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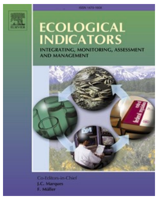

Original Articles

Evaluation of the water quality of a high Andean lake using different quantitative approaches

Fernando García-Avila [a,b], Pablo Loja-Suco [a], Christopher Siguenza-Jeton [a], Magaly Jiménez-Ordoñez [c], Lorgio Valdiviezo-Gonzales [d,*], Rita Cabello-Torres [e], Alex Aviles-Añazco [a,b]

[a] *Universidad de Cuenca, Facultad de Ciencias Químicas, Carrera de Ingeniería Ambiental, Cuenca, Ecuador*
[b] *Grupo de evaluación de riesgos ambientales en sistemas de producción y servicios (RISKEN), Departamento de Química Aplicada y Sistemas de Producción, Universidad de Cuenca, Ecuador*
[c] *Direccion de Gestion Ambiental, Gobierno Provincial del Azuay, Ecuador*
[d] *Universidad Tecnológica del Perú, Facultad de Ingeniería, Lima, Peru*
[e] *Universidad César Vallejo, Escuela profesional de Ingeniería Ambiental, Lima, Peru*

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ABSTRACT

This study assessed a high Andean lake's trophic state and water quality using methodologies with eutrophication and water quality indexes. Water samples were collected at six points in the lake, with a monthly frequency, for three winter and three summer months. Dissolved oxygen, pH, phosphates, nitrates, transparency, chlorophyll-a, fecal coliforms, biological oxygen demand (BOD), temperature, and turbidity were determined at each point. The trophic state of the lake was categorized by applying the Organization for Economic Cooperation and Development (OECD) eutrophication index, Carlson's trophic state index (CTSI) and trophic index (TRIX). In addition, National Sanitation Foundation water quality index (NSF-WQI), Canadian Water Quality Index (CCME-WQI) and Oregon Water Quality Index (OWQI) were used to evaluate water quality. Results indicated that the lake had a high level of eutrophication, suggesting an excessive accumulation of nutrients in the water. CTSI and TRIX index showed that the lake was in a hyper-eutrophic state, while according to the OECD methodology, the trophic state related to phosphorus and transparency was hypereutrophic, and according to chlorophyll, it varied from mesotrophic to eutrophic. The NSF index classified the lake with average quality, the CCME index indicated fair water quality, and the OWQI classified it as very poor. Therefore, the water quality of the high andean lake assessed by eutrophication and water quality indexes presented significant differences based on physicochemical characteristics. The human influence was identified as the main cause of eutrophication, including tourism and agriculture. These results suggest that measures should be taken to reduce human activity in the area and control pollution in the lake.

1. Introduction

Surface water quality is a critical environmental issue worldwide because it is essential for socioeconomic development, agriculture, healthy ecosystems, and human health (Elsayed et al., 2021). Water resource degradation is caused by natural processes and anthropogenic activities (Alves Martinset al., 2015; García-Avila et al., 2021). Natural processes that can contribute to the degradation of water resources are, for example, soil erosion, geological changes, sedimentation of rivers and lakes, and climate variability (Nagaraju et al., 2016). Some of the anthropogenic activities that contribute to the degradation of water resources include pollution, urbanization, intensive agriculture, water extraction, deforestation (Akhtar et al., 2021). Livestock and agriculture represent the main activities responsible for the loss of water quality, mainly in rivers and lakes (Akhtar et al., 2021). Using fertilizers in agriculture releases nutrients that leach into streams, rivers and lakes, increasing the risk of eutrophication (Bhateria and Jain, 2016). Eutrophication is a natural phenomenon that influences the quality of water bodies caused by the excessive increase in nutrients, affecting flora, fauna and biodiversity.

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* Corresponding author.
E-mail address: lvaldiviez@utp.edu.pe (L. Valdiviezo-Gonzales).

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The evaluation of the water quality of a high andean lake is presented using different quantitative approaches. For a comprehensive and rigorous evaluation of the water quality of this body of water, three eutrophication indices and three water quality indices were applied. It must be emphasized that this study focused on a high andean lake, which differentiates it from previous studies that have focused on lakes with different geographic and climatic characteristics (Ortiz-Jiménez et al., 2000; Quevedo-Castro et al., 2019: Fukushima et al., 2023). By addressing the assessment of a unique environment such as a high Andean Lake, this study provides valuable knowledge and specific perspectives that can contribute significantly to the global understanding of water quality in fragile and diverse ecosystems.

Lakes are expanses of water in the interior of the earth with no direct connection to the oceans (Bhateria and Jain, 2016). The ecological systems in these aquatic bodies include physical, chemical and biological aspects (Vasistha and Ganguly, 2020). Lakes can hold fresh or salt water, especially in arid areas, and vary in depth and permanence (Bhateria and Jain, 2016). They are ideal habitats for investigating ecological dynamics, as the interactions between biological, chemical, and physical processes often differ quantitatively or qualitatively from those that occur on land or in the air (Lennox et al., 2021; Liu et al., 2019). This characteristic causes these bodies of water to be very sensitive to nutrient over-enrichment and accelerated eutrophication (Domingues et al., 2017).

Lakes are ecosystems with enormous biogenic capacity, since they constitute unique habitats for characteristic flora and fauna, providing a variety of ecosystem services (Schallenberg et al., 2013). They allow the recharge and discharge of wastewater and play an important role in natural flood control, flow regulation, erosion and salinity (Brookes et al., 2022). They provide nutrients to geochemical cycles, protect watersheds, sequester carbon, and regulate climate (Newton et al., 2018).

High Andean lakes are vulnerable to environmental changes, such as climate variability and human activities, which can affect the quality of their waters (Liu et al., 2019; Farías et al., 2019). These bodies of water are found in mountainous regions and high altitudes, which exposes them to extreme environmental conditions and is sensitive to disturbance (Machate et al., 2023). Human activities have a significant impact on the water quality of these lakes (Khatri and Tyagi, 2015). Ranching, agriculture, and urbanization in surrounding areas can result in contamination of the lakes due to runoff from fertilizers, pesticides, and other chemicals (Bashir et al., 2020). Industrial effluent discharges also represent a threat to the water quality of high Andean lakes (Machate et al., 2023). Since high mountain lakes are fragile and unique ecosystems, the evaluation of their water quality becomes even more important. Only through a full understanding of the water quality in these water bodies can adequate measures be taken to conserve and protect these valuable ecosystems (Yao et al., 2019).

Over the years and the growing concern for taking restorative measures towards eutrophic bodies, a variety of methods have been developed to identify and classify bodies of water in different trophic states in order to know their health (Vinçon-Leite and Casenave, 2019). In this context, the evaluation of water quality is essential to ensure its sustainability and proper use (Jung et al., 2016; Kwon and Jo, 2023). Considering the aforementioned, the objective of this study was to evaluate the water quality using different quantitative approaches in Lake San Martín located in the city of Girón, located south of Ecuador.

The San Martín lake of Girón does not have an official protection status or protection category recognized nationally or internationally. However, an agreement is currently being drawn up between the Provincial Government of Azuay, the Municipal Government of Girón and the Ministry of the Environment of Ecuador for the environmental recovery of this body of water. The protection of San Martín lake is essential to preserve biodiversity, it has a direct impact on the supply of fresh water for local and regional communities. The lake acts as a source of drinking water supply, agricultural irrigation and support for economic activities related to tourism and fishing. The preservation of the lake's water quality is of vital importance to maintain a sustainable use of this resource and guarantee the availability of clean and safe water for future generations. Until now, no information on the water quality of this lake has been collected, which underscores the need for this study as a reference point for future research and to support decision-making by local and national authorities regarding its conservation.

This evaluation was carried out by applying trophic state indices (TSI) and water quality indices (WQI). A TSI is a measure that is used to evaluate the degree of enrichment of a body of water with nutrients, especially nitrogen and phosphorus, it is determined as a quantitative measure of the degree of eutrophication of a lake, lagoon, reservoir or the general health of these aquatic bodies (Mamun et al., 2021, Li et al., 2022). It is a classification system designed to value water bodies based on their biological productivity (El-Serehy et al., 2018). The water quality index is a tool used to assess and summarize overall water quality based on various physical, chemical, and biological parameters (Shaaban, 2022). It provides a quantitative and comparative measure of the condition of water in relation to established standards and water quality objectives (Hosseini et al., 2021).

The methodology of the Organization for Economic Cooperation and Development (OECD), Carlson's Trophic State Index (CTSI) and the TRIX index were used to estimate the trophic state of the lake water. While the WQIs applied were the National Sanitation Foundation's water quality index (NSF - WQI), the Canadian Council of Ministers of the Environment's water quality index (CCME - WQI) and the water quality index of Oregon (OWQI).

One difficulty for the development of this study was the lack of validated equations for high mountain lakes and the few studies that have applied trophic state indices (TSI) and WQI water quality indices in high andean aquatic ecosystems. The TSIs and WQIs have been developed and validated in low-altitude water bodies corresponding to tropical and temperate climates (Loaiza et al., 2021; Mnyango et al., 2022). For this reason, applying these indices to a high andean lake implied facing a challenge when using criteria and limits established in these methodologies developed in other parts of the world. Through this study it was possible to compare the results of the different indices used, which allowed establishing a general panorama of the trophic state and the water quality in the lake or lagoon. By analyzing and comparing the results of the indices, it was possible to identify differences and inconsistencies between them, which provides valuable information to improve and adjust the evaluation methods. This multidimensional approach provided a more comprehensive and robust view of the condition of the water, contributing to informed decision-making and effective management of these aquatic ecosystems.

2. Materials and methods

2.1. Studies area

The San Martín lake is located in the town of San Gerardo, city of Girón, province of Azuay, Ecuador (Fig. 1). It is located at the coordinates, 3°08′28.3″S–79°13′04.0″W; at an altitude of 2720–2800 m and maximum depth of 8 m. The summer and winter seasons are marked in the study area, and they were selected in order to obtain representative samples for the correct analysis of the eutrophication process and the calculation of the water quality index. Its surface is approximately 28 ha. The population near the lake is approximately 1159 inhabitants. The meteorological conditions of the basin include a temperature that varies from 8 to 16 °C, the annual precipitation varies from 500 to 1250 mm. Regarding the hydrological conditions, the effluent from the lake is discharged into the San Martín stream, Rircay river micro-basin, Jubones river basin.

The advantage of using Lake San Martin as a case study lies mainly in the fact that high Andean lakes are located in remote areas and are little

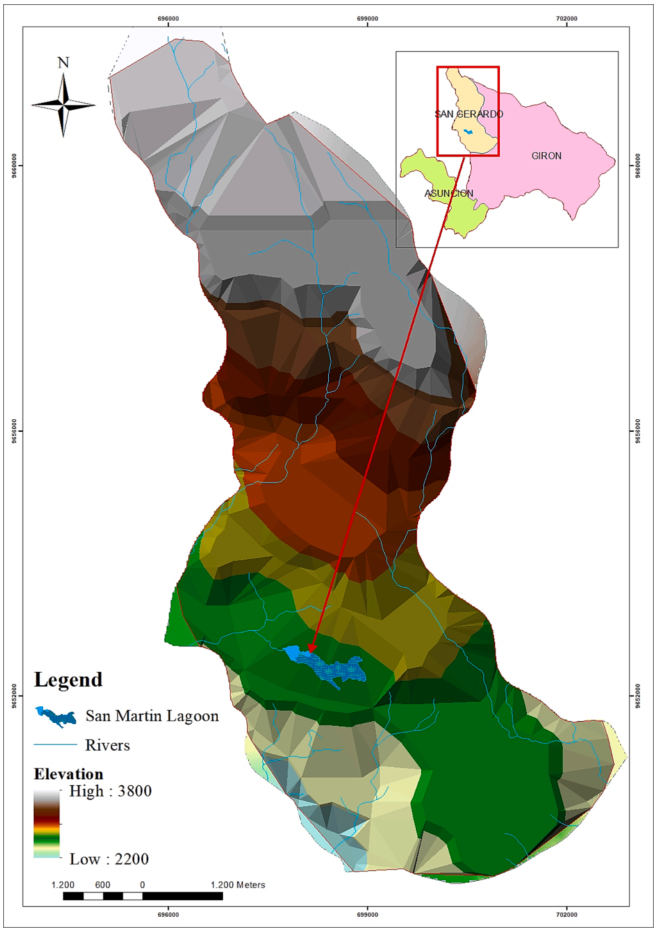

Fig. 1. Geographical location of Lake San Martín. This lake is located in the town of San Gerardo, city of Girón, province of Azuay, Ecuador.

disturbed by human activity. This allows one to study ecosystems with less anthropogenic influence and better understand natural impacts on water quality and biodiversity (Guevara et al., 2021). Therefore, by focusing on these high-mountain aquatic ecosystems, researchers can contribute new insights and help fill in the gaps in the scientific literature. Studying the quality of water in these environments allows us to understand and value its ecological importance and raise awareness about the conservation of these unique ecosystems (Catalan et al., 2017). High mountain lakes have often been less studied compared to low-lying bodies of water (Machate et al., 2023). Therefore, this case study can contribute to understanding the applicability and precision of trophic state and water quality indices in high mountain contexts (Moser et al., 2019; Quevedo-Castro et al., 2019). This is relevant considering that high mountain lakes are common in different mountain ranges, and the identified challenges and solutions may be applicable in similar contexts (Schirpke et al., 2021).

2.2. Sampling and laboratory analysis

The definition of the sampling points was carried out taking into account the methodology of the “Guide for participatory monitoring of water quality” published by the IUCN (2018). A total of 36 water samples were collected at the six selected points in the San Martin lake. The six sampling points were chosen to represent the different ecological conditions that prevail in the lake. The points were made to be as representative as possible and aspects such as the presence of algae, eutrophication zones, wind action (turbulence) and location of inputs (tributaries) and outputs (effluents) were considered.

Each sampling point was visited monthly in the summer season between the months of August, September and October 2021 and the winter season between the months of February, March and April 2022. These seasons were selected in order to obtain representative samples for the correct analysis of the eutrophication process and the calculation of the water quality index. To reach the sampling points presented above and take samples, an inflatable boat with a capacity to support four people was used.

The locations of the sampling points are shown in Fig. 2, while the coordinates and descriptive characteristics of the anthropogenic activities of the four sampling points are shown in Table 1.

Table 1 presents the location of the six sampling points in geographic coordinates and their respective identification codes with which they will be identified throughout this study.

Single samples were collected at each sampling point, using clean, labeled sampling bottles stored in a refrigerator. For chlorophyll-a, the sampling was carried out in 100 mL amber glass bottles. All sample containers were pretreated with dilute hydrochloric acid and distilled water. For fecal coliforms, the sample was taken in small plastic bottles, previously sterilized and sealed in bags to avoid possible contamination of the sample. pH, temperature, dissolved oxygen (DO) and turbidity were measured in the field using digital instruments after their calibration. In the case of transparency, the analysis was carried out in situ and using the Secchi disk methodology. The process begins by introducing the Secchi disk from the boat into the lake and the depth at which it is no longer visible is calculated as a measure of the transparency of the water column.

Methods (APHA, 2005) were used. The BOD (biochemical oxygen demand), COD (chemical oxygen demand), total phosphorus (TP), total nitrogen (TN), nitrates (NO3) were determined using a HACH DR6000 UV–VIS Spectrophotometer. Chlorophyll-a was determined using a Hewlett Packard model 8452 A spectrophotometer. Fecal coliforms were determined by membrane filtration. Dissolved oxygen (DO) by volumetry; pH by Electrometry using HQ40D HACH Multi-Parameter Meter; turbidity by the Nephelometry method using TL2300 HACH Turbidimeter, transparency through the Biologika brand Secchi Disc and temperature using HQ40D HACH Multi-Parameter Meter.

The above physicochemical and bacteriological parameters were selected in view of the fact that these parameters have already been determined and validated to be applied in the trophic and water quality indices chosen for this study (Wu et al., 2023a; Wu et al., 2023b). In addition, these parameters are adopted since total phosphorus and total nitrogen allow a more complete evaluation of the nutrients present in the water, which is essential to understand and address the eutrophication processes in the high andean lake, chlorophyll is necessary to consider because it is a direct indicator of the biomass of algae and aquatic plants, which provides essential information on the trophic status and primary productivity of the aquatic ecosystem (Liang et al., 2020). Fecal coliforms are a crucial bacteriological parameter to assess water safety and potential health risks (Sitotaw et al., 2022). The BOD allows the evaluation of the presence of organic pollutants that in turn contributes to eutrophication (Bhateria and Jain, 2016). However, other authors such as Alizadeh et al. (2018) propose using other quality parameters such as salinity, temperature and turbidity, as well as flow data.

There are other parameter alternatives that could have been considered in the evaluation of the water quality of a high andean lake; such as alkalinity, which provides information about the ability of water to resist changes in pH and can help assess the acidification or alkalinization of the body of water (Alizadeh et al., 2018; Kouadri et al., 2021). Another alternative would have been electrical conductivity, which is an indirect measure of the concentration of dissolved salts in the water and can provide information about the salinity and ionic quality of the water (Alizadeh et al., 2018). Likewise, heavy metals could have been considered, which may be indicators of anthropogenic contamination (Christophoridis et al., 2019).

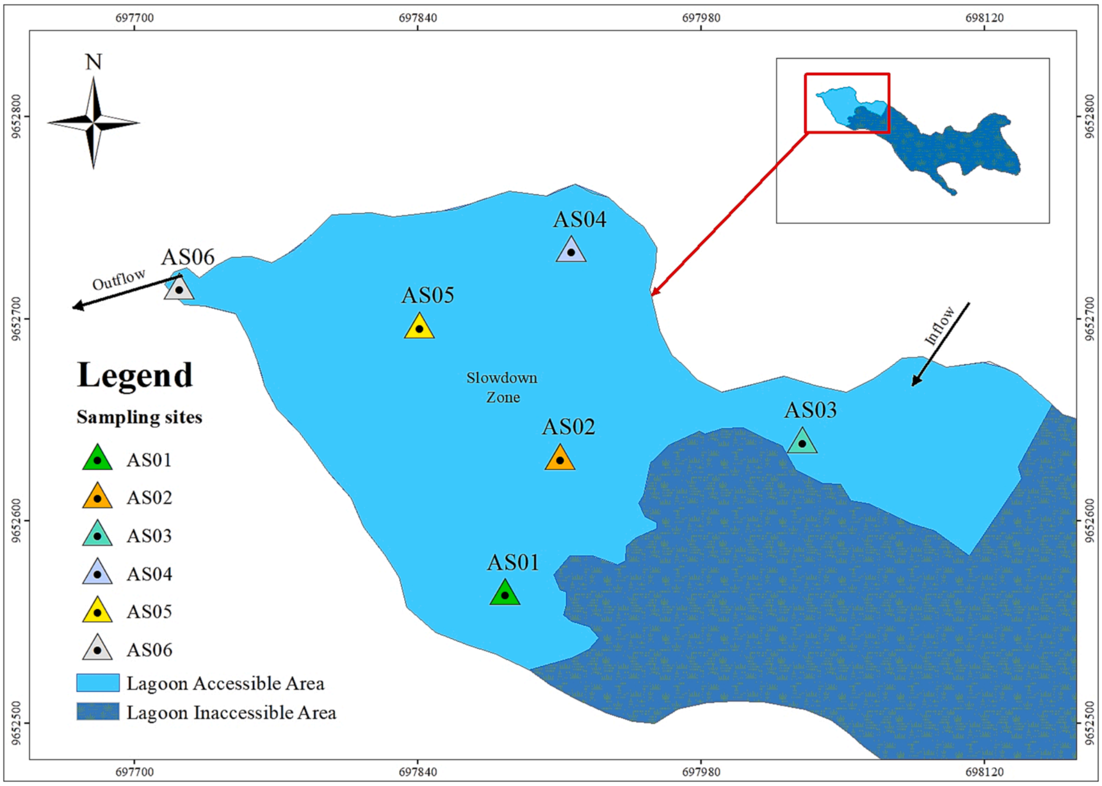

Fig. 2. Location map of the sampling points of Lake San Martín. The six sampling points in the lake were chosen for their geographical representativeness and their strategic distribution to cover different areas and depths of the body of water.

Table 1
Spatial distribution of sampling points and detailed description of human activities in Lake San Martin.

Sampling sites	Code	Coordinates		General features of anthropogenic activities
		X	Y	
Point 1	AS01	697890.87	9652561.29	Low aquatic vegetation reduced depth nearby grazing area wire fenceAccess road for farmers
Point 2	AS02	697910.39	9652632.26	accessible area high aquatic vegetation large amount of sediment high Whitall et alPresence of birds such as ducks.
Point 3	AS03	698030.24	9652640.59	Vegetal material Close to a cattle area Lawn Chemical ApplicationPresence of fecal feces from cattle
Point 4	AS04	697915.85	9652724.06	Low amount of vegetation Effluent from a livestock areahigh turbidity
Point 5	AS05	697841.06	9652724.75	Low amount of vegetation Lettuce cleaning workPresence of mounds of floating vegetation
Point 6	AS06	697722.37	9652716.46	It represents the mouth Solid waste and other anthropic activities. presence of a dike Recreational beach on the shores of the lake little algaeNearby ground covered with rocks

Failure to consider other parameters will not influence the results of the water quality assessment, since the parameters selected in this study already effectively address fundamental issues related to eutrophication, bacteriological health, and overall water quality in a high andean lake. However, Kouadri et al. (2021) highlights the importance of considering other additional physicochemical factors in the model, in order to improve predictive accuracy compared to conventional models.

2.3. *Assessment of the water quality of the San Martín lake*

Three water quality indices were used, the National Sanitation Foundation Water Quality Index (NSF-WQI), the Canadian Council of Ministers of the Environment Water Quality Index (CCME-WQI), the Oregon Water Quality Index (OWQI) (Uddin et al., 2021). The main reason is to assess the current state of contamination of the lake and also to compare the three main international water quality indices. In addition, three eutrophication indices were used, the Carlson trophic status index (CTSI), the Organization for Economic Cooperation and Development (OECD) index and the TRIX index (Primpas and Karydis, 2011; Lin et al., 2022).

In addition to the WQIs chosen for this study, there are other feasible index alternatives that could have been considered, such as the Dinius, Prati, Smith water quality index, weighted arithmetic index among others, these indices were developed by researchers and scientists with specific approaches and criteria to assess and classify water quality (Zotou et al., 2019; Chidiac et al., 2023). Therefore, applying the NSF-WQI, CCME-WQI and OWQI presents advantages over other alternative indices; for example, the selected indices have been developed and validated through rigorous scientific research and have been applied in various regions of the world, giving them a broad base of knowledge and experience (Alexakis et al., 2016; Cude, 2001).

The indices chosen for this study have a comprehensive approach when evaluating multiple water quality parameters, considering both physical–chemical and biological aspects (Calmuc et al., 2020; Chidiac et al., 2023). This allows a more complete and precise evaluation of the water quality in the high andean lake, addressing different aspects and variables that may influence its status. The NSF-WQI, CCME-WQI, and OWQI provide a standardized and uniform framework for evaluating and comparing water quality in different bodies of water (Cude, 2001; Chidiac et al., 2023). This facilitates the comparison of the results obtained in the high andean lake with other studies and allows the establishment of benchmarks for water management and conservation.

However, it must be considered that the adoption of these indices could affect the results of the study in terms of the classification and interpretation of the water quality in the high andean lake since each index has its own methodology and evaluation criteria, which could result in differences in the assignment of categories or quality ratings (Uddin et al., 2021). Therefore, it is important to understand and consider the specificities and limitations of each index when interpreting the results and making decisions based on them.

Machine learning techniques are presented as a promising alternative for the estimation of water quality in aquatic bodies such as lakes (AlDahoul et al., 2022; Deng et al., 2021). However, it is important to note that the development of these models requires quality and representative data, as well as proper validation and adjustment to ensure their reliability and accuracy in the specific context of the lake in question (Hadjisolomou et al., 2021).

2.3.1. Calculation of the NSF index

The NSF-WQI was calculated using the additive method that consists of the sum of the results of each subindex of the parameters analyzed. Taking into account the microbiological and physicochemical variables, this index uses 9 parameters (Brown et al., 1970); however, in this study 8 parameters were used: BOD, dissolved oxygen, phosphates, nitrates, fecal coliforms, pH, temperature and turbidity (Uddin et al., 2021). Equation 1 was used to calculate NSF-WQI.

$$\mathrm{NSF}-\mathrm{WQI} = \sum_{i=1}^{i=n} Ii^{*}Wi$$

where NSF–WQI is the Water Quality Index; Ii is the subindex of the parameter i, which is between 0 and 100; Wi is the weight between 0% and 100%, assigned to each parameter (Ii); i is each of the considered parameters. To calculate the subindex of each parameter, the equations found in the Annex 1 were used.

The weighted weights are weighting factors according to their importance in the application of the NSF – WQI. The following weights were assigned: DO: 17%, FC: 16%, pH: 11%, BOD: 11%, ΔT: 10%, PO_4: 10%, NO_3: 10%, Turbidity: 8 %, Total Solids TS: 7% (Abbasi and Abbasi, 2012). As total solids (TS) were not available, the weighting factor corresponding to that parameter was distributed among the other parameters, obtaining the following weight assignment: OD: 17.87%, FC: 16.87%, pH: 11.87%, BOD: 11.87%, ΔT: 10.87%, PO_4: 10.87%, NO_3: 10.87%, Turbidity: 8.87%. Table 2 presents the categorization of the NSF-WQI, CCME-WQI and OWQI (Marselina et al., 2022).

Table 2
Water quality classification according to its value and corresponding categorization for the NSF-WQI, CCME-WQI and OWQI indices.

NSF WQI		CCME WQI		OWQI	
Index	**Quality Status**	**Index**	**Quality Status**	**Index**	**Quality Status**
91–100	Excellent	95–100	Excellent	90–100	Excellent
71–90	Good	80–94	Good	85–89	Good
51–70	Medium	65–79	Fair	80–84	Fair
26–50	Bad	45–64	Marginal	60–79	poor
0–25	Look and Bad	0–44	Poor	0–59	Very poor

2.3.2. Calculation of the CCME-WQI

For the calculation of the CCME - WQI index, the parameters BOD, COD, dissolved oxygen, fecal coliforms, pH, temperature, turbidity, phosphorus, nitrates, nitrites, total nitrogen and fecal coliforms were used. These parameters were analyzed considering the environmental regulations corresponding to the criteria of water quality for recreational purposes. The calculation of the CCME - WQI was carried out using equation (2) and based on the aforementioned parameters; but before it was necessary to calculate the factors: scope (F1), frequency (F2) and amplitude (F3) using equations (3), 4 and 5 respectively proposed by the Canadian Council of Ministers of the Environment (CCME, 2017).

$$\mathbf{CMME}-\mathbf{WQI}\mathrm{CCME\_WQI} = 100 - \left(\frac{\sqrt{\mathrm{F1}^2+\mathrm{F2}^2+\mathrm{F3}^2}}{1.732}\right) \tag{2}$$

F1 (Scope) denotes the proportion of parameters that fail to meet their guidelines at least once during the specified time period (“failed parameters”), in relation to the overall number of parameters assessed.

$$\mathbf{Scope}(\mathbf{F}1)\mathrm{F1} = \left(\frac{\text{Number of failed variables}}{\text{Total number of variables}}\right)100 \tag{3}$$

F2 (Frequency) represents the percentage of individual tests that do not meet guidelines (“failed tests”):

$$\mathbf{Frequency}(\mathbf{F}2)\mathrm{F2} = \left(\frac{\text{Number of failed tests}}{\text{Total number of test}}\right)100 \tag{4}$$

F3 (Amplitude) indicates the extent to which unsuccessful test results deviate from their prescribed standards. F3 is computed through a three-step process.

$$\mathbf{Amplitude}(\mathbf{F}3)\mathrm{F3} = \frac{\mathrm{nse}}{0.01\mathrm{nse}+0.01} \tag{5}$$

where nse is the normalized sum of the excursions of the targets. In turn, nse was calculated using equation (6).

$$\mathrm{nse} = \frac{\sum_{i=1}^{n}\mathrm{excursion}_i}{\text{Number of test}} \tag{6}$$

The excursion was calculated using equation (7) when the test value should not exceed the target:

$$\mathrm{excursion}_i = \left(\frac{\text{Failed Test Value}_i}{\text{Objective}_i}\right) - 1 \tag{7}$$

Meanwhile, the excursion was calculated using equation (8) when the test value should not fall below the target:

$$\mathrm{excursion}_i = \left(\frac{\text{Objective}_i}{\text{Failed Test Value}_i}\right) - 1 \tag{8}$$

Table 2 presents the categorization of the CCME-WQI (Marselina et al., 2022).

2.3.2.1. Calculation of the Oregon index (OWQI).

The OWQI expresses a simple number about water quality allowing us to compare the quality of the water body at different points. This index uses 8 parameters; pH, total solids, total phosphorus, fecal coliforms, nitrates, BOD, dissolved oxygen and temperature (Dojlido et al., 1994). The OWQI method was used, whose formulas proposed by the Oregon Department of Environmental Quality are presented in equation (9). In the present study, only 7 parameters were used, excluding total solids.

$$OWQI = \sqrt{\frac{8}{\frac{1}{SI_T^2}+\frac{1}{SI_{DO}^2}+\frac{1}{SI_{BOD}^2}+\frac{1}{SI_{pH}^2}+\frac{1}{SI_{TS}^2}+\frac{1}{SI_N^2}+\frac{1}{SI_P^2}+\frac{1}{SI_{FC}^2}}} \tag{9}$$

where OWQI = Water Quality Index, SIi = Subindex of parameter i, n = Number of subindices. The equations for calculating the subindices are presented in Annex 2. Table 2 presents the categorization of the three indices evaluated in this study (Marselina et al., 2022).

2.4. Determination of trophic state indices

For the selection of the eutrophication indices applied in the San Martín Lake, a bibliographic review of all the existing indices was carried out and a selection was made according to the adaptability to the study area and other factors such as time, cost, etc. For this, three models were selected: Carlson Trophic Status Index (CTSI), Organization Model for Economic Cooperation and Development (OECD) and the TRIX Index. These indices are the most widely used globally (García-León et al., 2023).

The OECD and CTSI model have been widely used in the classification of reservoirs and lakes (El-Serehy et al., 2018). On the other hand, for the TRIX index, a large part of its applicability is focused on coastal areas, with a minimal number of case studies in lakes (Primpas and Karydis, 2011); however, this index was chosen to corroborate its reliability and applicability in the San Martín lake, comparing it with the results that will be obtained with the two previously mentioned indices.

In addition to the TSIs adopted in this study, there are other indices such as the Primpas eutrophication index, HEAT tool, TLI trophic level index, Toledo index, Lamparelli index, Cunha index that are also used to assess water quality (López Martínez et al., 2015; Neverova-Dziopak et al., 2023). However, the CTSI, OECD and TRIX Index are the most widely used worldwide, because they are robust and provide appropriate information to implement coastal zone management criteria (Ferreira et al., 2011; El-Serehy et al., 2018).

The advantage of using the CTSI, OECD and the TRIX Index is that these indices are widely used worldwide and have solid scientific support, which makes it easy to compare results with previous studies and to establish patterns and trends at global scale (Neverova-Dziopak et al., 2023). The other alternative indices have a specific focus and applicability to different contexts. The three indices selected for this study provide a comprehensive assessment of water quality, considering different parameters and aspects of the aquatic ecosystem, they are specifically designed to assess the degree of eutrophication and water quality in relation to nutrients and algae biomass (Jarosiewicz et al., 2011a; Jarosiewicz et al., 2011b). This is relevant in the case of a high andean lake, where eutrophication processes can have significant impacts on the aquatic ecosystem (Guevara et al., 2021).

The application of the indices chosen for this study allows for obtaining a complete and reliable vision of the state of contamination of the high andean lake. It contributes to decision-making for its management and conservation. However, adopting alternative indexes such as those mentioned above could provide a complementary perspective and broaden the understanding of water quality in the high andean lake. It should be emphasized that all the aforementioned indices use in their calculation methodology at least the parameters phosphorus, chlorophyll-a and depth (Mamun et al., 2021). The use of these established and widely used indices can allow the comparison of the results obtained in the high andean lake with previous studies carried out in different parts of the world. This helps to identify patterns and trends on a global scale, which can be especially useful to better understand eutrophication processes and water quality in a broader context (Neverova-Dziopak et al., 2023). Shamshirband et al. (2019) propose the use of ensemble models with uncertainty analysis for the multi-day forecast of chlorophyll concentration in coastal waters.

2.4.1. Carlson trophic status index (CTSI)

The methodology developed by Carlson (1977) was applied to know the trophic state of the San Martín lake. This index is based on three parameters: Secchi disk depth, total phosphorus and chlorophyll-a (Zhang et al., 2023). In equations 10–12 the respective equations for calculating the index of each parameter are presented, using equation (13) the final CSTI was obtained.

$$\text{Secchi Disk Depth (SD)} : \text{CTSI}_{SD} = 60 - 14.41\text{Ln}(\text{SD}) \tag{10}$$

$$\text{Total Phosphorus (TP)} : \text{CTSI}_{TP} = 14.42\text{Ln}(TP) + 4.15 \tag{11}$$

$$\text{Chlorophyll} - \text{a (Chl.a)} : \text{CTSI}_{\text{Chl.a}} = 9.81\text{Ln}(\text{Chl.a}) + 30.6 \tag{12}$$

$$\text{Final CTSICTSI} = \frac{(\text{CTSI}_{SD} + \text{CTSI}_{TP} + \text{CTSI}_{\text{Chl. a}})}{3} \tag{13}$$

The trophic level classification thresholds for CTSI are oligotrophic ($\text{CTSI} \leq 40$), mesotrophic ($40 < \text{CTSI} < 50$), eutrophic ($50 \leq \text{CTSI} < 60$), hypereutrophic ($\text{CTSI} \geq 60$) (Klippel et al., 2020).

2.4.1.1. OECD methodology. To calculate the level of eutrophication, the same parameters as the previous case were used: phosphorus, chlorophyll-a and transparency (Zurlini, 1996). The categorization of the trophic state through the application of the OECD methodology (1982) is based on comparing the data obtained in the analysis of each monitoring point around the lake with the limits proposed by the Organization for Economic Cooperation and Economic Development for each category (Table 3) (El-Serehy et al., 2018; Zhang et al., 2021).

2.4.1.2. TRIX index. The trophic index (TRIX) was also used to determine the eutrophication level of the sampling area and the water quality (Vollenweider et al., 1998). The TRIX index includes in its formula the deviation of oxygen saturation, total nitrogen, total phosphorus and chlorophyll-a, obtained at each sampling point. In the calculations, these mentioned variables have the same weight to determine the trophic status of the lake (Gomez Jakobsen, 2015). The TRIX index is calculated by analyzing the aforementioned parameters and using equation (14).

$$\text{TRIX} = \frac{\log(\text{Chla*DO*TN*TP}) + \text{K}}{\text{m}} \tag{14}$$

where Chla: Chlorophyll-a concentration (μg/L), DO: absolute value of the deviation of the dissolved oxygen saturation percentage (100 - % DO), TN: Total nitrogen concentration (μg/L), TP: concentration of Total Phosphorus (μg/L), K and m are constant where, $\text{K} = 1.5$ and $\text{m} = 1.2$ (Béjaoui et al., 2016).

TRIX was scaled from 0 to 10, with the value of 10 being the highest in the categorization and resulting in a hypereutrophic body of water, covering a range of four trophic states (0–4 high quality and low trophic level; 4–5 good quality and moderate trophic level; 5–6 moderate quality and high trophic level and 6–10 degraded and very high trophic level) (Giovanardi and Vollenweider, 2004; Penna et al., 2004).

2.5. Data analysis

The results of the water quality parameters were statistically treated spatially and temporally. The assumptions of normal distribution, homoscedasticity and independence were analyzed for each sampling point and each monitoring period. To verify the assumptions of normal distribution, the Shapiro-Wilk normality test was applied, since this test is applicable to samples containing less than 50 elements (Shapiro and Wilk, 1965). The assumption of homogeneity of variances or homoscedasticity was also verified using the Fligner-Killeen test. Subsequently, it

Table 3
Classification of the trophic index according to the value and categorization corresponding to the OECD index.

Trophic category	Transparency (m)	Phosphorus (μg/L)	Chlorophyll-a (μg/L)
Ultratrophic	> 12	< 4	<1
Oligotrophic	6–12	4–10	1 – 2.5
Mesotrophic	3–6	10–35	2.5 – 7.9
Eutrophic	1.5 – 3	35–100	8–25
Hypereutrophic	< 1.5	> 100	>25

was verified whether there are significant differences in the indices obtained for each sampling point; for which an analysis of variance was applied, one-way ANOVA when there was a normal distribution or Kruskal Wallis in the case of not fulfilling the assumptions of normal distribution. This analysis was carried out with the RStudio software.

In addition to the Shapiro-Wilk normality test, there are other feasible alternatives that can be used, such as the Kolmogorov-Smirnov test, Lilliefors Test, Anderson-Darling Test, these tests are also used to assess the normality of a distribution. It is important to note that there is no single perfect test to verify normality and results may vary depending on the sample size and the nature of the data and the specific context of the analysis (Razali and Wah, 2011).

The Shapiro-Wilk test has the advantage of not being affected by outliers compared to other normality tests, which makes it more robust. In general, the Shapiro-Wilk test tends to provide more accurate estimates of normality than other tests, it is known to be one of the most sensitive tests for detecting deviations from normality, and it is particularly effective in small samples ($n < 50$), which is why it was chosen for this study (Mishra et al., 2019). The Shapiro-Wilk test is relatively robust to minor deviations from normality compared to some other normality tests, such as the Kolmogorov-Smirnov test, which is suitable for larger samples (Ghasemi and Zahediasl, 2012).

In addition to the Fligner-Killeen test to assess variances, there are other alternative tests that can be used, such as Levene's test, Bartlett's test, Cochran's test, Brown-Forsythe's test, Welch's test. It is important to consider the characteristics of the data, such as sample size and group distribution when selecting the most appropriate test. Each test has its characteristics and assumptions, so it is essential to select the most appropriate test for the data and the statistical methods used later (Zhou et al., 2023).

The Fligner-Killeen test has the advantage of offering robustness and greater sensitivity compared to other tests of equality of variances, especially in situations where the data does not follow a normal distribution, or the sample sizes are unequal. Unlike the Bartlett test, which assumes normal distributions, the Fligner-Killeen test is more appropriate when the data does not follow a normal distribution. The Fligner-Killeen test is more sensitive than the Levene test for detecting differences in variances when groups have unequal sizes (Gastwirth et al., 2009).

In order to know whether or not there are significant differences in the indices obtained, the one-way ANOVA test was applied; however, there may be other options such as Student's T or MANOVA in the case of correlated dependent variables (Dattalo, 2013). When there is no normal distribution in the data, a non-parametric analysis of variance such as the Kruskal-Wallis test or the Friedman test can be applied (Neil, 2017). The advantage of using ANOVA compared to other statistical tests is its ability to assess differences between multiple sets of data simultaneously, making it a widely used statistical tool in data analysis and research (McIntosh et al., 2010; Neil, 2017).

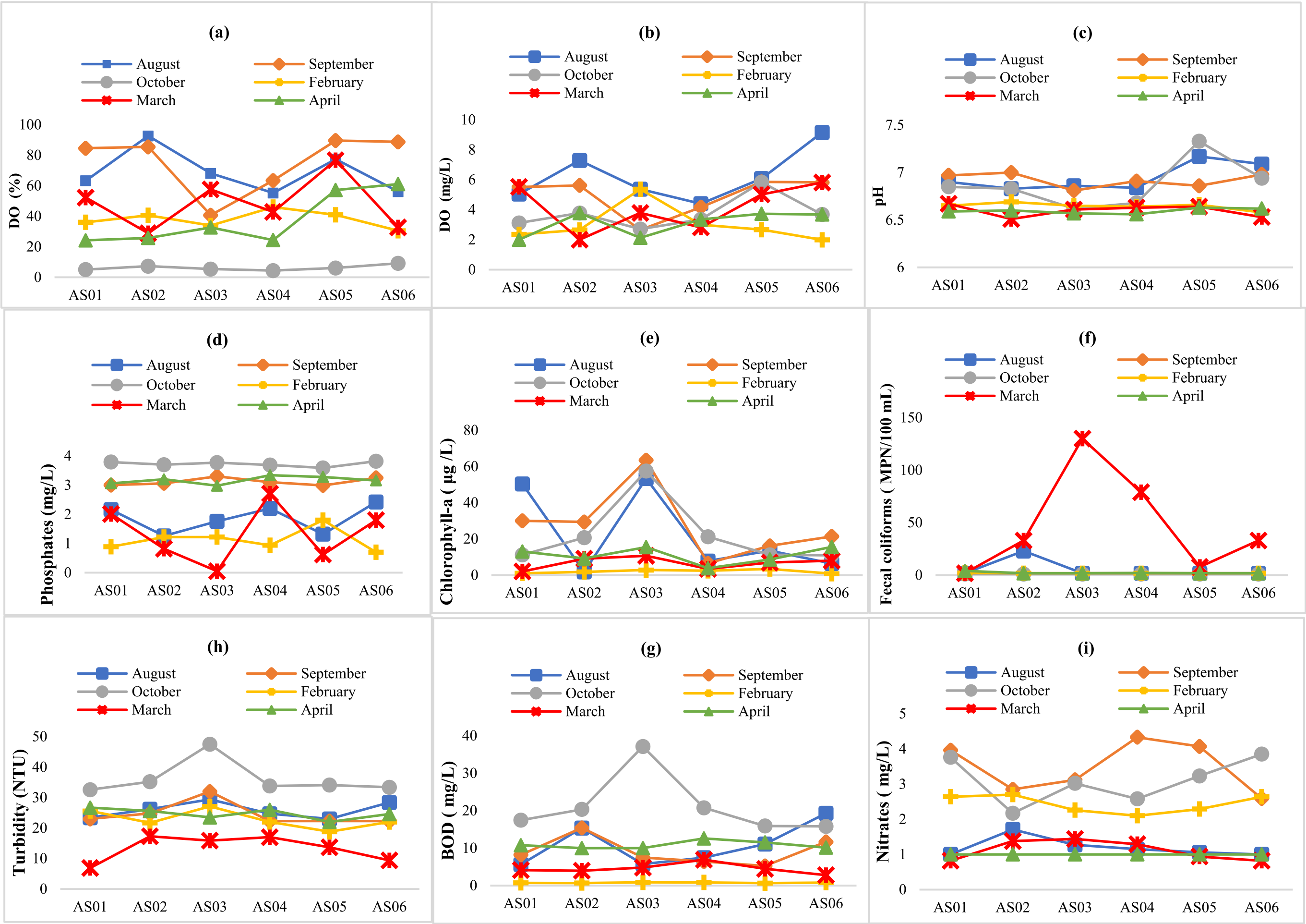

Fig.3. Variation of the average concentrations of the mean parameters in Lake San Martín during the months of monitoring. (a) DO percentage variation, (b) DO concentration variation, (c) pH variation, (d) Phosphate concentration variation, (e) Chlorophyll-a concentration variation, (f) Variation in the concentration of fecal coliforms, (g) Variation in the BOD concentration, (h) Variation in Turbidity, (i) Variation in the concentration of Nitrates.

3. Results and discussion

3.1. Spatiotemporal analysis of physical, chemical and microbiological parameters

In Fig. 3 (a) the saturated DO percentages measured at each sampling point are presented. The saturated oxygen percentage of the water refers to the amount of dissolved oxygen in the water in relation to the maximum amount of oxygen that can be dissolved in it at a certain temperature (Bozorg-Haddad et al., 2021). The relationship between oxygen saturation and temperature in this high andean lake was inversely proportional; thus, as the water temperature increased, the oxygen retention capacity decreased. Therefore, at higher temperatures, the oxygen saturation in the water tended to decrease. On the other hand, at lower temperatures, the oxygen holding capacity was higher, resulting in higher oxygen saturation in the water. This relationship is important because it directly affects aquatic life and biological processes in the aquatic ecosystem (Chapra et al., 2021). According to Fig. 3(a), the highest water temperature occurred in the month of October, which is why the oxygen saturation was lower in that month; meanwhile, in the months of September and August, the water temperature was lower, which is why the oxygen saturation was higher.

In Fig. 3 (b) the concentration of DO in summer had an average value of 4.97 mg/L and in winter an average value of 3.43 mg/L. Posada et al. (2013) ensure that the waste generated by poultry and livestock accumulates generating organic matter, which requires a high oxygen demand to carry out the oxidation process, decreasing the DO. This can be justified because in the surroundings of points AS03 and AS04 cattle could be observed, and it is where the lowest DO values were presented. The Ecuadorian regulations (TULSMA, 2013) indicate the water quality criteria for recreational purposes, recommending that the maximum permissible limit of %DO should not be less than 80%. Therefore, most of the results presented in Fig. 3(a) are below the limit, which decreases the water quality. Commonly, bodies of water should have an ideal oxygen concentration between 5 and 9 mg/L, observing Fig. 3 (b) the lake in most of the monitored months presented non-ideal conditions for aquatic life (Salmasi et al., 2021). According to Viessmann Jr et al. (2009) values below 1 mg/L of oxygen are lethal for aquatic life, with values close to the lethal limit such as points AS06 (February), AS02 (March) and AS01 (April), therefore, there are Please pay attention to these points.

The average pH value presented in Fig. 3 (c) in the summer season was 6.92 and in winter it was 6.61 on average; these pH variations are due to temperature, this being a determining factor since pH and temperature have a directly proportional relationship. According to Lopez Archilla et al. (2003) hypereutrophic systems present an increase in pH since primary production is high; the high pH concentration creates positive feedback in the water thus increasing the amount of carbon for primary production and helping to have a greater solubility of nutrients such as phosphorus. Therefore, the San Martín lake should not present a hypereutrophic state.

In Fig. 3 (d) the phosphates presented average values of 2.89 mg/L and 1.84 mg/L in summer and winter, respectively. The highest value occurred in the month of October with a value of 3.76 mg/L and the lowest value of 0.05 mg/L at point AS03 (March). In winter, the phosphate concentrations varied between 0.05 and 3.06 mg/L and in summer 1.32–3.76 mg/L. High concentrations are attributed to increased erosion due to periodic and intense rainfall that drags phosphates into the body of water (Rodríguez et al., 2016).

The concentration of chlorophyll-a is presented in Fig. 3 (e); in the summer season the highest values were presented, especially at point AS01 (August) a value of 50.43 μg/L was obtained; meanwhile, at point AS03 in the three summer months August, September and October presented values of 53.40 μg/L, 63.49 μg/L and 57.51 μg/L respectively; however, in the winter season it presented lower values on average, a value of 6.5 μg/L. Chlorophyll-a depends on the penetration of light, temperature and concentration of nutrients (N and P), therefore the high concentrations of chlorophyll-a are attributed to the concentration of nutrients such as phosphorus present in the lake (Bonansea et al., 2014). Chlorophyll-a is directly related to phosphorus as mentioned by Havens (2000) corroborating what was said by Bonansea et al. (2014). Another relationship of chlorophyll-a is the one demonstrated by Toapanta Aimacaña (2017) with the DO, whereas the DO decreases, chlorophyll-a increases, being an inversely proportional relationship.

In Fig. 3 (f) the variations of fecal coliforms in the San Martín lake are presented, average values of 2.7 MPN/100 mL in summer and 17.16 MPN/100 mL in winter were obtained. Ferguson et al. (1996) mention that coliforms are indicators of shorter life in sediments in the water, therefore, these will be influenced in winter, for this reason there is a variation of concentrations between summer and winter; indeed, the highest concentration of coliforms occurred during the month of March, which corresponds to winter. Fecal coliforms have greater survival in freshwater bodies compared to seawater, this explains the presence of fecal coliforms in the lake (Gerba and McLeod, 1976). The lake has an outlet channel that favors self-purification by decreasing the concentration of fecal coliforms (Vail, 1998).

Observing Fig. 3 (g), the BOD in the summer season at point AS03 (October) presented a high concentration of 37.12 mg/L and a low value of 5.23 mg/L at point AS05 (September). In winter, the lowest BOD value was 0.66 mg/L (AS01, March) and the highest value was 12.59 mg/L (AS04, April); On average, summer obtained a value of 13.69 mg/L and winter a value of 5.37 mg/L. Sardiñas et al., (2006) mention that high BOD concentrations occur due to low DO concentrations, this decrease is due to the fact that bacteria consume oxygen from the water; as observed in point AS01 (August) it has a BOD of 5.61 mg/L and DO of 5.04 mg/L, compared to point AS04 (August) with a BOD of 7.45 mg/L and DO of 4.4 mg/L, corroborating the above mentioned. This variation in BOD concentrations in the lake is attributed to factors such as the amount of organic matter, presence of organic carbon, high concentration of nutrients, pH and temperature, as indicated by Bellos and Sawidis (2005).

The monitored turbidity is presented in Fig. 3 (h), in the winter season it presented an average value of 20.32 NTU and in summer an average value of 28.80 NTU. The highest peaks for summer were 35.2 NTU and winter 26.70 NTU, while the lowest values for summer were 22.30 NTU and winter 6.90 NTU. Turbidity is caused by the presence of suspended particles, whether organic or inorganic, as mentioned by Parra et al. (2018). In summer there was high turbidity, this can be attributed to the fact that there was no high rainfall in winter during the monitoring year, rather there was sporadic rain, but high rainfall in summer, therefore, the presence of dragged sediments contributed to the high turbidity of the water body.

In Fig. 3 (i) the concentrations of nitrates are presented, which were between 1 and 5 mg/L in the summer season and concentrations between 0.8 and 2.7 mg/L in winter, where point AS04 (September) presented the highest value of 4.33 mg/L. Spalding and Exner (1993) indicates that nitrites are quickly transformed into nitrates, where nitrates have rapid mobility in water bodies, therefore, they easily infiltrate into the water, being a predominant contaminant in groundwater or surface water. The use of nitrogenous fertilizers in the soil are a source of nutrients since through runoff they drag these nutrients that reach the bodies of water (Xia et al., 2020). In the San Martín lake, nitrate concentrations are attributed to the use of fertilizers and grazing around the body of water.

3.2. Evaluation of water quality indices

3.2.1. National index sanitation foundation (NSF-WQI)

In Fig. 4 (a) the results of the NSF-WQI are presented, for summer the values did not vary significantly in the three months analyzed. At points AS06 (August), AS03 (September) and AS03 (October) low values of 59.24, 60.84 and 55.85 were obtained respectively, indicating medium

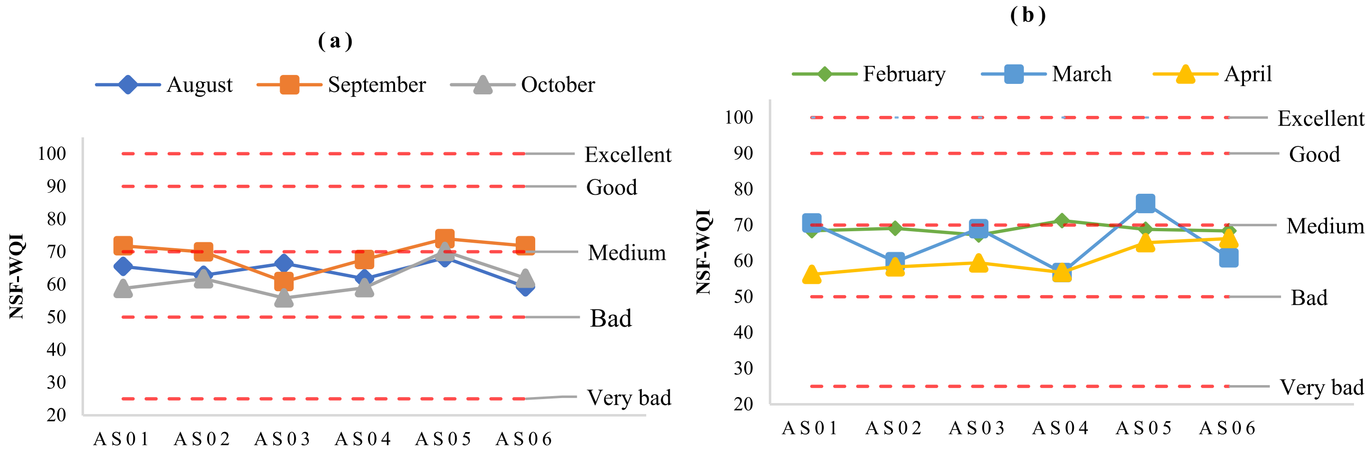

Fig. 4. (a) Distribution and classification of the NSF-WQI in the six sampling points for summer, (b) Distribution and classification of the NSF-WQI in the six sampling points for winter.

water quality. According to Fig. 4 (a) it can be observed that all the values are above the value of 50, therefore, an average quality was obtained in all the points, except for September where a good quality was obtained.

Regarding the winter season, Fig. 4 (b) shows that the lowest values of the NSF-WQI were presented in the month of April compared to the months of February and March. The highest values of February and March were 71.24 (AS04), 76.03 (AS05) respectively, corresponding to good quality; meanwhile, in April it was 66.23 (AS06) corresponding to medium quality. In general, the NSF-WQI values for both summer and winter were of medium quality.

A study carried out by Cusiche Pérez and Miranda Zambrano (2019) in Lake Junín determined an average quality with values between 57 and 61 in winter and summer with values between 47 and 50. Lake Junín, like the San Martín lake, have a contribution of nutrients from livestock activities affecting self-regulation, damage to biodiversity and ecological imbalance in the body of water. The reduction of the water mirror is another condition that causes the obstruction of light rays for the survival of aquatic life, in addition, Lake Junín perceives mining contamination, for which reason the NSF - WQIs in summer are lower compared to the San Martín lake.

4. Statistical analysis of the NSF-WQI

Table S1 of Supplementary Material shows the p-value obtained between each sampling point corresponding to the Tukey test and post-hoc ANOVA test.

4.1. *Canadian Council of Ministers of the Environment water quality Index (CCME-WQI)*

On average, this index presented a fair water quality in the San Martín lake, that is, the water is threatened or in constant deterioration. In Fig. 5, in the summer season the CCME-WQI values varied between 70 and 76.5 and the winter season varied between 51 and 72. The summer season shows values that classify quality as Fair, in some points (AS01, AS03, AS05) it was close to a Good classification; meanwhile, in the winter season the quality is classified between Marginal and Fair. Boyacioglu (2006) mentions that the greater runoff in summer increases erosion and in turn increases the concentration of pollutants causing high pollution; while, in winter, the runoff carries nutrients used in agricultural activities, affecting the water. However, increased runoff will help dilute pollutants improving water quality as mentioned by Shrestha and Kazama (2007).

In the study conducted by Ray et al. (2015) the evaluation of the water of the Goalichara canal was carried out, where a marginal quality of the body of water for aquatic life was obtained, the values oscillated between 47.86 and 60.37, for this study, the summer season presented worse water quality compared to the winter season due to soil erosion. Compared with the previous study, the present study presented the

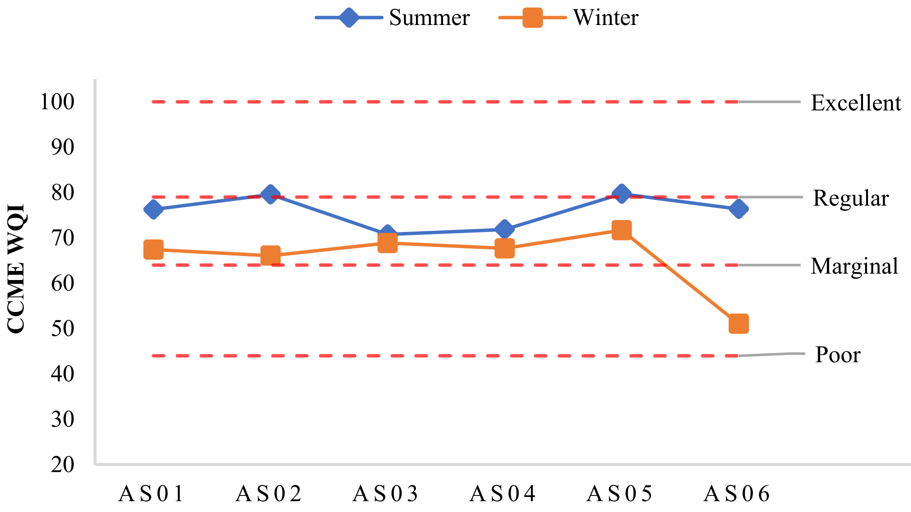

Fig. 5. Distribution and classification of the CCME-WQI for the six monitoring points during summer and winter.

worst water quality in winter due to the entry of nutrients through runoff. In winter, low temperatures and saturated moisture conditions can decrease the soil's ability to retain and absorb nutrients (Halecki, et al., 2022). The soil becomes more compact and less permeable, making it more difficult for nutrients to be retained and processed by natural soil processes. In the lakes, during the winter, biological activity tends to decrease due to low temperatures (Bhateria and Jain 2016). This means that there are fewer organisms, such as algae and aquatic plants, that could consume the nutrients present in the water. As a result, nutrients remain in the water and can lead to an increase in excessive algae and plant growth come spring (Farley, 2012).

Lake San Martín was affected by livestock and agricultural activities that lead to fair water quality. This is corroborated by the study carried out by Robledo Hernández (2022) where the quality of Lake Izabal was marginal with a value of 61, attributing to agricultural and livestock activities, presenting a high contribution of organic matter and sediments; In addition, in said study it is indicated that the discharge of residual waters and poor disposal of solid waste lead to a bad state of the water.

To determine the limiting nutrient, the N:P nutrient concentration is compared with the Redfield coefficient (1958) whose weight ratio is 7.2:1. If the bodies of water have a N:P ratio greater than the ratio, there will be a limitation of P, otherwise the limiting nutrient is N (Redfield, 1958). In the present study, a weight ratio of less than 7.2 was obtained, so the limiting nutrient is N. This can be corroborated by Lewis Jr (1996) and Talling and Lemoalle (1998) mention that the lakes and rivers located in South America South and Asia, there is a tendency for the limiting nutrient to be N.

Grizzetti et al. (2011) mention that the excessive contribution of nitrogen causes the elimination of the denitrification process, which could increase nitrous oxide (N_2O), in addition, the increase in N brings with it an increase in the production of phytoplankton, generating an imbalance between the production and consumption of algae. However, other authors mention that the increase of N in the water does not present any negative effect, even in some cases nitrogenous fertilizers have been used to improve productivity (Binkley et al., 1999).

Seasonal variation is of fundamental importance when making measurements and changing nutrient concentrations. However, Tian et al. (2019) ensured that no conclusion is reached if the water quality varies in the winter or summer season. While Wunderlin et al. (2001) mention that the season, be it summer or winter, has a great correlation with temperature, COD, nitrates, DO, calcium, chloride and suspended solids.

4.2. *Oregon water quality index (OWQI)*

The average values of the OWQI indicate that the water quality of the lake was very poor at all sampling points in the summer season, these values varied between 18 and 24.5. In Fig. 6 (a) you can see the OWQI values corresponding to the summer season, the lowest values were presented in the month of September compared to October and August; however, a similar quality is evident between these months. The very poor quality of the lake may be related to the high concentrations of phosphorus, since summer rainfall contributed to the dragging of nutrients into the lake. Another parameter that affects is the high concentration of BOD, which is attributed to the organic matter present in the lake.

In an aquatic ecosystem, there are various sources of organic matter, such as plant waste, animal waste, the decomposition of aquatic organisms, and contributions from urban or agricultural wastewater (Ferreira et al., 2020). In the case of this high Andean lake, where human influence is limited, organic matter comes mostly from the decomposition of plant matter, such as leaves, algae and other organic remains from the natural processes of the lake (Van Colen, et al., 2018). The leaves of surrounding trees and shrubs. They can fall into the lake and accumulate on its surface or sink to the bottom. These leaves contribute a significant amount of organic matter to the water as they decompose. Similarly, the algae present in the lake, which are photosynthetic organisms, also contribute to the production of organic matter through their life and death cycle. As the algae die and decompose, they release organic matter into the water. Fontalvo Julio and Tamaris Turizo (2018) affirm that high BOD concentrations decrease dissolved oxygen in water bodies, therefore, these low oxygen levels affect water quality.

In Fig. 6 (b) the OWQI values corresponding to the winter season are presented, it can be observed that all the sampling points were classified with a very poor quality. The month of April presented low values in comparison with the months of February and March, these months presented similar values in points AS02, AS04 and AS06. As in the summer season, BOD and phosphorus affected the quality of the water. According to Fontalvo Julio and Tamaris Turizo (2018) in the winter season the water quality should be better because the water acts as a diluent for contaminants; however, both in summer and winter the water quality was very poor.

This is corroborated in the study carried out by Goher et al. (2018) where OWQI values were obtained from 17.05 to 67.4, suggesting that the quality is very poor and is not recommended for fishing. Phosphorus is important in determining QWIs since it is found in different sources and is susceptible to appearing in water bodies. In a study conducted by Kareem et al. (2021) in a system of lakes and reservoirs in Shatt Al- Kufa,

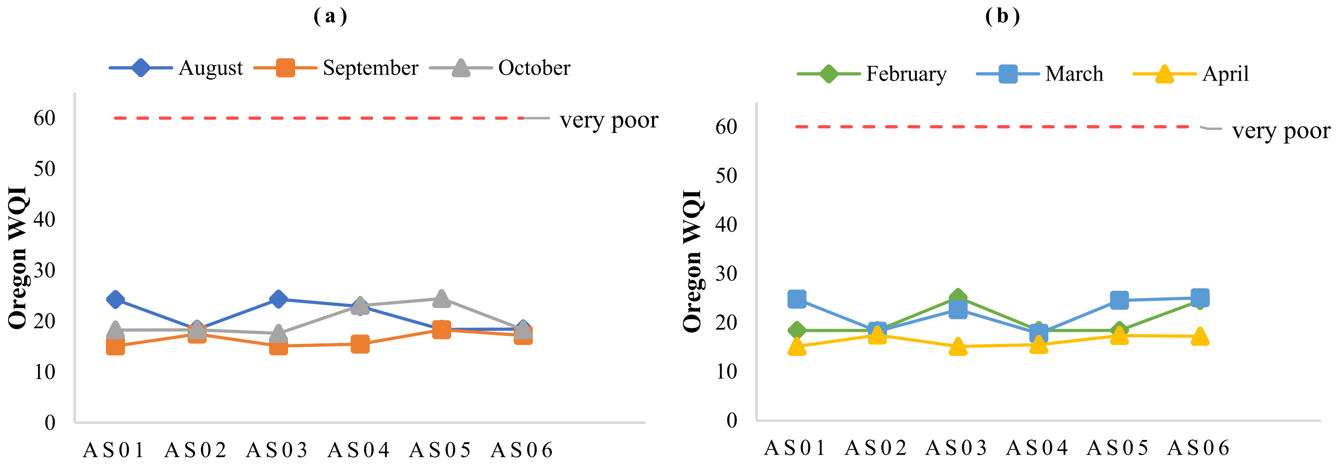

Fig. 6. (a) Distribution and classification of the OWQI in the six months of sampling for summer; (b) Distribution and classification of the NSF-WQI in the six months of sampling for the winter.

where phosphorus was considered as the main parameter, results were obtained with values ranging from 0 to 59, categorizing the system with very poor quality. In the present study, the phosphorus concentrations did affect the calculation of the index, since as mentioned by Kareem et al. (2021), a greater amount of phosphorus is toxic to animals and people and vice versa.

5. Statistical analysis of the OWQI

The statistical analysis determined that homoscedasticity and interdependence are met, but a normal distribution of the indices at the sampling points is not followed. For this reason, Kruskal Wallis was applied with a significance of 0.05. This analysis accepted the null hypothesis (H0) showing that there are no significant statistical differences, therefore, means of the quality indices can be obtained for each sampling point and determine the average quality of the entire lake. Table S2 of Supplementary Material shows the Mann-Whitney post-hoc test, in which the p-value between each sampling point does not indicate significant differences between the points. Fig. 7 (b) graphically shows the water quality of the accessible area of Lake San Martín, where there is a quality range from 20.448 to 23.64; where AS04, AS02 and AS01 have lower water quality. Finally, the lake was classified with a very poor quality.

5.1. Comparative analysis of the three water quality indices

Table 4 presents the comparison of the three indices analyzed in the six sampling points of the San Martín lake, it can be observed that the average values of the NSF-WQI and CCME-WQI categorized the lake with a medium and regular quality, respectively. While the Oregon index classifies with a very poor quality. Concluding that the Oregon index is more sensitive with high concentrations of the parameters analyzed.

Fig. 7 (a) shows the distribution of the water quality of the lake according to the NSF-WQI, where point AS03, AS02 and AS04 showed a lower value due to the high organic content and abundant aquatic vegetation. On the other hand, the points close to the lake outlet present a higher quality value (AS05). On average, the NSF-WQI covered a range of 58.8–69.07, classifying the San Martín lake with a medium quality.

In Fig. 7 (b) the distribution of the CCME-WQI is presented, it can be seen that the point with the best quality was AS05. The range oscillated between 63.71 and 75.7 classifying the body of water with a Fair quality.

Fig. 7 (c) shows the distribution of the water quality of the lake according to the OWQI, all the values were between 20.48 and 23.69, classifying the San Martín lake with a very poor quality.

5.2. Evaluation of trophic state indices

5.2.1. OECD methodology

a) Trophic level according to inorganic phosphorus

The three months of summer sampling maintained a hypereutrophic state at all points (Fig. 8a). For winter the results were similar in almost all points, also determining a hypereutrophic state with the exception of point AS03 (Fig. 8b). The highest peaks of phosphorus concentration correspond to the months of September (±1000 μg/L), October (±1230 μg/L) and April (±1000 μg/L), where minimal variations in its concentration occurred. Meanwhile, the lowest peak corresponds to point AS03 (16 μg/L) of March, classifying this point as mesotrophic.

According to Deborde et al. (2007), the variation in the concentration of P can be attributed to the fact that in shallow waters the changes of this nutrient are due to its rapid renewal time and its high reactivity with organic matter and suspended sediments. However, the low concentration of AS03 cannot be directly attributed to this phenomenon, but to problems or errors in sampling and analysis; since it is a value that is outside the normal distribution of the other concentrations.

All the points presented a hypereutrophic level, in both sampling periods. Paerl (2009), ensures that the main source of non-point nutrients is the excessive application of fertilizers or manure on farms, which causes the accumulation of P in the soils and consequently its runoff towards lakes and lakes. Considering the environmental and socioeconomic conditions of the study area, the excessive contributions can be attributed to a concentration of phosphorus in the native soil and/or to the change of its original state due to anthropogenic activities that include the use of phosphate fertilizers, grazing and manure applied to the soil.

In the case of this high andean lake, it is likely that the surrounding region has soils with a natural capacity to retain and accumulate phosphorus (Moser et al., 2019). This means that even without direct human activities, the natural release of phosphorus from the soils into the lake could occur due to geological or biogeochemical processes (Moser et al., 2019; Zhang et al., 2022). The presence of phosphorus in the lake may be due to the excessive application of fertilizers and manure, anthropic activities that alter the state of the soil, and environmental characteristics of the study area (Zhang et al., 2022). These factors contribute to the accumulation of phosphorus in the soil and its subsequent runoff into the lake, which may explain the hypereutrophic level observed in the mentioned study (Bhateria and Jain, 2016; Wu et al., 2023a; Wu et al., 2023b). Furthermore, biological processes can also contribute to the presence of phosphorus in lakes, aquatic plants, algae and bacteria present in the aquatic ecosystem require phosphorus for their growth and development (Gu et al., 2020). These organisms can take the phosphorus available in the water and use it in their metabolic processes, when these plants and organisms die and decompose, they release the phosphorus back into the water, which can increase its concentration (Feng et al., 2023).

b) Trophic level according to Chlorophyll-a

In summer, the concentration of chlorophyll-a varied from an oligotrophic to a hypereutrophic level; the highest peaks correspond to point AS03 in September (63.48 μg/L) and October (57.5 μg/L) classifying this point as hypereutrophic, while the lowest peak was found in

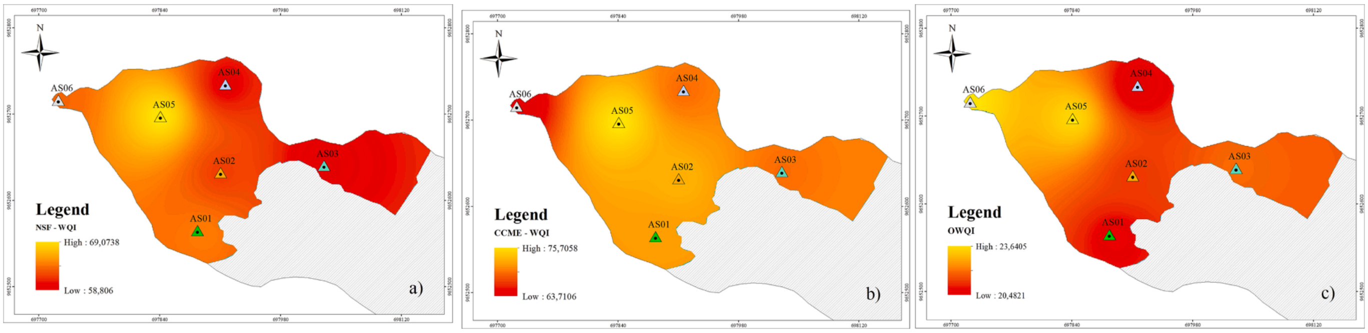

Fig. 7. Comparative analysis of the three water quality indices using water quality maps. (a) Distribution of the water quality of the lake according to the NSF-WQI; (b) Distribution of the water quality of the lake according to the CCME – WQI; (c) Distribution of the water quality of the lake according to the OWQI.

Table 4
Comparison of results of water quality indices at each sampling point in San Martín Lake.

Sampling points	NSF-WQI		CME-WQI		OWQI	
	Value	**Interpretation**	**Value**	**Interpretation**	**Value**	**Interpretation**
AS01	64.14	Medium	71.83	Fair	20.84	Very poor
AS02	61.72	Medium	72.83	Fair	21.31	Very poor
AS03	58.81	Medium	69.81	Fair	21.94	Very poor
AS04	59.87	Medium	69.78	Fair	20.48	Very poor
AS05	69.08	Medium	75.71	Fair	23.47	Very poor
AS06	63.27	Medium	63.71	Fair	23.69	Very poor

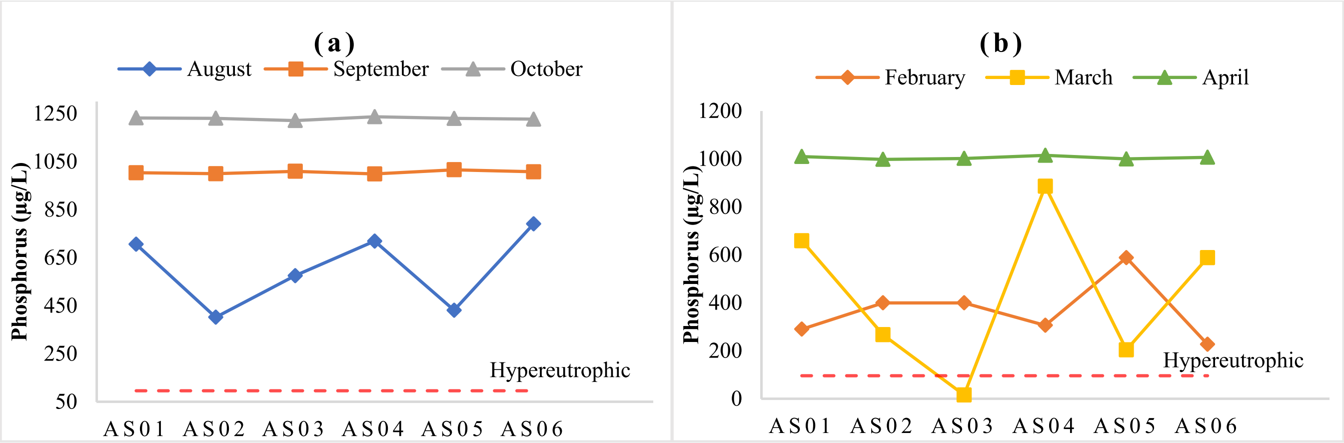

Fig. 8. Distribution and trophic classification of phosphorus at each monitoring point according to OECD (1982) for summer (a), for winter (b).

AS02 (1.78 µg/L) classifying as oligotrophic (Fig. 9a). In winter, the chlorophyll-a concentration was lower than in summer, ranging from ultraoligotrophic to eutrophic. The chlorophyll-a peaks in AS03 are associated with the presence of blooms of plant material that characterize this point (Fig. 9b).

The variability in the concentration of chlorophyll-a is comparable to that reported by Dorador et al. (2003) in Lake Chungará, where chlorophyll fluctuated between 0.34 mg/L and 8.74 mg/L, attributing these variations to an increase in temperature that affects phytoplankton less tolerant of higher temperatures. Although Chungará Lake and San Martín lake are cold polymictic lakes, the Chungará Lake study area presents well-defined seasons with constant temperature that influences the chlorophyll-a concentration, unlike the less-defined seasons of the San Martin lake.

Esteves (1988) recognizes the availability of nutrients, available solar radiation and precipitation as environmental factors with the greatest influence on the temporal variation of phytoplankton and chlorophyll. Naselli Flores (2000) confirmed the importance of light climate in the structure of phytoplankton species, recognizing that phytoplankton variation responds to temperature fluctuations and the amount of solar radiation. Since chlorophyll is an indicator of phytoplankton biomass that depends entirely on environmental conditions and that light conditions can influence phytoplankton biomass, the highly variable behavior of chlorophyll-a in the San Martín lake It may be related to factors such as nutrient availability and mainly to solar radiation.

Xu et al. (2022) demonstrated that chlorophyll-a concentrations under light limitation in Lake Okeechobee are significantly lower than those under nitrogen or phosphorous limitations and suggest that algal blooms occur primarily when nutrients are limiting. In this case, in the San Martín lake nitrogen is the limiting nutrient and they maintain similar light conditions, so the behavior of chlorophyll under these conditions is similar and comparable in both bodies of water.

c) Trophic level according to transparency

The transparency measured with the Secchi disc (depth) in summer is presented in the Fig. 10(a); meanwhile, for winter it is presented in

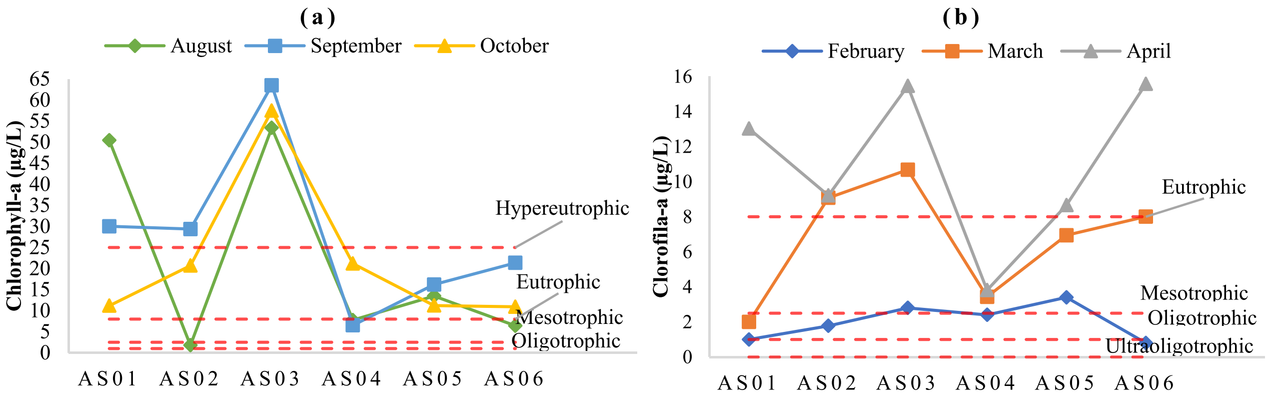

Fig. 9. Distribution and trophic classification of chlorophyll-a in the six monitoring points according to OECD (1982) for summer, (a); for the winter (b).

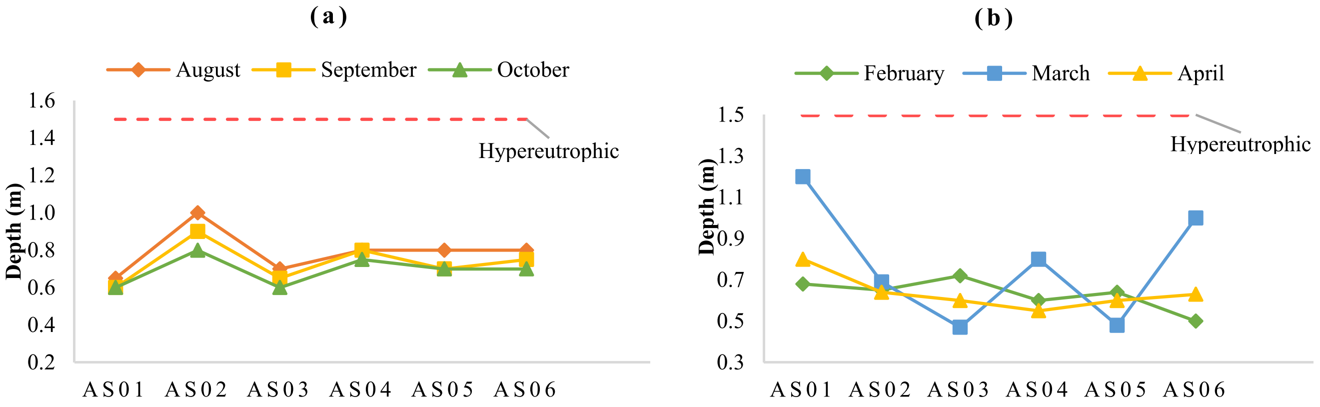

Fig. 10. Distribution and trophic classification of depth in the six monitoring points according to OECD (1982) for summer (a); for winter (b).

Fig. 10 (b), in the two figures no point exceeds one meter in depth, classifying all points as hypereutrophic. In summer, the highest depth peak corresponds to AS02 in August, which may be a consequence of its location in the center of the lake. In winter, the maximum peak corresponds to AS01 in March; In this period, the variations could be related to the increase in flow caused by the intense rains in February and March, characteristic of the study area.

The low visibility recorded is explained by the existence of aquatic vegetation and the high concentration of plankton that decrease visibility. According to Harvey et al. (2019), a greater abundance of phytoplankton increases light attenuation, that is, the gradual loss of light with depth, as lighter at visible wavelengths is absorbed and scattered. This phenomenon is occurring in the San Martín lake, since the high concentration of chlorophyll-a caused low levels of transparency, causing eutrophication.

The level of transparency of a lentic body is not only determined by the phytoplankton density, but also responds to other factors such as suspended particles, dissolved organic matter, and water properties (Nishijima et al., 2018). The low visibility recorded may be due to organic matter and suspended particles generated by anthropogenic activities. Although this study does not directly analyze the concentration of suspended solids, the low level of transparency and high levels of turbidity can be related to the high content of suspended solids, as demonstrated by Delgado et al. (2014) in their study applied to the natural wetland of the Cruces River.

In high mountain lakes, the factors that influence transparency vary with the particular characteristics of each lake. For example, Casallas and Gunkel (2001) determined transparency values in a range of 2.1 and 4.2 for Lake San Pablo in Ecuador, attributing their values to the high anthropic intervention and the strong eutrophication process. These values are much higher if compared to those of the San Martín lake, despite the fact that the environmental and social conditions are similar in both lakes, this suggests that the depth levels allow an idea of the trophic state.

Taking into account that the transparency in the San Martín lake is conditioned by chlorophyll and organic matter in suspension, it is recommended that efforts to control eutrophication be focused on reducing these contributions to the lake, as suggested by Blomqvist and Larsson (1994) and Chalar and Clemente (2005). While cleaning plant material can help reduce chlorophyll and increase transparency at some points; reducing the external contributions of nutrients and organic matter would improve the trophic state considerably.

6. Statistical analysis of the OECD index

6.1. Phosphorus

The concentration of P in this study complies with the assumptions of normality, homoscedasticity, and independence, therefore, one-way ANOVA was applied, and it was determined that the null hypothesis (Ho) is accepted, that is, that the means of the concentration of P for each point sampling did not present statistically significant differences. This allows obtaining an average value and determining the trophic state for each sampling point. The average obtained for the concentration of P classifies the San Martín lake as Hypereutrophic, according to the OECD. Fig. 11 (a) shows graphically the points where the concentration of P increases or decreases.

6.2. Chlorophyll-a

Chlorophyll-a concentrations do not meet the assumptions, so Kruskal Wallis was applied for the analysis of variance. The result showed that there are no statistically significant differences between the median concentrations of chlorophyll-a, accepting the null hypothesis (Ho). According to the OECD methodology, the San Martín lake is classified as Eutrophic according to the concentration of chlorophyll-a. Fig. 11(b) graphically shows the distribution of chlorophyll-a throughout the accessible area of the lake.

6.3. Transparency

The transparencies (depths) presented a free distribution, so the assumptions were not met and Kruskal Wallis was applied. The analysis showed that there are no significant differences between these depths, accepting the null hypothesis (Ho).

The general average of the depth measured in the 6 sampling points classifies the San Martín lake as hypereutrophic according to OECD. In Fig. 11 (c) it can be seen how the depth varies along the San Martín lake. Hypereutrophic state is observed in 2 of the 3 parameters. Chlorophyll-a varied between mesotrophic and hypereutrophic categories, making it difficult to integrate all trophic states and define a single state for the OECD index. However, this allows knowing the most influential parameters in the trophic state of the lake.

According to the average concentrations of phosphorus and chlorophyll-a; as well as the average depths of each sampling point, the trophic state was categorized for the summer and winter season, this classification is presented in the Table 5.

6.4. Carlson trophic status index

Fig. 12 (a) shows the CTSIs for the summer months and Fig. 12 (b) for winter. In summer almost all the points are above the hypereutrophic limit according to Carlson (1977), with the exception of AS02 in August. This difference in trophic state is directly related to the previously reported chlorophyll-a concentration (1.78 μg/L) and depth; because according to Carlson (1977), chlorophyll-a as an indicator of biomass plays

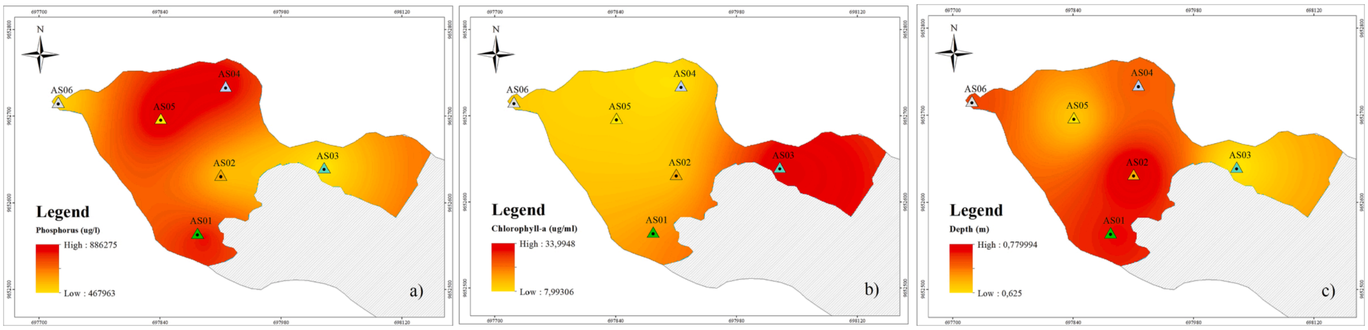

Fig. 11. Comparative analysis of the trophic state according to the OECD index of the San Martin lake through trophic maps (a) Map of trophic state according to phosphorus concentration; (b) according to the concentration of chlorophyll-a; (c) according to the level of depth.

Table 5
Classification of the trophic states for each sampling point according to the OECD index.

Sampling points	OECD		
	Phosphorus	**Depth**	**Chlorophyll-a**
AS01	Hypereutrophic	Hypereutrophic	Eutrophic
AS02	Hypereutrophic	Hypereutrophic	Eutrophic
AS03	Hypereutrophic	Hypereutrophic	Hypereutrophic
AS04	Hypereutrophic	Hypereutrophic	Mesotrophic
AS05	Hypereutrophic	Hypereutrophic	Eutrophic
AS06	Hypereutrophic	Hypereutrophic	Eutrophic

an important role in the calculation of the CTSI index. In the winter period, the trophic state changed in February and March, maintaining a eutrophic level. This change is related to the decrease in the concentration of phosphorus and chlorophyll-a that the lake suffered this season. On the other hand, a hypereutrophic state occurred in April, related to the increase in phosphorus concentration during this month.

7. Carlson index by variable

7.1. CTSI based on transparency ($CTSI_{SD}$)

For the $CTSI_{SD}$ there were minor variations, but almost always within the eutrophic range ($50 < CTSI_{SD} < 70$). In this case, the peaks corresponded to March (70.88 at point AS03 and 70.57 at point AS05) with

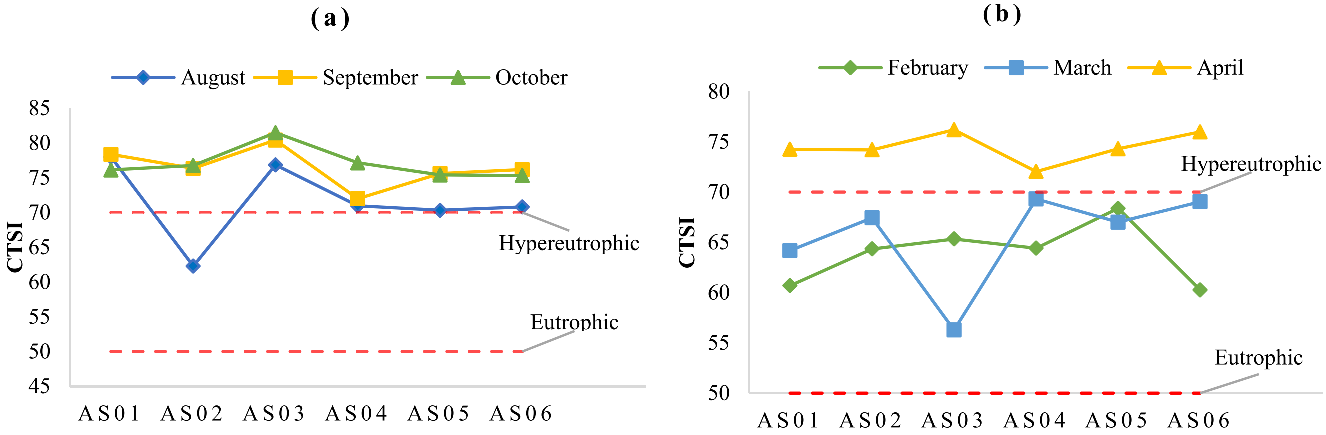

Fig. 12. Distribution and classification of the trophic state according to the CTSI in the six monitoring points for summer (a); for winter (b).

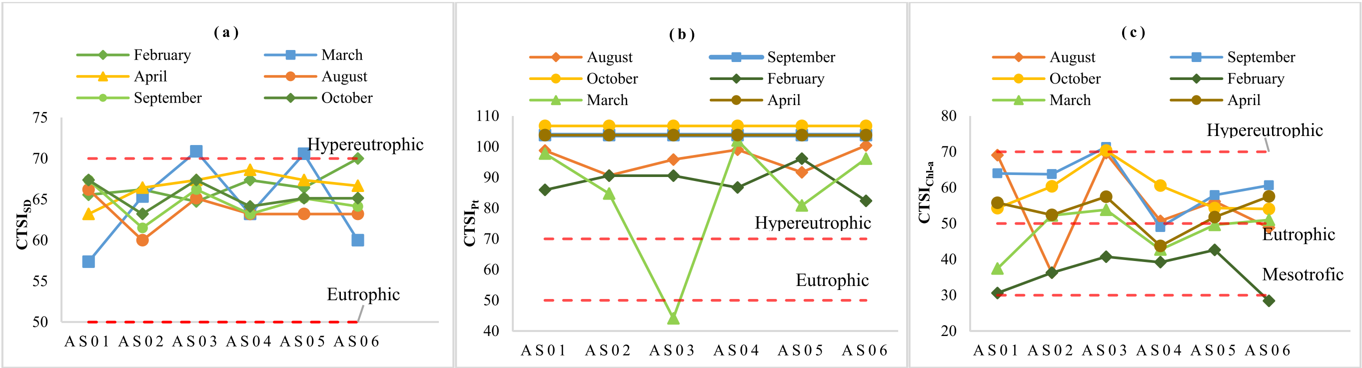

Fig. 13. Distribution and classification of the trophic state in the six monitoring points according to CTSI. (a) CTSI according to transparency; (b) CTSI according to the phosphorus concentration; (c) CTSI according to Chlorophyll-a.

values slightly higher than 70, which classifies it as hypereutrophic (Fig. 13 a).

7.2. *CTSI based on phosphorus concentration ($CTSI_{TP}$)*

For the $CTSI_{TP}$ much larger variations existed, covering the range from mesotrophic to hypereutrophic. In Fig. 13 (b) it is evident that, in March, point AS03 presented a much lower $CTSI_{TP}$ than the other points, classifying it as the only one with a mesotrophic state. The $CTSI_{TP}$ in September and April remained at 103.76, and October at 106.75 at all sampling points, due to the previously reported constant value of P.

7.3. *CTSI according to the concentration of chlorophyll-a ($CTSI_{Chl\text{-}a}$)*

The $CTSI_{Chl\text{-}a}$ presented variations in a wide range that categorized the lake from oligotrophic to hypereutrophic (Fig. 13 c). This variability is related to the chlorophyll concentrations presented above, where it was evidenced that there were fluctuations in the chlorophyll level throughout the monitoring period.

According to the OECD methodology, as well as the CTSI obtained in all the months of study of the San Martín lake, they indicated that the highest trophic status is associated with the highest phosphorus values in all the sampling points. Studies such as that of Jarosiewicz et al. (2011) reported a similar behavior, since, when analyzing the trophic level in eight lakes, they found that in all cases the $CTSI_{TP}$ presented higher values in relation to the other variables. Pełechata et al. (2006) studied the trophic state of 33 natural lakes and determined that, in the analysis of phosphorus concentrations, 22 lakes presented eutrophic characteristics and the other 11 lakes presented hypereutrophic characteristics, therefore, the CTSI calculated from of the P concentration, revealed higher values of IET_{TP} in all the lakes investigated.

Analyzing the trophic state of each variable separately makes it possible to know the deviations between the values of the trophic indices and to determine the potential causes of limiting the growth of phytoplankton according to the concept of Carlson modified by Havens (2000). When $CTSI_{Chl\text{-}a} \geq CTSI_{TP}$, P is generally limiting for algae growth, but when $CTSI_{Chl\text{-}a} \ll CTSI_{TP}$ there is less algal material present than expected. When the $CTSI_{Chl\text{-}a}$ is lower than the $CTSI_{TP}$ there could be another factor that limits the productivity of the algae. Jarosiewicz et al. (2011) ensure that these factors could be another nutrient or some physical parameter. In the case of the San Martín lake, these factors are nitrogen as a limiting nutrient and the availability of light, since, as previously mentioned, the N:P weight ratio of Redfield (1958) is less than 7.2, recognizing nitrogen as a nutrient. Limiting factor and the variations in the chlorophyll concentration were associated with the available solar radiation.

The results show a dominance in the $CTSI_{TP}$, which suggests that the trophic state of the San Martín lake is conditioned by the availability of light and the factors that influence its attenuation, such as dissolved organic and inorganic substances and suspended particles.

8. Statistical analysis of the Carlson index

The calculated CTSIs met the assumptions of normal distribution, homoscedasticity, and independence. Therefore, one-way ANOVA was applied (significance level 0.05). The analysis showed that there are no significant differences between the indices obtained at each point (p value > 0.05), accepting the null hypothesis (Ho). As there were no significant differences between the trophic states, it was possible to obtain the average value, both in winter and summer (Table 6) and a final value that represents the trophic state of the San Martín lake.

8.1. *TRIX index*

The TRIX methodology presented different trophic states for the monitored points in the San Martín lake, maintaining a hypereutrophic state in the summer period, except for point AS02 for the month of August (Fig. 14 a). Comparing with the trophic state indices previously presented in Fig. 12 (a) for all the sampling points, it can be seen that all the trophic states agree, even for AS02, which was the one that presented a variation towards a eutrophic state. This corroborates the fact that chlorophyll-a is a variable that strongly influences the calculation of trophic state indices, even though the TRIX index includes dissolved oxygen in its calculation.

Table 6
Average value according to the Carlson Trophic Status Index for winter and summer that classifies the trophic status of Lake San Martín.

Sampling points	IET Carlson			
	Summer	**Trophic state**	**Winter**	**Trophic state**
AS01	78.19	Hypereutrophic	68.74	Eutrophic
AS02	73.98	Hypereutrophic	70.17	Hypereutrophic
AS03	79.82	Hypereutrophic	71.07	Hypereutrophic
AS04	73.95	Hypereutrophic	69.17	Eutrophic
AS05	74.24	Hypereutrophic	71.02	Hypereutrophic
AS06	74.56	Hypereutrophic	70.87	Hypereutrophic
Average	75.79		70.17	

The winter trophic state was determined as eutrophic for the months of February and March; while it was determined as a hypereutrophic state for April (Fig. 14 b). Comparing the TRIX index with the CTSI shows a similar behavior at all sampling points, always staying between a eutrophic and hypereutrophic state. This variation in trophic status may be related to the low percentage of DO reported at these points (Fig. 3a).

It must be emphasized that TRIX index considers the inorganic N and the %DO, which influences the trophic state of the lake according to this index. Of the different forms of dissolved inorganic nitrogen (DIN), NO_2^- was the least predominant form with an average of 0.010 mg/L at all points; on the contrary, NO_3^- was dominant with an average of 2.59 mg/L, while ammoniacal nitrogen was not taken into account in this study. Zoriasatein et al. (2013) also did not take ammonium into account in the calculation of the TRIX index in the coastal zone of Arvand, and showed a behavior similar to that of the San Martín lake, where P and chlorophyll-a conditioned the trophic state of the water bodies. In this way, it can be assumed that the concentrations of inorganic N that were included in the calculation of the TRIX index did not significantly influence the trophic state of the San Martín lake.

In Fig. 3 (b) it was observed that DO fluctuated from 2.81 mg/L in AS02 in winter to 6.22 mg/L in AS06 in summer. This variation in the availability of DO mean that on average the TRIX index will present higher values in summer (8.35) than in winter (7.81).

9. Statistical analysis of the TRIX index

The statistical analysis for TRIX index made it possible to determine that all the assumptions are met, so the variations between the indices were analyzed using one-way ANOVA statistical tests. The analysis showed that, like the CTSI, there are no significant differences between the indices obtained and the null hypothesis (Ho) is accepted. The differences between the indices were not significant, which allowed obtaining an average value for each sampling point. Table 7 shows the average TRIX index for summer and winter.

9.1. *Comparative analysis of the three eutrophication indices*

Table 8 presents a compilation of the trophic status of all sampling points for each applied eutrophication index. The indices that allowed to know a unique value related to the trophic level (CTSI and TRIX index), determined a hypereutrophic state for all the sampling points; being able to attribute this trophic state with the high concentration of phosphorus registered in the lake during both sampling periods.

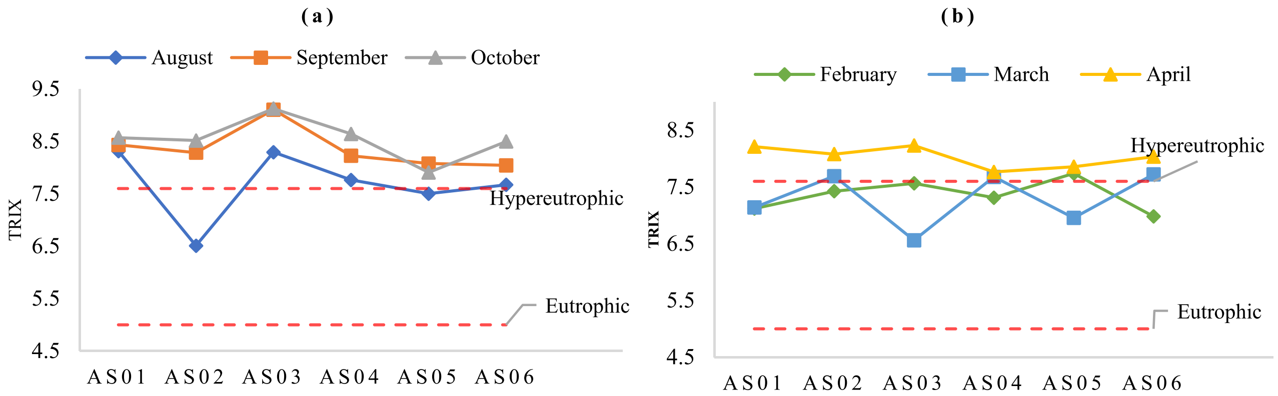

Fig. 14. Distribution and classification of the TRIX trophic state according to Vollenweider et al. (1998) in the six monitoring points for summer (a); for winter (b).

Table 7
Average value according to the TRIX index for winter and summer that classifies the trophic state of Lake San Martín.

Sampling points	TRIX index			
	Summer	**Trophic state**	**Winter**	**Trophic state**
AS01	8.61	Hypereutrophic	7.80	Hypereutrophic
AS02	8.09	Hypereutrophic	7.91	Hypereutrophic
AS03	8.90	Hypereutrophic	7.89	Hypereutrophic
AS04	8.32	Hypereutrophic	7.66	Hypereutrophic
AS05	7.95	Hypereutrophic	7.67	Hypereutrophic
AS06	8.23	Hypereutrophic	7.91	Hypereutrophic
Average	8.35	Hypereutrophic	7.81	Hypereutrophic

On the other hand, the OECD methodology allowed us to identify how both the phosphorus concentration and the transparency (depth) conditioned the trophic level of the lake, presenting a hypereutrophic state throughout the study at all points. Finally, fluctuations in chlorophyll-a influenced eutrophication indices by indicating changes in the amount of algae present in the water, which can increase or decrease the amount of available nutrients and negatively affect water quality and aquatic ecosystems.

Fig. 15 (a) indicates the current state of the San Martín lake at all the sampling points in the accessible area. The range goes from 71.56 to 75.44 classifying the body of water as hypereutrophic. The trophic range in which the accessible zone of the San Martín lake was found was between 7.8 and 8.39, classifying it as Hypereutrophic according to TRIX index. In Fig. 15 (b) it can be seen how the trophic state is distributed in the study area.

Table 8
Summary results of the trophic state of all the sampling points for each index applied in Lake San Martín.

Sampling points	OECD			CTSI	TRIX
	Phosphorus (µg/L)	**Chlorophyll-a (µg/L)**	**Depth (m)**	**Interpretation**	**Interpretation**
AS01	Hypereutrophic	Eutrophic	Hypereutrophic	Hypereutrophic	Hypereutrophic
AS02	Hypereutrophic	Eutrophic	Hypereutrophic	Hypereutrophic	Hypereutrophic
AS03	Hypereutrophic	Hypereutrophic	Hypereutrophic	Hypereutrophic	Hypereutrophic
AS04	Hypereutrophic	Mesotrophic	Hypereutrophic	Hypereutrophic	Hypereutrophic
AS05	Hypereutrophic	Eutrophic	Hypereutrophic	Hypereutrophic	Hypereutrophic
AS06	Hypereutrophic	Eutrophic	Hypereutrophic	Hypereutrophic	Hypereutrophic

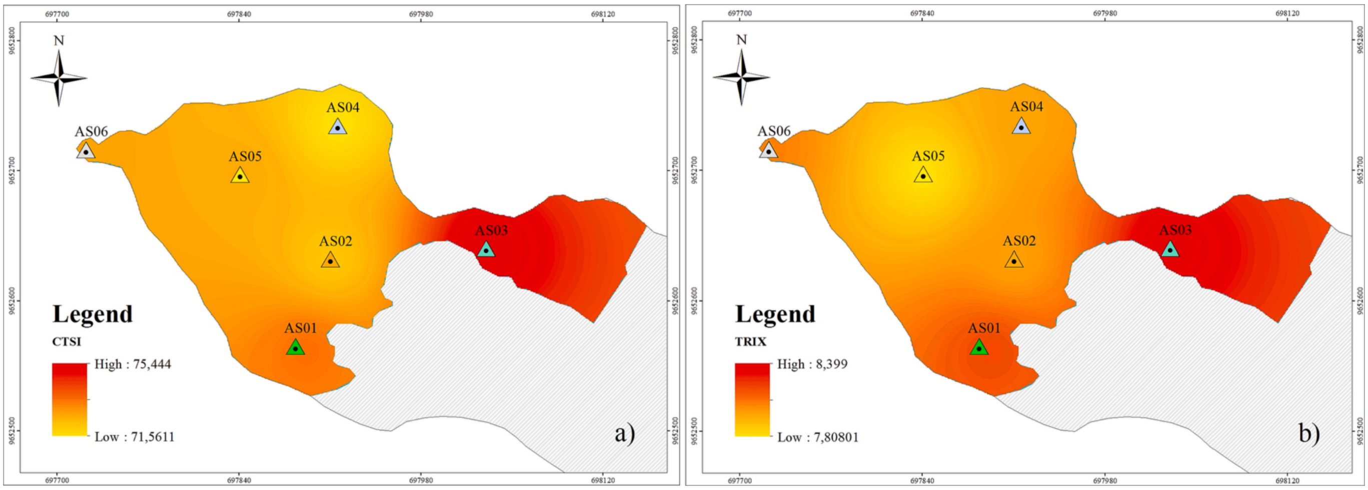

Fig. 15. Comparative analysis of the trophic state according to the CTSI and TRIX index of Lake San Martin through trophic maps. (a) Carlson TSI trophic index map, (b) TRIX trophic index map.

Considering that the focus of a study was the application and validation of trophic indices and water quality index in the high Andean lake, a sensitivity analysis was not carried out. The mathematical models used to calculate the indices have been validated and their stability demonstrated in previous studies; for this reason, it could be considered that it is not necessary to carry out a sensitivity analysis. The models have undergone rigorous testing and analysis, providing confidence in their ability to produce consistent and accurate results (Kachroud et al., 2019). In addition, it was possible to measure the concentrations of all the parameters defined in each index; that is, there was complete and accurate information to feed the mathematical model.

9.2. *Comparison of the results with other studies*

Table 9 presents a comparison of the trophic state obtained for Lake San Martín in relation to other studies that applied similar methodologies. Regarding the OECD index, Lake San Martin presented a eutrophic state for chlorophyll-a concentration, while the state was hypereutrophic for transparency and phosphorus concentration. These results agree with what was reported by Diaz Medina and Sotomayor Maguiña (2013) for the Conococha lake in Peru, to which the OECD index was applied, classifying it as hypereutrophic according to the concentration of phosphorus, transparency and chlorophyll-a. This similarity in the results is because both lakes present characteristics of Socio-environmental factors that considerably influenced the bodies of water such as livestock and population activities, the presence of animals around the lake, runoff of feces from rain into the lakes, among others. Although the average concentration of chlorophyll-a for Lake Conococha was higher than that reported in the San Martín lake.

In their study, Bougarne et al. (2019) applied to the Bab Louta lake according to the OECD methodology determined an Eutrophic state for phosphorus and transparency; meanwhile, an Oligotrophic state for chlorophyll-a. For its part, as mentioned above, Lake San Martin according to the OECD methodology presented a eutrophic state for the chlorophyll-a concentration, while for transparency and phosphorus, the state was hypereutrophic. In both aquatic bodies, chlorophyll-a showed significant fluctuations, the maximum values were observed in summer during the period from June to September, while the lowest values were observed in winter. This could be explained by the contrasting conditions that prevail during these two periods, such as the availability of nutrients, the light and temperature conditions that keep the Bab Louta dam and the San Martín lake in common.

Table 9
Comparison of the results of the trophic state of the present study with other studies.

Author	Lake/Place	Trophic state index applied	Obtained categorization
Diaz Medina and Sotomayor Maguiña (2013)	Conococha lake/ Perú	OECD	Hypereutrophic for phosphorus, transparency, and chlorophyll-a
Bougarne et al. (2019)	Bab Louta lake/ Marruecos	OECD	Eutrophic for phosphorus and transparency Oligotrophic for chlorophyll-a
Present study (2023)	San Martín lake/ Ecuador	OECD	Hypereutrophic for phosphorus and transparency Eutrophic for chlorophyll-a
Almanza-Marroquín et al. (2016)	Urban lakes/ Chile	CTSI	Hypereutrophic
Jarosiewicz et al. (2011a), Jarosiewicz et al. (2011b)	Pomeranian lakes/ Polonia	CTSI	Hypereutrophic
Present study (2023)	San Martín lake/ Ecuador	CTSI	Hypereutrophic
Campos Sousa (2019)	Amazon estuaries/ Brasil	TRIX	Eutrophic
Sánchez Rodríguez and Calvario Martínez (2020)	Urías estuary/ México	TRIX	Eutrophic
Present study (2023)	San Martín lake / Ecuador	TRIX	Eutrophic

In the case of the CTSI, Lake San Martín was classified as hypereutrophic in all its sampling points, where the CTSI based on the phosphorus concentration was the one that determined the general trophic status of the lake. This situation was similar to the results of other studies that applied the CTSI methodology. Thus, Almanza-Marroquín et al. (2016) determined that three of their four lakes studied presented a hypereutrophic state related to the contribution of nutrients (especially phosphorus) from the urban basin, also ensuring that this contribution explains the high concentration of chlorophyll-a. For their part, Jarosiewicz et al. (2011) analyzed the trophic level in eight lakes, likewise determined that in all cases, the trophic status index based on phosphorus presented higher values in relation to the other variables; however, the trophic level of these lakes was within the mesotrophic and eutrophic states.

According to the limits established by the OECD index, the San Martín lake presented a eutrophic state for the chlorophyll-a concentration, while for transparency and phosphorus, the state increased to hypereutrophic. These results maintain similarity with the behavior of the concentrations presented by the Bab Louta lake in Morocco, in which it was evidenced that the lake presented a eutrophic state, in terms of total phosphorus and transparency, and its trophic state decreased to oligotrophic in terms of chlorophyll-a. Chlorophyll-a showed significant fluctuations in both bodies of water, the maximum values were observed in summer during the period from June to September, while the lowest values were observed in winter. This could be explained by the contrasting conditions that prevail during these two periods, such as nutrient availability, light and temperature conditions that keep Bab Louta lake and San Martín lake in common.

According to the Trix index, the San Martín lake was classified with a hypereutrophic state, considering the percentage of dissolved oxygen and organic nitrogen for its analysis. Sánchez Rodríguez and Calvario Martínez (2020) presented similar results ranging between a eutrophic and hypereutrophic state during the study period and at each selected point in the Urías estuary. Values between 5 and 8 were obtained, corresponding to a high trophic state (poor quality water) and a very high trophic state (poor quality water). Carrying out an annual average of the TRIX index, the result was a value of 6.57, characterizing the entire body of water in a poor trophic state (Eutrophic). These variations in the trophic state during the months of January and December are attributed to the increase in the population around the estuary, the discharge of wastewater, the aquaculture farms, and the excessive contribution of nutrients. Comparing the trophic status according to the TRIX index of the San Martin lake with the Urías estuary, these bodies of water maintain similarities, since they present an excessive contribution of nutrients, due to agricultural and livestock activities.

9.3. *Main contributions of the study results*

The results of this study contribute to the advancement of scientific knowledge in applying trophic state indices and water quality indices in mountain lakes. By using different methodologies, a more complete and detailed view of the water quality in the studied high Andean Lake is provided, which may have broader implications for the understanding of aquatic ecosystems in high mountain environments. The results demonstrated that the NSF-WQI index is a more robust indicator compared to the CCME-WQI, due to its lower seasonal variability. This information is valuable for future studies and assessments of water quality in mountain lakes, where seasonal variability may affect measurements.

The application of the methodology of trophic indices and water quality indices made it possible to identify that the phosphorus concentration, oxygen percentage, temperature and transparency are key factors that affect the trophic state of Lake San Martín. This information is valuable for understanding eutrophication processes and the main sources of nutrients in the lake. Likewise, the revelation that the chlorophyll-a concentration did not become a relevant indicator of eutrophication. For this reason, future research highlights the need to consider multiple parameters for water quality and eutrophication indices, in order to obtain more reliable results in the area.

The results showed that the lake is in a hypereutrophic state, indicating a high concentration of nutrients and an algal bloom. As mentioned above, knowing the current state of the lake will help decision-making in the management and conservation of the lake, since the deteriorated state of the lake is given by the excess of nutrients. This allows immediate action to be taken on the sources of nutrients and the associated impacts.

By not obtaining acceptable results both in trophic indices and in water quality indices for agricultural purposes or recreational activities, it is necessary to develop sustainable management strategies and mitigate the impacts of pollution in the lake by competent authorities. The findings have important practical implications for decision-making and conservation actions in Lake San Martín and may inspire future research in the field of aquatic ecology and environmental management.

9.4. Limitations and future prospects of the study

The search for suitable tools to assess the lake's water quality proved challenging, and no common criteria could be identified to determine its quality status. Although three trophic indices and three water quality indices were applied, limitations were found when using only physical–chemical parameters and not incorporating biological parameters. The integration of biological and physicochemical data presents analytical and methodological challenges, which affected the complete assessment of water quality (Lukhabi et al., 2023). High Andean lakes experience significant seasonal variability in temperature and precipitation from one day to the next, which could have influenced the results (Vuille et al., 2000). The lack of historical data on the lake's water quality made it difficult to assess trends over time and natural variability. Additionally, the lack of formally accepted procedures to validate water quality indices was another limitation.

There is a need to integrate physicochemical, biological, heavy metal and risk indicators when applying or developing WQIs. Non-subjective statistical approaches could provide even more uniformity in WQI model development. However, the potential to develop WQIs for high Andean lakes is vast.

It has been found that, despite the use of statistical methods, WQI models continue to suffer from eclipsing, ambiguity or uncertainty limitations because natural ecosystems such as lakes tend to be complex for these methods (Mogane, et al. 2023).

Studies such as those developed by Elsayed et al. (2021) have argued that natural ecosystems are too complex for these statistical models and suggest using models based on machine learning, such as artificial neural networks (ANNs). The use of statistical methods together with machine learning techniques requires further exploration in the WQI development process to remove WQI inaccuracies and uncertainties and improve the scope of application (Lukhabi et al., 2023). Extreme gradient boosting (XGB) has been reported to be an effective machine-learning tool for coping with uncertainties during parameter selection, setting parameter weights, and determining accurate classification schemes (Mogane et al., 2023).

Although the use of different indices can provide a more comprehensive view of water quality, cross-validation of these indices was not considered to ensure their applicability and reliability in the specific context of the high Andean lake. Cross-validation is a critical stage in the evaluation of water quality using different trophic indices and water quality indices. By ensuring that the indices are adequate and accurate for the high Andean lake, the scientific basis for decision-making and protection of this important high mountain aquatic ecosystem is strengthened (Uddin et al., 2023).

The incorporation of machine learning techniques or artificial intelligence in future studies could improve the accuracy and efficiency in the assessment of water quality. These techniques can help analyze large data sets and reveal hidden patterns and complex relationships between variables, which can improve the precision and predictive capacity of the indices used. In general, addressing these limitations and considering future perspectives will improve the quality and applicability of the results obtained, which will contribute to a more solid and effective understanding of the water quality in the high Andean lake.

10. Conclusions

Based on the results obtained, this study contributes to research and decision-making in several ways. Advances were made in knowledge about the application of trophic state indices and water quality indices in mountain lakes. The results of the NSF-WQI classification are closer to those of the CCME-WQI, categorizing the water quality as medium and fair, respectively. In addition, it is concluded that the OWQI is quite strict, giving, on average, estimates of very poor quality. The NSF-WQI can also be considered a more robust water quality index (compared to the CCME-WQI) as it has less seasonal variability.

The application of the OECD methodology, CTSI and the TRIX index allowed us to identify that the phosphorus concentration and transparency are factors that affect the trophic state of Lake San Martín. However, variations in chlorophyll-a concentration did not turn out to be a relevant indicator of eutrophication. According to the CTSI, all the sampling points of the lake were classified as hypereutrophic. The main source of nutrients comes from the excessive application of fertilizers and manure in the surrounding area, which causes the accumulation of phosphorus in the soil and its runoff into Lake San Martín. The TRIX index also classified this lake as hyper-eutrophic.

The combination of different methodologies such as trophic state indices and water quality indices, turned out to be a valuable tool to evaluate the water quality of a body of water. By using multiple methodologies, it was possible to more easily identify the water quality problems of this lake. The evaluation of the water quality of these high mountain aquatic bodies is essential to promote alternatives for the protection and conservation of water sources, especially those that are used by the population for agricultural purposes or recreational activities. It would be interesting to implement future studies that incorporate additional water quality indices and machine learning techniques to obtain a more complete and accurate evaluation. However, it is important to note that the application of machine learning techniques requires adequate availability of quality data and the appropriate choice of algorithms and models.

CRediT authorship contribution statement

Fernando García-Avila: Conceptualization, Methodology, Formal analysis, Investigation, Project administration, Writing – review & editing. **Pablo Loja-Suco:** Data analysis and interpretation, Experimental development, Writing. **Christopher Siguenza-Jeton:** Data analysis and interpretation, Experimental development, Writing **Magaly Jiménez Ordoñez:** Writing – original draft, Investigation. **Lorgio Valdiviezo-Gonzales:** Project administration, Writing – review & editing. **Rita Cabello-Torres:** Methodology, Formal analysis. **Alex Aviles-Añazco:** Writing – original draft, Investigation.

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecolind.2023.110924.

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