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Application of Different Indices to Assess the Trophic Status of a Warm Monomictic Reservoir in the Lesotho Highlands, Southern Africa

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Abstract

Katse Dam(KD), a strategic raw water source to South Africa, is exposed to pollution from mining and aquaculture production. The organic pollution index (OPI), the modified pollution index (MPI), and Carlson's trophic state index (CTSI) have not been previously applied to KD. The current study applies these indices to assess the trophic status of KD in the first decade (FD) (2003-2013), when the intensity of mining and aquaculture activities was minimal, and compares with the second decade (SD) (2014-2024) when production was higher. The Pollution Index of KD revealed that it transitioned from contaminated during the FD to greatly contaminated during SD. KD shifted from eutrophic status to hypereutrophic status in the lacustrine zone during the SD. The cyanobacteria *Radiocystis* sp. replaced *Asterionella* sp. and became the most pollution-tolerant algae in the SD, followed by the diatom *Flagilaria* sp. The pollution index (PI) values of physico-chemical parameters increased from 65 in the FD to 160 in the SD. OPI classifies KD as extremely polluted, with values above the threshold of 5 OPI in the SD. Application of the different indices, attribute mining, and aquaculture as influential to the transition of KD from mesotrophic to eutrophic in the transitional zone. The findings provide environmental managers with a basis to mitigate pollution at source to secure good water quality.

Keywords: nutrients; trophic status; phytoplankton; concentration; index; genera

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1. Introduction

Water is essential for driving the economy, supporting socio-economic development and the provision of ecosystem services that sustain life [1]. Yet the quality and quantity of water available in freshwater ecosystems is rapidly declining due in part to nutrient enrichment exacerbated by anthropogenic activity [2], so much that one quarter of people on earth lack access to clean water [3]. Katse Dam (KD), thermal characteristics reveal that it is a warm monomictic reservoir that stratifies in summer and mixes only once a year in winter [4]. Stratification and mixing affect nutrient cycling, vertical migration, and biological processes, which selectively cause dominance of certain phytoplankton genera in the photic zone [5]. Further, Paris et al. [6] argue that adaptive responses to physico-chemical parameters by phytoplankton drive succession, diversity , and tolerance to pollutants.

Mining and aquaculture production are two major sources of pollution that influence the trophic status of the KD. The opening of Liqhobong mine and Kao mine in the Lesotho highlands in 2011 [7] marked the commencement of prolonged and intense mining upstream of KD. Mining contributes nitrates, whose source is ammonium nitrates embedded in the explosives used for blasting the ore [8,9]. It increases metal concentrations in water bodies, inhibiting biological processes of fish and pollution-sensitive algae such as *Asterionella* sp. [10]. Notwithstanding, pollution-tolerant phytoplankton such as *Fragilaria* sp. and fish such as brown trout adapt and thrive in polluted environments and replace sensitive species [6]. In addition, aquaculture production causes organic

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pollution, which increases phytoplankton biomass and affects its trophic status [11]. This sequence of events indicates that the organic pollution and eutrophication processes are highly correlated and cyclic processes [12]. The noted water quality challenges necessitate the development of monitoring tools to profile the trophic status of KD to avert water quality degradation and enable sustainable water resources management [13].

Previous attempts to profile the trophic status of KD remain limited to a few studies. These include Roos [4], who investigated the influence of pollutants on trophic status using descriptive statistics. The application of modern indices to characterize the trophic status of the KD using phytoplankton as biological pollution indicators remains unexplored. Particularly, the direct correlation of biological indicator parameters to physico-chemical parameters to understand the dynamics that lead to eutrophication has not been researched at the KD, similar to studies by Oberholster et al. [14] and Akter et al. [15]. Consequently, an in-depth investigation into the association of physico-chemical parameters with phytoplankton composition, diversity, and dominance of pollution-tolerant algae represents a necessary and valuable research direction for a strategic raw water source like KD. The proposed study seeks to close the existing knowledge gap by finding scientific evidence that links anthropogenic activities to the pollution status of the KD. It brings a unique approach by using more than one index, each focusing on a specific type of pollution as suggested by Mishra et al. [16].

Researchers worldwide have developed different indices to assess water quality and pollution status of various aquatic ecosystems [17,18]. These include the organic pollution index [19], the eutrophication index [20], the comprehensive diatom index [21], the pollution index developed by [22], and Carlson's trophic state index [23]. Various researchers modified these indices to fit different environmental conditions. While phytoplankton has been used extensively to assess pollution in aquatic systems in Europe [24], the development of indices that incorporate biological indicators has not been explored adequately worldwide [25]. According to Oberholster et al. [14], an effective index uses a single value on a numerical scale to represent the complex interaction between phytoplankton and physico-chemical parameters to indicate their tolerance or sensitivity towards pollution.

The current study introduces a unique approach through the application of advanced statistical methods to investigate how changing concentrations of physiochemical parameters influence phytoplankton composition, and the trophic status of Katse Dam [26]. Canonical correspondence analysis (CCA) was applied to discover the association between physico-chemical parameters and the phytoplankton assemblage [14,15]. Principal component analysis (PCA) was employed to highlight the major temporal distribution of pollutants that influenced the water quality of KD [26]. The novel contribution of this study further lies in its ability to use indices to highlight the links between organic pollutants, the concentration of physicochemical parameters, and phytoplankton assemblage and their influence on the status of a warm monomictic reservoir over space and time. The study deviates from the approach of a study by Erlangga et al. [27], who instead used phytoplankton as bioindicators of organic pollution to assess the trophic status of the estuary in Indonesia. The current study aims to apply indices to determine changes in the trophic status, and phytoplankton composition and assemblage between the FD and the SD. It explores the spatial and temporal distribution of pollutants and phytoplankton assemblage in the KD due to the impact of pollution from mining and aquaculture production. The aim of the study will be achieved through the following objectives: (1) determine the change in Trophic status of KD using modified Carlson's Trophic state Index(CTSI); (2) investigate the succession and changes in phytoplankton composition of KD using Modified Pollution index over two decades from 2003 to 2024; (3) and assess the pollution status of KD using the organic pollution index (OPI). Overall, KD increased organic pollution above the 5 OPI threshold and shifted from eutrophic to hypereutrophic conditions during the SD.

2. Materials and Methods

2.1. Study Area Description and Selection of Water Sampling Sites

The Katse Dam (29.3368 °S, 28.5062 °E) is located in the Lesotho highlands 2 kilometres downstream of the Bokong River and the Malibamatšo River confluence. Two diamond mining companies, Liqhobong Mine and Kao mine, operate upstream of the Malibamatšo River catchment and potentially bring an influx of pollutants into KD, as shown in Figure 1. In addition, two aquaculture production companies, Katse Fish Farm and Sanlei Trout, operate in the KD, potentially imparting pollution through organic waste from fish feed, excreta of fish, fish scales and fish mortality [28].

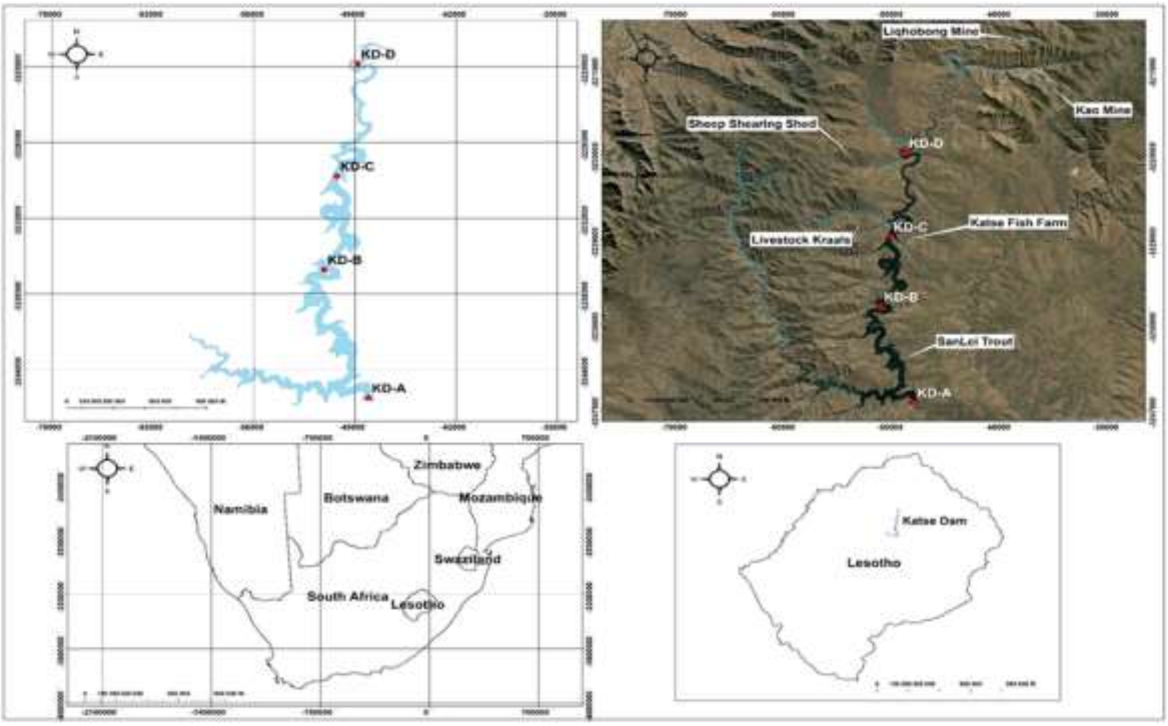

Figure 1. Map of Katse Dam in Lesotho, showing the location of water sampling sites; KD-A, KD-B, KD-C and KD-D.

The Lesotho Highlands Water Project (LHWP) is an inter-basin water transfer project abstracting water from the Senqu River basin in Lesotho for delivery to the Gauteng region of South Africa [4]. The morphometric characteristics of KD are shown in Table 1.

Table 1. Shows the morphometric characteristics of the Katse Dam (adapted from [4]).

Morphometric characteristics	Magnitude
Catchment area	1869 km^2
Crest length	710 m
Maximum width	900 m
Surface area at full supply level	38.5 km^2
Intake tower position upstream of Damwall	18 km^2
Total length	Approximately 35 km
Hight above foundation	185 m
Capacity at full supply level	1950 x 10^6 m^3

Water quality samples for the current study were collected from four water sampling sites(WSS), namely: KD-A, located at Katse Dam wall (lacustrine zone), KD-B, located at the Island (transitional zone), KD-C, located at the Intake (transitional zone), and KD-D, located at the Upstream (riverine zone) as shown in Table 2.

Table 2. The location of the four water sampling sites at Katse Dam.

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Site Number	Katse Dam site name	Transitional zones	GPS Coordinates	
			Latitude	Longitude
KD-A	Dam wall	Lacustrine	29.332604	28.504942
KD-B	Island	Transitional	29.240807	28.473924
KD-C	Intake	Transitional	29.173980	28.483194
KD-D	Upstream	Riverine	29.093910	28.498472

2.2. *Methodological approach*

The methodological approach employed in the current study follows steps shown in Figure 1: (1) Identify environmental impacts that potentially lead to eutrophication; (2) method and variable selection; (3) application of the selected indices to (4) determine their effectiveness in assessing the trophic status of Katse Dam.

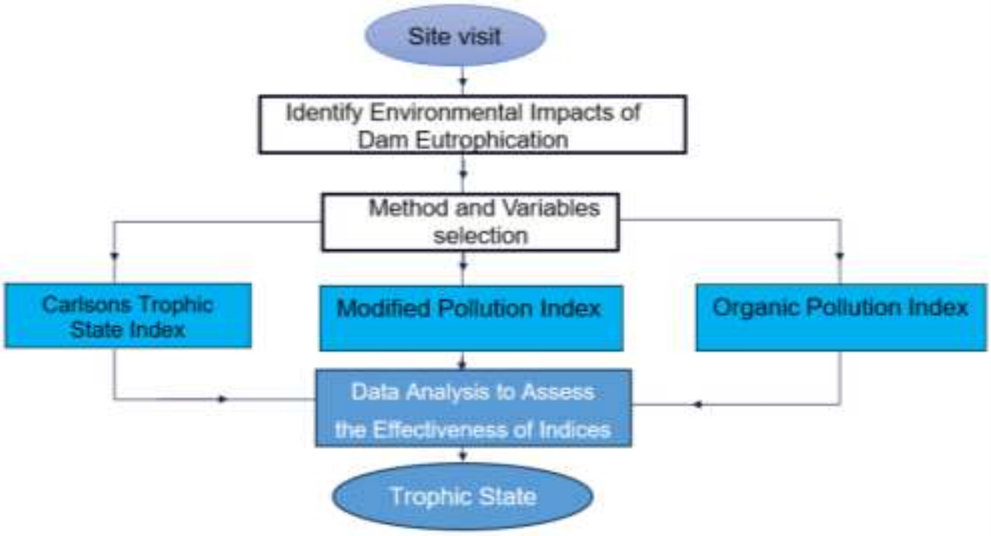

Figure 2. Conceptual framework for assessment of the trophic status of Katse Dam.

2.2.1. Selection of water quality parameters

The selection of parameters for the current study was based on identified environmental pressures in the catchment. In addition to mining activities, aquaculture production is a major pollution source in the Katse Dam. Maleri et al. [28] adopted parameters related to aquaculture to characterise the water quality status of Nietvoorbij Dam in the Western Cape, South Africa. Oberholster et al. [14] incorporated parameters associated with mining and sewage to study their association with phytoplankton assemblage at Loskop Dam, South Africa. Both observations influenced the selection of parameters for incorporation into the indices.

2.2.2. Data collection and laboratory analysis

The Secchi disk was measured using a round 10 cm radius black and white disk suspended from a 15-meter string graduated at each meter interval. Measurements of physical parameters, such as dissolved oxygen (DO), electrical conductivity (EC), and potential hydrogen (pH), were taken in situ according to the Randwater Method numbers 2.1.3.01.2, and 1.1.2.15.1 [29] and [30] using a potable hand-held meter YSI v2-4 6600 multiparameter probe instruments. At each WSS, geographic coordinates were taken using a Garmin eTrex® 10 GPS device. At each WSS, a Von Dorn sampler was used to sample water from a depth of 1.5 m of the photic zone and redistributed into four labelled 1-liter polypropylene bottles pre-rinsed with dilute sulphuric acid for analysis of *chlorophyll*-a, phytoplankton, nutrients, and metals as suggested by Oberholster et al. [14]. *Chlorophyll*-a was analysed using spectrophotometry based on methods prescribed by Swanepoel et al. [31]. The water samples for the analysis of phytoplankton were fixed and preserved with 1% Lugol's iodine solution before sedimentation at the Randwater laboratory according to methods prescribed by [32]. The water samples for analysis of metals were preserved with nitric acid [14]. The water samples were cold-preserved with ice packs during transport to the laboratory and analysed within 24 hours of sampling using standards and automated analytical techniques, based on methods described by American Public Health Association (APHA) [33]. All analysis were conducted at the chemistry and hydrobiology sections of the Analytical Services Laboratory of Rand accredited under South African National Accredited System. Dam water was sampled every month for the study period 2003 to 2010 and every third month for the study period 2011 to 2024 as suggested by Pasztaleniec [25] for a monomictic reservoir like KD.

2.2.3. Thermal stratification effect on trophic status of Katse Dam

The temperatures were taken using the YSI 6600 Sonde fitted with temperature probes and programmed to take measurements every 1 meter down the water column up to 2 m above the bottom sediments at each WSS. The maximum depths obtained were corrected using meters above sea level (masl) readings at the time of sampling. The temperature readings were plotted against corresponding masl depths on an Excel spreadsheet to illustrate mixing in winter and the three distinct layers of stratification in summer: the upper epilimnion, middle thermocline, and the lower hypolimnion.

2.2.4. Phytoplankton analysis

Phytoplankton identification and enumeration to genus and species level were done by the Hydrobiology Section of Rand Water Analytical Services where all water samples were subjected to a centrifugation and sedimentation technique described by Van Vuuren et al. [34]. After settling, all algal cells were counted with an inverted light microscope at a magnification of 250x using a technique described by [32]. The concentration of individual phytoplankton genera and species was expressed in terms of cell numbers as cells per millilitre (cells ml -1). All phytoplankton counts were used to determine the presence, abundance, and dominance of genera and species in each sample [34]. Phytoplankton diversity, dominance, composition, tolerance, and sensitivity are essential to measure for the assessment of the trophic state of reservoirs [35]. A technique used by Oberholster et al. [14] was employed to measure evenness or dominance of each algal species using the Berger-Paker Index (BPI) [36] following the equation:

$$\mathbf{D} = \frac{\boldsymbol{Nmax}}{\boldsymbol{N}} \tag{1}$$

Where Nmax refers to the count of the most abundant individual species present in each sample, and N refers to the sum of individual species sampled at each WSS. The current study focused on calculating PVT values only for identified dominant species per site for each year.

2.3. Data Analysis

2.3.1. Statistical analysis

Physico-chemical parameters and identified phytoplankton data were subjected to Canonical Correspondence Analysis (CCA) using CANOCO version 4.5. The CCA was utilised to evaluate the degree of association between selected water quality parameters and identified phytoplankton species in the FD and in the SD. In the resulting ordinations, parameters are correlated when their pointers are at (90°) angle and showed strong positive correlation if their pointers delimit a small angle and showed strong negative correlation if their pointers were in opposite directions subtending towards (180°) angle [37]. Application of CCA highlights the correlation between phytoplankton species and certain water quality parameters and indicates potential sources of pollution that require

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mitigation to reduce pollution ([38,26]. CCA has been used by researchers to reduce the dimensionality of data, to identify correlations between parameters, and to assist in exploring the water quality and ecological status of investigated aquatic ecosystems [39]. PCA and CCA were performed on the combined data for all four WSS, and for each WSS separately. The PCA and CCA results for individual WSS proved to be almost similar to those obtained for the combination of all four WSS. Therefore, only the combined PCA and CCA results from all four WSS were included, thereby reflecting conditions in the entire dam. The use of PCA minimizes complexity in the data and reveals sources of variability to assist environmental managers to locate areas that require attention [26,37].

2.3.2. Modified Pollution Index

The pollution index developed by Jiang and Shen [22] and modified by Oberholster et al. [14] for the assessment of pollution status of Loskop Dam was applied by following the three steps:

1. The initial step was to calculate the pollution Index (PI) values of the physico-chemical parameters of KD to represent each season of three months using the following formulae

$$\mathrm{PI} = \sum_{i=1}^{n} \frac{C}{CL} \tag{2}$$

Where C is the concentration or measurement of the variable in the KD and CL is the limiting value of the parameter, and in this case, the WHO [40] water quality guidelines and Department of Water Affairs and Forestry (DWAF)[41] guidelines for aquaculture were used. The selected parameters used in this calculation were Secchi disk transparency (SDT), EC, DO,pH, Calcium (Ca), Manganese (Mn), Sodium (Na), Total Dissolved Solids (TDS), Magnesium (Mg), Iron (Fe), Chemical Oxygen Demand (COD), Zinc (Zn), Cadmium (Cd), Copper (Cu), Phosphorus (P), Orthophosphates (PO_4), Ammonia (NH_3), Nitrate (NO_3), Nitrite (NO_2), Chlorophyll-a (Chl-a), Total Organic Carbon (TOC) and Total Suspended solids (TSS), Aluminum (Al), Chloride (Cl) based on their association with aquaculture [28] and with effluent from mining [14]. The aggregation of PI values for each of the physicochemical parameters gives PI for KD, which changes for different years in each decade. The PI values for selected parameters obtained for each year are summed to obtain a total PI value for the decade for the KD.

2. The second step is to evaluate the pollution value of taxa (PVT) for each dominant phytoplankton species for all the FD and SD years per WSS. The formula used was:

$$\boldsymbol{PVT =} \ \left(\sum_{i=1}^{n}\left(\frac{\frac{PI}{s}}{n}\right)\right)/N \tag{3}$$

Where n is the number of physicochemical parameters, PI is the value calculated in step 1 above. N is the number of WSS used in this study based on methods applied by Castro-Roa and Pinilla-Agudelo [24] and s is the total number of years for each decade.

3. The last step is to calculate the pollution index for KD (PIKD) value for the algae community in the KD for each quarter, according to the following formulae:

$$PIKD = \left(\sum_{i=1}^{n}(\boldsymbol{PVT})\boldsymbol{i}\right)/\boldsymbol{n}_5 \tag{4}$$

Where n_5 is the total number of species, PVT is the pollution value per taxa calculated for each species and represents presence of the species at KD. This value is an indicator of the level of pollution of the Katse Dam for the corresponding months. The PIKD was converted to a percentage, where a 100% represented the highest value from which the phytoplankton values were subtracted [24,14].

The modified pollution index method is consistent with Indicator 6.3.2 of the SDG 6 that require methods focusing on physicochemical characteristics of water, including nutrient enrichment as well as biological indicators, including the measurement of algae [2].

2.3.3. Organic Pollution Index

OPI is an important tool that was used by Mishra et al. [16] to classify the water quality of Surah lake in India based on four physico-chemical parameters: COD, (DO, Dissolved Inorganic Nitrogen (DIN) and Dissolved Inorganic Phosphates (DIP). These were estimated by adding up the dissolved and particulate measurements of each nutrient in milligrams per Liter to provide minimum estimates for nutrients [16,19]. Opiyo et al. [43] employed OPI to assess the quality status of Marshes in Basra Province in Iraq. OPI was used in the current study to compare the levels of organic pollution of the KD for the period from 2003 to 2013 and for the period 2014 to 2024. It is expressed as follows [16,19]:

$$\text{OPI} = \frac{COD}{CODs} + \frac{DIN}{DINs} + \frac{DIP}{DIPs} - \frac{DO}{DOs} \qquad (5)$$

The numerators used in equation (5) represent measured concentrations after analysing water samples. DINs is the total limiting concentration of nitrate, nitrite, and ammonium; DIPs is the concentration of Phosphate [19]. According to Son et al. [19], OPI classifies water quality as: Excellent (<0), Good (0-1), Polluted (1-4); Extremely polluted (4-5).

2.3.4. Carlson's Trophic State Index

The Calrson's Trophic State Index (TSI) is based on water clarity (measured as Secchi Disk Transparency (SDT)), nutrient concentration (measured as Total Phosphorus (TP) and the algal biomass (measured as Chlorophyll-a (Chl-a) being the major components that influence eutrophication state [43]. The Trophic State Index ranges from 0 to 100 as shown in Table 2 [43]. It is essential to apply TSI to characterise the eutrophication state of Katse Dam using the following equations developed by Carlson [43]:

TSI for water clarity, TSI (SDT) = 60 – 14.41 ln Secchi Disk Transparency (m) (6)
TSI for Total Phosphorus, TSI (TP) = 14.42 ln Total Phosphorus (ug/l) (7)
TSI for *Chlorophyll* -a, TSI (Chl-a) = 9.81 ln *Chlorophyll*-a (ug/l) + 30.6 (8)
Trophic State Index, TSI = [TSI(TP) + TSI(CA) + TSI (SDT)] /3 (9)

Where ln is the natural logarithm, SDT is in meters and TP and Chlorophyll -a are in microgram per Liter (µg/l). The Trophic State Index ranges from 0 to 100 (Table 2).

Despite Karpowicz et al. [44] arguing that TSI components lack reliability during mixing of large reservoirs, the current study uses TSI to classify the KD Trophic state according to Table 3. The state of nutrient enrichment of aquatic ecosystems is described as trophic state and depends on the concentration of total nitrogen, phosphates, *chlorophyll*-a, and SDT [45].

Table 3. Carlson's Trophic State Index classification (Opiyo et al. [43]).

TSI	Trophic Status	Secchi Disk Transparency (SDT)	Total Phosphorus (TP)	*Chlorophyll*-a (Chl-a)
0-40	Oligotrophic	>8 - 4	0 - 12	0 – 2.6
40 -50	Mesotrophic	4 – 2	12 – 24	2.6 – 7.3
50-70	Eutrophic	2 – 0.5	24 – 96	7.3 – 56
70-100	Hypereutrophic	0.5 < 0.25	96– 384	56– 155 +

3. Results and Discussion

3.1. Analysis of Physico-chemical and biological parameters

The average values and standard deviations of selected parameters are shown in Table 4 and Table 5 for the FD and SD, respectively. The parameters are compared with the World Health Organization [40] and the South African Department of Water Affairs and Forestry [41] guidelines for aquaculture. The average nitrates values ranged from 0.13 mg/l to 0.17 mg/l between 2003 and 2013 and were relatively lower than levels between 2014 and 2024, which were in the range 0.25 mg/l to 0.6 mg/l at the four WSS. Variations in the values of EC indicated that average values were higher in the SD with a range of 7.44 mg/l to 8.46 mg/l as compared to the FD, with a range between 6.88 mg/l and 7.09 mg/l. These significant elevations in the concentrations of these key parameters suggest that the KD experienced an influx of pollutants from a point source in the SD. Phosphate levels increased significantly in in the SD, with a range between 0.09 mg/l and 0.12 mg/l, relative to the FD, with a lower range of 0.03 mg/l to 0.04 mg/l. The ammonium (NH_4) range of 0.08 mg/l to 0.13 mg/l is noncompliant with DWAF [41]. Ammonia in both its ionic (NH_4) and non-ionic (NH_3) forms originates from feed residues and fish faeces and has implications of toxicity to fish in the aquaculture cages [46]. DO, which supports aquatic life, is higher in the FD with a range of 7.8 mg/l to 8.3 mg/l relative to the SD range of 6.1 mg/l to 8.0 mg/l due to respiration by fish, decomposition of faeces, fish scales, and fish feed [15,28] following intensified aquaculture production.

Table 4. Average physico-chemical parameters from 2003 to 2013 at Katse Dam (*guideline value not stipulated).

2003-2013		**water quality monitoring sites**				**Guidelines**	
Variable	Units	KD-A	KD-B	KD-C	KD-D	WHO (2018)	DWAF (1996f)
		Chemical parameters					
NH4	mg/l	0.07±0.04	0.07±0.05	0.08±0.04	0.07±0.04	*	< 0.025
NO_3	mg/l	0.13±0.08	0.13±0.06	0.16±0.10	0.17±0.06	0-50	< 300
NO_2	mg/l	0.03±0.03	0.04±0.03	0.03±0.02	0.04±0.02	0-3	< 50
P	mg/l	0.07±0.05	0.07±0.03	0.07±0.04	0.07±0.04	*	<1
PO_4	mg/l	0.04±0.01	0.03±0.02	0.04±0.02	0.04±0.03	*	*
TOC	mg/l	2.34±0.43	2.14±0.40	2.28±0.39	2.21±0.42	*	*
Ca	mg/l	9.03±0.42	8.79±0.41	9.12±0.67	8.88±0.92	*	*
Cu	mg/l	0.01±0.01	0.01±0.00	0.01±0.00	0.02±0.01	0-2	< 0.005
Zn	mg/l	0.01±0.00	0.01±0.01	0.01±0.00	0.01±0.00	0-3	*
Cd	mg/l	0.00±0.00	0.00±0.00	0.00±.0.00	0.07±0.11	*	*
Fe	mg/l	0.02±0.01	0.04±0.05	0.02±0.01	0.04±0.02	0-2	*
Mn	mg/l	0.01±0.01	0.01±0.02	0.01±0.00	0.01±0.01	0.4	< 0.1
Na	mg/l	2.37±0.99	2.16±0.86	2.41±1.01	2.52±1.75	0-50	*
Mg	mg/l	3.16±0.22	3.33±0.20	3.24±0.21	3.14±0.20	*	*
K	mg/l	0.30±0.12	0.26±0.14	0.3±0.08	0.33±0.16	*	*
DIN	mg/l	0.34±0.23	0.36±0.25	0.49±058	0.57±0.7	*	*
DIP	mg/l	0.093±0.06	0.07±0.03	0.04±0.03	0.078+0.05	*	*
		Physical parameters					
EC	mS/m	7.09±0.64	7.17±0.39	7.10±0.20	6.88±0.41	*	*
pH	at 25°C	8.71±0.45	8.32±0.49	8.53±0.30	8.58±0.60	*	6.5-9.0
SS	mg/l	5.19±0.90	6.15±2.23	6.25±3.18	8.22±0.17	*	*
SDT	m	6.56±0.74	5.61±0.54	4.48±0.66	3.01±0.72	*	*
COD	mg/l	6.00±1.17	5.62±1.09	5.96±1.03	6.01±1.18	*	*
DO	mg/l	7.99±0.48	7.96±0.49	7.97±0.53	8.25±0.61	*	5.0-8.0
		Biological Variable					
Chl-a	µg/l	5.00±1.03	4.50±1.56	5.08±2.49	7.95±4.68	0-30	*

KD displayed a relatively higher SDT in the FD, with a range of 3.01 m to 6.56 m, as compared to a lower SDT with a range of 2.82 m to 5.01 m in the SD. This observation isconsistent with lower TSS with a range between 5.19 mg/l and 8.22 mg/l in the FD relative to a range of 10.9-12.03 mg/l in the SD. The inverse relationship observed between TSS and SDT was more pronounced at KD-D, located in the riverine zone, and was attributed to sediment runoff from the inflowing river overlayed by mining (Figure 1) and suspended organic matter from aquaculture [4]. The intensity of both activities increased inin the SD and contributed to degraded watger qualityw. The average concentrations for most parameters are higher in the FD (Table 4) than in the SD (Table 5), which provides evidence of degraded water quality in the KD.

Table 5. Average physico-chemical parameters measured from 2014 to 2024 at Katse Dam.

2014 - 2024		Water Quality monitoring sites				Guidelines	
Variable	Unit	KD-A	KD-B	KD-C	KD-D	WHO (2018)	DWAF (1996f)
		Chemical parameters					
NH4	mg/l	0.09±0.06	0.08±0.07	0.08±0.04	0.13±0.09	*	< 0.025
NO_3	mg/l	0.25±0.12	0.31±0.11	0.34±0.30	0.60±0.50	0-50	< 300
NO_2	mg/l	0.02±0.01	0.02±0.02	0.04±0.07	0.02±0.03	0-3	< 50
P	mg/l	0.26±0.08	0.46±0.46	0.18±0.13	0.30±0.09	*	<1
PO_4	mg/l	0.10±0.05	0.12±0.15	0.06±0.03	0.09±0.04	*	*
TOC	mg/l	2.01±0.52	2.19±0.69	2.83±1.21	1.96±0.46	*	*
Ca	mg/l	9.73±0.65	9.81±1.13	9.43±0.74	9.47±0.75	*	*
Cu	mg/l	0.01±0.00	0.01±0.00	0.01±0.00	0.01±0.00	0-2	< 0.005
Zn	mg/l	0.01±0.00	0.31±1.01	0.01±0.00	0.01±0.00	0-3	*
Cd	mg/l	0.00±0.00	0.02±0.03	0.00±0.00	0.01±0.02	*	*
Fe	mg/l	0.19±0.23	0.06±0.07	0.04±0.05	0.17±0.16	0-2	*
Mn	mg/l	0.01±0.00	0.01±0.00	0.01±0.00	0.02±0.01	0.4	< 0.1
Na	mg/l	2.43±0.57	2.24±0.45	2.29±0.75	2.53±0.59	0-50	*
Mg	mg/l	3.59±0.95	3.32±0.62	3.28±0.25	3.27±0.26	*	*
K	mg/l	0.57±0.20	0.37±0.12	0.43±0.18	0.61±0.24	*	*
DIN	mg/l	0.2±0.16	0.12±0.15	0.23±0.14	0.24±0.13	*	*
DIP	mg/l	0.04±0.04	0.036±0.05	0.04±0.03	0.043±0.05	*	*
		Physical parameters					
EC	mS/m	7.44±2.34	8.31±1.2	7.63±0.68	8.46±0.98	*	*
pH	at 25°C	8.67±0.62	8.30±0.37	8.35±0.33	8.28±0.4	*	6.5-9.0
TSS	mg/l	10.22±2.32	9.65±4.14	10.90±9.82	12.03±5.44	*	*
SDT	m	5.04±1.39	4.30±1.42	3.80±1.10	2.82±1.05	*	*
COD	mg/l	7.81±0.53	9.67±6.58	7.85±0.50	7.93±0.50	*	*
DO	mg/l	8.04±6.38	7.30±3.59	6.09±1.56	7.85±3.86	*	5.0-8.0
		Biological parameters					
chl-a	µg/l	2.75±0.77	1.0±2.20	4.01±1.44	9.11±7.31	0-30	*

3.2. Phytoplankton distribution and Succession

The physico-chemical changing concentrations of physico-chemical parametersdrive the selective succession of phytoplankton communities and diversity of phytoplankton [15,46]. The phytoplankton composition, diversity, and succession in KD for the FD and SD were highlighted by BPI results, shown in Table 6. According to Pasztaleniec [25], diatoms tend to dominate mesotrophic reservoirs, while the blue-green algae dominate hypereutrophic reservoirs. *Cosmarium* sp. was the dominant species in 2003 at all WSS with a range of 0.32 – 0.95 BPI. *Cosmarium* sp. is normally found in clean oligotrophic and alkaline organic-rich reservoirs [47]. *Cosmarium* sp. was replaced by *Asterionella* sp., which was dominant at all WSS in 2005 with a range of 0.28 to 0.64 BPI. The *Asterionella* sp. is indicative of low phosphate values and moderate to high nitrate concentrations in temperate oligotrophic reservoirs [48]. Notably, there was evidence that over the years, a community of *Radiocystis* sp. became dominant towards the end of the FD and was later succeeded by *Fragilaria* sp. in the early years of the SD. Both *Radiosyctis* sp. and *Fragilaria* sp. are indicative of increased eutrophic conditions and phosphate loading in semi-mesotrophic reservoirs [48]. The BPI value of 1 for *Fragilaria* sp. in 2014, with ranges of 0.64 to 0.78 and 0.39 to 0.86 in 2021 and 2022, respectively, indicated an aquatic ecosystem that is dominated by pollution-tolerant algae species. While several phytoplankton species were identified at the four WSS at varying counts, the current study focused on calculating PVT values only for those that dominated based on the application of the BPI per site for each year (Table 6).

Table 6. Longitudinal distribution of dominant species at the Katse Dam in the FD and SD.

Year	KD-A	BPI	KD-B	BPI	KD-C	BPI	KD-D	BPI
2003	*Cosmarium* sp.	0.71	*Cosmarium* sp.	0.95	*Cosmarium* sp.	0.32	*Cosmarium* sp.	0.38
2004	*Chlamydomonas* sp.	0.35	*Oocystis* sp.	0.47	*Asterionella* sp.	0.69	*Asterionella* sp.	0.79
2005	*Asterionella* sp.	0.34	*Asterionella sp.*	0.28	*Asterionella* sp.	0.43	*Asterionella* sp.	0.64
2006	*Asterionella* sp.	0.26	*Asterionella* sp.	0.15	*Radiocytis* sp.	0.69	*Asterionella* sp.	0.54
2007	*Radiocystis* sp.	0.33	*Radiocytis* sp.	0.41	*Radiocytis* sp.	0.66	*Fragilaria* sp.	0.48
2008	*Radiocystis* sp.	0.72	*Radiocytis* sp.	0.79	*Radiocytis* sp.	0.33	*Radiocytis* sp.	0.46
2009	*Monoraphidium* sp.	0.33	*Radiocytis* sp.	0.32	*Radiocytis* sp.	0.43	*Radiocytis* sp.	0.44
2010	*Quadrigula* sp.	0.50	*Radiocytis* sp.	0.90	*Radiocytis* sp.	0.62	*Fragilaria* sp.	0.74
2011	*Radiocystis* sp.	0.97	*Cosmarium* sp.	0.38	*Radiocytis* sp.	0.49	*Radiocytis* sp.	0.77
2012	*Radiocytis* sp.	0.60	*Cosmarium* sp.	1.00	*Radiocytis* sp.	0.74	*Pennate diatoms*	0.90
2013	*Microcytstis* sp.	0.95	*Fragilaria* sp.	0.33	*Radiocytis* sp.	0.63	*Radiocytis sp.*	0.69
2014	*Fragilaria* sp.	0.59	*Fragilaria* sp.	0.53	*Radiocytis* sp.	0.72	*Fragilaria* sp.	1.00
2015	*Cryptomonas minor*	*0.50*	*Fragilaria* sp.	0.73	*Fragilaria* sp.	0.70	*Fragilaria* sp.	0.59
2016	*Radiocystis sp*	0.96	*Radiocystis* sp.	0.93	*Radiocystis* sp.	0.97	*Radiocystis* sp.	0.53
2017	*Dynobryon* sp.	0.50	*Fragilaria* sp.	0.81	*Fragilaria* sp.	0.91	*Fragilaria* sp.	0.60
2018	*Cosmarium* sp.	0.43	*Fragilaria* sp.	0.90	*Fragilaria* sp.	0.87	*Fragilaria* sp.	0.66
2019	*Radiocytis* sp.	0.53	*Centric diatoms*	0.89	*Radiocytis* sp.	0.41	*Fragilaria* sp.	0.47
2020	*Radiocytis* sp.	0.22	*Centric diatoms*	0.31	*Nitzschia* sp.	0.33	*Fragilaria* sp.	0.50
2021	*Fragilaria* sp.	0.70	*Fragilaria* sp.	0.67	*Fragilaria* sp.	0.78	*Fragilaria* sp.	0.64
2022	*Fragilaria* sp.	0.39	*Fragilaria* sp.	0.47	*Fragilaria* sp.	0.86	*Fragilaria* sp.	0.77
2023	*Radiocystis* sp.	0.92	*Radiocytis* sp.	0.95	*Radiocystis* sp.	0.75	*Radiocystis* sp.	0.82
2024	*Radiocystis* sp.	0.65	*Fragilaria* sp.	0.61	*Fragilia* sp.	0.60	*Radiocystis* sp.	0.44

The dominance of *Radiocystis* sp. in the FD from 2007 to 2013 and the dominance of *Fragilaria* sp. in the SD at varying degrees, indicated fluctuating PVT values in Table 7. This was evidence of the presence of specific water quality parameters. The data reveal that the highest detection frequency of the diatom species *Fragilaria* sp. was in the SD, samples, particularly from the KD-D site, indicating eutrophic conditions at the riverine zone. Overall, while several species occurred at low frequencies and abundance, there were ten dominant species in the FD, while there were seven dominant species in the SD based on the application of the BPI. Many reservoirs, which serve as raw water sources for potable water, are assessed for the presence of toxic cyanobacteria, which tend to dominate the phytoplankton community structure [49]. The *Radiocystis* sp is one such toxic cyanobacterial species that dominated the KD in the FD at the transitional zone at site KD-C.

Species, which dominated less in terms of frequency and abundance in the FD were *Microcystis* sp., *Monoraphidium* sp, *Quadrigula* sp. *Chlamydomonus* sp and Pennate Diatoms with BPI of 0.95, 0.33, 0.50, 0.35, and 0.90, respectively. Dominance of *Microcystis* sp. at site KD-A in 2013 was concerning because it is a toxic cyanobacterium that thrives in warmer conditions [27,50]. In the SD, *Cryptomonas* minor, *Dynobryon* sp., Centric diatoms and *Nitzschia* sp. were dominant with BPI of 0.5,0.5,0.89 and 0.33, respectively. The modified pollution index (MPI) assigns each biological community a single numerical value, referred to as PVT, that indicates its resilience to contamination [14]. *Radiocystis* sp. showed the highest abundance and tolerance with a PVT of 37.8 in 2023 (Table 7).

Table 7. PVT values of dominant phytoplankton species observed in the Katse Dam.

Year	Dominant Species	PVT	Year	Dominant Species	PVT
2003	*Cosmarium* sp.	10.06	2014	*Fragilaria* sp.	29.39
2004	*Asterionella* sp.	10.52	2015	*Fragilaria* sp.	26.31
2005	*Asterionella* sp.	9.98	2016	*Radiocytis* sp.	35.14
2006	*Asterionella* sp	10.66	2017	*Fragilaria* sp.	29.15
2007	*Radiocytis* sp.	12.00	2018	*Fragilaria* sp.	29.77
2008	*Radiocytis* sp.	8.37	2019	*Radiocytis* sp.	24.75
2009	*Radiocytis* sp.	12.76	2020	*Fragilaria* sp.	14.27
2010	*Radiocytis* sp.	14.05	2021	*Fragilaria* sp.	28.90
2011	*Radiocytis* sp.	16.53	2022	*Fragilaria* sp.	25.48

2012	*Radiocytis* sp	15.64	2023	*Radiocystis* sp.	37.77
2013	*Radiocytis* sp.	4.70	2024	*Fragilaria* sp.	25.00

3.3. Phytoplankton relationship with physico-chemical parameters

In addition to hydrodynamics such as thermal stratification and mixing, phytoplankton assemblage structure is influenced by changes in trophic conditions, physical and chemical variable concentrations [15]. The SD was characterized by a few dominant phytoplankton genera with higher PVT values and higher PI values for physical and chemical parameters compared to the FD. While this observation was consistent with the assertion by Castro-Roa and Pinilla-Agudelo [24] that higher PVT values represented higher tolerance to degraded water quality, while lower values represented sensitivity [38], it contrasts with findings by Ladera et al. [38] that aquatic ecosystems with more degraded water quality had many high PVT genera. This study modifies an existing pollution index by Oberholster et al. [14] using the premise that phytoplankton composition and assemblage are influenced by changes in nutrient and chemical concentration of the water body [51]. This premise was confirmed by Oberholster et al. [52] who suggested that metal pollutants like aluminum (Al) and iron (Fe) were found to increase in phytoplankton and organs of fish at varying extents.

Research by Paris et al. [6] revealed that Cd, Cu, Ni, and Zn affect biological processes and induce oxidative stress through biomagnification in the liver of brown trout, which potentially indicate that biological processes of pollution-sensitive phytoplankton are in turn affected, thereby inhibiting their growth. According to Jones et al. [10][53], the replacement of *Asterionella* sp. with more pollution-tolerant species like *Radiocytis* sp. and *Fragillaria* sp. is attributed to the increase in mercury (Hg) and cadmium (Cd), which form complexes with enzymes responsible for metabolism, thereby inhibiting growth and proliferation of these pollution-sensitive algae. Furthermore, research by Saros et al. [48] that Nitrogen availability favored the thriving of *Fragilaria sp.* over *Asterionella* sp. provides reason why the latter was replaced by *Fragilaria* sp. in the SD due to increased nitrate [9] and ammonia [28] from intensified mining and aquaculture production, respectively.

To augment the positive trajectory observed on pollution index (PI) values in Table 8 and PVT values in Table 7, an association of physico-chemical parameters with phytoplankton genera physico-chemical was analysed over the FD and SD on PCA Biplots as shown in Figure 3a and Figure 3b. It was observed in Figure 3b that, in contrast to their weak correlation in the FD (Figure 3a), Na, Ca, Fe, Mg, and pH have a strong positive correlation in the SD (Figure 3b), indicating a point source potentially from mining activity from the upper catchment in the SD [54][10]. A combination of environmental factors, such as trace elements, nutrients, pH, temperature and light, causes phytoplankton growth in aquatic systems [38]. The current study provided evidence that phytoplankton genera have varying sensitivity towards increased concentration of the selected water quality parameters, and they responded appropriately with increased pollution from the FD to the SD, as shown in Table 7. The PCA biplot in Figure 3b shows that Secchi depth, NH_4, PO_4, NO_3, and NO_2 are strongly correlated, which could indicate increased nutrient loading in the SD due to decomposition of fish excreta and scales [28].

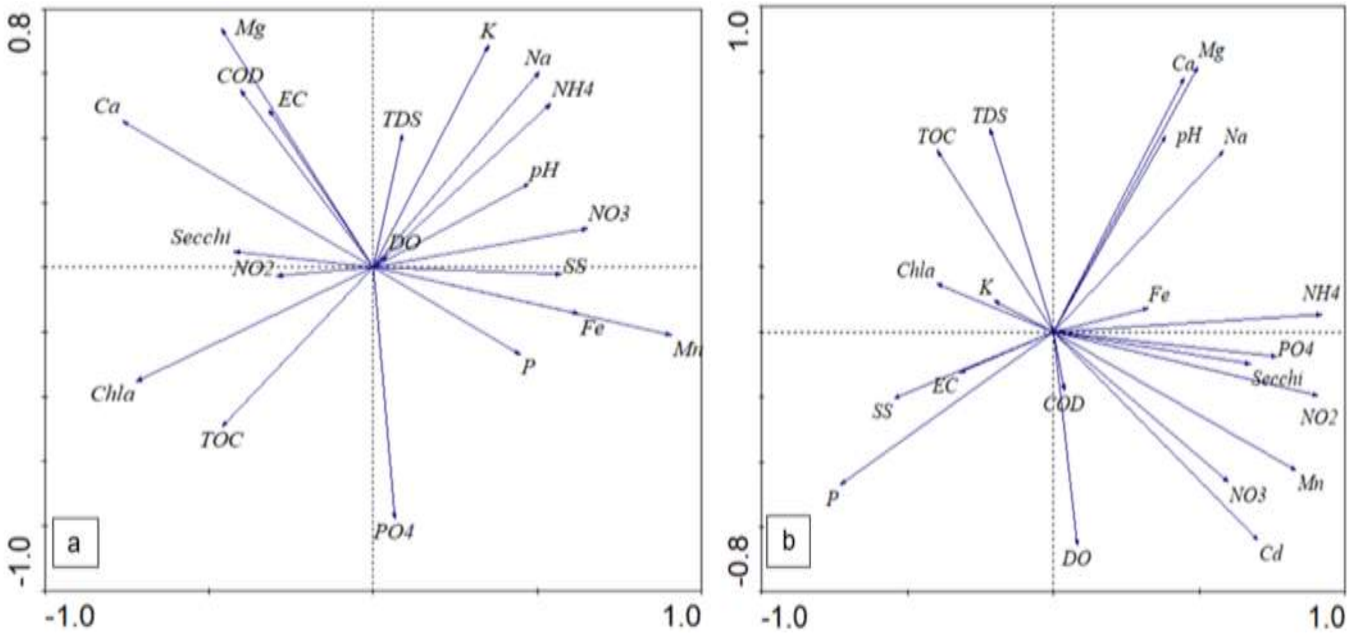

Figure 3. Illustrates Principal Component Analysis (PCA) biplots indicating the association among water quality parameters (PO_4, NO_3, Secchi, pH, NH_4, TDS, SS, EC, TOC, Na, Mg, Cd, Fe, K, COD, P, Chlorophyll-a (Chla), Cl, Mn) in the Katse Dam in the First Decade (2003-2013) and in the Second Decade (2014-2024), respectively.

The CCA was plotted between 11 physico-chemical parameters to illustrate their correlation with dominant phytoplankton genera and species. Figure 4a and Figure 4b illustrate the CCA biplots that draw an association between dominant phytoplankton genera and species with physico-chemical parameters in the FD and SD, respectively. The eigevalue of axis 1 (0.94) indicated a 29.2 % correlation in the FD, while the eigenvalue of axis 1(0.84) indicated a higher 56.2% correlation in the SD, reflecting an increasing trend in the influence of nutrients, PO_4, and NO_3 on *Fragilaria* sp. in the SD. The eigenvalue of axis 2(0.801) indicated a 54.1% correlation in the FD while an eigenvalue of axis 2 (0.34) indicated a 79.2% correlation in the SD between the physico-chemical parameters and dominant phytoplankton, which is attributed to a point source such as mining [14] and consistent with other previous studies [15]. There was a strong correlation between the parameters COD, P and *Cosmarium* sp. in the FD. *Radiocystis* sp. was correlated strongly with parameters, NO_2, NH_4, pH in the FD. In the SD, there was a significant correlation between *Fragilaria* sp. and EC, *Chlorophyll* -a and Ca. There was also a significant positive correlation between *Radiocystis* sp., Secchi depth and COD.

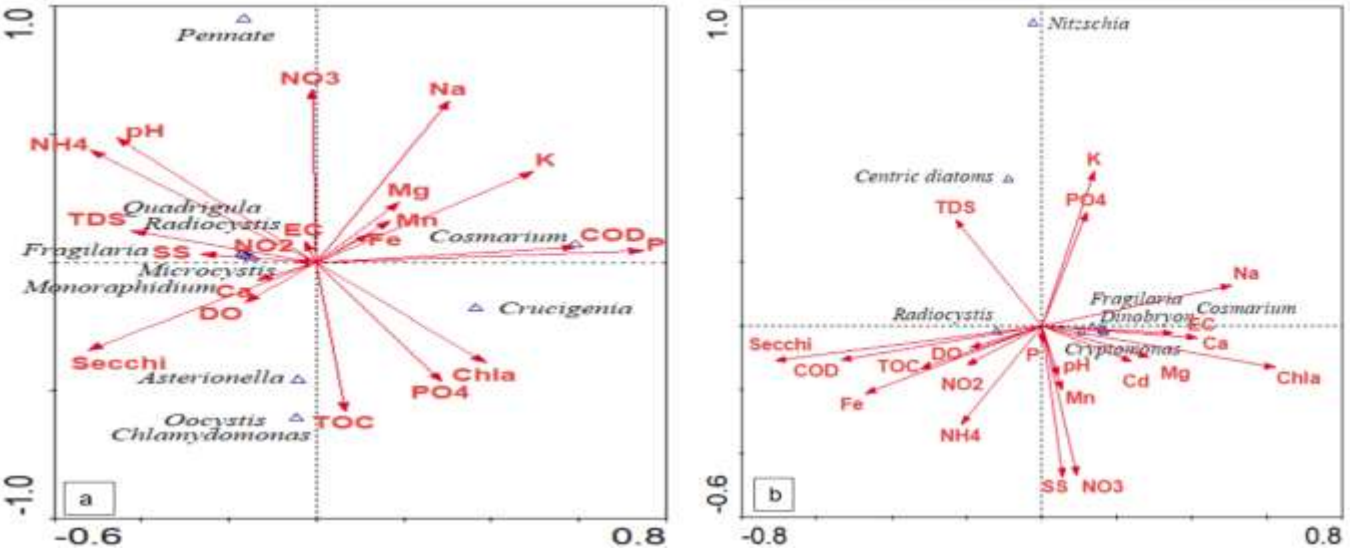

Figure 4. Illustration of Canonical correspondence analysis (CCA) biplot indicating association between dominant phytoplankton species (*Quadricula* sp., *Asterionella* sp., *Radiocystis* sp., *Fragilaria* sp., *Crucigenia* sp., *Monorophidium sp.*, *Microcystis* sp., *Pennate* sp. *Cosmorium* sp., *Chlamydomonas* sp., *Nitzschia* sp., *Centric diatoms*) and water quality parameters PO_4, NO_3, Secchi, pH, NH_4, TDS, SS, EC, TOC, Na, Mg, Cd, Fe, K, COD, P, Chlorophyll-a (Chla), Cl, Mn) in the Katse Dam in the First Decade (2003 – 2013) and in the Second Decade (2014-2024), respectively.

3.4. Pollution Index analysis of Katse Dam

The PI values of water quality parameters in the FD are lower relative to the PI values in the SD. The cumulative PI value is 65.6 in the FD, while it was 160.3 in the SD (Table 8). These results indicate high metal concentrations from a point source of pollution, such as the Liqhobong mine and the Kao mine in the SD (Figure 1). The observations are consistent with a previous study by Oberholster et al. [14] on Loskop Dam that high metal concentrations are indicative of mining effluent. The concentration of P and PO_4 increased in the SD relative to the FD (Table 4 and Table 5). The increment is reflected in the higher PI values of P in the range between 1.04 mg/l and 2.59 mg/l in the SD, relative to the lower range from 0.15 mg/l to 0.44 mg/l in the FD. In addition to the release of P and PO_4 from sediments due to reservoir mixing [54], another major source of P and PO_4 is sewage, laundry, and household detergents, which are washed by runoff from point sources and non-point sources following rainfall [15] in rural catchments like KD, where running water and sanitation are limited or not provided.

Table 8. PI values of water quality parameters measured over FD and the SD at Katse Dam.

Year	DO mg/l	COD mg/l	NH4 mg/l	NO3 mg/l	P mg/l	PO4 mg/l	TDS mg/l	SS mg/l	SD m	TOC mg/l	Ca mg/l	Cu mg/l	Zn mg/l	Cd mg/l	Fe mg/l	Mn mg/l	Na mg/l	Mg mg/l	Chla ug/l	EC mS/m	pH	Total PI
2003	0.25	0.22	0.25	0.14	0.21	0.27	0.38	0.43	0.38	0.38	0.28	0.04	0.07	0.18	0.14	0.06	0.32	0.28	0.47	0.25	0.28	5.27
2004	0.25	0.21	0.24	0.14	0.27	0.27	0.36	0.71	0.33	0.36	0.27	0.05	0.06	0.34	0.14	0.06	0.31	0.26	0.37	0.24	0.27	5.51
2005	0.23	0.20	0.23	0.13	0.23	0.26	0.34	0.60	0.31	0.35	0.25	0.04	0.06	0.28	0.13	0.05	0.30	0.25	0.50	0.23	0.25	5.23
2006	0.26	0.22	0.26	0.14	0.24	0.28	0.39	0.55	0.38	0.39	0.28	0.05	0.07	0.24	0.15	0.06	0.33	0.29	0.48	0.26	0.29	5.58
2007	0.31	0.27	0.30	0.16	0.31	0.33	0.47	0.54	0.50	0.47	0.34	0.06	0.09	0.22	0.18	0.09	0.38	0.34	0.28	0.31	0.35	6.29
2008	0.21	0.18	0.20	0.11	0.20	0.22	0.30	0.45	0.30	0.31	0.22	0.04	0.05	0.20	0.12	0.05	0.26	0.22	0.32	0.20	0.23	4.39
2009	0.33	0.28	0.32	0.17	0.28	0.34	0.50	0.52	0.51	0.50	0.36	0.06	0.09	0.21	0.19	0.09	0.41	0.37	0.45	0.33	0.37	6.68
2010	0.35	0.30	0.33	0.18	0.41	0.38	0.52	0.74	0.53	0.53	0.38	0.06	0.11	0.33	0.19	0.09	0.43	0.37	0.41	0.34	0.39	7.36
2011	0.42	0.36	0.41	0.22	0.38	0.44	0.62	0.81	0.63	0.62	0.45	0.08	0.11	0.35	0.25	0.11	0.52	0.46	0.56	0.41	0.46	8.66
2012	0.38	0.33	0.37	0.20	0.44	0.42	0.57	0.87	0.56	0.57	0.41	0.07	0.11	0.40	0.21	0.09	0.47	0.40	0.51	0.37	0.42	8.19

2013	0.09	0.08	0.09	0.06	0.15	0.11	0.13	0.54	0.09	0.12	0.10	0.02	0.02	0.29	0.06	0.02	0.12	0.09	0.09	0.09	0.11	2.46
First decade cumulative pollution index value																						65.6
2014	0.59	0.57	0.71	0.79	2.22	1.49	0.77	0.66	0.60	0.97	0.60	0.05	0.94	0.24	1.36	0.18	0.65	0.60	0.31	0.53	0.56	15.4
2015	0.52	0.50	0.59	0.67	1.76	1.39	0.67	0.57	0.54	0.90	0.54	0.04	1.24	0.24	1.10	0.14	0.58	0.54	0.25	0.48	0.51	13.8
2016	0.69	0.68	0.78	0.84	2.36	1.88	0.91	0.77	0.77	1.22	0.74	0.05	1.60	0.29	1.51	0.16	0.77	0.73	0.32	0.64	0.69	18.4
2017	0.58	0.56	0.66	0.75	1.88	1.54	0.77	0.65	0.61	1.04	0.61	0.05	1.36	0.26	1.18	0.15	0.64	0.60	0.28	0.53	0.56	15.3
2018	0.60	0.56	0.67	0.76	1.90	1.58	0.77	0.65	0.61	1.04	0.62	0.05	1.50	0.29	1.18	0.16	0.65	0.61	0.29	0.54	0.57	15.6
2019	0.49	0.47	0.53	0.58	1.65	1.34	0.58	0.48	0.49	0.77	0.51	0.04	1.48	0.27	1.03	0.12	0.54	0.50	0.21	0.44	0.47	13.0
2020	0.29	0.28	0.34	0.39	1.04	0.73	0.37	0.31	0.28	0.47	0.29	0.02	0.54	0.13	0.64	0.09	0.31	0.29	0.15	0.26	0.27	7.5
2021	0.57	0.56	0.66	0.73	2.02	1.52	0.75	0.64	0.62	0.99	0.60	0.05	1.17	0.24	1.27	0.15	0.64	0.60	0.28	0.53	0.56	15.1
2022	0.51	0.49	0.62	0.70	1.77	1.30	0.70	0.60	0.53	0.93	0.53	0.04	0.83	0.20	1.10	0.16	0.57	0.53	0.28	0.47	0.49	13.5
2023	0.71	0.70	0.81	0.89	2.59	1.91	0.90	0.75	0.75	1.16	0.73	0.05	1.59	0.37	2.45	0.19	0.76	0.78	0.33	0.65	0.70	19.8
2024	0.47	0.46	0.53	0.58	1.66	1.27	0.61	0.52	0.52	0.81	0.49	0.03	1.02	0.23	1.63	0.12	0.50	0.52	0.22	0.44	0.47	13.1
Second decade cumulative pollution index value																						160

3.5. Phytoplankton Community structure of the Katse Dam

The current study provided evidence that pollution-tolerant phytoplankton replaced pollution-sensitive phytoplankton during the SD (Table 6). During the initial year of the FD, the dominant species were *Cosmarium* sp., *Asterionella* sp., *Monoraphidium* sp., *Quadrigula* sp. and Pennate diatoms at varying frequency and abundance (Table 6). Particularly, Saros et al. [48] associated *Asterionella* sp. with oligotrophic trophic state, which confirms that KD had better water quality in the FD. In the years between 2010 to 2013 when aquaculture and mining activities increased in intensity, these green algae and diatom species were replaced by the *Radiocystis* sp. cyanobacteria and *Fragilaria* sp. diatoms. The successive changes in composition from sensitive genera to tolerant genera indicate increased nutrient loading and a transition from good to poor water quality conditions over the two study periods (Table 7) [38]. The succession is attributed to the decomposition of organic matter from fish feed pellets, fish mortality and waste from excreta of fish in cages [28] and influx of nitrates from the upper catchment. Cyanobacteria store large amounts of nutrients relative to the green algae and are referred to as more tolerant to pollution conditions [34]. This attribute enabled cyanobacteria to survive the poor water quality conditions and replace the more sensitive chlorophyceae species as the dominant genera [34]. The above result could stem from various factors, including an observation by Oberholster et al. [14] that oligotrophic systems are characterized by low phytoplankton biomass and high species diversity, relative to eutrophic and hypereutrophic reservoirs, which allow few taxa to thrive and dominate at high algal biomass. Notably, the current study characterized KD as greatly contaminated with poor limnological conditions (Table 9), as evidenced by PIKD % that ranged between 1% in 2021 to 7% in 2014 (Table 11).

Table 9. Categories of contamination based on Pollution Index (Oberholster et al. [14]).

PIKD %	Interpretation	Profile
> 85	Slightly contaminated	Significant Phytoplankton diversity. Limnological conditions of dam are good to acceptable
65 - 85	Moderately contaminated	Signs of nutrient enrichment. Limnological conditions of the dam are intermediate
33 - 65	Contaminated	Only pollution-resistant species are abundant. Sensitive species reduced. Limnological conditions of the Dam are insufficient
<33	Greatly contaminated	Significantly reduced phytoplankton diversity. A limited number of tolerant phytoplankton species are dominant. Limnological conditions of the dam are poor

The observed replacement of pollution-sensitive phytoplankton in the early years of the FD by pollution-tolerant phytoplankton in the early years of the SD demonstrates a gradual deterioration in the water quality status of the KD (Table 10).

Table 10. Categories of phytoplankton diversity based on the Beger-Parker Index (Oberholster et al. [14].

BPI	Interpretation	Profile
0.8 – 1.0	Extreme dominance	Ecosystem potentially at risk
0.5 – 0.7	High Dominance	Warrants investigation
0.3 – 0.4	Moderate Dominance	Typical in various ecosystems
0 – 0.2	Low Dominance	Indicates high diversity

The pollution Index of Katse Dam (PIKD) data (Table 10) classified KD as greatly contaminated in the SD and worse than the contaminated status in the FD (Table 11).

Table 11. General classification of the Katse Dam according to PIKD over the FS and SD.

Year	PIKD %	Interpretation based on Phytoplankton	Year	PIKD %	Interpretation based on Phytoplankton
2003	29	Greatly contaminated	2014	7	Greatly contaminated
2004	63	contaminated	2015	3	Greatly contaminated
2005	66	contaminated	2016	8	Greatly contaminated
2006	72	contaminated	2017	4	Greatly contaminated
2007	60	contaminated	2018	2	Greatly contaminated
2008	40	contaminated	2019	3	Greatly contaminated
2009	58	contaminated	2020	68	Moderately contaminated
2010	30	Greatly contaminated	2021	10	Greatly contaminated
2011	6	Greatly contaminated	2022	2	Greatly contaminated
2012	6	Greatly contaminated	2023	4	Greatly contaminated
2013	55	contaminated	2024	6	Greatly contaminated

Thermal Stratification effects on phytoplankton assemblage

The middle thermocline layer of deep reservoirs like KD inhibits nutrient cycling from the lower hypolimnion layer during stratification in summer [52,54]. Stable thermocline during stratification selectively encourages *Fragilaria* sp., which thrives in ecosystems with high nitrates and low phosphates to adapt [54]. This is consistent with an observation by Sirunda et al. [49] that higher temperature causes dominance by pollution-tolerant phytoplankton genera. Conversely, turnover releases hypolimnetic nutrients from sediments to the phytoplankton community in the upper epilimnion layer, which promotes rapid algal growth [4,5,25]. Nevertheless, Harding and Paxton [50] argue that, following winter turnover, while the concentrations of dissolved nitrogen and phosphorus compounds in the surface waters are high, low temperatures inhibit algal growth. The thermal stratification phase of the KD is stable from October to April (Figure 5b and 5c), while the turnover phase occurs between May and September (Figure 5a and 5d). The 2003 and 2024 illustrations in Figure 5 represent the two phases attributable to the warm monomictic characteristic of KD.

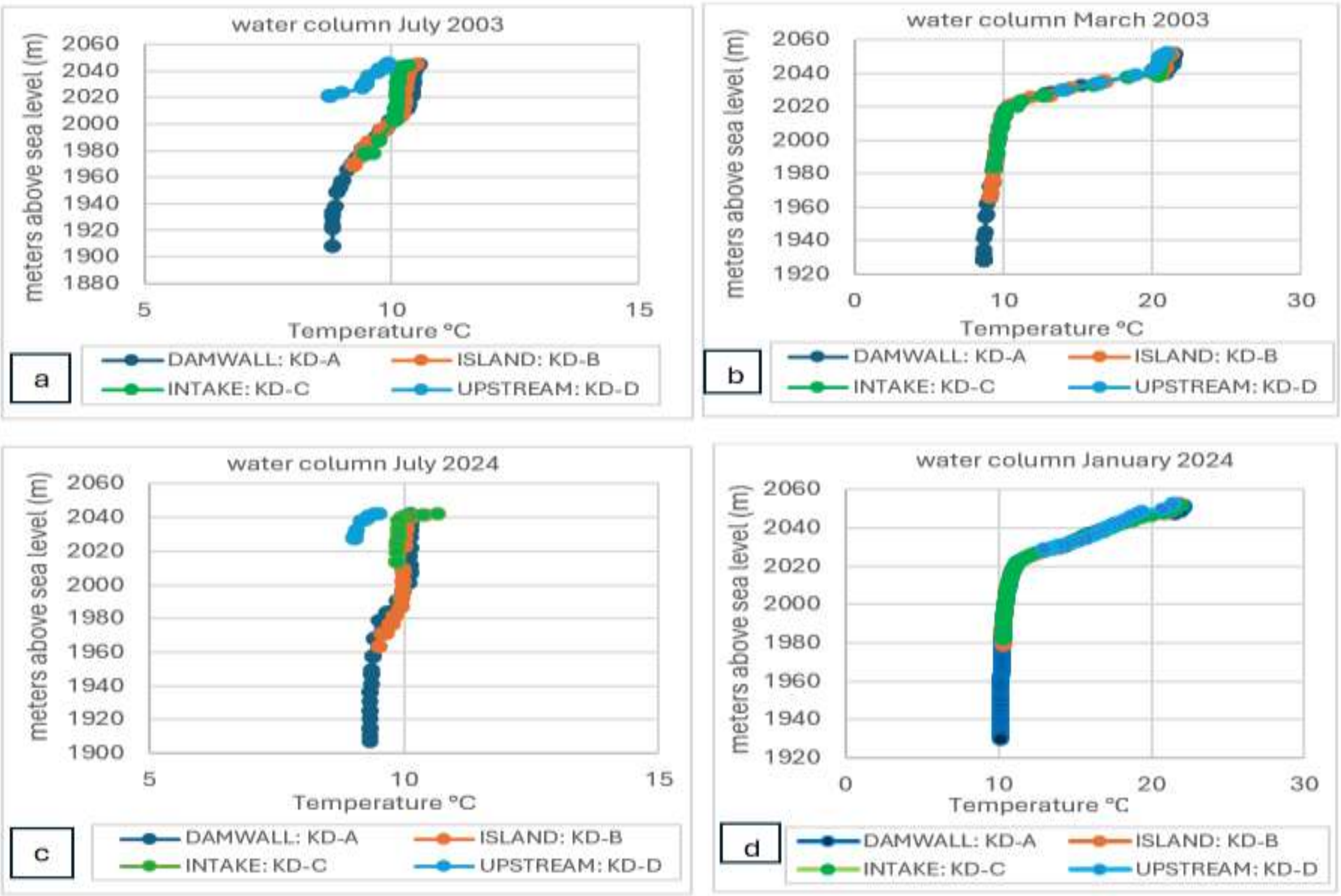

Figure 5. Shows the thermal properties of Katse Dam (a) mixed water column in July 2003, (b) stratified water column in March 2003, (c) mixed water column in July 2024, and (d) a stratification in January 2024.

3.6. Organic Pollution analysis of Katse Dam

The eutrophication process increases algae decomposition and reduces the dissolved oxygen concentration [12]. The increased amount of organic matter increases turbidity and reduces light penetration [56][55]. The events indicate that the organic pollution and eutrophication process are highly correlated and cyclic nature [12]. The observed increase in organic pollution at sited KD-A (Katse Dam wall) (Figure 6) in the early years following impoundment of the KD is attributed to elevated decomposition of a large amount of debris from submerged plant shrubs, tree leaves and branches, similar to the one reported by Van Vuuren et al. [34] following the impoundment of Mohale Dam, Lesotho. Most of the WSS recorded organic pollution levels less than the OPI value of 4, which indicates pollution in the FD (Figure 6) relative to the SD where most WSS recorded OPI values above 5, indicating that the KD has reached extreme organic pollution levels. Phytoplankton directly uses organic nutrients for growth [57][56], hence the increase in OPI values in the SD is associated with increased PVT values (Table 7) and the greatly contaminated classification of the KD in Table 11.

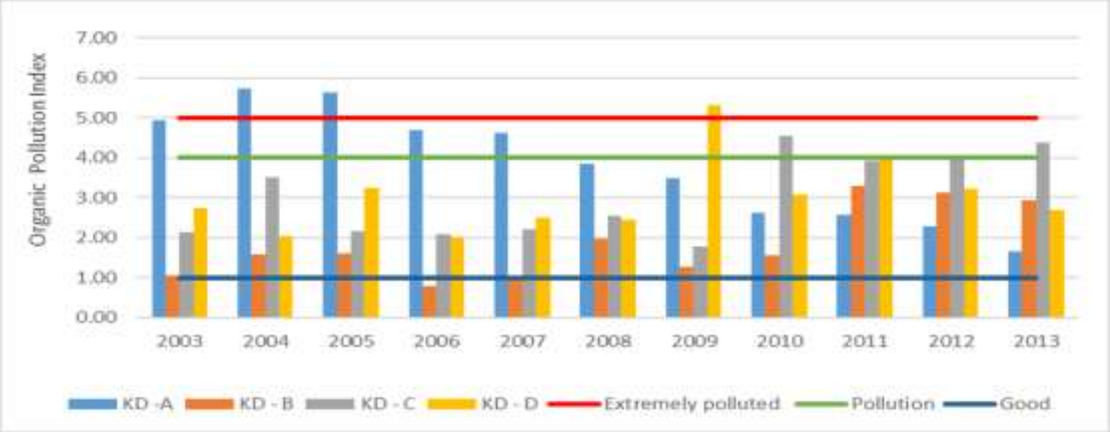

Figure 6. Organic Pollution Index values at the Katse Dam 2003 to 2013.

Based on the results shown in Figure 7, the Organic Pollution Index (OPI) values are above the threshold level of 5 OPI for extremely polluted water bodies. Therefore, we reason that Katse Dam experienced significant organic pollution in the SD due to the influx of nutrients from mining and aquaculture production.

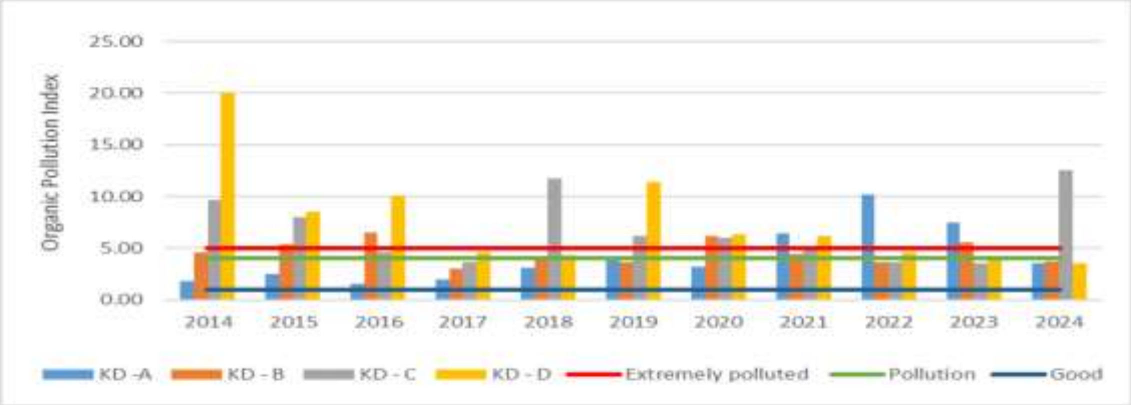

Figure 7. Organic Pollution Index values at the Katse Dam from 2013 to 2024.

3.7. Trophic State Classification of Katse Dam

The trophic state depends on the concentration of total nitrogen, phosphates, *chlorophyll*-a, and SDT [58][57][57]. The radar diagram in Figure 8 (a-d) shows that $TSI_{SDT} > TSIT_{P} > TSI_{chl-a}$ at the lacustrine zone (KD-A) and $TSIT_{P} > TSI_{SDT} > TSI_{chl-a}$ at the riverine zone(KD-D). KD is classified as a system with high water clarity and phosphate-limited because the SDT and phosphates were relatively higher than *Chlorophyll*-a [44,45]. The result that phosphate contributed significantly to eutrophication in the Katse Dam resembles the findings of Mnyango et al. [45] that the Roodepoort Dam was phosphate-limited. In such a case, Mnyango et al. [26] suggest that authorities should derive strategies that reduce the influx of phosphates into KD. An assessment of phosphate loads in the ten largest global reservoirs indicates that Lake Victoria experiences significant P loading due to anthropogenic pollution [58]. Similarly, untreated sewage spills from the Kao mine sewage plant into the riverine zone of KD are a potential source of phosphates [10]. This observation is supported by Oberholster et al. [59], who assert that an influx of phosphates from untreated sewage increases eutrophication and leads to toxic cyanobacterial blooms. In addition, aquaculture potentially contributes to phosphate loads into the KD through fish waste and fish feed [28]. Besides the noted phosphate-limited nature of phosphates, Omoregie et al. [51], highlight the need to manage the influx of nitrates from their source to slow down the eutrophication rate.

Figure 8. Radar diagram comparison of TP, *Chlorophyll*-a, and clarity of Katse Dam in the first decade (a,b) and second decade (c,d).

The CTSI is a trophic state classification system that forecasts the eutrophication potential of reservoirs based on the amount of biological productivity they sustain [45]. It provides a simplified way of assessing the cumulative influence of biotic and abiotic factors, including thermal stratification, nutrient availability, light intensity, photosynthetic rate, and phytoplankton composition, on the trophic state of reservoirs [44]. Karpowicz [44], insists that CTSI is more accurately used in monomictic than in dimictic and polymictic reservoirs, which experience mixing more than once and show a higher variability over the components TSI_{sd}, $TSIT_{P}$, $TSI_{chl\text{-}a}$. Obviously, Rossouw et al. [57] support the use of CSTI for assessing the trophic state of reservoirs; despite their caution that indices do not scale with the extent of productivity and its dynamics. Roos [4], previously characterized KD as oligo-mesotrophic with the potential of shifting to eutrophic due to P loading mainly from aquaculture production. KD exhibited mesotrophic condition in 2009, 2010 and 2012 as illustrated in Figure 9.

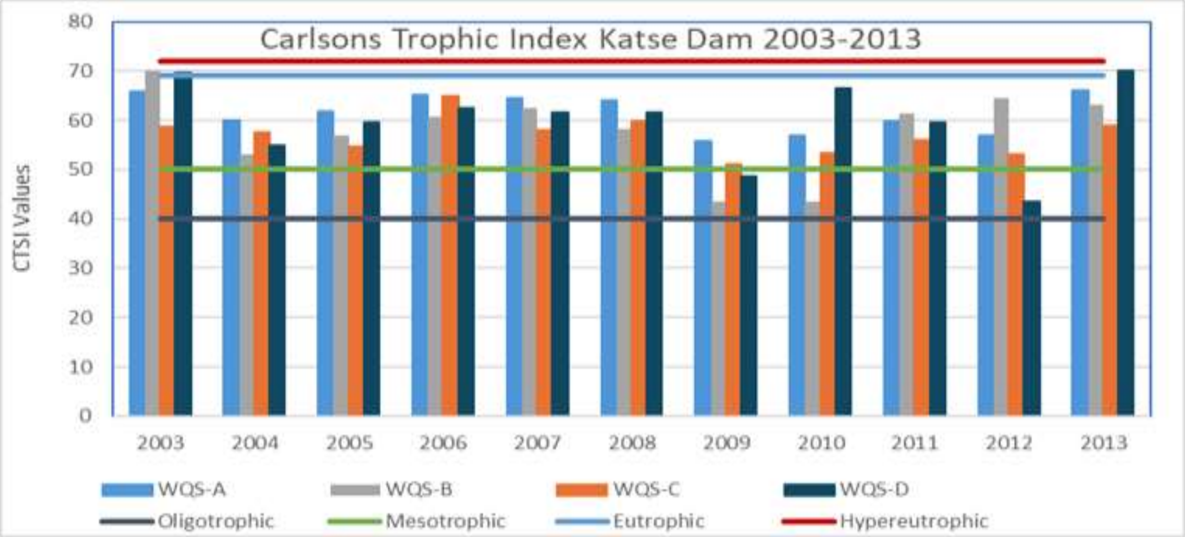

Figure 9. Carlson Trophic State Index for Katse Dam in the first decade.

Comparison of Figure 9 and Figure 10 indicates a marked transition from eutrophic state to hypereutrophic state at KD-A (lacustrine zone) in 2015, 2016, 2019 and 2023. The Katse Dam maintained an eutrophic state at most of the WSS sites in the SD as shown in Figure 10.

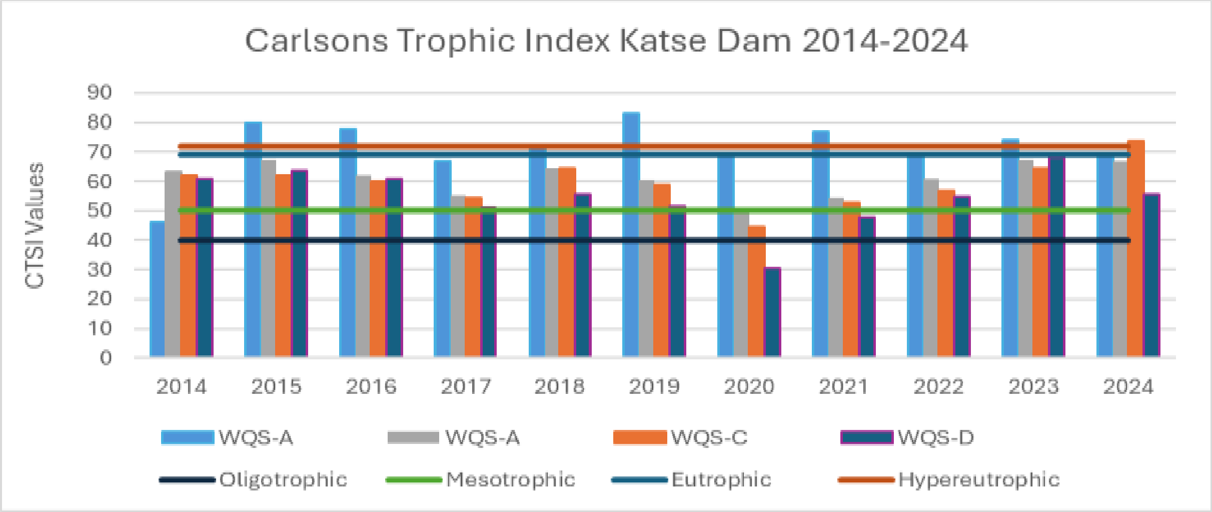

Figure 10. Carlson Trophic State Index for Katse Dam in the second decade.

The analysis of data from the current study provided evidence that mining and aquaculture contributed significantly to the water quality deterioration of the Katse Dam in the SD. The result from application of different indices provides water managers with: (1) A precise and accurate representation of the trophic status and organic pollution status of the KD (2) A structured and simple presentation of the data to both technical and non-technical stakeholders (3) Pollution index values of dominant phytoplankton and their association with specific water quality parameters which highlights a potential pollution source and (4) a clear indication of the transition of the KD from mesotrophic in the FD to eutrophic status in the SD.

4. Limitations and future considerations

Using the Modified pollution index to investigate changes in phytoplankton community structure as indicators of ecosystem state has some limitations in a deep reservoir that experiences stratification and mixing, as observed by Bai et al. [5]. Furthermore, vertical migration along the water column causes irregular distribution of phytoplankton assemblage and dominance of some species below the surface [14]. Despite these observations, the current study took water samples from 1.5 m depth of the photic zone. It did not account for phytoplankton that prefer low-light conditions that exist several meters below the surface of the photic zone. Literature reveals that the horizontal and vertical heterogeneity of phytoplankton distribution is influenced by thermal stratification and mixing [25]. Therefore, future studies should account for the thermal stratification and mixing effects of the Katse Dam reservoir by comparing integrated samples along the vertical column during mixing and comparing with water samples taken during stratification, similar to a study by Bai et al. [5].

The Carlsons Trophic State Index is limited in that it overestimates trophic levels [45] and its components (TSI_{SDT}, TSI_{TP}, TSI_{chl-a}) do not conform during turnover (mixing) of reservoirs [43,44]. Therefore, its use in the current study has considered these limitations. Future studies may consider the application of modified Trophic state indices, such as the Van Ginkel trophic state index [45].

Although the use of different indices has highlighted the eutrophication trends in the KD, future research should explore integrating advanced real-time monitoring tools, remote sensing, and satellite imagery to elucidate reservoir spatial and temporal trends to predict algal blooms [51,60]. Machine learning algorithms can be applied to model phosphate and nitrate inputs using historical datasets to predict the carrying capacity of KD based on P loading rates, dam capacity, flushing rates, and current and future production rates [4,51,60].

Authorities should engage with existing stakeholders in the KD catchment, namely aquaculture and mining companies, to derive innovative policy frameworks and regulatory instruments to reduce the influx of nitrates and phosphates from identified sources. Innovative localized initiatives such as wetland restorations, construction of artificial wetlands, awareness-raising about sustainable cultivation methods, and relocation of livestock posts to minimize localized pollution should be considered. Addressing the negative trajectory in the trophic status of KD requires an integrated approach that seeks to optimize and allocate resources where they are most needed to mitigate and deter eutrophication of the strategic raw water source, the Katse Dam.

5. Conclusions

The current research classified KD as hypereutrophic in the lacustrine zone near the dam wall and eutrophic along the longitudinal zonation from the dam wall to the riverine zone. The KD is classified as greatly contaminated in the SD relative to the contaminated status in the FD. The cumulative Pollution Index (PI) values of water quality parameters increased from 65 in the FD to 160 in the SD. OPI classifies KD as extremely polluted with values above the threshold level of 5 in the SD. Overall, the KD is classified as a system with high water clarity and phosphate-limited.

The successive replacement of pollution-sensitive phytoplankton by pollution-tolerant phytoplankton is attributed to increased organic pollutants, increased trace metal concentration and increased primary productivity and transition of KD to hypereutrophic status. The dominance of *Cosmarium* sp. and *Asterionella* sp. in 2003 and 2005, respectively, is indicative of oligotrophic conditions and low phosphate availability in Katse Dam in the FD. These are pollution-sensitive species which were replaced by the more pollution-tolerant species such as *Radiocystis* sp. and *Fragilaria* sp. in the SD. *Fragilaria* sp. is competitive in high-nitrogen and low-phosphate water.

The results from the application of different indices in the current study have served as decision-support tools for environmental managers to plan source water protection strategies based on known levels of pollution. The method adopted in the current study can be applied to monitor water quality in other warm monomictic mountainous reservoirs with catchments that are exposed to a myriad of pollutants, including mining and aquaculture. The hypereutrophic condition in the lacustrine zone is an alert trigger for deteriorating water quality and algal bloom formation in the Katse Dam. Environmental managers can use the results to direct resources to mitigate conditions that are likely to compromise good water quality.

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Abbreviations

The following abbreviations are used in this manuscript:

KD	Katse Dam
UNEP	United Nations Environmental Program
BPI	Beger Parker Index
CTSI	Carlsons Trophic State Index
TSI	Trophic State Index
OPI	Organic Pollution Index
MPI	Modified Pollution Index
CCA	Canonical Correspondence Analysis
PCA	Principal Component Analysis
FD	First decade
SD	Second Decade
LHWP	Lesotho Highlands Development Authority
WSS	Water sampling sites
SDT	Secchi disk transparency
Chla	*Chlorophyl*l-a
PI	Pollution Index
PIKD	Pollution index of Katse Dam

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