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Association of coal fired power plants with river water quality in South Africa

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ABSTRACT

The national power utility owns and operates approximately 95% of the coal-fired power plants (CFPPs) in South Africa. It has been hypothesised that power generation activities lead to the acidification and salination of surface water sources in the vicinity of CFPPs, with upwind sites more polluted than downwind sites. For the purpose of this study, three of power utility's CFPPs were selected, namely Kriel, Komati and Camden Power Plants, which will be reaching the end of their operating lifespan during the mid-to-late 2020 s. The main aim of the study was to analyse the raw water quality data upstream and downstream of these three CFPPs. Raw water supply to the CFPPs for power generation was abstracted from the Rietspruit, Koringspruit and Witpuntspruit streams, respectively. To determine whether the particulate and gaseous emissions affected the water quality from 2012 to 2018, multivariate statistical analyses were applied. The water quality data indicated poor water quality both downwind and upwind of the power plants when thirteen out of 20 (65%) selected water quality variables exceeded the resource quality objectives (RQO) limits, which could be attributed to anthropogenic activities such as agriculture, coal burning and coal mining; causing increased acidity and salinity in the various water sources. In conclusion, the study suggested that there is no direct correlation between the emissions from coal burning and the coal-fired power plants receiving streams; an indication that power generation may not be the only anthropogenic factor influencing the water quality of the streams.

1. Introduction

Good water resource governance in a water-scarce environment such as South Africa is a strategic issue in setting national sustainable development priorities (Hobbs et al., 2008). To add further pressure on the country's sustainable development, Southern Africa's water resources would decrease due to climate change. Falkenmark et al. (1997) suggested that various countries in Southern Africa will be in a water-deficient class by 2025 with less than 500 cubic metres of water per year per person, while South Africa bears absolute water shortages (Al-Gamal, 2021). Despite the potential impacts of climate change on water resource governance, the country has a limited response to climate change and coal-fired power plants (CFPPs), which are the primary emitters of greenhouse gases (GHGs) and dominate the energy sector (Wassung, 2010). The national power utility, Eskom, owns and operates approximately 95% of the CFPPs responsible for all the electricity produced in South Africa and 45% of that produced on the African continent (Department of Public Enterprises (DPE), 2014). The national power utility relies mainly on coal for this generation capacity, providing over 90% of the country's energy needs from CFPPs operations (Eskom, 2020).

Wassung (2010) suggested that, given the significantly higher water usage by CFPPs than that of most renewable energy (Department of Energy (DoE), 2015), the transition to a clean energy infrastructure might be more successfully motivated by water scarcity than by the promise of reduced carbon emissions. Additionally, water quality is under-reported and under-studied in the Mpumalanga Province of South Africa, where the majority of the CFPPs lie, due to the primary focus

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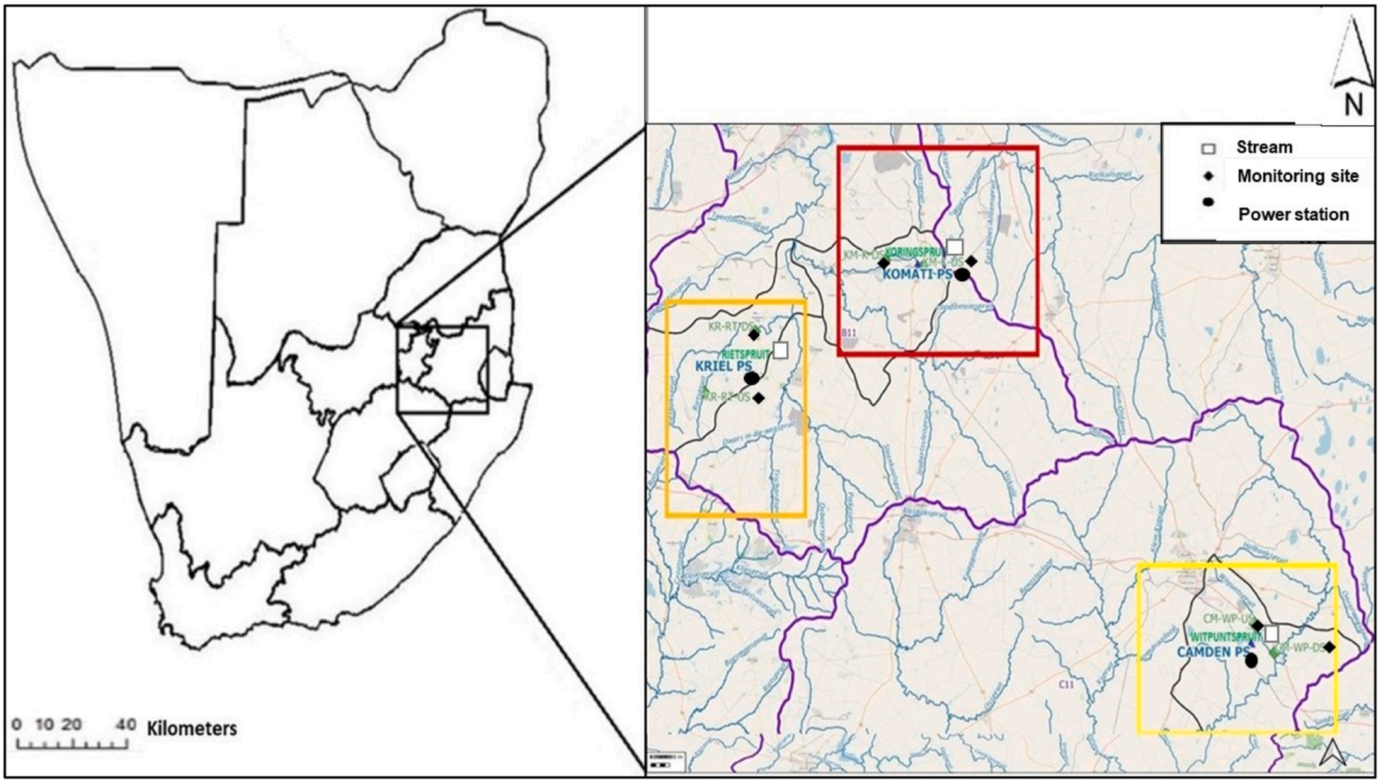

Fig. 1. Map of biomonitoring network sites from 2012 to 2018 with water management areas sub divided into sub-quaternary reach codes B11 and C11, with B11 situated in the Olifants WMA and C11 located in the Vaal WMA, respectively (Eskom, 2020).

being on sufficient water supply (McMahon et al., 2007). Furthermore, the discharge of domestic and industrial effluent wastes, leakage from water tanks, radioactive waste and atmospheric deposition have been the major causes of acid mine drainage from coal mines and water pollution in the Mpumalanga area (Haseena et al., 2017).

Previous studies yielded different conclusions on whether the atmospheric deposition from CFPP affects the water quality of the neighbouring water sources. Examples of these old studies include Garstang et al. (1996); Piketh et al. (1998); Weathers and Lovett (1998) as well as Van Tienhoven and Fey (1999), which further pointed out that atmospheric deposition does not always happen near the pollution source. Moreover, industrial emissions are generally a local concern, with the transportation of trace chemicals with industrial signatures occurring over thousands of kilometres (Molebatsi, 2002a; Durgapersad, 2008; Maliba, 2016). Although, none of the studies could demonstrate the effects of particulate matter (PM) on aquatic communities, PM coupled with sulphur dioxide (SO_2), nitrogen dioxide (NO_2) and metal is associated with harmful effects on the health of aquatic communities near the CFPPs (Nkambule, 2015).

The US Department of Energy (2009), Russell et al. (2017) and Crawford et al. (2018) have all mentioned in their studies, although not demonstrated, air pollutants' effects when deposited in the water body, which can potentially negatively influence the quality of open water bodies and subsequently aquatic flora and fauna. Long-term water quality surveillance schemes are an exceptional technique providing insight into river hydrochemistry and pollution, but they process high volumes of information, which are often difficult to construe (Dixon and Chiswell, 1996; Vega et al., 1998; Huang et al., 2017; Logan and Stillwell, 2018; Stefanidis et al., 2019). However, these longer-term studies are scarce in South Africa and that limits the awareness and effects associated with CFPPs' activities. Although longer-term studies prior to the 1990 s exist in the national power utility, the historical dataset (1990–2008) is limited, as it lacks the inclusion of the same array of sites used in the current (2012–2018) and detailed dataset.

The current study follows these papers in statistical analysis and focuses on three of the national power utility's CFPPs, namely Kriel, Komati and Camden, which are situated in the Mpumalanga Province of South Africa, from 2012 to 2018. The study focussed on the gaseous and particulate emissions from the CFPPs due to the power plants not discharging any effluents to the environment. The surface runoff pathways were excluded in the current study due to Eskom CFPPs adopting a zero liquid effluent discharge (ZLED) policy, where 100% of the freshwater is reclaimed and the liquid waste removed by producing solid salt. The ZLED is the method used in the national power utility to reduce water use and treat water before recycling it for use within the specific CFPP. Moreover, the power plants do not receive their cooling water from the investigated streams and do not discharge any effluents, hence the focal point of the article on emissions.

The current study aimed at analysing the water quality data obtained by the power utility from the CFPPs' receiving streams to determine whether the particulate and gaseous emissions have affected their water quality. The hypothesis tested was that the water quality of sites upwind of the CFPPs is in a more deteriorated state compared to the water quality of downwind sites. Although there is a great deal of literature on the air quality impacts of these pollutants, and literature on acid rain impacts, PM_{10} impacts on water bodies seem to be a gap and therefore the current study needed to investigate the linkages of the particulates and other gaseous pollutants (SO_2 and NO_2) to water quality using the multivariate statistical analyses. The study is of significance since there is continued pressure to move away from fossil fuel power generation. Therefore, the analysis of cumulative impacts from multiple sources of chemical and non-chemical stressors in the downwind and upwind rivers of Upper Vaal and Upper Olifants sub-catchment areas is related to how well the changes in CFPP's impacts on the water quality are managed.

2. Methods

2.1. Study area

The study area comprises the quaternary drainage regions B11B (Koringspruit), B11E (Rietspruit), and C11B (Witspuntspruit), with the former two situated within the Olifants Water Management Area (WMA), while the latter region is located in the Vaal River WMA, as shown in Fig. 1. The first of these selected streams, Rietspruit, has two sampling sites, namely KR-RT-US, which is located upwind of the Kriel Power Plant, and KR-RT-DS, located downwind of the CFPP. The second stream, the Koringspruit, has two sites, namely KM-K-US, found upwind of the Komati Power Plant, and KM-K-DS, located downwind of the Komati Power Plant. Lastly, Witsputspruit has two sampled areas, namely CM-WP-US, which is located upwind of the Camden Power Plant, and the CM-WP-DS, which is located downwind of the CFPP.

The study area represented a range of highly industrialised areas such as Secunda and Ermelo, where the Kriel and Camden power plants are located, to the more rural area of Komati, where the Komati Power Plant is located. The air pollution sources in the area include nearby coal mining and handling company, along with haul truck exhaust emissions; domestic fuel use; agriculture and biomass burning as well as small industries. The Camden Power Plant is situated near the coal mining operations including a railroad siding. All three sites are influenced by coal fired power plants and, further afield, a large petrochemical refinery.

2.2. Data availability

2.2.1. Water quality data

In this study, water quality and physical habitat variables were monitored at each sampling site.

Water quality samples were collected from six sampling sites biannually between 2012 and 2018. The first dataset of the national power utility from 1990 to 2008 has a six-year gap where no sampling was done. The six-year gap is divided into two periods, from 2005 to 2007, and from 2009 to 2011, and sampling resumed in 2012. The Council of Scientific Industrial Research (CSIR) was responsible for gathering data from 1990 to 2001, thereafter, CSIR was accompanied by the author and jointly collected data between 2002 and 2004. Furthermore, in 2008, the data was collected by Durgapersad (2008). However, this first old dataset was limited to sites that do not match the 2012–2018 dataset, and therefore, for the purposes of this study, only data from 2012–2018 collected by Maliba and Mkhoza (2018) was considered due to its detail and completeness.

The sampling entailed both in-situ (pH, temperature, dissolved oxygen and electrical conductivity) and ex-situ water quality assessments at all sites where the South African Scoring System (SASS5) was performed. The ex-situ collection of water samples for chemical analysis was conducted at the analytical chemistry section of the power utility's Research, Testing and Development (RT&D) department. Furthermore, the SASS5 analyses and Integrated Habitat Assessments System (IHAS) were conducted at all selected sites. The SASS5 included rinsing two 1 L plastic bottles and then filling them with a water sample. The first 1 L bottle was stored in a cooler box, and the second sample was preserved with nitric acid (HNO_3) for metal analysis before being placed in the cooler box.

The samples were analysed for a number of water quality variables, including total alkalinity ($CaCO_3$), aluminium (Al), ammonia (NH_4^+), cadmium (Cd), calcium (Ca^{2+}), chloride (Cl), electrical conductivity (EC), potassium (K), magnesium (Mg^{2+}), manganese (Mn), mercury (Hg), sodium (Na), nitrate (NO_3^-), lead (Pb), pH, sulphate (SO_4^{2-}), total dissolved solids (TDS), total hardness ($CaCO_3$), turbidity (NTU), and Zinc (Zn). All samples were analysed by the South African National Accreditation System (SANAS)-accredited laboratory in RT&D. The RT&D personnel measured the water quality variables on-site during the sampling trips with a YSI 556 Multiparameter system (MPS). In addition, the variables included pH, electrical conductivity and water temperature, whereby the Hanna Instruments HI98129 handheld meter was used to measure the pH on-site. Calibration of all handheld meters was done to ensure the accuracy of the results.

The study utilised the resource quality objectives (RQOs) as the criteria for assessment, as shown in Supplementary material Table A 1. Where the RQOs were not available, the South African Water Quality Guidelines compiled by DWAF (1996) for the Vaal River catchment were used for the Upper Vaal River Sub-catchment area, C11. In addition, the ecosystem guidelines set by Australian and New Zealand Environmental Conservation (ANZECC, 2000) and the South African Water Quality Guidelines for aquatic ecosystems, as shown in Supplementary material Table A 1, were used as an alternative for both the Vaal and Olifants River Sub-catchment areas. The purpose of analysing the water quality data was for the effective water quality and impact management from power generation through coal combustion.

The integrated water management plan (IWMP), as stated in the DWS (2016) regulations for both the Upper Vaal and Upper Olifants River Sub-catchments, recommends the use of RQOs listed in Supplementary Table A1 for the respective river catchments. The RQOs of the nutrients for the catchments were used to ensure that the nutrient concentration is maintained in the river at a mesotrophic or better Trophic State Index (TSI) of 40–60, having a moderate level of biological productivity (DWS, 2016). Additionally, it was to ensure that adequate and improved water quality levels avoid nuisance conditions for recreation, and the salt concentrations were maintained at levels that do not render the ecosystem unsustainable (DWS, 2016). Therefore, the current study utilised the RQOs as a priority and used ANZECC Fresh Water Quality Guidelines and South African Ecosystem Guidelines as an alternative for all selected sites (Upper Vaal and Upper Olifants Sub-catchment areas), as shown in Supplementary material Table A 1.

2.2.2. Macroinvertebrate data

The biomonitoring of macroinvertebrates in the Upper Olifants (B11B, B11E) and Upper Vaal (C11B) sub-catchment areas was based on a standardised macroinvertebrate sampling method (Dickens and Graham, 2002). Benthic macroinvertebrate communities of the selected sites were investigated according to the South African Scoring System, version 5 (SASS5) approach (Dickens and Graham, 2002). The SASS method is an adequate, effective and efficient method that has survived four different upgrades with the current Version 5 conforming and competing with other world accreditation protocols (Enviross and Fishway, 2012). A macroinvertebrate kick net, of 30-x 30 cm square opening with 1 mm mesh netting, was used to collect the organisms. The current study identified the available biotopes at each site and different methods described below were used to sample each biotope, except when the river was in flood. The combined methods comprised three different groups sampled and assessed separately. These different groups were stone biotope (in current, in bedrock and out of current), vegetation (VG) biotope (both marginal and submerged) as well as gravel, sand and mud (GSM) biotope. The sampling method included identifying the organisms sampled in each biotope group and noting their relative abundance on the SASS5 datasheet as seen in Supplementary material Table A3 to A37.

The current study used accredited and trained power utility personnel, as SASS is a highly specialised field, and also as a legal requirement. On-site, habitat assessments were conducted using existing habitat evaluation indices (McMillan, 1998). The SASS5 monitoring was aimed at determining an ecological category using a regional or Biological Bands and catchment-specific approach (Dallas and Day, 2007). The organisms were identified to the lowest possible taxonomic level and this was mostly family level. The purpose of biomonitoring was to assess the condition of aquatic ecosystems, thereby providing a good reflection of the possible impacts of CFPP's operations on receiving waters. Furthermore, the purpose was to assess whether or not CFPP's operations have had a negative effect on the aquatic ecosystems upwind

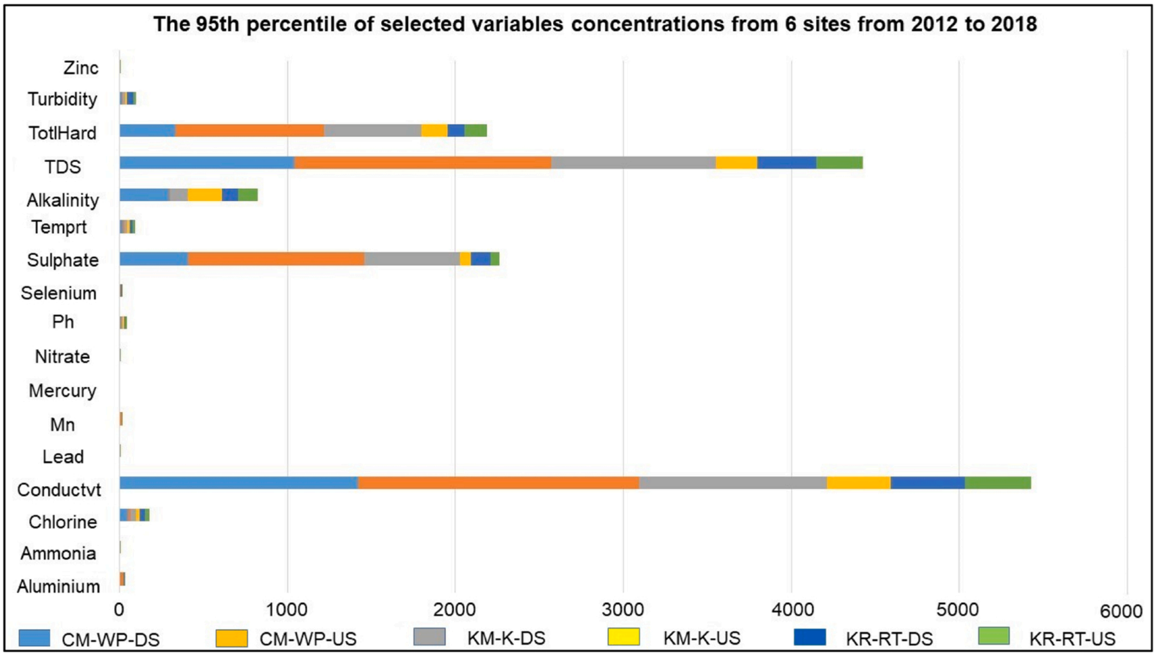

Fig. 2. The 95th percentile concentrations of selected variables present in water samples collected bi-annually from four Upper Olifants Sub-catchment B11B and B11E areas and two sites in the Upper Vaal Sub-catchment C11B area from 2012 to 2018.

and downwind of the CFPPs. The multivariate analysis accompanied the assessment in identifying the water quality trends of the Rietspruit, Koringspruit and Witpuntspruit rivers.

2.3. Data analysis

Statistical analyses were completed using both univariate and multivariate as well as trend (spatial and temporal) analyses. Firstly, the principal component analysis (PCA) was used to explore the relationship between water chemistry variables and spatial distribution of sampling sites, using CANOCO, version 5 software. The CANOCO software is an extension of DECORANA and formerly stood for canonical correspondence analysis (Hill, 1979; Ter Braak, 1986); however, the program has recently been extended to cover PCA as well. Then, the macroinvertebrate community analysis was completed for seasonal box and whisker plots to show differences in distribution using GraphPad Prism version 5.00 for Windows (GraphPad Software, San Diego California USA, www.graphpad.com) (Wepener et al., 2011) to show differences in distributions. In the current study, box and whisker graphs depicted minimum, maximum, mean, standard deviation, 5th percentile and 95th percentile values. The clustering and grouping of the data were done in accordance with the average score per taxon (ASPT) scores and comparable individual SASS biotope scores in gauging the potential effect of reduced water quality on the biotic integrity.

3. Results and discussion

The results section describes the physical, chemical and biological conditions at six riverine sites in the Upper Olifants (B11B, B11E) and the Upper Vaal (C11B) sub-catchment areas. The study also provided an opportunity to assess the biological integrity of these sub-catchments as a basis to later develop reference sites for long-term biological monitoring. An assessment of the spatial and temporal trends of various water quality variables in the Upper Olifants (B11B, B11E) and Upper Vaal (C11B) sub-catchments was undertaken by analysing water quality data obtained from the routine water quality monitoring from 2012 to 2018.

3.1. Water quality data analysis

The water quality data analysis results indicated that RQOs were exceeded by sulphate at CM-WP-US and KM-K-DS, while total dissolved solids exceeded ANZECC guidelines at the CM-WP-US, KM-K-DS and KM-K-US sites, as seen in Fig. 2. There was no trend shown by these two salts in indicating that the upwind sites had lower salinity than the downwind sites, as both sites occasionally exceeded the sulphate and TDS concentrations. This could be due to the mines surrounding the CFPPs releasing the waste water to the upstream site of the Koringspruit River, as shown in Fig. 1. Furthermore, South African Water Quality guidelines were exceeded by the aluminium and electrical conductivity at all the sampled sites, as observed in Fig. 2 and Supplementary material Table A 1, as a guide. Moreover, South African Water Quality guidelines were exceeded by pH at the Witpuntspruit upwind site, as seen in Fig. 2 and Supplementary material Table A 1, showing that the Witpuntspruit upwind site had more alkalinity than the downwind site. Thirteen out of 20 (65%) selected water quality variables exceeded the limits of the guidelines with nine variables exceeding the RQOs, while three exceeded the South African Water Quality guidelines, with only one (TDS) exceeding the ANZECC limits.

The aluminium, selenium, chloride and mercury exceeded the RQO limits at all six sampled sites, indicating that pollution existed at both the upwind and the downwind sites. Furthermore, manganese exceeded the RQO limits only at the upper Vaal Sub-catchment area sites and by zinc at the Witpuntspruit upwind site. Moreover, at all four Upper Olifants Sub-catchment area sites, total alkalinity exceeded the RQO limits, again proving that pollution existed along the two Upper Olifants River sites, regardless of the river reach position. These Upper Olifants Sub-catchment area sites, exceeding acceptable limits, indicate that pollution could be from both the mining and the agricultural activities showing that the pollution in the rivers is not solely coming from the CFPPs. Similarly, the same pollution origin was found by Dabrowski and De Klerk (2013) when once-off sampling was conducted at a number of sites located upstream and downstream of mines and agriculture. The number of areas within the river reach had exceedingly lower phosphate compared to nitrate concentrations (Dabrowski and De Klerk, 2013). However, in Dabrowski and De Klerk’s (2013) study, an increase in

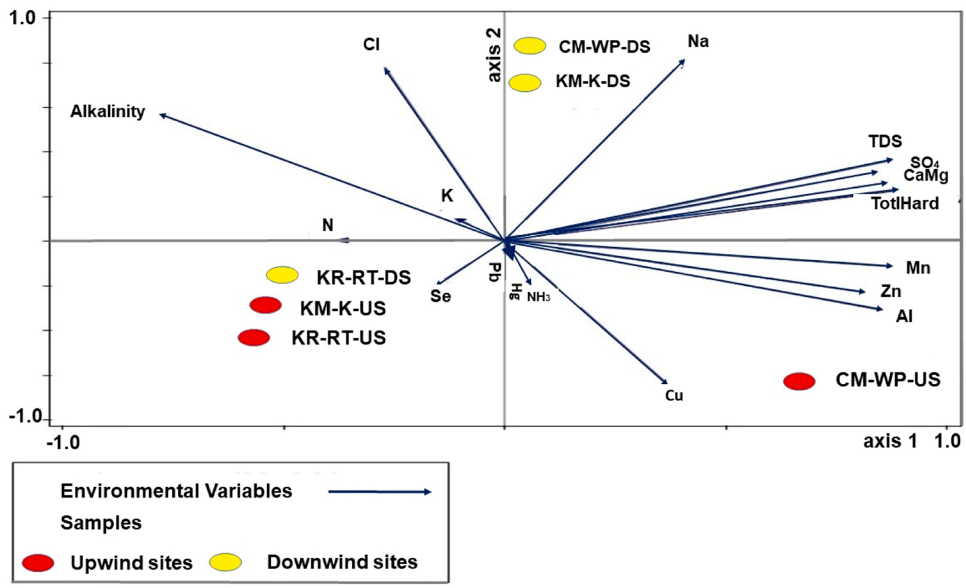

Fig. 3. Principal component analysis bi-plot showing the influence of selected water quality parameters at sites in the Upper Olifants Sub-catchment B11 B & E and Upper Vaal Sub-catchment C11 B areas for the mean concentrations of selected variables present in water samples collected bi-annually from the sampling period 2012–2018.

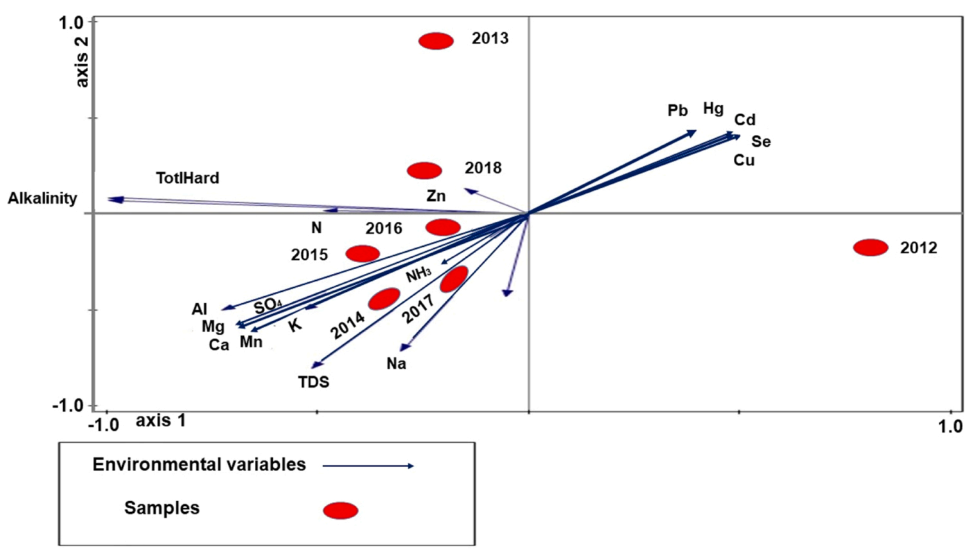

Fig. 4. Principal component analysis biplot showing associations between selected water quality parameters throughout the sampling period 2012–2018, in the Upper Olifants Sub-catchment B11B & E and Upper Vaal Sub-catchment C11B areas. Mean concentrations of selected variables present in water samples were collected bi-annually.

sulphate concentrations from upstream to downstream indicated that mining activities have a greater impact on water quality, although there was no observable trend from upstream to downstream.

3.2. Temporal and spatial variation in water quality data using principal component analysis

The present study used mean water quality parameters from 2012 to 2018 to draw up a PCA, as observed in Fig. 3. The first and second axes explained 72.73% and 18.7% of the variation, respectively, when focusing on spatial trends. Total dissolved solids, sulphate, calcium, magnesium, and total hardness were co-linear and depicted a strong relationship on the first axis. A significant positive correlation between total dissolved solids, sulphate, calcium and magnesium was found at sample sites CM-WP-DS and KM-K-DS. These sample sites showed an association with sodium concentration. On the second axis, manganese, zinc, and aluminium showed to be co-linear and depicted a strong relationship with each other. A significant positive correlation was found at sample site CM-WP-US between manganese, zinc and aluminium. A significant negative correlation was found in this sample point between total alkalinity, cadmium and potassium concentrations.

When focusing on the temporal trends using the PCA plot for 2012–2018, as shown in Fig. 4, the first and second axes explained 87.9% and 6.3% of the variation, respectively. On the first axis, aluminium, magnesium, calcium, sulphate, manganese, potassium, total dissolved solids, sodium, ammonia, and chloride showed to be co-linear and depicted a strong relationship between each other, although ammonia and chloride had low concentrations. A significant positive correlation was found during sampling years 2014–2017 between aluminium, magnesium, calcium, sulphate, manganese, potassium, total

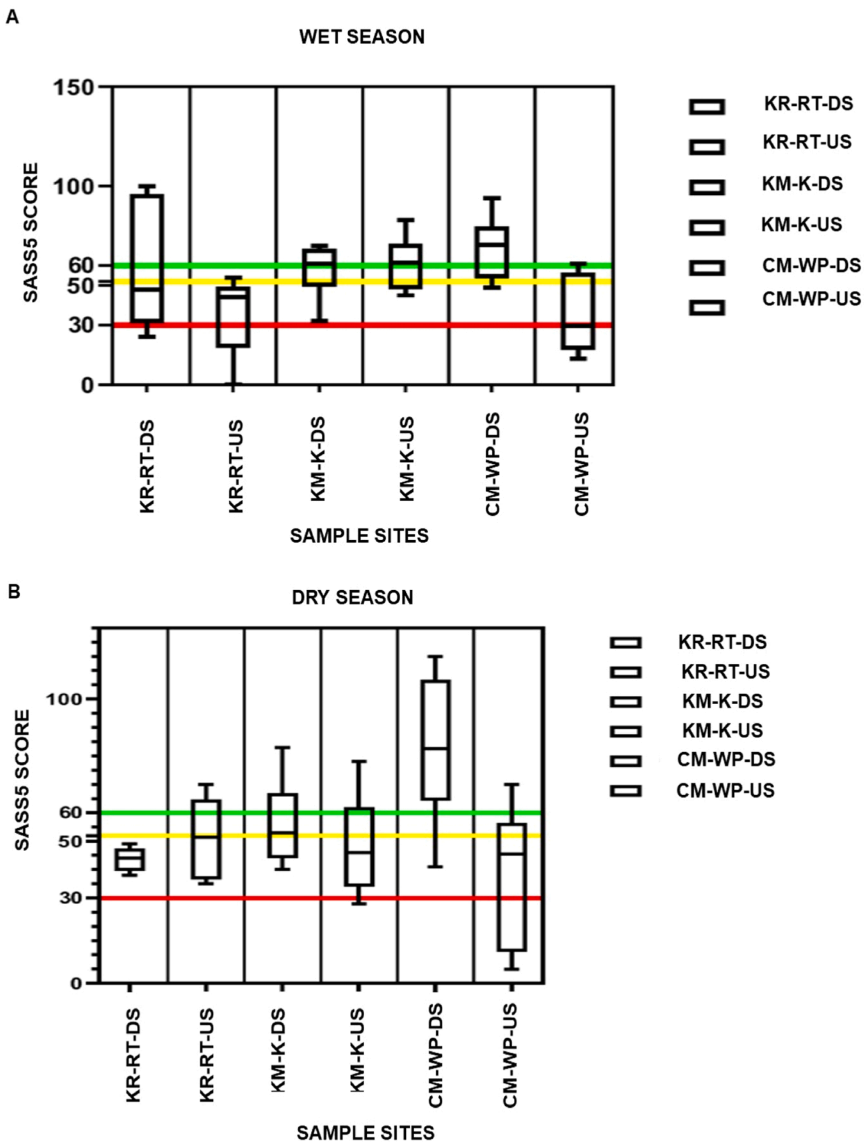

Fig. 5. Box and whisker plot showing the SASS5 scores recorded at six sampling sites during the (A) wet and (B) dry season surveys (2012–2018). The coloured lines represent the ecological category (slightly modified SASS score represented by a green line, moderately modified SASS score represented by a yellow line while the considerably modified SASS score is represented by a red line).

dissolved solids, sodium, ammonia and chloride. On the other hand, a significant negative correlation was found from the 2014–2017 sampling years between copper, selenium, cadmium and mercury concentrations.

On the second axis, total alkalinity, total hardness and zinc were co-linear, although the zinc concentration was low. A positive correlation between total alkalinity, total hardness and zinc was found in sampling year 2018. This correlation showed that the most impacted years were 2014, 2015, 2016, 2017 and 2018, where most of the water quality parameters were present in higher concentrations in the riverine water system. These findings showed increasing trends in all the sampling sites during the period of 2014–2018. The PCA results showed that for the observed data period, total hardness, sulphate, magnesium, total dissolved substances, and calcium were the high-scoring components. These components were followed by aluminium, manganese, and zinc as the second highest-scoring components found on the second axis. In Fig. 3, as much as the components found on the first axis are associated with high scores, driven by CM-WP-DS and KM-K-DS, the impacts at these downwind sites cannot be attributed solely to the CFPPs' operation as there are other anthropogenic activities operating in these areas. On the second axis, the highest-scoring components were associated with the CM-WP-US site, while the lowest-scoring components were associated with KM-K-US, KR-RT-US and KR-RT-DS sites.

3.3. Macroinvertebrate data analysis

The aim of the RQOs for the two sub-catchments was to assess whether the macroinvertebrates' ecological category remains greater or equal to the SASS score and range/score of B (82) for the Upper Vaal C11 sub-catchment and greater or equal to the range/score of D (42) for Upper Olifants sub-catchment B11 (DWA, 2011). The results shown in Table 2 indicate that downwind sites KM-K-DS and KR-RT-DS were moderately modified (C), while the CM-WP-DS site was slightly modified (B). The results can be interpreted to mean that the Komati upwind site was moderately modified (C) compared to the downwind site that was slightly modified (B) as far as pollution from CFPP is concerned; with A–blue (SASS score > 82) category representing the naturally unmodified conditions; the B–green (SASS score < 82) category referring to slightly modified conditions; while the C–yellow (SASS score > 52) category refers to moderately modified conditions. Furthermore, the

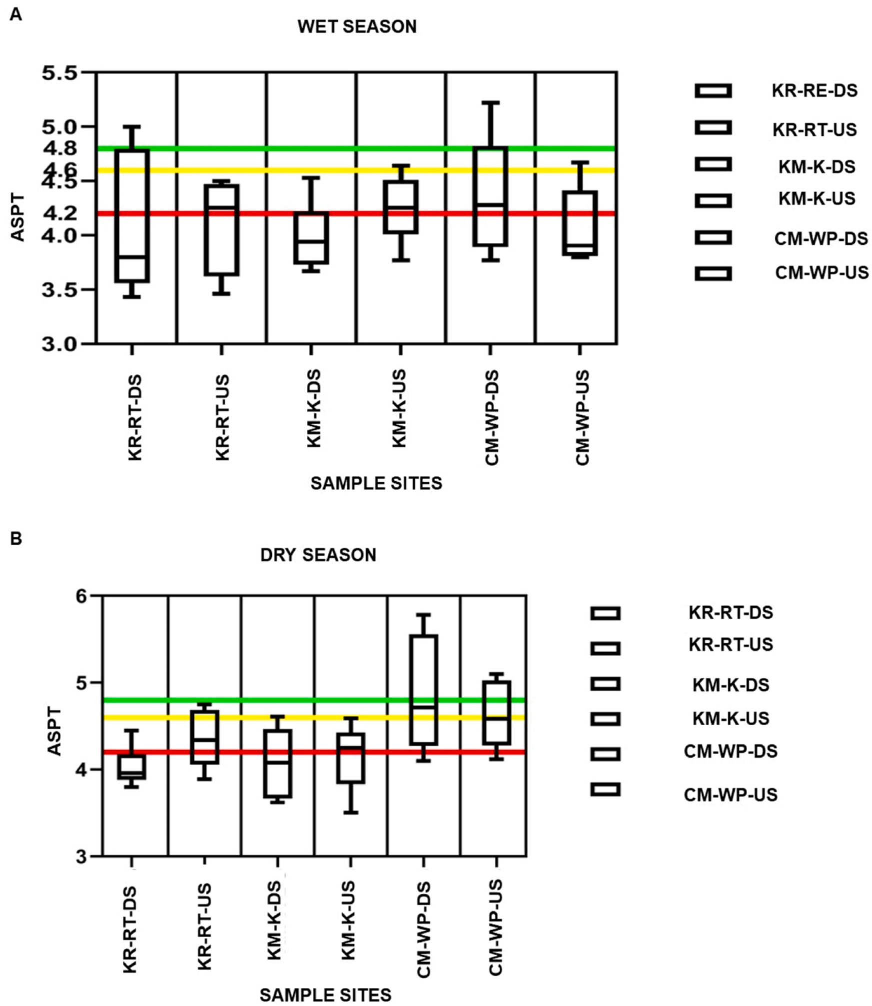

Fig. 6. Box and Whisker plot showing the ASPT scores recorded at the six sampling sites during the (A) wet and (B) dry season surveys (2012–2018). The coloured lines represent the ASPT scores for each sample site (slightly modified ASPT score represented by a green line, moderately modified ASPT score represented by a yellow line while the considerably modified ASPT score is represented by a red line).

D–red category represents the range between 31 and 52, referring to a largely or considerably modified conditions, while the E–purple and F–black (<31) categories refer to seriously or critically modified conditions (Dallas, 1995; Munyika et al., 2014).

The Komati downwind (KM-K-DS) site improved in terms of the modification than their upwind counterpart. Moreover, the upwind sites were mainly considerably modified (D) even as observed at sites KR-RT-US and CM-WP-US, although only the KM-K-US site proved to be moderately modified (C). The SASS5 score for the KM-K-US site was found in the 30–51 range compared to the downwind site range of 52–59. These results are indicative of the downwind sites (KM-K-DS, KR-RT-DS and CM-WP-DS) that have adequate/fair integrity of habitat assessed compared to the upwind sites, as shown in Table 2. However, the ASPT score was variable between 4.2 and 4.6 for all the assessed sites, except for site CM-WP-DS, which was variable between 4.6 and 4.8, as shown in Table 2. The results showed that the upwind sites of the three sampled rivers were more polluted than the downwind sites, suggesting the existence of other upstream sources impacting the water quality of the three rivers, be it agricultural, mining or industrial activities. Therefore, the CFPPs alone could not be attributed to the catchments' water quality deterioration.

Box and whisker plots, as shown in Figs. 5 to 7, illustrate biomonitoring data as an indication of the status of the river health for the years 2012–2018. The surveys were separated into dry and wet seasons for the SASS5, ASPT and IHAS results for linking to emissions data. The dry season was from June to August, while the wet season was from December to February. On average, during both dry and wet seasons, the Rietspruit and Witpuntspruit upwind sites were observed to have considerably modified (D) average SASS5 scores of 44 and 36, respectively, while all Rietspruit, Koringspruit, and Witpuntspruit downwind sites showed some moderately modified (C) SASS5 scores of 61, 61 and 58, respectively, as shown in Fig. 5 A and B. The results suggest that the upwind sites of the three CFPPs are more polluted than the downwind sites where other anthropogenic activities such as mining could be found, as shown in Fig. 1. Another possibility is that these results could suggest the inherent seasonal differences in benthic macroinvertebrate communities affecting SASS5 scores where the highest ASPT value appears to be in the wet season.

As per box and whisker plots for the SASS5 scores, all sites indicated high variability during the dry season, except site KR-RT-DS. In contrary, a low variability at all other sites was seen during the wet season, except KR-RT-DS, as shown in Fig. 5 B and 5 A, respectively. Furthermore, there was an increase in the SASS5 scores during both the wet and dry seasons between sites CM-WP-DS and KM-K-DS, as shown in Fig. 5 A and 5 B. Historically, the SASS5 scores mirror the number of macroinvertebrate families found in that particular site.

The general trend in ASPT values for the various streams is similar between seasons and when all data from seasons is combined (Dallas, 1995). In terms of the ASPT, site KR-RT-DS indicated a high variability during the wet season compared to the other sites along the Upper Vaal

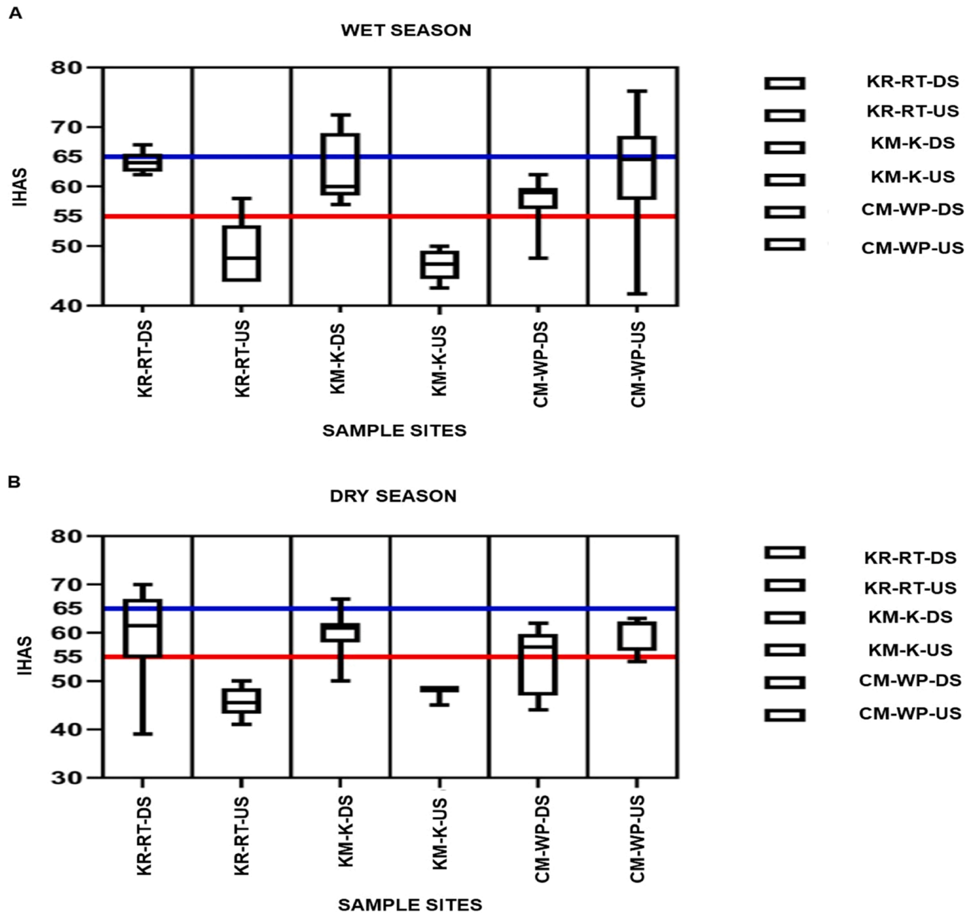

Fig. 7. Box and Whisker plot showing the IHAS scores recorded at the six sampling sites during the (A) wet and (B) dry season surveys (2012–2018). The coloured lines represent the IHAS scores for each sample site (good IHAS score represented by the blue line while the poor IHAS score is represented by the red line).

River sub-catchment. In contrast, site KR-RT-DS showed the least variation during the dry season as shown in Fig. 6 A and 6 B, respectively. Again, an increasing trend in SASS5 and ASPT scores was observed at CM-WP-DS, KM-K-DS and KR-RT-DS, as shown in Fig. 5 A, 5 B, 6 A and 6 B.

During the dry season period, the integrated habitat availability and suitability (IHAS) was significantly higher at most of the downwind sites than at the upwind sites, as shown in Fig. 7 A and 7 B. The results show that the sites downwind to the CFPPs in the three receiving rivers of the national power utility's operations are less modified than the upwind sites where other anthropogenic activities might be taking place.

Wassung (2010) and Mathetsa et al. (2019) have conducted studies with similar results when analysing more critically the impact of CFPPs on climate change and South Africa's water resources, which culminate into a water-energy climate change (WECC) nexus. Wassung (2010) expressed that several studies written on the energy-water nexus emanate from a US perspective, many of which were commissioned by the US Department of Energy, while Mathetsa et al. (2019) suggested that South Africa is one of those sub-Sahara African (SSA) countries likely to be affected by impact originating from WECC due to about 90% of the energy produced from water-reliant coal-combustion, nuclear, hydropower and pump-storage technologies. Molebatsi (2002b) also argued that the primary variables of concern to aquatic organisms are pH and metals (such as Al concentration), and Al has been affecting fish as early as the mid-1970 s

River flows throughout the Upper Vaal and Upper Olifants rivers catchment are heavily dependent on groundwater base flows – especially during the dry season (McCartney et al., 2004). According to McCartney et al. (2004), naturally occurring sources of fluoride and nitrate in the surface water of the Upper Olifants and Upper Vaal rivers pose risks to human health, wildlife and the environment in general. However, impact of surface water by mining, industrial and domestic effluents is an emerging risk across both catchments. Annual volume of flow and annual TDS load were carried by the main stem of the Upper Vaal and Upper Olifants rivers and its tributaries (Smakhtin, 2001) for the 2012–2018 hydrological year (January 2012 to December 2018). During the 2012–2018 hydrological year, the available data indicate that the Rietspruit and Koringspruit rivers did not contribute measurable flows to the Upper Olifants River. Simultaneously, the Witpuntspruit River did not contribute measurable flows to the Upper Vaal River.

4. Conclusion

The current study results supported the hypothesis that the upwind sites to the CFPPs are more polluted than the downwind sites of the receiving rivers. Two thirds of the PCA spatial and temporal analyses results showed that the river sites downwind to the CFPPs, namely CM-WP-DS and KM-K-DS became more polluted than their upwind counterparts, over time, while the KR-RT-DS showed the opposite. In addition, the macroinvertebrate data analysis using box and whisker plots showed explicitly that the upwind sites are more polluted than the downwind sites. Although the other possible causes of pollution were not investigated by the current study, it was clear that CFPPs were not the sole polluters of their neighbouring streams, namely Rietspruit, Koringspruit and Witpuntspruit.

Currently, South African water legislation is effective in monitoring the water use license conditions for listed activities and operations around the rivers and streams. However, for future purposes, separation and predictive methods such as plume modelling and Bayesian network approaches for relative risk assessment can assist in predicting the future pollution trends and identifying the primary contributing sources of pollutants in both the Upper Olifants and Upper Vaal Sub-catchment areas. Therefore, it is recommended that continuous monitoring of gaseous and particulate emissions as well as that of water quality and macroinvertebrates be continued in the study area in order to advise management of the current pollution status. In addition, further studies involving an analysis of detailed metal concentrations and speciation in the water quality of riverine systems neighbouring the CFPPs could assist in understanding the level of eco-toxicological risk inherent in the study area.

CRediT authorship contribution statement

Conception of design of study: **NB Ngamlana, Dr W. Malherbe & Dr G. Gericke.** Analysis and/or interpretation of data: **NB Ngamlana, Dr W. Malherbe & Dr G. Gericke.** Drafting the manuscript: **NB Ngamlana, Dr W. Malherbe & Dr G. Gericke.** Revising the manuscript critically for important intellectual content: **NB Ngamlana, Dr W. Malherbe, Dr G. Gericke**. Approval of the version of the manuscript to be published. **NB Ngamlana, Dr Wynand Malherbe & Dr Gerhard Gericke**.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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This is contribution number 837 of the North-West University (NWU) Water Research Group.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.limno.2023.126140.

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