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Using Multiple Indices for the Water Resource Management of a Monomictic Man-Made Dam in Southern Africa

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Abstract: This study employed different indices, namely the weighted arithmetic water quality index (WQI), Carlson Trophic State Index (TSI), van Ginkel TSI, and Trophic Level Index (TLI) to determine the water quality status of a man-made dam for the needs of sustainable water resource management in Southern Africa. The selection of indices for the study was based on the impacts of anthropogenic activities on the dam. The Roodeplaat Dam exhibited the spatial variation of physicochemical characteristics, indicative of influence by point-source pollution. Although the dam was classified as being eutro-hypertrophic, it was evident that water clarity was not a limiting factor but was P-limited, which was an indication of limiting conditions on primary production. Moreover, the WQI calculated for the dam with an average of 93.94 demonstrated very poor water quality that could be used for crop irrigation purposes only. As such, continued nutrient enrichment must be mitigated to sustain fitness for irrigation, at least. However, strategic goals should involve widening fitness for use. The selected indices were found to be effective for water resource management and could be applied to dams impacted by point-source pollution in Southern Africa. Thus, this study recommends the implementation of an integrated management approach, which needs to prioritize nutrient management to retain societal resource value.

Keywords: water resource management; water quality assessment; water quality index; trophic status; Roodeplaat Dam

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1. Introduction

Water is a highly abundant natural matter, covering approximately 70% of the earth's surface, of which over 97% of total water volume is in the oceans, 2% is in ice caps and glaciers, soils, and atmospheric moisture, and the remaining 1% is found in freshwater lakes, rivers, and shallow groundwater [1]. Humans predominantly rely on freshwater (*ca* 1%), a resource that is deteriorating rapidly due to intensive abstraction and pollution, as well as the influence of global climate change. The overall global state of deteriorating water resource quality threatens socio-economic development, livelihoods, and biodiversity due to the reduced fitness-for-use of water resources. Unlike energy, which comes from various alternative sources, water has no alternative, hence the critical need for sustainable management [2]. Rapid urbanization and population growth exert water demand pressure. In addition, unsustainable land management practices, poor operation andlack of maintenance of wastewater treatment works (WWTWs) are considered key drivers of water resource quality decline [3–6]. This is a major concern to water quality authorities as the outcome affects water quality and increases treatment costs, which have direct implications for the economy. Treatment costs and the quality of domestic water are highly correlated with raw water in dams [7]. In South Africa, the estimated unit cost for various options (i.e., primary, secondary, and advanced treatment—the removal of suspended solids) of WWTWs is estimated to be R 9,857,094.00/Mℓ ($559,594.45/Mℓ) [8]. In addition, thermal stratification is considered to be the most important limnological feature of aquatic ecosystems affecting a water column's chemical characteristics [9]. Thermal stratification has a significant role in the water quality status of dams as it influences many physiochemical and biological processes [10,11]. Noori et al. [12] observed that the cycling of water quality constituents in lakes is affected by thermal stratification and other factors such as eutrophication.

Freshwater resources are strategic socio-economic assets in semi-arid Southern African countries and water supply systems depend predominantly on dams. The concerning fact is that the most important dams used for water supply in Southern Africa, such as Lake Chivero in Zimbabwe, the Vaal and Hartbeespoort dams in South Africa, and the Von Bach Dam in Namibia, suffer from excessive nutrient enrichment, with some already in a chronic eutrophic state [13–17]. The declining water resource quality threatens current and future water supply availability. Sustainable water quality management, particularly of dams, is, therefore, a priority for countries to be water-secure in the future, as the forecast by the Department of Water and Sanitation (DWS, Pretoria, South Africa) suggests water scarcity by 2025 if effective management plans are not actioned [18].

Moreover, Roodeplaat Dam (RD), which was selected as a case study in the current study (described in Section 2.1), is rated among the most polluted dams in Southern Africa. The RD inlet is highly impacted by hyacinth, consequently adversely affecting the surrounding landowners, business and recreational activities, crop irrigation, and abstraction for water purification [16,19]. RD was selected in this study due to its socio-economic value with associated activities, including conservation areas, tourism, commercial crop irrigation, domestic and industrial water supply, and sport and recreational purposes (fishing, swimming, boating, jet-skiing; local, national, and international rowing; as well as international training for canoeists during summer). RD is part of the Dinokeng Project, which aims to establish a Big Five collaborative game reserve, with a mix of savanna, wetland, and different kinds of land use in the vicinity ranging from high-density urban development to diverse tourism establishments. The project was designed for job creation and to promote socio-economic development. The status quo assessment of the project noted that the area has high natural resource quality in terms of species richness due to the convergence of various biomes [20,21]. Water users such as commercial farmers who rely on potable water from this dam for irrigation purposes, locals who are dependent on this dam, as well as businesses who use this dam for recreational activities will be affected if no actions are put in place to curb the deteriorating water quality of this dam. Therefore, there is a need to maintain the water quality and access to the dam as well as a healthy environment through proper management practices such as monitoring and assessment, which may trigger action measures to reverse water quality deterioration to meet user needs, encourage tourism, and conserve and protect the aquatic resource for recreational use.

The monitoring and assessment of water resources provide important information for effective water quality management. This makes water quality monitoring programs an indispensable part of assessing the health of water bodies and their effective management [22]. Monitoring can also be used as an early warning system for effective and strategic planning. Approaches for assessing and monitoring water quality status are diverse, and each country has its preferred water quality assessment tools for use depending on underlying conditions and factors influencing the state of water resources in each country. The traditional methods used around the globe include statistical analysis, modeling techniques, Geographic Information Systems (GIS), and water quality indices [23–26]. Each method has its advantages and disadvantages, as detailed in a review by Lencha et. al. [5]. For instance, Klippel et. al. [27] compared different trophic state indices in six interconnected tropical reservoirs, and each method resulted in a different trophic state classification, with the Carlson Trophic State Index (cTSI) [24] resulting in higher trophic classifications compared to other trophic indices that were applied in the study. Meanwhile, Wojtkowska and Bojanowski [28] observed that both the cTSI and Trophic Level Index (TLI) were sufficient and effective for sustainable water protection and the management of water quality in dams.

The Vollenweider model [29] was developed to determine the trophic conditions in water bodies and for eutrophication management purposes. However, the shortfall of this model was that it assumes that a system is in a steady state. When this model was applied to South African conditions, it was found that there is a certain degree of potential for predicting the steady state of a system [30–32]. Recent studies have reported that remote sensing can play a significant role in monitoring water quality and supplementing water quality data gaps. The satellite remote sensing of inland water bodies has great potential for obtaining reliable data that can support decision-making in water quality management processes [33]. However, the disadvantage of this approach is that remote sensing is restricted to surface water visible from space [34]. Many different water quality index (WQI) models have been developed with variations in model structure, parameters included, their associated weightings, and the methods for use for sub-indexing and aggregations [35,36]. WQIs such as the Horton index, Canadian Council of Ministers of the Environment (CCME), National Sanitation Foundation (NSF-WQI), and the Comprehensive Pollution Index (CPI) are widely used to determine the water quality suitability for the intended use. The WQI technique has proved to be the most efficient and has played a pivotal role in effective water resource management [22]. However, these tools have been criticized for producing uncertainties in converting large amounts of water quality data into a single index [37]. Most WQI model components have been developed based on expert views and local guidelines, which make them region specific [36]. Therefore, there needs to be a critical review of the application of water quality indices and a blanket approach in the application of these indices should be avoided.

These methods and tools are being modified and applied to various water bodies; however, their applications by the decision-makers are lacking due to their complexity and gaps in historical data due to the lack of monitoring. It is for this reason that the current study is exploring easy-to-use tools taking into consideration land use impacts on water resources. In addition, several authors [19,38–40] have previously evaluated the water quality of the RD; however, the assessments have been based on single-approach assessments. This suggests a need to investigate other approaches to assessing dams associated with multipurpose uses for effective management. Therefore, this study argues that there is a need to employ different indices and approaches to assess water quality to make an informed decision on water resource protection. The study aims to apply quantitative water quality assessment using different indices to determine the water quality status of monomictic man-made dams receiving pollution from different sources, for the needs of sustainable water resource management in Southern Africa. The objectives of the study were: (a) to explore factors responsible for water quality variation in the RD using the Principal Component Analysis (PCA), (b) to assess the trophic status of the dam using relevant indices, (c) to determine the overall water quality status of the dam using suitable WQIs, and (d) to establish if these indices can be applied to dams receiving different pollution sources to serve as a decision support tools for catchment managers.

2. Materials and Methods

2.1. Description of the Study Area and Selection of Sampling Sites

The RD (25.6289° S, 28.3506° E) is situated in the Crocodile (west) Marico Catchment, Water Management Area A23A, within the City of Tshwane Metropolitan Municipality, approximately 25 km northeast of Pretoria in the Gauteng Province (GP) of South Africa (Figure 1). RD is a warm, monomictic, man-made dam with stable thermal stratification during summer [41].

For the purpose of this study, the dam was divided into three zones:

- The inflowing riverine zone (no sampling sites), which represents high flows and rapid water flashing rates;
- The transitional zone (sampling sites A and D), which represents reduced flows and flushing rates;
- The lacustrine zone (sampling sites B and C), which represents slow flows and slow flushing rates.

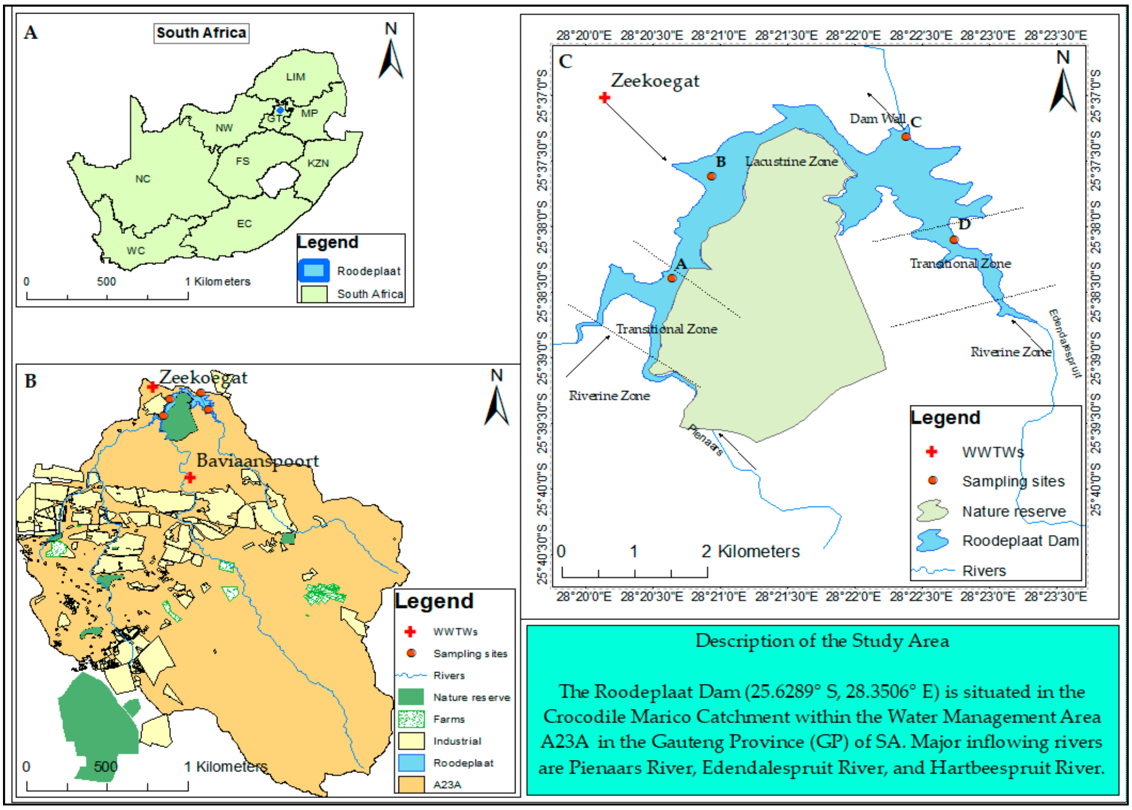


Figure 1. The map of the study area, indicating (**A**) the location of the Roodeplaat Dam in South Africa; (**B**) dominant land uses in Water Management Area A23A; and (**C**) the sampling sites, the flow direction, and the different zones of the dam.

The construction of this dam was completed in 1959 to supply water for irrigation purposes but it is now among the sources of potable water supply to the northern parts of the City of Tshwane Metropolitan Municipality through the Montana, Wonderboom, and Magaliesberg reservoirs and supplies directly to the Doornpoort area [42]. Water resources in this catchment support major economic activities and a population of approximately 5 million people [43].

Three major rivers flow into RD, namely the Pienaars River, Edendalespruit River, and Hartbeespruit River, which enter the dam from the south and exit in a northerly direction beyond the dam wall. The RD and its three inflowing rivers are highly impacted by surrounding anthropogenic activities [44]. The two notable point sources of nutrients in the vicinity are the Baviaanspoort WWTW which is located approximately 10 km upstream of the dam on the eastern bank of the Pienaars River and the Zeekoegat WWTW which is located immediately to the west of the dam and discharges effluent directly into the dam at the Rowing/Canoe Club. There are also non-point sources surrounding the dam, which include formal and informal settlements, agricultural land use activities along the banks of these tributaries, urbanization, and industrial effluent [43]. The catchment area is 668 km^2 and the dam has a net capacity of 41.9 × 10^6 m^3, of which 50% is from the return flows from the Baviaanspoort and Zeekoegat WWTWs, a mean depth of 10.6 m, and a maximum depth of 43 m [38,39]. RD's characteristics are summarized in Table 1.

Table 1. Summary of the catchment characteristics of Roodeplaat Dam (adapted from 38,39,42).

Catchment Characteristics	
Total catchment area (km^2)	668
Height above sea level (m)	1214
Surface area (fsl) * (km^2)	3.97
Volume (fsl) (10^6 m^3)	41.9
Maximum depth (fsl) (m)	43
Mean depth (fsl) (m)	10.6
Minimum water surface temperature (°C)	15.2
Maximum water surface temperature (°C)	27.8
Annual precipitation (mm/a)	583.1
Catchment type	Dense urban, industrial cultivated land, grassland, and bushveld
Tributaries	Pienaars River, Hartbeespruit River and Edendalespruit River
Water usage	Domestic, irrigation, and recreation

* fsl = full supply level.

2.2. Selection of Parameters and Data Collection

The study followed a case-study design where a quantitative methodology was used. Secondary water quality data sourced from the Water Management System (WMS) of the DWS national database were used in the investigations. The data had been collected from January 2001 to December 2021 using an integrated sample technique with a 5 m hosepipe and a surface-grab sampling technique. All samples were collected in the phonic zone in intervals of 0–5 m every second week. It has been reported that there is no standard procedure or specific rules for selecting parameters for assessing water quality status; these are selected based on data availability, expert opinion, the environmental significance of a water quality parameter, and/or their application types, such as drinking water quality assessment or urban environmental impacts [45].

Banda and Kumarasamy [45] further suggested that minimizing the input parameters can significantly reduce the time, effort, and cost required to evaluate water resources, which results in a more feasible and economically viable process. Therefore, the selection of parameters for this study was based on their impacts on potable water quality in relation to the trophic status. The following water quality parameters were selected for the study: pondus hydrogenium (pH), nitrate and nitrite (NO_3 + NO_2), ammonium nitrogen (NH_4^+), orthophosphate (PO_4^{3-}) as phosphorus (P), and suspended chlorophyll-*a* (Chl-α).

Briefly, water samples collected for physicochemical analysis (pH, NH_4^+, NO_3 + NO_2, PO_4^{3-}) were transferred into full-capacity sterile 250 mℓ polyethylene sampling bottles to minimize headspace volume (to avoid the loss of target compounds) and labeled accordingly. Samples were placed into a cooler box filled with ice packs (to maintain low temperatures) and transported to the Resource Quality Information Services (RQIS) laboratory of the DWS, where they were stored under darkness at 4 °C until analysis. The chemical analyses were conducted by following approved standard laboratory methods using techniques such as Flammable Atomic Absorption Spectrophotometry (FAAS) and Inductively Coupled Plasma-Optical Emission Spectrometry (ICP-OES). In situ temperature measurement was collected with a digital thermometer (Yellow Springs Instrument (YSI) meter) at a 0 m depth interval.

Additional to the normal samples, the Kjeldahl Nitrogen (KN) (summation of NH_3 + Organic Nitrogen) and total phosphorus (TP) were measured using the digestion methods (32). The total nitrogen (TN) concentration was determined by summing up the KN and NO_3 + NO_2; this formula is used to measure nitrogen at WWTWs. Samples for suspended Chl-α were collected using 500 mℓ of sample water filtered through a 45 μm Whatman filter paper before being extracted from the filter paper into 10 mℓ ethanol. Thereafter, it was measured in the extract using a spectrophotometer between wavelengths 666.5 and 750 [32]. Secchi disk (SD) readings were taken by lowering the 20 cm black and white disc into the water and measuring the depth at which the disc was not visible [32,46]. Thereafter, the results from the sample analysis were captured in the WMS national database.

Several authors [21,26,47] have identified TP as a good forecaster of algal growth, Chl-α as a reliable algal biomass indicator, and SD as the best measure for water clarity. Therefore, for the current study, samples for determining the trophic state analysis were collected at sampling Site C at the dam wall. The dam wall is regarded as the most preferable position [21,45] for determining the relationships between Chl-α, TP, and trophic status because this is where potable water is abstracted for transfers and treatments and/or where the sample is deemed more likely to be representative of the greater water volume [48]. Meanwhile, samples for the overall water status of the dam were collected across the longitudinal gradient of the dam at sampling sites A–D to represent the overall physical, chemical, and biological characteristics of the dam.

2.3. Data Analysis

2.3.1. Statistical Analysis

Surface water quality raw data were populated and analyzed in a Microsoft Excel 2016 spreadsheet using descriptive statistics. Analytical precision, as per the principle of electro-neutrality [48], ensured the reliability of the analysis. This was achieved by calculating the percentage of charge balance error (% CBE) using Equation (1).

$$\%\mathrm{CBE} = \frac{\sum \mathrm{cations} - \sum \mathrm{anions}}{\sum \mathrm{cations} + \sum \mathrm{anions}} \quad (1)$$

In this study, only samples with % CBE falling within ±5% were considered for analysis. Water quality parameters considered for analysis included common major cations (NH_4^+), anions (NO_3^-, NO_2^-), and one system water quality parameter (pH).

Although there were missing periods from the 2001–2021 dataset that was used in this study, due to challenges of not sampling caused by the expired license registration of the boat and a lack of human capacity as well as financial constraints, the study used a long-term data set analysis [17] that proved to be sufficient to provide insights into the water quality of the dam. The study employed the analysis of annual mean concentrations, which were then presented with Microsoft Excel 2016 surface graphs that showed the temporal and spatial distribution of the selected parameters.

In addition, the Principal Component Analysis (PCA) method was used in this study to assess associations between water quality parameters in RD over time. The period 2001 to 2018 was analyzed and 2019 to 2021 was excluded due to low sampling frequency at the time. The mean values of the four sampling locations per calendar year were applied. The water quality parameters assessed included $NO_3 + NO_2$, NH_4^+, PO_4^{3-}, electrical conductivity (EC), Chl-α, pH, and temperature. A further PCA was performed using annual mean values for the dam wall (Site C), including further water quality parameters SD, TN, and TP. PCAs were run and biplots were created using Canoco V5 (Microcomputer Power, Ithaca, NY, USA). Water quality data were log-transformed and centered during analysis. Generally, PCA is designed to transform the original variables into new, uncorrelated variables called Principal Components (PC), which are linear combinations of original variables [49,50]. It has been noted from previous studies [51–55] that the PCA method is mostly applied to evaluate temporal-spatial variations and interpret large, complex water quality datasets to define and standardize parameters that are responsible for the deterioration of water quality for rivers; however, for the purpose of this study, it was applied to a man-made dam.

2.3.2. Comprehensive Trophic Status Assessment

Trophic state classification provides information about the condition of the lentic ecosystems and is indicative of ecosystem services such as potable water supply, recreational opportunities and aesthetics, and disservices such as cyanobacteria blooms [20]. The Trophic State Index (TSI) is a valid scientific tool that can be used for investigations whereby an objective for the trophic state is necessary, and it can also be used as a valuable tool in the management of surface water resources [56]. However, currently, there is no consensus as to what should be the single criterion for determining the trophic status [56], and it is doubtful that an index based on a single parameter would be widely accepted [24]. It is for this reason that the current study opted to apply different methods to determine the water quality status of the dam.

Firstly, the TSI was calculated using a natural logarithmic (In) of three variables: TP concentration in microgram per liter (μg/ℓ), Chl-α (μg) concentration, and SD in meters (m) according to Equations (2)–(5) by Carlson [24,25,57].

$$\mathrm{TSI(TP)} = 4.15 + 14.42\mathrm{In}\ (\mathrm{TP}) \quad (2)$$

$$\mathrm{TSI(Chl)} = 30.6 + 9.81\mathrm{In}\ (\mathrm{Chl}) \quad (3)$$

$$\mathrm{TSI(SD)} = 60.0 - 14.41\mathrm{In}\ (\mathrm{SD}) \quad (4)$$

$$\mathrm{CTSI} = \frac{\mathrm{TSI(TP)} + \mathrm{TSI(Chl)} + \mathrm{TSI(SD)}}{3} \quad (5)$$

where CTSI is the Carlson Trophic State Index. TSIx is the Carlson Trophic State Index calculated for each parameter, namely, TP, Chl-α, and SD.

The Carlson Trophic State Index (cTSI) categorizes the trophic states into 4 classes, namely oligotrophic (low levels of nutrients, low amount of productivity, and good water quality) with TSI values below 40; mesotrophic (intermediate levels of nutrients, moderate productivity, and fair water quality) with TSI values ranging between 40 and 50; eutrophic (high levels of nutrients, high productivity, and poor water quality) with TSI values ranging between 50 and 80; and hypertrophic (excessive levels of nutrients, excessive productivity, and unacceptable water quality) with TSI values above 80.

The limitation of the cTSI as reported by the literature is that this model tends to overestimate the trophic levels, partly due to its consideration of the highest productive seasons such as spring and summer in temperate lakes. Consequently, researchers and different studies have adopted different approaches to assess the trophic status of lakes in tropical and subtropical regions and dams that are sensitive to data variability [7].

The second method applied in the study was the van Ginkel TSI [21], modified from [58,59], to develop a method of trophic status determination as a management tool for the South African National Eutrophication Monitoring Programme for impoundments (dams). Van Ginkel's TSI uses statistical analysis to classify the trophic status, it requires the mean annual TP concentration and mean annual Chl-α concentration. Values and ranges for trophic status are presented in Table 2.

Table 2. Trophic status indicators and the appropriate ranges used to classify dams.

Variable	Oligotrophic	Mesotrophic	Eutrophic	Hypertrophic
Mean Chl-a (μg/l)	0–10	10–20	20–30	>30
Mean TP (mg/l)	<0.015	0.015–0.047	0.047–0.130	>0.130
Variable	**Highly Turbid**	**Turbid**	**Clear**	
SD Depth (m)	<0.2	0.2–0.8	>0.8	

Thirdly, the study applied the TLI, modified from the cTSI by Burns et. al. [60] to monitor and manage lakes in New Zealand. The TLI uses the same variables (TP (μg/ℓ), Chl-α (μg/ℓ), and SD (m)) used in the cTSI; however, the TLI also includes the TN (μg/ℓ) [61] to overcome the one-sided element of a single-factor evaluation of eutrophication [62]. Zhang et al. [62] suggested the TLI as the current most suitable method for the evaluation of lake eutrophication. The numerical values of the TLI for this study were calculated using Equations (6)–(10).

$$\mathrm{TL(TP)} = 0.218 + 2.92\log(\mathrm{TP}) \quad (6)$$

$$\mathrm{TL(Chl)} = 2.22 + 2.54\log(\mathrm{Chl}) \quad (7)$$

$$\mathrm{TL(SD)} = 5.10 + 2.60\log\left(\frac{1}{\mathrm{SD}} - \frac{1}{40}\right) \quad (8)$$

$$\mathrm{TL(TN)} = -3.61 + 3.01\log(\mathrm{TN}) \quad (9)$$

$$\mathrm{TLI} = \frac{\mathrm{TL(TP)} + \mathrm{TL(Chl)} + \mathrm{TL(SD)} + \mathrm{TL(TN)}}{4} \quad (10)$$

where TLI is the Trophic Level Index. TLx is the Trophic Level Index calculated for each parameter, namely TP, Chl-α, SD, and TN.

The TLI values (modified from [61,63]) were categorised as follows: <3, oligotrophic; 3–5, mesotrophic; 5–6, eutrophic; and 6–8, hypertrophic.

2.3.3. Water Quality Assessment

WQIs are considered significant methods for classifying water quality as a contribution to water resource management and are important and necessary for simplifying the reporting of complex and technical water quality information [64] into usable and easily understood information [65,66]. Since the development of the first WQI [23], several complex approaches have been used to establish a more accurate WQI [67]. However, it is evident that some are poorly contextualized; for instance, the limited consideration of the influence of water allocation objectives on weighting factors [68]. There are many methods of determining the WQI and none are regarded as supreme and favorable for developing water quality indices [69].

The WQI employed in the study was based on the weighted arithmetic sum method, with parameters related to eutrophication problems, weight coefficients, and sub-index values established based on extracts from the literature. Generally, the WQI is developed following four common steps [36,37]: 1) selection of parameters; 2) creation of sub-indices by assigning a weight factor to each parameter; 3) the assignment of parameter weight values, depending on their significance in the assessment; and 4) the computation of a final index.

The study followed a five-step procedure that has been performed to determine the WQI for rivers [45] and groundwater [66]. The same method was extended in this study to determine the overall water quality status of the RD:

1. Assign a weight (wi) to each of the selected parameters (pH, PO_4^{3-}, NH_4^+, $NO_3 + NO_2$, and Chl-α) according to their relative importance for domestic and recreational use, as per South African Water Quality Standards (si), where one represents less importance and five is the most important variable.
2. Calculate the relative weight (Wi) for each parameter using Equation (11).

$$\mathrm{Wi} = \frac{\mathrm{wi}}{\sum_{i=1}^{n}\mathrm{wi}} \quad (11)$$

where wi is the weighted significance rating of the ith water parameter (one being the lowest rating and five being the highest rating) and n is the total number of rated water quality parameters. The coefficients are represented as decimals and they sum up to one to guarantee that the overall index value does not exceed a hundred percent. If this value exceeds a hundred percent, the aggregation of sub-indices will be compromised and the WQI deemed dysfunctional [69].

3. Calculate and assign a quality rating scale (qi) for each parameter by dividing the concentration of each water quality parameter (Ci) by its respective South African water quality standard (si). The results are then presented as percentages using Equation (12). Sub-indices are applied to convert different units into a single common-dimensional scale [45]. South African Water Quality Guidelines and numerical limits

for the catchment prescribed by the DWS were consulted in this process for water quality ranges.

$$qi = \frac{Ci}{si} \text{ x } 100 \quad (12)$$

4. Calculate the sub-index (Sb) for each water quality parameter. Sb is calculated using Equation (13).

$$Sb = Wi \text{ x } qi \quad (13)$$

5. Sub-indices are summed (Equation (14)) to give a single value for water quality for the dam.

$$WQI = \sum Sb \quad (14)$$

The water quality values are categorized using five water quality classes [65,70–72], as presented in Table 3.

Table 3. Estimations of water quality index method for suitability of water uses (classification for decreasing scale index).

Class	WQI Value	Rating of Water Quality	Possible Uses
Class 1	<25	Excellent	Domestic usage, irrigation, and industrial
Class 2	26–50	Good	Domestic usage, irrigation, and industrial
Class 3	51–75	Poor	Irrigation and Industrial
Class 4	76–100	Very poor	Irrigation
Class 5	>100	Unsuitable	Proper treatment is required before use

3. Results and Discussion

3.1. Physicochemical Characterisation of the Roodeplaat Dam

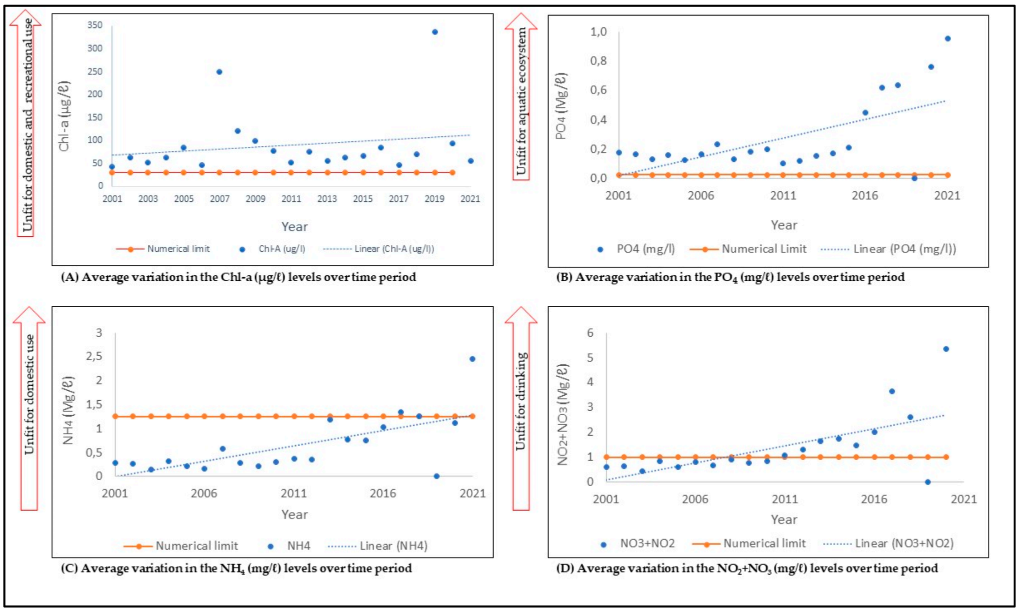
The primary statistical analysis for physicochemical parameters was performed on the measured data series. The results are presented in a synthetic form in Table 4.

Table 4. Descriptive statistics of water quality across the four monitoring sites across the Roodeplaat Dam.

Parameters	Descriptive Statics	Site A	Site B	Site C	Site D
Chlorophyll-a (µg/ℓ)	Min	35.57	36.34	36.23	28.98
	Mean	102.12	69.37	146.35	39.94
	Max	520.20	140.21	1116.05	47.58
	SD	102.84	25.92	237.98	5.92
Ammonium nitrogen (mg/ℓ)	Min	0.15	0.12	0.12	0.19
	Mean	0.94	0.73	0.67	0.28
	Max	3.83	3.80	1.84	0.48
	SD	0.92	0.86	0.57	0.09
Nitrate and nitrite (mg/ℓ)	Min	0.40	0.52	0.31	0.33
	Mean	1.70	1.70	1.63	0.68
	Max	5.13	4.74	5.37	1.16
	SD	1.33	1.18	1.43	0.23
Orthophosphate as P (mg/ℓ)	Min	0.13	0.08	0.06	0.12
	Mean	0.35	0.33	0.28	0.13
	Max	1.21	1.49	0.94	0.19
	SD	0.30	0.36	0.27	0.02
pH	Min	7.95	8.10	8.10	8.44
	Mean	8.41	8.50	8.50	8.60
	Max	8.98	9.08	9.13	8.99
	SD	0.29	0.31	0.29	0.18

Considerable spatial variations were observed in Figure 2; this indicated point-source (localized) pollution influence in various zones [73]. For instance, the highest annual mean concentration of NH_4^+ (0.94 mg/ℓ), $NO_2 + NO_3$ (0.94 mg/ℓ), and PO_4^{3-} (0.35 mg/ℓ) were recorded at Site A, which is the first dam site recipient of wastewater effluent discharge from Baviaanspoort WWTW via the Pienaars River. In 2004, a reported fish kill event at the dam was linked with treatment inefficiencies at the Baviaanspoort WWTW. At that time, high NH_4^+ and dissolved zinc, as well as traces of cyanobacterial (*Microcystis*) scums, were reported in the dam [74]. Site B, which is the immediate recipient of partially treated wastewater directly from the Zeekoegat WWTW before the dilution effect takes place, showed the joint highest mean concentrations of NH_4^+ and the second highest mean concentration of PO_4 (0.33 mg/l). Site C recorded the highest annual mean Chl-α (146.35 µg/ℓ), as it is the furthest downstream site that accumulates inputs from the rest of the sites. Lastly, Site D recorded the highest mean concentration of pH (8.60).

The results were further compared with the numerical limits and the Resource Quality Objectives (RQOs) for the catchment [75]. Over the period, there was a 100, 95, 14, 48, and 33% exceedance rate for the Chl-α, PO_4^{3-}, NH_4^+, $NO_2 + NO_3$, and pH (Table S1). The findings indicate that the dam water quality commonly fell below the required resource quality status. Once in the water bodies, the organic and inorganic pollutants increase the concentration of physicochemical parameters to exceed the required standard guideline limit and, in turn, influence the concentration of biological variables [67,76]. The consequence of pollutants emanating from anthropogenic activities in catchment areas is reported to be eutrophication caused by excessive nutrient enrichment. This is a major socio-economic concern to the country, as it leads to a high cost to treat water for public use. Hence, there is a need to develop proper management interventions.



(A) Average variation in the Chl-a (µg/ℓ) levels over time period
(B) Average variation in the PO_4 (mg/ℓ) levels over time period
(C) Average variation in the NH_4 (mg/ℓ) levels over time period
(D) Average variation in the NO_2+NO_3 (mg/ℓ) levels over time period

Figure 2. Annual mean variations of selected water quality parameters ((**A**) chlorophyll-a levels, (**B**) orthophosphate levels, (**C**) ammonium nitrogen levels, (**D**) nitrite and nitrate levels) across the longitudinal zone of the Roodeplaat Dam compared to the numerical limits of the gazetted RQOs of the catchment.

There was an irregular upward trend for Chl-α (Figure 2a) during the study period, with the minimum and maximum being 34.6 and 200.6 µg/ℓ, respectively, in 2001 and 2019. A steep rise in PO_4^{3-} concentration (Figure 2b) was observed, with the highest concentration of 1 mg/ℓ recorded in 2021, and it was noteworthy that the PO_4^{3-} average (1 mg/ℓ) was above the numerical limit of 0.025 mg/ℓ. Generally, the amount of algae in the surface water is limited by the concentration of nutrients, particularly nitrogen and phosphorus [77]. Therefore, the increasing trends of Chl-α and PO_4^{3-} pointed to a rising primary production rate of algae, which affects the resource's fitness for use, for instance, as the taste and odor of water can impact recreational activities and pose serious health problems to humans. There was also a rising trend for NH_4^+ (Figure 2c) and $NO_2 + NO_3$ (Figure 2d). In the case of NH_4^+, the lowest (0.1 mg/ℓ) was recorded in 2003 and the maximum (2.5 mg/ℓ) in 2021, whereas for $NO_2 + NO_3$, the minimum (0.4 mg/ℓ) and maximum (5.4 mg/ℓ) were, respectively, in 2003 and 2020. Notably, NH_4^+ was predominantly below the RQOs during the study period. Lastly, the annual mean pH records were predominantly in compliance with the respective RQOs, the state being slightly alkaline.

In addition to water quality parameters, the temperature of the RD was assessed (Figure 3). There was notable seasonality, as the summer average was 25 °C, followed by 21.33 °C in autumn, 21 °C in spring, and 16 °C in winter. The seasonality profile was expected due to seasonal ambient variation. Further, the findings indicated the dam to be monomictic with stable thermal stratification during summer [41]. In monomictic dams, the temperatures do not drop below 4 °C, as observed in this study. Summer stratification is characterized by an upper stratum of more or less uniform warm circulating and turbulent water, the epilimnion [78], which is the surface layer of a dam, is typically characterized as well-mixed and is decoupled from the metalimnion due to a steep change in density [79]. The epilimnion has a direct impact on the available nutrients as it influences algal growth.

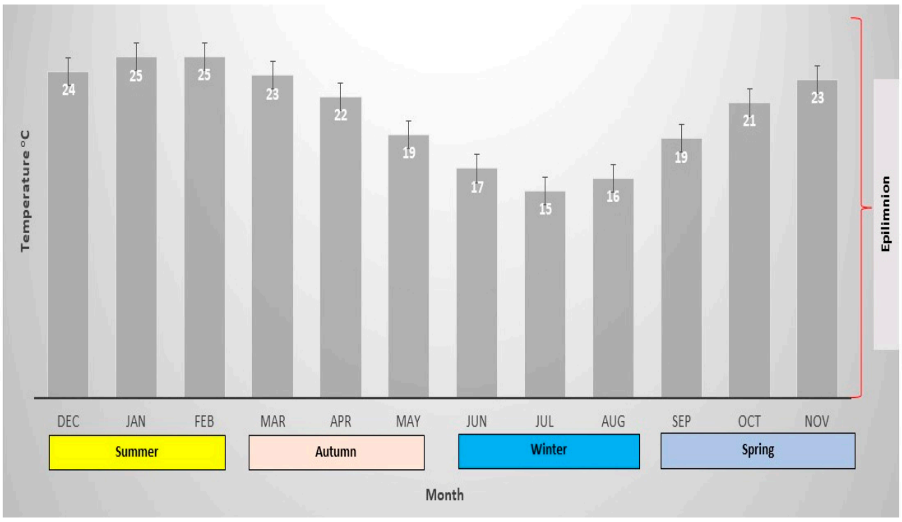


Figure 3. Monthly variations in the average surface temperatures (°C) of the Roodeplaat Dam (bars indicate standard deviations).

3.2. Principal Component Analysis of Water Quality over Time

Variations in selected water quality variables over time in RD were explored using PCA. Parameters representing nitrogen and phosphate loads were highly correlated over the study period (Figure 4).

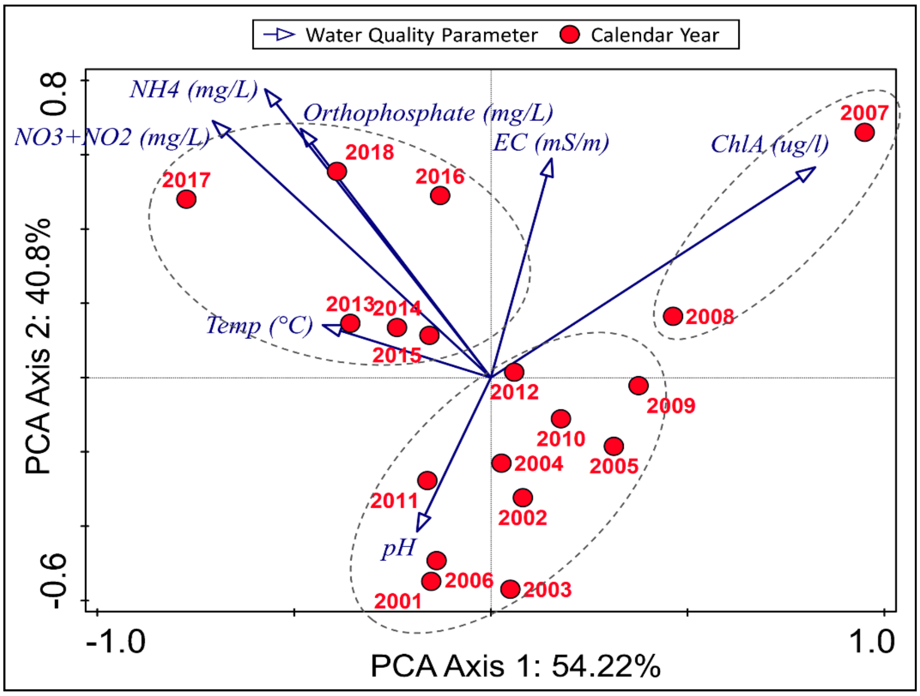


Figure 4. Principal Component Analysis (PCA) biplot indicating variation in selected water quality variables in Roodeplaat Dam from 2001 to 2018. Individual data points are mean values representing four sampling locations (A, B, C, and D) for each calendar year.

A similar pattern was evident when the dam wall (Site C) was evaluated independently, and the parameters "total nitrogen" and "total phosphate" were also considered (Figure 5).

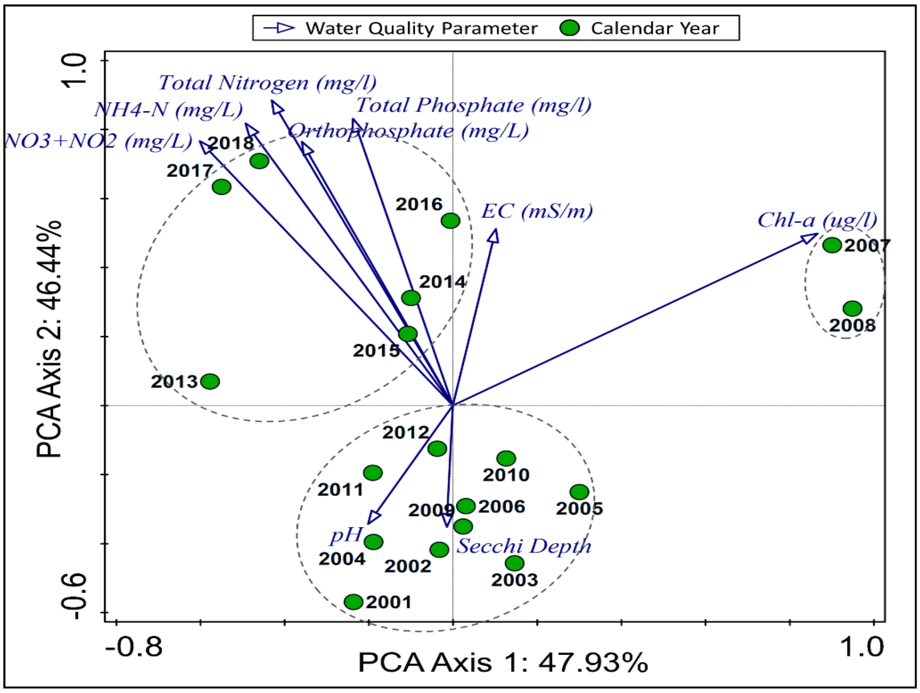


Figure 5. Principal Component Analysis (PCA) biplot indicating variation in selected water quality variables in Roodeplaat Dam from 2001 to 2018 at the dam wall (Site C). Individual data points are mean values representing each calendar year.

Secchi depth was negatively correlated with nitrogen and phosphate load, and EC. The PCA biplots (Figures 4 and 5) further indicated segregation in ordinal space with three major groupings of calendar years being apparent. In particular, the more recent years under investigation (2013–2018) were associated with increased phosphate and nitrogen loads, the years of 2007 and 2008 with increased Chl-α, and the remainder of the years investigated were negatively associated with indicators of nitrogen and phosphate loads. The PCA data suggested a deterioration in water quality in RD, with the later years of sampling, 2013–2018, associated positively with parameters representing nitrogen and phosphate loads.

3.3. Trophic State Classification

Trophic status refers to the water quality of water bodies corresponding to the content of nutrients [80], mainly nitrogen and phosphorus. TSIs are classification systems designed to rate water bodies, particularly dams, on the amount of biological productivity they sustain. They make it possible to describe dams in terms of the production continuum, predict system behavior, judge fitness for use, and assign perceived utility [81]. The results of the Trophic Status obtained from 2001 to 2021 are presented in Tables 5, S2, and S3. Accordingly, the cTSI method used in the study (Table 5a), revealed that the dam was eutrophic during 2001–2006 and 2009–2014 and hypertrophic from 2007 to 2008 and 2015 to 2021. Conversely, both the van Ginkel (Table 5b) and TLI (Table 5c) methods classified the RD as being hypertrophic throughout the period of the study. Although the mean annual TP concentrations were at the lowest in 2003–2005, 2009, 2011, and 2012, the concentrations were still consistently above 0.047–0.130 mg/ℓ which is the eutrophic range according to van Ginkel's method. The cTSI and van Ginkel methods do not take TN into consideration; however, van Ginkel et. al. [21] indicated that TN may be included in the classification in the future.

Table 5. Results of trophic state classified as per (A) the Carlson method, (B) the van Ginkel method, and (C) Burns et al.'s Trophic Level Index.

Year	(A)		(B)				(C)	
	TSI	Trophic Status	Mean Chla-α (µg/ℓ)	Mean TP (mg/ℓ)	SD Depth (m)	Trophic Status	Trophic Level Index	Trophic Status
2001	65.42	E	36.23	0.21	2.11	HE and clear	5.88	E
2002	67.22	E	53.11	0.22	1.99	HE and clear	6.09	HE
2003	67.07	E	65.15	0.19	2.06	HE and clear	6.05	HE
2004	65.47	E	44.26	0.19	2.15	HE and clear	6.01	HE
2005	68.78	E	94.47	0.19	1.84	HE and clear	6.20	HE
2006	67.83	E	64.81	0.23	2.09	HE and clear	6.14	HE
2007	76.78	HE	350.28	0.44	1.94	HE and clear	7.03	HE
2008	73.30	HE	341.85	0.23	2.06	HE and clear	6.61	HE
2009	66.99	E	61.01	0.18	1.87	HE and clear	6.07	HE
2010	68.89	E	80.37	0.24	2.04	HE and clear	6.31	HE
2011	65.71	E	51.93	0.17	2.04	HE and clear	6.09	HE
2012	69.06	E	66.35	0.17	1.20	HE and clear	6.36	HE
2013	64.96	E	37.80	0.21	2.36	HE and clear	6.20	HE
2014	69.53	E	87.02	0.25	1.92	HE and clear	6.53	HE
2015	71.74	HE	77.75	0.38	1.75	HE and clear	6.64	HE
2016	77.38	HE	112.67	0.66	1.20	HE and clear	7.11	HE
2017	73.87	HE	60.12	0.82	2.00	HE and clear	6.94	HE
2018	75.22	HE	71.73	0.78	1.63	HE and clear	7.02	HE
2019	00.00 *	—	1116.05	00.00 *	1.29	HE and clear	00.00 *	HE
2020	86.79	HE	94.26	2.15	0.49	HE and turbid	7.76	HE
2021	00.00 *	-	106.22	1.20	00.00 *	HE	00.00 *	HE

* Insufficient data.

Nutrient availability is a primary factor that influences the dam's ability to support the ecosystem, such that identifying factors that limit phytoplankton growth is crucial in understanding the dam's ecology [82]. A nutrient ratio (N:P) has been used to identify a nutrient enrichment factor [1,83]. The results in Figure 6A show that the $CTSI_{TP} > CTSI_{Chl\text{-}\alpha} > CTSI_{SD}$, which is an indication that water clarity was not a limiting factor on the trophic status in the dam and concurred with the results obtained using van Ginkel's method (Table 5c), which classified the dam as being a clear system. Meanwhile, Figure 6B depicts that $TLI_{TP} > TLI_{TN}$. If a TLI_{TN} value is significantly lower than the TLI_{TP} values, that is an indication that the dam is probably N-limited, and if TLI_{TN} and TLI_{TP} have similar values, that is an indication of co-limitation [61]. Therefore, the RD can be classified as being P-limited since the TLI_{TP} values were above the TLI_{TN}. Vollenweider [29] demonstrated that the TP generally increases with lake production; therefore, when the dam is P-limited, that means dam conditions are limiting primary production. Therefore, it can be concluded that the dam is affected by anthropogenic eutrophication and the major contributor is phosphate.

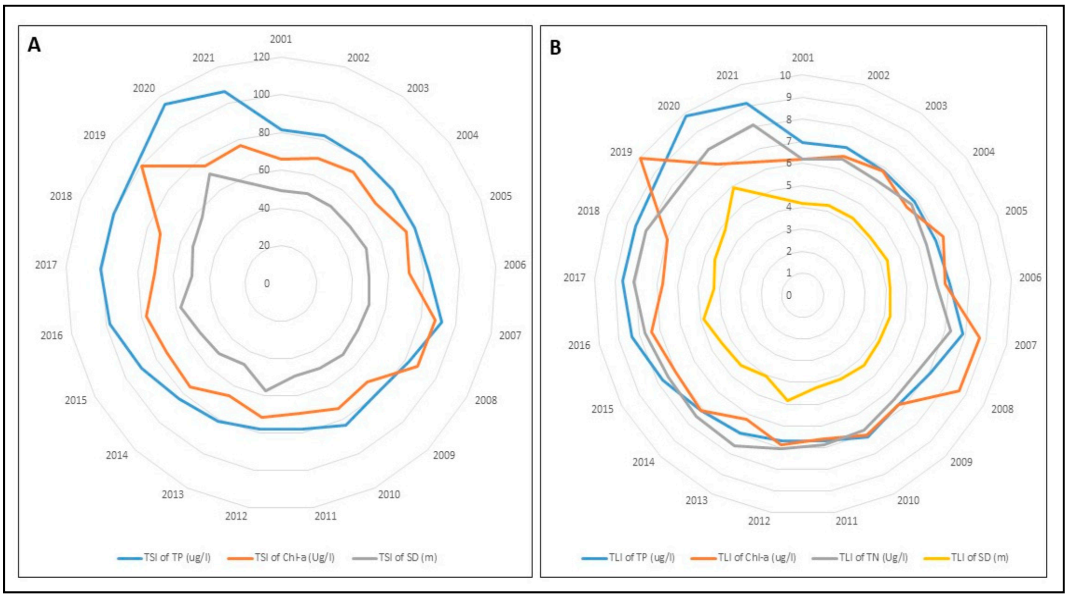


Figure 6. Radar diagram of the nutrient ratio of the Roodeplaat Dam as per (**A**) the Carlson TSI and (**B**) the Trophic Level Index.

Eutrophication is a state of excessive nutrient input from land-use activities such as untreated wastewater municipal and industrial effluent, as well as urban and agricultural surface runoff from agricultural fields. Eutrophication can naturally occur as lakes age with inputs from rocks and soils, for instance. Eutrophication causes algae blooms, which, in severe instances, can generate toxic algal substances that affect human and wildlife health. Further unwanted effects of algal blooms include the generation of foul odor and a reduction in biodiversity [84,85]. The occurrence of potentially toxic cyanobacteria species in drinking water dams leads to the abstraction of poor raw water quality for inter-basin and potable water provision, and this could be more severe in subtropical dams located in climate regions characterized by low rainfalls and high evaporation, such as the Vaal Dam in South Africa and Swakoppoort Dam in Namibia [17].

Toxic cyanobacterial blooms are one of the potential health hazards in freshwater reservoirs, which makes predicting bloom events an important goal for the monitoring and assessment of freshwater ecosystems [13]. Cyanobacterial toxins that cause illness in humans are categorized into three categories, namely (a) gastroenteritis, (b) allergies and irritations, and (c) liver diseases. Cyanobacterial toxins present in drinking water can lead to lethal outbreaks; for instance, 88 child fatalities from over 2000 cases of gastroenteritis occurred over 42 days in Brazil, and about 25–75% of algal blooms in Europe and North

America produce cyanotoxins [13]. The increased purification cost of eutrophic water is an additional economic pressure and crops irrigated with such water can experience hindered productivity, thus costing considerable income for a country. Such scenarios have been documented in South Africa, for instance, in Hartbeespoort and Loskop irrigation schemes due to the eutrophic conditions of the Hartbeespoort and Loskop dams, respectively [14,15].

3.4. Overall Assessment of Water Quality Status

The overall water quality status (WQI score) of the RD was calculated to be 93.94, which falls under Class 4 (Table 6). Class 4 is an indication of very poor water quality that is predominantly not fit for use for both direct domestic and recreational uses. However, water in the dam may still be used for irrigation purposes.

Table 6. Calculated water quality index for the Roodeplaat Dam.

Parameter	Standard Limit * (*Si*)	Weight (*wi*)	Relative Weight (*Wi*)	Concentration (*Ci*)	Quality Rating Scale (qi)	Sub-Index (*SIi*)	Index Score	Class	Rating	Possible Use **
Chl-α [(b)]	30	4	0.19	90.29	300.98	57.33		4		
PO_4^{3-} [(c)]	5	5	0.24	0.29	5.85	1.39				
NH_4^+ [(a)]	1.5	3	0.14	0.67	44.84	6.41	**93.94**		**Very poor**	**Irrigation**
NO_2+NO_3 [(a)]	6	4	0.19	1.58	26.27	5				
pH [(a)]	8.5	5	0.24	8.50	100	23.81				

* South African Water Quality Guidelines: [(a)] Volume 1: Domestic Use [77], [(b)] Volume 2: Recreational Use [86], and [(C)] Volume 7: Aquatic Ecosystems [87]. ** Possible use before treatment.

Putri et. al. [7] indicated that Africa has adopted the WQI as a monitoring program because it is a strong and reliable index composed of physical, chemical, and biological variables for the determination of water quality. However, this current study contradicts the background provided by Putri et. al. [7], as there is no known country in Africa that is using the WQI as part of their management practices, except for researchers exploring this option for consideration by decision-makers. Instead, this present study concurs with El-Serehy et. al. [63], that the WQI allows for several water resource uses and can be more robust and used effectively as a comprehensive tool for water quality quantification. Therefore, the current study argues that the WQI alone cannot be used as a tool to access and classify dams' trophic status. Hence, there is a need for an integrated approach (TSI and WQI) for the sustainable management of water resources, particularly dams.

4. Conclusions

RD exhibited the spatial variation of physicochemical characteristics, an indication of the high influence of point-source pollution. It was evident from the study that sites A and B characteristically were associated with inputs from the point-source pollution of WWTWs, leading to the continuous degradation of the water quality of the dam. Furthermore, the dam exhibited considerable anthropogenic impact, and as such, most of the parameters were not compliant with the established numerical limits and the RQOs. The PCA data suggested a deterioration in water quality in RD, with later years of sampling, 2013–2018, associated positively with parameters representing nitrogen and phosphate loads. It was further established that phosphate is the major driver of eutro-hypertrophic conditions in the RD. Although the dam was eutro-hypertrophic, according to the WQI, raw water could still be used for irrigation purposes before treatment. As such, continued nutrient enrichment must be mitigated to sustain fitness for irrigation, at least; however, strategic goals should involve widening fitness for use.

The selected indices were found to be effective for water resource management and could be applied to dams impacted by point-source pollution. Additionally, the PCA successfully related water quality results to environmental factors and pollution sources.

Therefore, to improve the water quality of the dam, an integrated management approach must be implemented and prioritize nutrient management to retain societal resource value. In that context, the discharge of suitably treated municipal effluent should be prioritized by improving effluent compliance by the associated WWTWs. The study further proposes the following interventions:

- The development of an integrated approach that will take into consideration the inclusion of trophic status and nutrient loading capacity for dams, such as the development of total maximum daily loads specifically designed for man-made dams in Southern African countries, which are highly impacted by anthropogenic activities;
- The establishment and/or update of a customized water quality standard system to improve the instream conditions of rivers, which will result in the decline of eutrophication and the improvement in the WQI to cater for the trophic status of dams;
- Green technologies to complement the engineered WWTWs must be considered, mostly in cases of poor WWTW performance; poorly treated municipal effluent is a major driver for deteriorating water resource quality in Southern Africa. Such is highly applicable for the RD, which receives most of its inflows from the wastewater return flow.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/w14213366/s1, Table S1: Mean annual water quality for the Roodeplaat Dam and the compliance status of numerical limits for the catchment; Table S2: Expanded results of trophic state as per the Carlson Index; Table S3: Expanded results of trophic state as per the Trophic Level Index.

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