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ASSESSMENT OF THE TROPHIC STATE OF YAGUARCOCHA LAGOON USING AQUATOX SOFTWARE

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ABSTRACT

Objective: The aim of this study was to evaluate the trophic state of Yahuarcocha Lagoon using the AQUATOX simulation model. We sought to understand the dynamics of eutrophication in this aquatic ecosystem and assess the effectiveness of *Myriophyllum spicatum* as a bioremediation strategy to mitigate the adverse effects of eutrophication.

Methodology: We implemented an experimental design to measure key variables reflecting the trophic state of Yahuarcocha Lagoon, including Secchi disk depth, total phosphorus, and chlorophyll concentrations. Over four months, from September to December, eight sampling sessions were conducted to collect essential data. The AQUATOX software was used to model these environmental variables and mean squared error and relative error were employed to validate the model's accuracy. Additionally, the potential of *Myriophyllum spicatum* to improve the water quality of the lagoon was investigated.

Results and Conclusions: Our findings indicated that Yahuarcocha Lagoon exhibited a hypereutrophic state based on total phosphorus concentrations and a eutrophic state regarding chlorophyll and Secchi disk depth. Although the AQUATOX model did not achieve a fully satisfactory level of validation, the introduction of *Myriophyllum spicatum* as a bioremediation agent proved to be an effective measure, facilitating a notable improvement in water quality from a hypereutrophic to eutrophic state in terms of total phosphorus and chlorophyll a, as well as an advance in water transparency from a eutrophic to mesotrophic state.

Research Implications: This study emphasizes the significant vulnerability of lakes to eutrophication and underscores the importance of adopting effective management strategies to preserve water quality. The results support the use of *Myriophyllum spicatum* as a viable bioremediation technique, offering an environmentally sustainable alternative to traditional chemical interventions for treating eutrophic lake ecosystems.

Originality / Value: This research contributes to the understanding of eutrophication in Yahuarcocha Lagoon and highlights the effectiveness of bioremediation with *Myriophyllum spicatum*, a strategy scarcely explored in this specific context. By integrating environmental modeling with practical applications of bioremediation, this study provides innovative insights into the sustainable management of eutrophication in tropical lakes. The findings not only have implications for local environmental conservation but also establish an applicable framework for other similar aquatic ecosystems globally.

Keywords: AQUATOX, Eutrophication, Eutrophication Modeling, Bioremediation Simulation.

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AVALIAÇÃO DO ESTADO TRÓFICO DA LAGOA DE YAGUARCOCHA USANDO O SOFTWARE AQUATOX

RESUMO

Objetivo: O objetivo deste estudo foi avaliar o estado trófico da Lagoa Yahuarcocha utilizando o modelo de simulação AQUATOX. Buscou-se compreender as dinâmicas da eutrofização neste ecossistema aquático e avaliar a eficácia de *Myriophyllum spicatum* como uma estratégia de biorremediação para mitigar os efeitos adversos da eutrofização.

Metodologia: Implementamos um desenho experimental para medir variáveis-chave que refletem o estado trófico da Lagoa Yahuarcocha, incluindo a profundidade do disco de Secchi, fósforo total e concentrações de clorofila. Ao longo de quatro meses, de setembro a dezembro, oito sessões de amostragem foram conduzidas para coletar dados essenciais. O software AQUATOX foi utilizado para modelar essas variáveis ambientais, e o erro quadrático médio e o erro relativo foram empregados para validar a precisão do modelo. Adicionalmente, investigou-se o potencial de *Myriophyllum spicatum* para melhorar a qualidade da água da lagoa.

Resultados e Conclusões: Nossos achados indicaram que a Lagoa Yahuarcocha exibiu um estado hipereutrófico com base nas concentrações de fósforo total e um estado eutrófico em relação à clorofila a e à profundidade do disco de Secchi. Embora o modelo AQUATOX não tenha alcançado um nível de validação totalmente satisfatório, a introdução de *Myriophyllum spicatum* como agente de biorremediação provou ser uma medida eficaz, facilitando uma melhora notável na qualidade da água de um estado hipereutrófico para eutrófico em termos de fósforo total e clorofila a, bem como um avanço na transparência da água de um estado eutrófico para mesotrófico.

Implicações da Pesquisa: Este estudo enfatiza a vulnerabilidade significativa dos lagos à eutrofização e sublinha a importância de adotar estratégias de gestão eficazes para preservar a qualidade da água. Os resultados apoiam o uso de *Myriophyllum spicatum* como uma técnica viável de biorremediação, oferecendo uma alternativa entável às intervenções químicas tradicionais para tratar ecossistemas lacustres eutróficos.

Originalidade / Valor: Esta pesquisa contribui para a compreensão da eutrofização na Lagoa Yahuarcocha e destaca a eficácia da biorremediação com *Myriophyllum spicatum*, uma estratégia pouco explorada neste contexto específico. Integrando modelagem ambiental com aplicações práticas de biorremediação, este estudo oferece insights inovadores sobre o manejo sustentável da eutrofização em lagos tropicais. Os achados não apenas têm implicações para a conservação ambiental local, mas também estabelecem um quadro aplicável a outros ecossistemas aquáticos semelhantes globalmente.

Palavras-chave: AQUATOX, Eutrofização, Modelagem de Eutrofização, Simulação de Biorremediação.

EVALUACIÓN DEL ESTADO TRÓFICO DE LA LAGUNA DE YAGUARCOCHA USANDO EL SOFWARE AQUATOX

RESUMEN

Objetivo: El objetivo de este estudio fue evaluar el estado trófico de la Laguna Yahuarcocha utilizando el modelo de simulación AQUATOX. Se buscó comprender las dinámicas de eutrofización en este ecosistema acuático y evaluar la eficacia de *Myriophyllum spicatum* como una estrategia de biorremediación para mitigar los efectos adversos de la eutrofización.

Metodología: Implementamos un diseño experimental para medir variables clave que reflejan el estado trófico de la Laguna Yahuarcocha, incluyendo la profundidad del disco Secchi, el fósforo total y las concentraciones de clorofila. A lo largo de cuatro meses, desde septiembre hasta diciembre, se realizaron ocho sesiones de muestreo para recoger datos esenciales. El software AQUATOX se utilizó para modelar estas variables ambientales, y el error cuadrático medio y el error relativo sirvieron para validar la precisión del modelo. Adicionalmente, se investigó el potencial de *Myriophyllum spicatum* para mejorar la calidad del agua de la laguna.

Resultados y Conclusiones: Nuestros hallazgos indicaron que la Laguna Yahuarcocha presentaba un estado hipereutrófico basado en las concentraciones de fósforo total y un estado eutrófico con respecto a la clorofila a y la profundidad del disco Secchi. Aunque el modelo AQUATOX no alcanzó un nivel de validación completamente satisfactorio, la introducción de *Myriophyllum spicatum* como agente de biorremediación demostró ser una medida efectiva, facilitando una mejora notable en la calidad del agua desde un estado hipereutrófico a eutrófico en cuanto

al fósforo total y la clorofila a, así como un avance de la transparencia del agua de un estado eutrófico a mesotrófico.

Implicaciones de la Investigación: Este estudio enfatiza la significativa vulnerabilidad de los lagos a la eutrofización y subraya la importancia de adoptar estrategias de gestión efectivas para conservar la calidad del agua. Los resultados avalan la utilización de *Myriophyllum spicatum* como una técnica de biorremediación viable, ofreciendo una alternativa ambientalmente sostenible a las intervenciones químicas tradicionales para el tratamiento de ecosistemas lacustres afectados por eutrofización.

Originalidad / Valor: La presente investigación aporta a la comprensión de la eutrofización en la Laguna Yahuarcocha y destaca la efectividad de la biorremediación con *Myriophyllum spicatum*, una estrategia poco explorada en este contexto específico. Al integrar la modelización ambiental con aplicaciones prácticas de biorremediación, este estudio proporciona perspectivas innovadoras sobre el manejo sostenible de la eutrofización en lagos tropicales. Los hallazgos no solo tienen implicaciones para la conservación ambiental local, sino que también establecen un marco aplicable a otros ecosistemas acuáticos similares a nivel global.

Palabras clave: AQUATOX, Eutrofización, Modelado de Eutrofización, Simulación de Biorremediación.

1 INTRODUCTION

Natural lakes are fundamental components of terrestrial ecosystems and play crucial roles in hydrological processes, biodiversity and human well-being, however, they are significantly exposed to various types of pollution that can affect their water quality especially by pollutants and eutrophication (Terneus, 2014).

Eutrophication is a process caused by pollution, where an excess of nutrients leads to the growth of plants and algae (Maridueñas et al., 2011). When these organisms die, they decompose, settle, and consume oxygen, resulting in the death of the lagoon's flora and fauna (Ongley, 1997; Oliveira, et al., 20223). Although natural causes can contribute to eutrophication through biological cycles of water bodies (Goita, 2011), eutrophication of the Yahuarcocha Lagoon has anthropogenic origin (Conci, 2020).

The estimation of the Trophic State Index (TSI) of the Yahuarcocha Lagoon allows to detect eutrophication processes. This index is based on the measurement of certain parameters that reflect the availability of nutrients, especially phosphorus and nitrogen, and their impact on the biological productivity of the aquatic ecosystem (Ongley, 1997). These parameters are related to the amount of available nutrients, phytoplankton biomass and water transparency. This index provides a quantitative measure of trophic status, such as water quality and the ability to sustain aquatic life (Muyón, 2022)Oh, yeah.

Simulation models play a crucial role in environmental research by providing insights into the behavior of complex systems and forecasting their future states (Clough, 2014). However, to obtain accurate results, these models require extensive data collection and validation (EPA, 2014). AQUATOX software is widely used to simulate aquatic ecosystems and predict nutrient and chemical behavior in water bodies, especially in lakes and reservoirs (Perez et al., 2005). This software considers factors such as nutrients, temperature, light, and others to model biological and chemical processes in water (Lei et al., 2008).

The objective of this research is to evaluate the trophic state of the Yahuarcocha Lagoon in Ecuador using AQUATOX software, as well as to propose remediation strategies to improve water body conditions.

2 METHODOLOGY

2.1 STUDY AREA

The study area included the Yahuarcocha Lagoon, located in the province of Imbabura, city of Ibarra. The basin of the lagoon extends from an altitude of 3750 meters above sea level in the moorland of the humid montane forest to 2200 meters above sea level in the low montane dry forest (Ministry of the Environment, 2015)Oh, yeah. The lagoon experiences annual rainfall ranging between 1000 and 2000 mm, with a liquid loss of 24 cm per year. The geographical parameters are detailed in Table 1.

Table 1

Geographical Parameters of the Yaguarcocha Lagoon

Parameter	Unit	Value
Length of water body	km	2.41
Surface area	m2	2405116.08
Average depth	m	4.81
Maximum depth	m	6.25
Latitude	Degrees	0.3783
Volume	M^3	11568608.35

Source: Self-authored (2023)

2.2 DATA COLLECTION

AQUATOX software (Li, 2020) was used for water body analysis. The parameters were determined by analyzing satellite images, and depth measurements were made during field visits. The meteorological data (wind speed and solar radiation) were obtained from the NASA POWER web portal, while the average evaporation was obtained from the National Institute of Meteorology and Climatology of the meteorological station (INAMHI), the M1240 station, located in the city of Ibarra, Table 2 (INAMHI, 2022).

Table 2

Weather data obtained from INAMHI- Station M1240.

Parameter	Unit	Value
Average evaporation	inch/year	52.52
Wind speed	m/s	2.3
Solar radiation	Ly/d	267.46

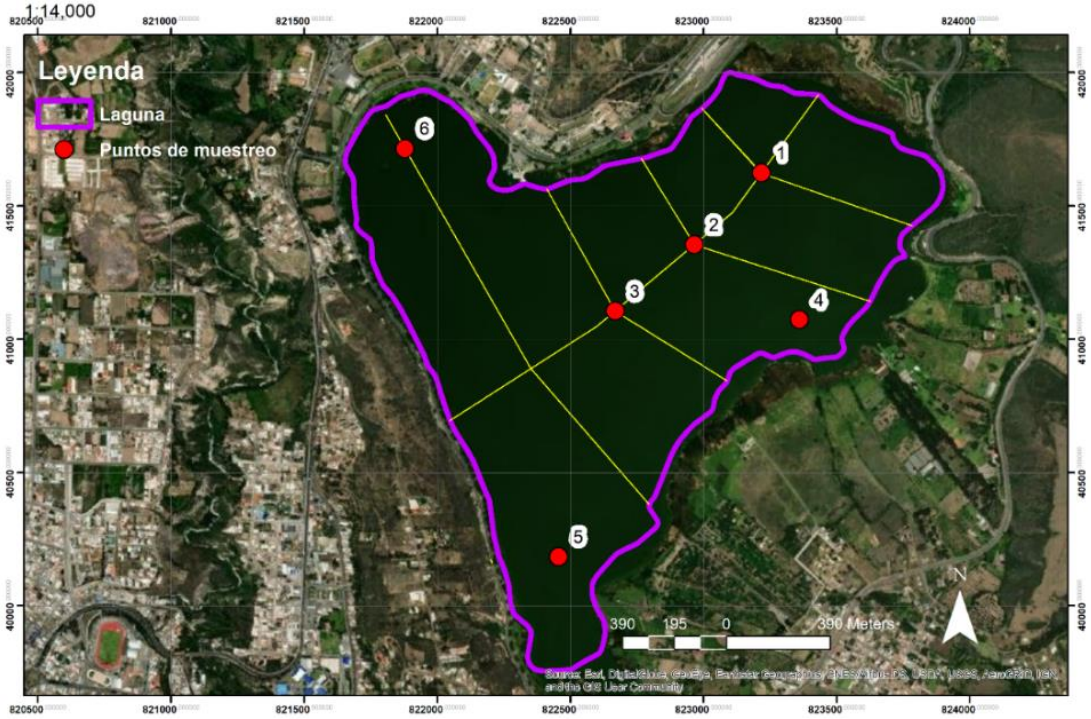
Source: Self-authored (2023)

2.3 WATER BODY STUDY

Six sampling points were selected following the methodology established by the Illinois Environmental Protection Agency (IEP Agency, 1998). These points were chosen considering the shape of the lake and the identified water tributaries. Initial sampling was carried out at these points to determine the initial conditions and parameters of the lagoon (Bridge, 2017)Oh, yeah. Subsequently, a monitoring was carried out (Figure 1), to measure the trophic state variables and validate the AQUATOX model.

Figure 1

Study area and sampling points



Source: Self-authored (2023)

2.4 ANALYSIS OF WATER SAMPLES

On 8 September 2021, the initial conditions and parameters required for AQUATOX software were estimated through the first sampling. Following the guidelines of the APHA (APHA, 2017), the samples were kept in cold chain by ice coolers until they were transferred to the CICAM laboratory of the National Polytechnic School for the analysis of nutrient concentration. The detritus samples were sent to the Environmental Engineering laboratories of the Salesian Polytechnic University. The concentrations of the main plants present in the lagoon were obtained from a previous study (Guerra, 2021; Reséndiz, 2022). Finally, the average values of all collected data were entered into the AQUATOX software, as presented in Table 3.

Table 1

Initial conditions and parameters of the lagoon

Stage	Parameter	Unit	Value
Nutrients	Nitrogen as Ammonia	mg/L	0.18
	Nitrogen as nitrate	mg/L	3.52
	Phosphorus as phosphorus	mg/L	0.29
	Carbon Dioxide	mg/L	1.88

	Oxygen	mg/L	11.68
Detritus	Labile Detritus	g/m^2	88.1
	Refractory Detritus	g/m^2	11.89
	Organic matter	mg/L	115.13
	Percentage of particulate matter	%	10
	Percentage of refractory debris	%	20
Plants	Plants Fragilaria sp.	g/m^2	0,007
	Nitzschia sp.	g/m^2	0.112
	Marine Green Phytoplankton (Chlorophyceasp)	mg/L	0.0825
Water Temperature	Epilinmion	°C	22.43
	Hypolymonium	°C	21.92
pH of water	pH		8.49

Source: Self-authored (2023)

2.5 STUDY OF THE TRAFFIC STATE

The trophic status of the lagoon was monitored through eight sampling campaigns conducted between September and December 2021. During each sampling, measurements were taken to estimate the variables needed to calculate the Carlson Trophic State Index, such as total phosphorus, chlorophyll a, and depth of the Secchi disk (Carlson, 1977). The averages resulting from these variables were also used in the calibration and validation of the AQUATOX model, as presented in Table 4. Sensitivity analysis involved varying the model parameters by ±20% and evaluating the variables that had the greatest influence on the observed changes in total phosphorus, chlorophyll a and Secchi disk depth (German, 2009)Oh, yeah. To validate the model, the mean square error (MSE) was used, and to compare the results of the model with those obtained in the monitoring of the trophic state (Sánchez & Álvarez, 2021), relative error (RE) was used.

Table 4

Average trophic status monitoring variables of the Yaguarcocha lagoon

Sampling	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Data	**08/09**	**09/22**	**04/10**	**18/10**	**04/11**	**11/15**	**28/11**	**12/13**
TP (mg/l)	0.91	0.82	1.11	1.74	1.17	1.99	1.21	1.51
Ca(µg/l)	41.72	27.73	26.04	143.29	67.09	85.52	121.75	66.09
SC(m)	0.21	0.14	0.15	0.16	0.21	0.36	0.29	0.39

Source: Self-authored (2023)

2.6 SIMULATION OF REMEDIATION STRATEGY

A simulation was carried out using the macrophyte Myriophyllum macrophyta as a bioremediation agent (Viñas, 2005)Oh, yeah. This macrophyte, present in Lake San Pablo in Imbabura province, has been studied for its phosphorus removal capacity in eutrophic lakes, with an estimated rate of 12 mg/m2/day (Gómez, 2017). To simulate the bioremediation potential of the macrophyte plant *Myriophyllum,* an initial concentration of 0.00012 mg/m3 of this plant was introduced in the simulation (Madueño, 2021)Oh, yeah.

3 RESULTS AND DISCUSSION

Based on the monitoring results, the Carlson Trophic State Index (TSI) was calculated, revealing that the lagoon exhibited a hypereutrophic state (TSI between 90 and 100) for total phosphorus. In contrast, it was in a eutrophic state for both chlorophyll a and Secchi disk depth (TSI between 60 and 90), as detailed in Table 5.

Table 5

Trophic status index during monitoring

Sampling	1	2	3	4	5	6	7	8
TP (TSI)	100	100	100	100	100	100	100	100
Ca (TSI)	67.2	63.2	62.6	79.3	71.9	74.2	77.7	71.7
SC (TSI)	82.5	88.3	87.3	86.4	82.5	74.7	77.8	73.6

Source: Self-authored (2023)

In relation to the sensitivity analysis, the parameters with the greatest impact on the variation of total phosphorus, chlorophyll and Secchi disk depth were identified (Table 6). These parameters were adjusted according to the guidelines provided in the AQUATOX manual (EPA, 2014).

The results of the calibrated model are displayed in Figure 3, while the calculated errors are presented in Table 7. However, the model did not achieve an acceptable level of validation, as errors persist at high levels. The Trophic State Index (TSI) calculation suggests that the lagoon maintained a hypereutrophic state for total and eutrophic phosphorus for chlorophyll a and the depth of the Secchi disk until 11 November 2022, without undergoing significant changes.

Regarding the Remediation simulation, the results showed a notable decrease in the concentration of total phosphorus and chlorophyll, along with an increase in the depth of the Secchi disk as evidenced in Figure 4.

This intervention led to an improvement in the trophic state of the lagoon, marking a transition from a hypereutrophic to eutrophic state for total phosphorus and chlorophyll a, and from a eutrophic to mesotrophic state for the depth of the Secchi disk.

Table 6

Calibrated parameters

Parameter	Original Value	Calibrated Value
pH: Multiply the load by	1	0.8
pH: Constant charge (pH)	8.49	6.79
Remin: maximum pH for degradation	6.85	5.48
Temp: Constant load (°C)	22	21
Temp: Multiply the load by	1	0.8
Site: Maximum Depth (m)	7	5.2
Site: Water extinguishing coefficient (1/m)	0.2	0.16
Remin: Optimal temperature (°C)	25	20

Source: Self-authored (2023)

Table 7

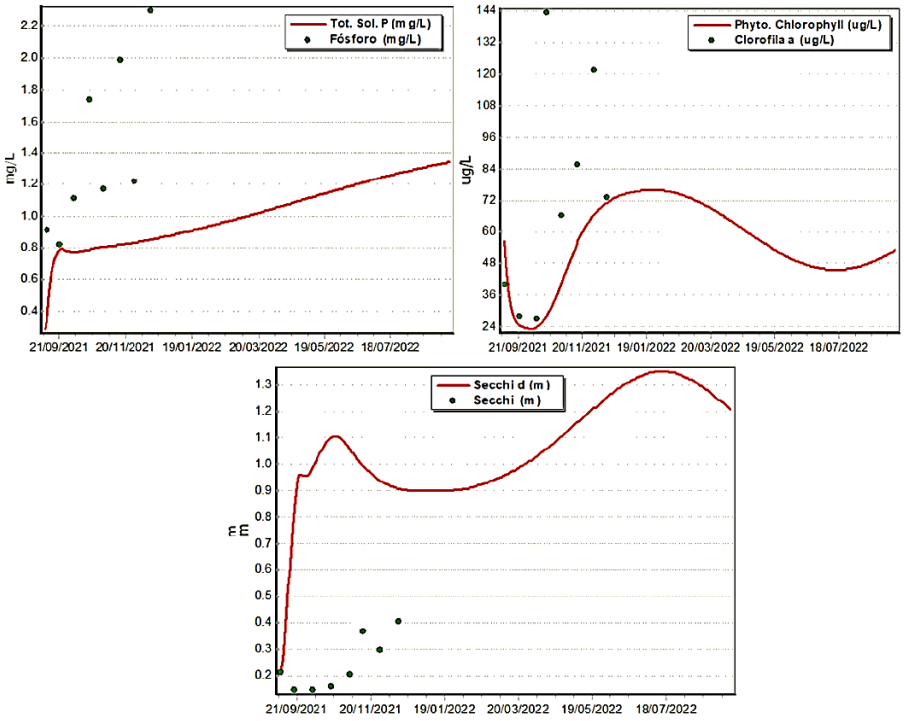
Root Mean Quadratic Error (RSME) and Relative Error for Model Calibration and Validation

Variable	Total Phosphorus		Chlorophyll		Disco Secchi	
Stage	RSME	RE %	RSME	RE %	RSME	RE %
Calibration	4395	160.82	31.5014	126,1817	0.6767	1005.57
Validation	0.8259	161.67	59,5931	129.4986	0.7869	1033.76

Source: Self-authored (2023)

Figure 1

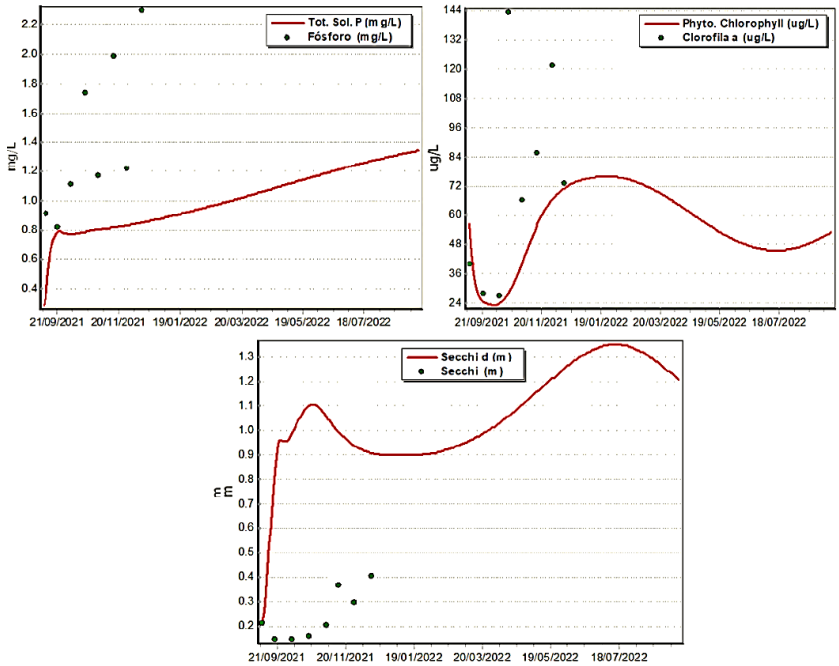
Simulation with the calibrated model of total phosphorus, chlorophyll, and Secchi disk as appropriate



Source: Self-authored (2023)

Figure 4

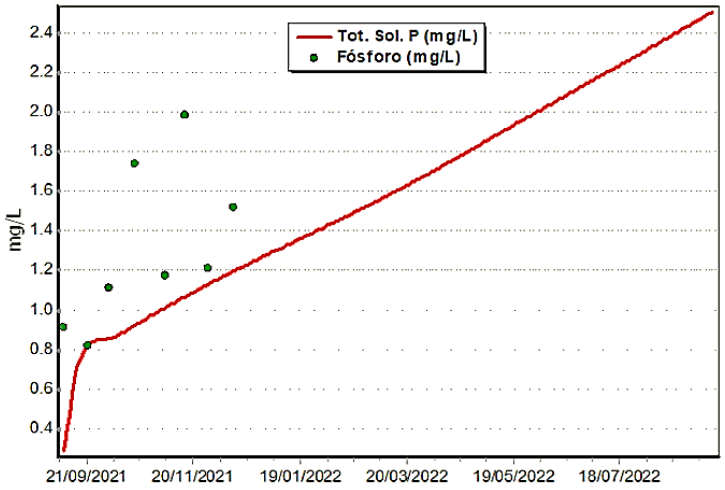
Simulation of bioremediation strategy



Source: Self-authored (2023)

Figure 5

Total phosphorus simulation with a phosphorus input load of 1 mg/day



Source: Self-authored (2023)

The validation results indicate that the model has not reached an acceptable level of reliability, as detailed in Table 7. This finding is further supported by comparing it with other studies that have reported lower errors, such as assessing the risk of eutrophication of the Danjiangkou reservoir using the EFDC model, which obtained an RMSE of 0.03 (Ramos, 2018), or the eutrophication studies of Wuliangsuhai and the San Marcos lagoon, where an AQUATOX model achieved a relative error between 11 and 19% (Goitia, 2011).

The presence of higher errors in this study can be attributed to the fact that, during the monitoring sampling campaign, water inlets were found to be dry, making it impossible to model incoming nutrient concentrations in the water body, despite recognizing that wastewater discharges are an important factor contributing to the actual trophic state of the lagoon (Larrea, 2021)Oh, yeah. However, as shown in Figure 5, by incorporating a total phosphorus incoming contaminant load of 1 mg/d, the simulation results for total phosphorus improved significantly, indicating the importance of accurately considering incoming loads in the model.

To improve the calibration of the model, it is suggested to collect additional data on the pollutant loads entering the lagoon. This could be achieved by more comprehensive monitoring or by estimating population and economic activities in the area (Dam, 2020)Oh, yeah. Another source of error influencing the results of this research is that most of the plants present in the Yaguarcocha lagoon, as reported in (Mollocana, 2021), are not included in the AQUATOX library. In addition, the characterization of these plants does not include the growth parameters necessary to incorporate them in the software library. In addition, there are no studies that characterize the biomass of fish and macroinvertebrates.

4 CONCLUSIONS

In this study, a preliminary approach was presented to model the trophic state of the Yaguarcocha lagoon using AQUATOX software. The results obtained allowed to identify key factors to develop an applicable model and design remediation strategies for the lagoon. Monitoring indicated that excess phosphorus was the main cause of eutrophication, attributed to unregulated discharge of domestic and agricultural wastewater. This irregular discharge presented a challenge in the implementation of remediation measures, being difficult to model and generating errors in the calibration of the model.

The simulation showed that the presence of the macrophyte Myriophyllum had a significant positive impact on the trophic state of the lagoon. Given its common presence in similar ecosystems, this macrophyte was a promising option for future research as a remediation strategy.

Additional studies were suggested to improve the characterization of plants, macroinvertebrates and fish in the Yaguarcocha lagoon, focusing on estimating kinetic parameters required by AQUATOX. This could have improved model validation and facilitated the development of effective remediation strategies.

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