks and channel. This flora on the canal bed, as well as the long travel distance and time to the estuary, has previously been found to effectively remove toxins before entering the estuary (Mackay, 1994). However, due to recent expansion of the industrial area, this filtrating capacity may have been exceeded. Preliminary studies have confirmed poor water quality in the Markman Canal. The impacts of leachate and runoff from waste disposal facilities are yet to be determined (Mackay, 1994). Faecal pollution in the Markman Canal is most

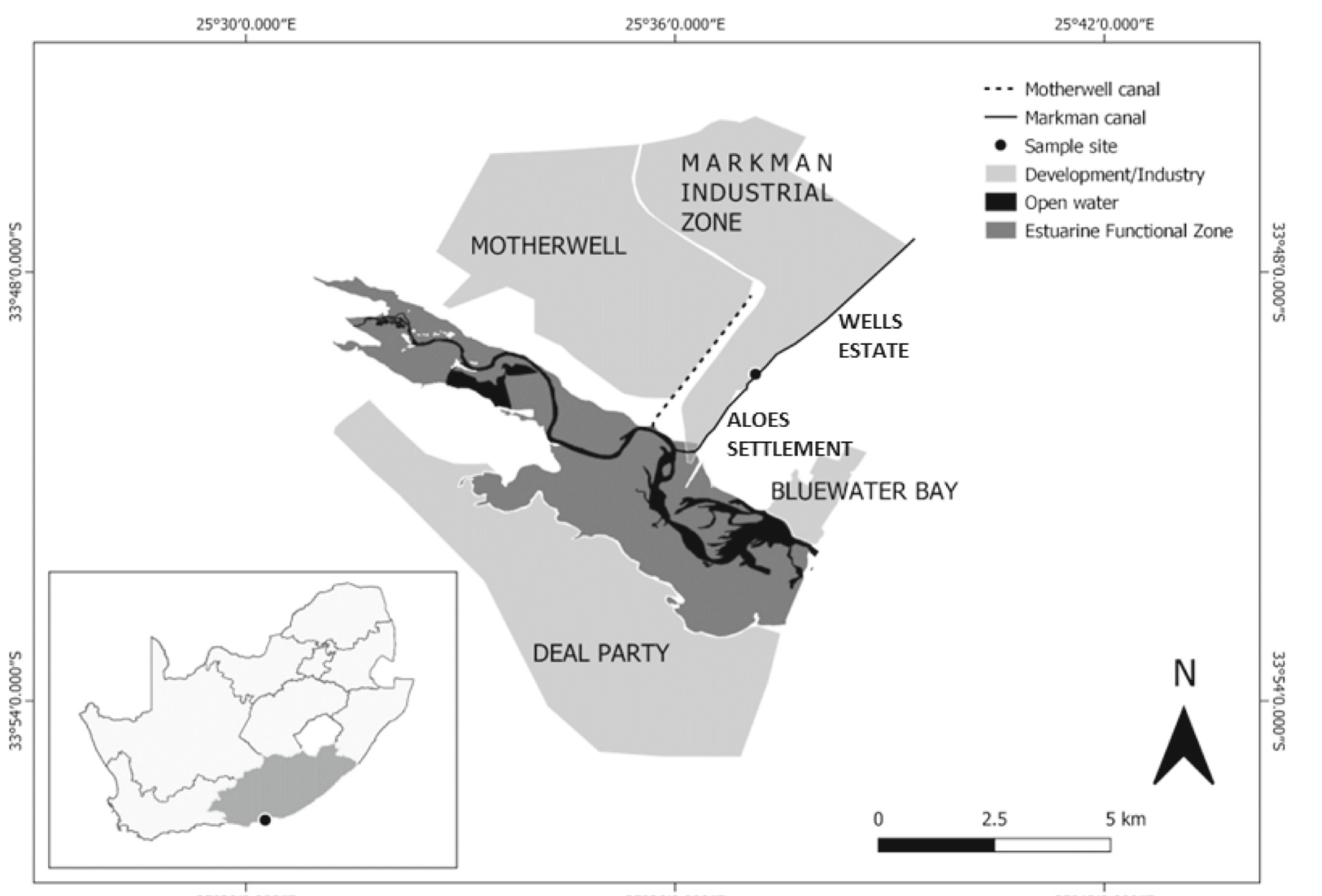

Fig. 1. Locality map of the sampling site showing the Markman Canal entering the Swartkops Estuary, South Africa.

likely the result of informal settlements around the canal, such as Wells Estate, however, the Aloes- and Studebaker sewerage pump stations are both dysfunctional and have had an impact on the canal's water quality (Mmachaka, 2022) discharging domestic and industrial effluent into the Markman Canal.

The present ecological state (PES) of the highly developed Swartkops Estuary has deteriorated due to ongoing urbanisation and industrialisation, causing higher quantities of pollution from treated effluent and stormwater, to enter the system (Adams et al., 2019). Pollution in the estuary has been documented since the 1970's and include metals (e.g., Watling and Watling, 1979; Binning and Baird, 2001; Nel, 2014; Nel et al., 2020), macronutrient (e.g., Adams et al., 2019; Lemley et al., 2022), organic pollutants from pesticides (e.g., Olisah et al., 2019, 2020, 2022) and faecal bacteria (Adams et al., 2019). The pollution has resulted in algal blooms, hypoxic areas, and toxic accumulation in fish and birds, which has also decreased the socio-economic value of the estuary and is a health risk to the local communities. Raw sewage entering the estuary is a common occurrence when local wastewater treatment infrastructure is overwhelmed. The Swartkops Estuary has numerous other point sources that receive stormwater from urban and industrial wastewater, as such water quality has deteriorated (Adams et al., 2019). A further component of this research will therefore be to test the efficiency of faecal bacteria (*Escherichia coli*) removal by the treatment train. Appropriate management interventions are needed to improve the PES, and SuDS provide an opportunity for cleaner discharges and to divert stormwater from the estuary for local irrigation use. The study area has been experiencing a long-lasting drought, which has placed considerable strain on the potable water resources in the area. Since South Africa is a water scarce country, the treated wastewater could be a possible source for irrigation and reduce demand on potable water. The input and output concentrations were therefore compared to general discharge and irrigation limits.

The Markman Canal lacks flow gauges, therefore a float method was used to calculate the flow at the study site as recommended by Dobriyal et al. (2017). Two points were marked at 3 m spacing along the canal's length. Three depths across the channel cross section were measured and averaged. The representative width of the channel was determined using a tape measure. A 500 mL bottle was partially filled with water and released into the canal. The time taken for the bottle to travel from the top point to the bottom point was recorded. The flow measurement for the Markman Canal was found to be 2000 L per day.

The SuDS treatment train for this present study was designed to treat nutrients, trace metals and faecal bacteria from the Markman Canal. This treatment train was based on the experimental design by Armitage et al. (2014). The treatment train consisted of five interconnected plastic tanks (JoJo tanks), with the tops cut off each and a capacity of approximately 500 L each (Fig. 2). The width and length of each tank was approximately 2.6 m and 1.2 m, respectively. The width of the conduit pipe connecting the tanks was 50 mm to ensure unrestricted flow. The tanks were spaced on a downward gradient throughout the treatment train. The five tanks included sedimentation (Tank 1), sand filtration (Tank 2), stone medium filtration (Tank 3), biodegradation (Tank 4), and floating wetland (Tank 5). Stormwater meant for the Markman Canal was diverted and sequentially pumped into this treatment train through each of the five tanks (Fig. 2).

Tank 1 allowed suspended particles to settle out and form a sludge at the bottom of the tank. The sludge was removed on a quarterly basis and disposed of at a landfill site. The runoff suspension water was then treated by passing through a sand filter bed (fine filter; 0.4–0.6 mm) in Tank 2, and a gravel bed (19 mm) in Tank 3. The filters were supported by an underdrain leading to the next tank. Both tanks were designed to eliminate finer suspended particles, hydrocarbons, and metals, while maintaining microbial activity and aeration. Tank 4 contained a combination of micro-organisms (proteobacteria and betaproteobacteria), which broke down pollutants through biodegradation. The microorganisms were diluted in the system according to the manufacturers specifications (Bio Enzyme Digester, BKB Store). The microorganism health was ensured by providing a stone substrate (19 mm width), where microbial biofilms could form. The runoff was then transferred to Tank 5, for the last step, wherein an artificial wetland was created. Recyclable materials (e.g., Hessian mats, fish nets) were used to support the floating wetland in Tank 5. Emergent wetland plants that grow in the Markman Canal, i.e., common reed *Phragmites australis* and bulrush *Typha capensis* were grown in Tank 5. The structure provided buoyancy

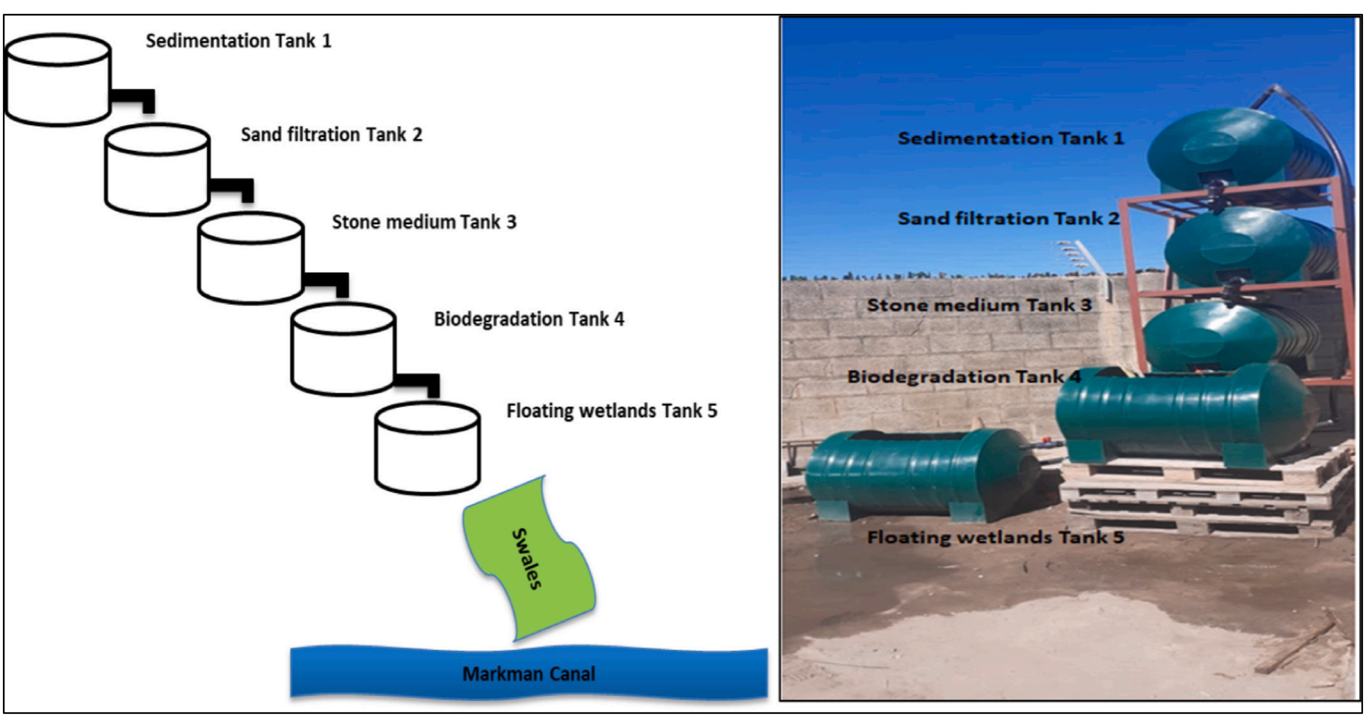

Fig. 2. Schematic diagram and photograph of the SuDS treatment train.

while also supporting aquatic plant growth and allowing plant roots to penetrate the water column. To facilitate biological activity, each tank was always saturated with stormwater. The treated stormwater was then discharged back into the canal via grass swales which also served as a tertiary treatment.

The tanks were an example of SuDS options, which aim to mimic natural processes in the treatment of pollutants from industrial areas. The pollutants carried in the Markman Canal influenced the SuDS option selected for this study. The tanks were arranged systematically to represent natural processes (sedimentation, filtration, bioremediation). The runoff residence time in each tank was calculated using the ratio of tank volume, as well as a quantification of the outflow using the following formula:

$$\text{Residence time} = \text{Volume in the tank } (500\ \text{L})/\text{outflow } (6\ \text{L/min}) = 83\ \text{min}$$

Water at the inlet and the outlet of the treatment train was sampled monthly for a period of 12 months (June 2020 – May 2021), and included analysis of macronutrients (nitrate, ammonium, orthophosphate), trace metals (As, Hg, Pb, Cd, Fe, Cu), electrical conductivity, total suspended solids, and *Escherichia coli* concentrations. Plastic bottles (1 L) were thoroughly rinsed with the sampled water before the water samples were taken for physico-chemical analysis in the laboratory. Sterilized plastic bottles (500 mL) provided by the Talbot & Talbot Laboratories were used to take microbiological samples for *E. coli* analysis. All laboratory analysis was performed by the South African National Accreditation System (SANAS) Talbot & Talbot laboratory – T0122 (ISO/IEC 17025), Gqeberha, South Africa.

In the laboratory, using the collected water samples, electrical conductivity (mS m^{-1}) was measured using a calibrated bench top conductivity probe (Hanna Instruments) until a stable reading was obtained. Quality control was tested at 17 mS m^{-1} with a potassium hydrogen phthalate solution. Likewise, total suspended solids (TSS; mg L^{-1}) were measured using standard gravimetric methods, which entails vacuum filtering the water sample through glass fibre filters and drying the filtrate in a desiccator and drying oven at 180 °C until a constant weight was achieved (Clasceri et al., 1999). Quality of the TSS analysis was tested with a Kieselguhr solutions.

Water samples were also taken for selected macronutrient and elemental analysis. Nitrate, ammonium, and orthophosphates were measured in the water samples using a Gallery Plus Discrete Analyser (Thermo Scientific) with a detection range of 0.001 mg L^{-1}, 0.08 mg L^{-1}, and 0.1 mg L^{-1}, respectively. The samples were analysed for selected trace metals (As, Hg, Pb, Cd, Fe, Cu) using an Inductively Coupled Plasma Optical Emissions Spectrometer (Agilent ICP-OES 700 series) with detection range of 0.01 μg L^{-1}. The standard curve method was used for the analysis. Blanks were run concurrently, and certified reference materials were used during the method validation phase, to ensure the accuracy and precision of the results.

Escherichia coli concentrations were measured in the water samples via membrane filtration using defined substrate technology (Colilert, SANS 5211:2007; Clasceri et al., 1999). Samples were incubated before analysis. The lab used *E. coli* (ATCC 25922) as a positive control, and *Pseudomonas aeuginosa* (ATCC 27853) as a negative control, before each analysis. Analysis is conducted in a sterile environment, and sterility is ensured by running blanks concurrently, and sterilizing all equipment in an autoclave.

Statistical analysis and graphical representations were created using R in the "ggplot2" package (R Core Team, 2021). General discharge limits (DWAF, 2013) and the South African irrigation guidelines (DWAF, 1996), were compared with the measured parameters. Pearson correlation analysis was used for all biotic and abiotic parameters. Percentage change was also calculated between the inlet and outlet for all parameters, as a measure of the efficiency of the SuDS treatment train. The subsequent dataset was tested for normality using the Shapiro-Wilk test, and then an ANOVA was implemented to test for significant differences between monthly treatments amongst the analysed parameters. All analysis were treated as significant at a 95 % confidence level.

Over the one-year period, concentrations of all parameters at the inlet of the treatment train were almost always higher than the outlet (Fig. 3). Nitrate concentrations ranged from 0.04 to 16.6 mg L^{-1} and 0.012–4.5 mg L^{-1} at the inlet and outlet, respectively. Ammonium concentration ranged from 0.21 to 36 mg L^{-1} in the inlet and 0.22–6 mg L^{-1}, at the outlet. Ammonium concentrations were below the discharge limit (6 mg L^{-1}) after passing through the SuDS treatment train, except for the initial reading in June when it was the same as the discharge limit. The orthophosphate concentration was always lower than the discharge limit (10 mg L^{-1}) and ranged from 0.18 to 3.11 mg L^{-1} at the inlet, but was even further lowered to a range between 0.04 and 0.77 mg L^{-1} after the SuDS treatment train. Inlet concentrations of TSS were almost always higher than the discharge limit (25 mg L^{-1}), except in June 2020 and October 2020. The TSS concentrations were however suitable for both discharge (< 25 mg L^{-1}) and irrigation (< 50 mg L^{-1}), ranging from 3 to 20 mg L^{-1}, in the outlet.

Although the SuDS treatment train reduced concentrations of all the trace metals, these were not reduced below that of the discharge or irrigation limits (Fig. 3). Arsenic, Hg and Fe concentrations stayed above both limits even after passing through the SuDS treatment train, which meant that even the treated stormwater was not suitable for discharge or irrigation. Arsenic concentration ranged from 41 to 74 μg L^{-1} at the inlet and were reduced to 10–22 μg L^{-1} at the outlet, which is above the discharge (0.02 μg L^{-1}) and irrigation limit (2 μg L^{-1}). Mercury concentration ranged from 3 to 17 μg L^{-1} at the inlet and were reduced to 0.9 to 6 μg L^{-1} at the outlet. Iron concentration ranged from 300 to 980 μg L^{-1} and 120–310 μg L^{-1} at the inlet and outlet respectively. Cadmium concentration at the inlet ranged from 0.02 to 0.18 μg L^{-1}, and 0.005–0.05 μg L^{-1} at the outlet. Lead concentration ranged from 2 to 6 μg L^{-1} and 0.5–0.99 μg L^{-1}, in the inlet and outlet, respectively, Copper concentration ranged from 4 to 6 μg L^{-1} in the inlet and was reduced to 0.99–1.8 μg L^{-1} at the outlet. Trace metals were generally significantly ($p > 0.05$) and positively correlated ($r = 0.52$ to 0.92) with each other, and with TSS concentrations ($r = 0.48$ to 0.75; Supplementary Table S1).

The *E. coli* counts in the inlet samples ranged from 74 to 20 000 CFU per 100 mL, while those in the samples taken at the outlet of the SuDS treatment train ranged from 16 to 5 000 CFU per 100 mL (Fig. 3). The SuDS treatment train effectively reduced the *E. coli* counts from the stormwater to below the discharge limit and water quality limits for irrigation at 1 000 CFU per 100 mL. During June 2020 and October 2020, however, *E. coli* counts exceeded the limits with an outlet concentration of 3000 CFU per 100 mL and 5000 CFU per 100 mL, respectively. *E. coli* concentrations increased significantly with ammonium and orthophosphate concentrations ($p > 0.05$; $r = 0.65$ and $r = 0.56$, respectively).

Table 1 shows the mean relative efficiency of the SuDS treatment train, by comparing concentrations before (inlet) and after (outlet) the treatment train and converting the value to a percentage. Values across months were consistent and within a 10 % range of each other ($F = 0.866$; $p = 0.575$). Standard error for all the parameters were very low (<1.6), and the treatment was still as effective in the last month (May 2021) compared to the first month (June 2020). The percentage change ranged from 69.3 % (Pb) to 82.6 % (TSS). Although the SuDS treatment train did not reduce the concentrations of all parameters measured to below the discharge and irrigation limits, this setup still reduced concentrations by an average of 75.6 ± 0.5 %.

Through the implementation of a SuDS treatment train composed of soil filtration, artificial wetlands, and proteobacteria/betaproteobacteria, the water quality of stormwater and effluent originating from a highly developed and industrial area discharged into a receiving water body, the Swartkops Estuary, was largely improved. The concentrations of macronutrients, total suspended solids, trace metals and faecal bacteria at the inflow of the SuDS treatment train were all above the discharge limits, set by the local authorities in South Africa. The SuDS

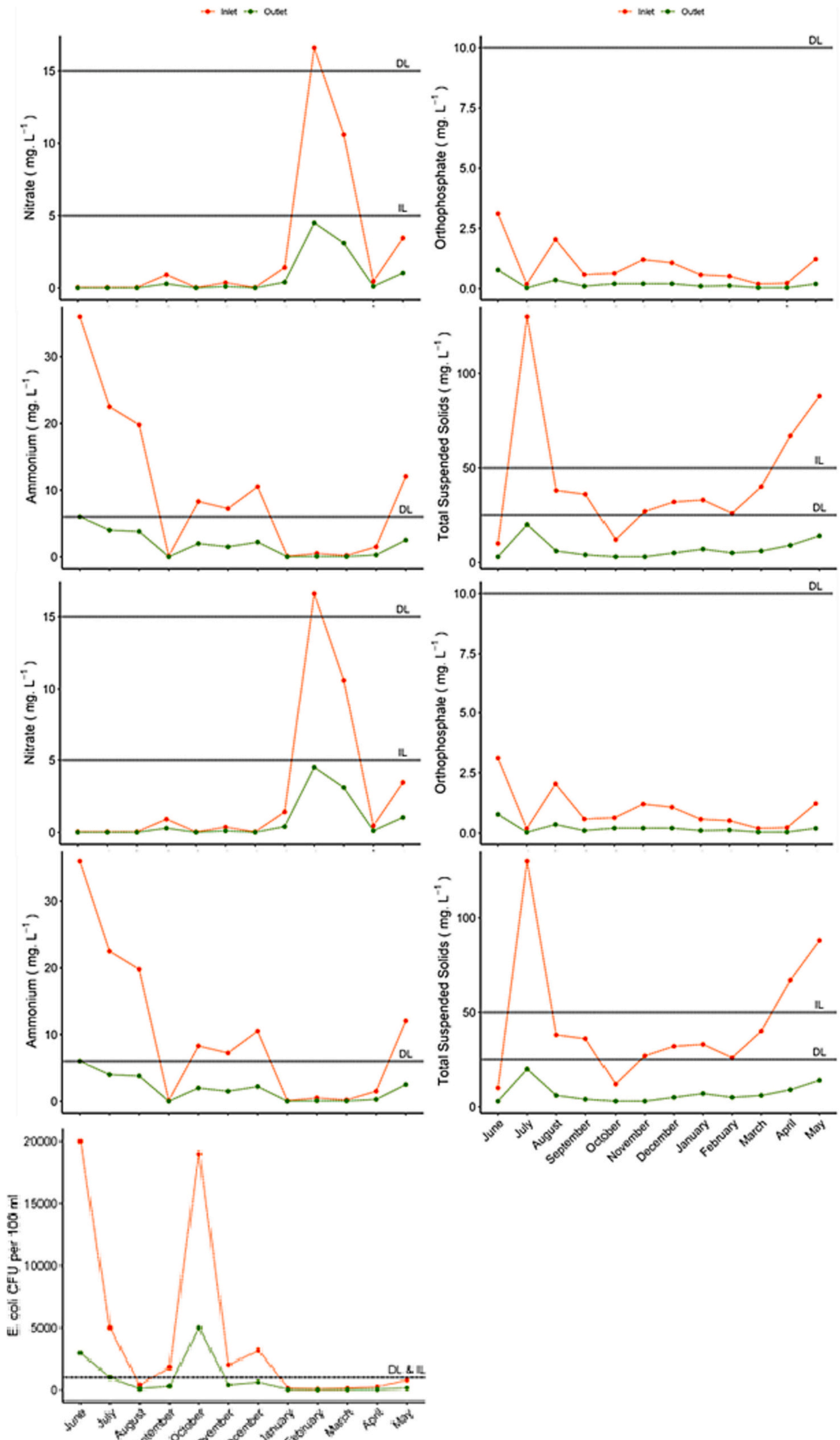

Fig. 3. A. Macronutrients ammonium (mg L^{-1}), nitrate (mg L^{-1}), orthophosphates (mg L^{-1}); total suspended solids (mg L^{-1}, TSS); trace metals arsenic (μg L^{-1}), cadmium (μg L^{-1}), mercury (μg L^{-1}), iron (μg L^{-1}), lead (μg L^{-1}), copper (μg L^{-1}); and *Escherichia coli* (CFU per 100 mL) in the inlet and outlet of the SuDS experiment, where DL = discharge limit and IL = irrigation limit.

Table 1
Percentage change (%) between the inlet and the outlet of the SuDS treatment ($N = 12$).

Percentage change (%)	Mean ± SE
Total suspended solids	82.6 ± 1.6
Nitrate	70.7 ± 0.5
Ammonium	79.8 ± 0.6
Orthophosphate	80.1 ± 1.3
Arsenic	72.7 ± 1.1
Mercury	69.3 ± 1.2
Lead	78.0 ± 0.8
Cadmium	74.6 ± 1.9
Iron	71.7 ± 1.4
Copper	72.8 ± 1.9
E. coli	79.5 ± 0.9
Mean	75.6 ± 0.5

treatment train however significantly decreased the concentrations of the macronutrients nitrate, orthophosphate and ammonium, as well as the concentration of total suspended solids that now complies with both general discharge and irrigation limits.

Persistent eutrophic and hypoxic conditions have been identified in the middle and upper reaches of the Swartkops Estuary, which has caused harmful algal bloom (HAB) events in the past (Lemley et al., 2017; Adams et al., 2019) resulting in fish kills. The treatment at the SuDS train entails the filtration through soil components which naturally assimilate, and acts as a sink for these macronutrients specifically under well-oxygenated conditions (Human et al., 2020). Soluble nitrate and ammonium form insoluble complexes with sediment constituents (i.e., metals) under aerobic conditions (Libes, 2011), and higher macronutrient flux to the water column in past studies is recorded at higher temperatures (Clavero et al., 2000). Building the SuDS treatment train in a shaded area could improve the filtration capacity of the soil components. Treatment efficiency should be measured regularly for decline, as trapped organic components in the soil can decompose, reduce oxygenation and act as a source of ammonium. The floating artificial wetland also filters for macronutrients by assimilating nutrients while growing. Tara et al. (2019) and Tuttolomondo et al. (2020) both reported efficient removal of macronutrients by artificial wetlands. The latter reported a 60–66 % removal while the current study acquired an efficient removal of 76.7 % of the macronutrients, likely due to the addition of the soil filtration, compared to the previous study. Outflow macronutrient concentrations may further be assimilated into the wetland plants growing naturally in the Markman Canal. Harvesting these wetland plants may reduce macronutrient contribution from the Markman Canal, as is implemented by the artificial wetland project in the Motherwell Canal further upstream (Lemley et al., 2022).

The by-product of many manufactured products are trace elements like metals and metalloids, which are discharged with the treated effluent. The regulations around metal and metalloid discharges are stricter due to the chemistry of these elements in the environment, as they are accumulated in sediment and the biota rather than broken down like macronutrients. In our study, the SuDS treatment train effectively removed on average 70 % of the trace metals found in the effluent. Moreover, TSS concentration was reduced by 82.6 %, which in turn would also reduce the concentration of metals introduced to the catchment, as metals readily adsorb onto small but large surface area sediments and organic matter (Zhang et al., 2014).The treated effluent in our study did however not comply with any of the discharge limits set for the specified trace metals (As, Cd, Hg, Fe, Pb, Cu). High concentrations of trace metals are expected in treated industrial wastewater, due to the pulsating nature of stormwater inflow. Trace metal concentrations for the non-essential micronutrients (Pb, Cd) were however well below irrigation limits after the SuDS treatment train, but the high toxicity of As, which exceeded irrigation limits may prevent the use of the outflow of the SuDS treatment train for irrigating consumable crops. It may however be viable to expand the SuDS treatment train to include the vegetated section of the Markman Canal outlet, which may act as a bioswale (Jurries, 2003). The wetland plants that grow in the canal (e.g., *Phragmites australis, Typha capensis*) have been shown to accumulate trace metals within their roots (Phillips et al., 2015). Phillips et al. (2015) also showed that Cd, Cu, Pb, and Zn concentrations on the sediment were higher in the upper Markman canal compared to the lower. Lim et al. (2015) showed that sludge and compost materials had a >90 % removal efficiency of heavy metals and could be implemented in the sludge treatment train to improve metal removal. Alternatively, Tedoldi et al. (2016) showed that metal only infiltrated the first 10–30 cm of soil filtration media, and retention time did not have an influence past 20 min, which indicates that the SuDS treatment train could also be improved by increasing the surface area of the biofilters.

The results of the current study support evidence (Adams et al., 2019) that the Markman Canal had high faecal bacteria counts, which are currently flowing unaddressed into the Swartkops Estuary. The SuDS treatment train on the Markman Canal reduced *E. coli* concentrations by 79.5 %, which effectively reduced concentrations to levels appropriate for general discharge and irrigation for the majority of the experimental treatment duration. *Escherichia coli* concentrations are reduced by microbial competition in the SuDS treatment train (Decamp and Warren, 2000; Gagliardi and Karns, 2002). Sovann et al. (2015) reported a 99 % reduction of *E. coli,* solely using an artificial wetland system, while Kumar et al. (2020) and Eregno and Heistad (2019) reported a 58 % and <99 % reduction respectively, with soil filtration methods. The latter studies indicated that *E. coli* removal was more efficient in finer grained soil. Decamp and Warren (2000) showed that *E. coli* removal can be improved by placing a gravel artificial wetland after the soil artificial wetland, which increased the retention time. In our study *Escherichia coli* concentrations were significantly, but weakly correlated with the macronutrient concentrations, indicating a potential growth response of the bacteria to the macronutrients. However, it is more likely that the macronutrients and *E. coli* are introduced by the same transport pulses and events as seen for *E. coli* and TSS in urban stormwater in Melbourne, Australia (McCarthy et al., 2012).

This treatment train falls under tertiary and secondary treatment measures, which also includes designs such as grass swales, permeable pavements and infiltration trenches, artificial wetlands, all which requires substantial space to effectively reduce the pollution load in a system (Prajapati et al., 2017). The advantage of using the 500 L plastic tanks to contain filtered media is that it can be housed in a much smaller space, close to the source, and still be effective (height 4 m, length 5 m). The SuDS treatment train can process 6 L/min or 8 640 L day^{-1} of water once filled, which exceeded the capacity of the Markman canal that had a flow rate of 2000 L day^{-1}, at the time of the study. The materials of the treatment train were recycled or were available at local hardware stores, which makes it cost effective and readily available for anyone to construct (approximate cost 1300 USD). The design is simple and can be easily replicated or upscaled/downscaled to increase the capacity and efficiency of the treatment train.

The SuDS treatment train in our study was based on the water sensitive urban design (WSUD) guidelines for South Africa (Armitage et al., 2014). This study was the first in the country to design and test a SuDS treatment train for pollution inputs into estuaries. The design of the SuDS treatment train includes utilising the treated water for local irrigation purposes or discharge into the estuary. Recycling the water for irrigation reduces demand on the potable water supply and is the preferred end point for this experiment. This this assessment of the effectiveness of the SuDS treatment train can be an incentive for local authorities to implement such interventions.

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CRediT authorship contribution statement

Conceptualization, T.M.; methodology, T.M.; formal analysis, all authors; resources, T.M. and J.A.; data curation, writing—original draft preparation, T.M.; writing—review and editing, all authors; visualization, T.M. & M.N.; project administration, T.M., B.S.; funding acquisition, T.M., J.A. All authors have read and agreed to the published version of the manuscript.

Institutional review board statement

Ethical review and approval were not applicable for this study due to no involvement of human or animal subjects.

Informed consent statement

Patient consent was not applicable due to no involvement of human subjects.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Thandi Mmachaka reports financial support and administrative support were provided by Republic of South Africa Department of Water and Sanitation. Thandi Mmachaka reports a relationship with Republic of South Africa Department of Water and Sanitation that includes: employment.

Data availability

The raw data supporting the conclusions of this article will be made available by the authors, on request.

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