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Seasonal Eutrophication Dynamics in Ahmed El Hansali Reservoir, Morocco: A Multivariate Statistical Approach

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ABSTRACT

In Morocco, dams are essential for supplying drinking water, supporting agriculture, and regulating watercourses, but these aquatic ecosystems face increasing pressures, particularly eutrophication, which degrades water quality and threatens biodiversity. This study analyzed the seasonal dynamics of eutrophication in the Ahmed El Hansali reservoir (Moroccan Middle Atlas) between 2019 and 2023, utilizing multivariate statistical analysis (Principal Component Analysis and multiple linear regression). A limitation was quarterly data collection, which might not capture short-term fluctuations. Results revealed a significant correlation between phytoplankton biomass and nutrient levels, especially total Kjeldahl nitrogen (NTK) ($r=0.656$ $p<0.01$). NTK was the most significant predictor, positively impacting chlorophyll-a (Chl-a) in surface waters (for each unit increase in NTK, Chl-a increased by 15.16 µg/L). Other parameters had minimal effects. Marked seasonal variability in water quality was observed, ranging from oligotrophic in winter and autumn to mesotrophic in spring and summer. Maximum productivity (15.73 µg/L Chl-a) was in summer, while the lowest (5.92 µg/L Chl-a) was in winter. Excessive nutrient inputs from agricultural runoff during the rainy season were recorded, highlighting the need for continuous monitoring, especially during peak productivity, to mitigate eutrophication risks. Recommendations include optimizing agricultural practices to reduce nutrient inputs and implementing integrated water resource management strategies to preserve the reservoir's ecological quality. This research provides valuable information for decision-makers and environmental managers aiming to improve water quality and protect aquatic biodiversity in Morocco.

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INTRODUCTION

Dams play a central role in managing water resources and preserving aquatic ecosystems worldwide. By regulating hydrological regimes, filtering water, and supporting biodiversity, they also contribute to local and regional climate stability (Rolls et al., 2018; Oyekanmi & Mbossoh, 2018). However, these aquatic ecosystems are facing increasing pressures due to eutrophication and climate change. Eutrophication, a consequence of excess nutrients linked to

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human activities, degrades water quality and threatens biodiversity (Sitote & Gebremedhine, 2024; Naderian et al., 2025). The eutrophication of transboundary water bodies is a major environmental issue, stimulating multidisciplinary research. Satellite remote sensing has emerged as a crucial tool to monitor its spatial and temporal dynamics, as demonstrated for the Caspian Sea (Modabberi et al.,2020). Simultaneously, the integration of traditional water quality indices with machine learning models is improving the accuracy and predictability of real-time ecosystem assessments (Kim et al.,2024). In Morocco, a country facing significant water challenges, dams are essential to ensure the supply of drinking water, support agriculture, and regulate watercourses. At the same time, climate change is altering precipitation patterns and increasing the variability of water resources, thereby exacerbating challenges in the quality and quantity of available water (Li et al., 2024). The dam construction policy, initiated in the 1960s, has helped secure water supplies and irrigate nearly one million hectares, supporting the country's economy and water resilience. Today, Morocco has 145 large dams and several more under construction, with a storage capacity exceeding 18 billion cubic meters (BADRAOUI et al., 2011; REEM, 2020). However, persistent challenges, including increased eutrophication from recurrent droughts, are causing major disruptions to aquatic ecosystems and impacting associated goods and services, related economic activities, and human health (Pinay et al., 2017). Improving the quality of surface waters is a general objective in Morocco, particularly dam water. In this context, water quality monitoring systems are essential for the success of management and restoration programs for these aquatic environments. Reliable data, measured continuously over long periods of time and supported by multivariate statistical methods, are essential to understand environmental pressures on dams and to determine the state of water resources, implement effective conservation and rehabilitation programs and properly evaluate their performance (Ouhakki et al., 2024). Eutrophication events were identified and determined using statistical models such as principal component analysis (PCA) and multiple linear regression (Bharti et al., 2018). By combining these two models, it is possible to create a quantitative model for chl-a and to identify the key variables to confirm their influence (Chen et al., 2018). The Ahmed El Hansali dam has been the subject of a few rare studies (El Orfi et al., 2020; Ouhakki et al., 2024), but none have addressed eutrophication using multivariate analysis methods. This study aims to assess the quality of the dam water based on indicator 6.3.2 of the Sustainable Development Goals and by analyzing the relationships between environmental factors and phytoplankton biomass, which will allow us to deepen our understanding of the quality of water resources in this biogeographic region of Morocco where the intensification of human activities impacts both their availability and quality. We aim to provide decision-makers and managers with key data to develop and implement strategies to ensure the supply of drinking water, preserve the quality of water intended for irrigation and protect aquatic biodiversity (Bahouar et al., 2024).

MATERIALS AND METHODS

Description and location of the study area

The Ahmed El Hansali dam, located near Zaouyat Cheikh 50 km from Kasbat Tadla on the Oum Er-Rbia, is a strategic structure for Morocco (Figure 1). The country's first rockfill dam with a concrete upstream mask, it forms a reservoir of 740 million m^3, regulates 473 million m^3 and offers a head of between 51 and 82 meters for electricity production. In addition to the supply of drinking water, it supports the irrigation of 36,000 hectares in the Beni Amir plain.

Climate of the study area

The climate of the area is Mediterranean with rainy and mild winters and hot and dry summers. The average interannual rainfall recorded in the rain gauge stations of the watershed

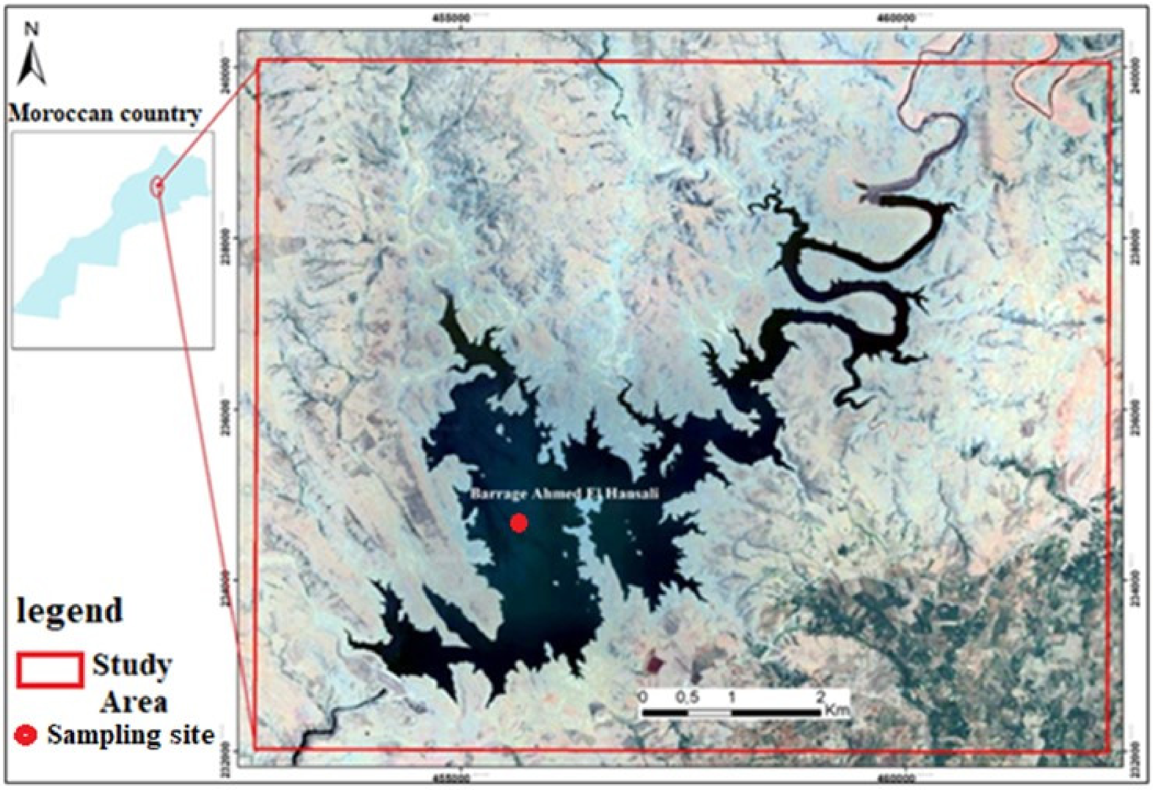

Fig. 1. Location map of the study area.

between 1974-75 and 2016-17 is of the order of 508mm in the Taghzoute station, 570mm in Tarhat and 692mm in Tamchachat (El Orfi et al.,2020).

Sampling and measurement of parameters

The data presented in this study was collected quarterly from 20 sampling campaigns carried out between 2019 and 2023, the samples were taken at 50 cm below the water surface, at the central monitoring site of the Ahmed El Hansali reservoir (coordinates X = 454502, Y = 233980), this choice is based on scientific criteria of representativeness and logistical accessibility, in accordance with the hydrographic data provided by the Oum Er-Rbiâ Hydraulic Basin Agency, the competent authority for the management of water resources in the studied reservoir. Furthermore, this approach is corroborated by the significant decrease in the reservoir's storage capacity, a direct consequence of the increased frequency of drought episodes affecting the region. Following the collection of samples, various parameters including temperature, pH, conductivity, and dissolved oxygen were recorded in situ. After sampling, the collected samples were preserved in a cooler maintained at 4 °C and conveyed to the laboratory expeditiously for comprehensive analysis in accordance with the protocol delineated by Rodier et al. (2016). Physico-chemical analyses were conducted in accordance with standardized protocols. The parameters were ascertained utilizing specialized instruments: a WTW OXI 320 temperature sensor, a WTW (pH3110) for measuring pH, conductivity was evaluated with a WTW (Cond3110) conductivity meter, and concentrations of dissolved oxygen were quantified using a HQ30d multi-parameter probe. Other parameters (suspended solids, ammonium, nitrates, Kjeldahl nitrogen, total phosphorus, orthophosphate and chlorophyll a) were analyzed spectrophotometrically (JASCO) according to NF T 90 standards and methods described in Rodier et al (2016).

Data preparation and statistical analysis

The parameters used for the analysis were water temperature (Twater), pH, suspended solids (MES), dissolved oxygen (DO), ammonium (NH4+), nitrates (NO3-), Kjeldahl nitrogen (NTK), total phosphorus (TP) and chlorophyll a (Chl-a). The variability of phytoplankton biomass was analyzed using multivariate statistical approaches with the R studiox64 4.3.3 software. Initially, we aimed to determine the correlations between the various variables and visually assess if multiple linear regression would be a suitable model to fit these data (Husson et al., 2018). Specifically, we examined if there was a linear relationship between the response variable (Chl-a) and the predictive variables. The PCA was then performed to identify the primary environmental factors that account for the fluctuations in chl-a concentrations (Chen et al., 2022).

RESULTS AND DISCUSSION

Exploratory analysis

Exploring seasonal patterns in the overall surface water analysis results of the Ahmed El Hansali dam (figure 2), reveals seasonal patterns and distinct variability in the data, highlighting

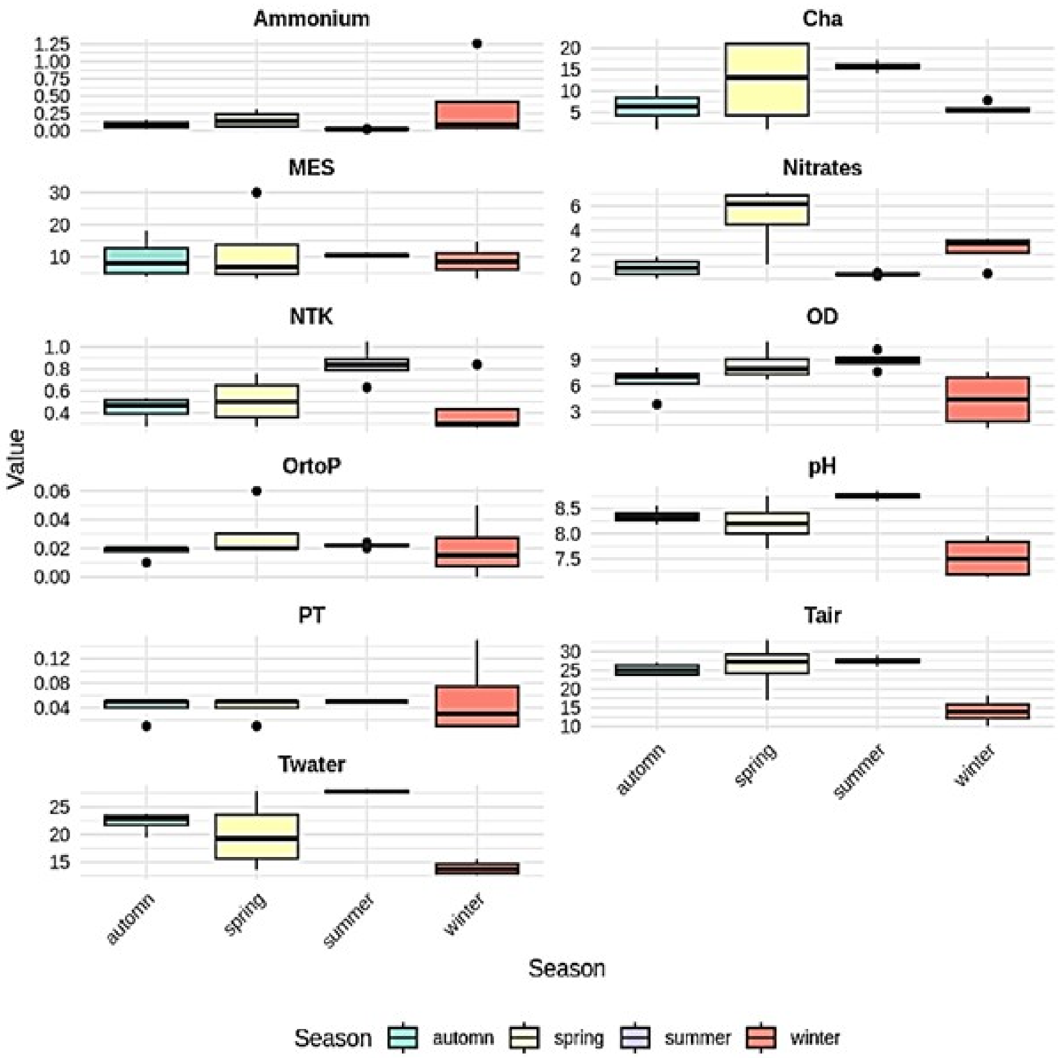

Fig. 2. Seasonal variation of parameters

differences in means and distributions across seasons for each variable.

For the temperature (Tair & Twater) we note a maximum in summer (26-28°C) and a minimum in winter (13-15°C), the pH follows the evolution of the temperature (Mukhethwa Judy Mukwevho et al., 2020), it is higher in summer (8.7-8.8), lower in winter (7.2-7.5). Temperature variations affect biogeochemical reactions including the processes of remineralization of organic matter (Jeppesen et al.,2009). For the nutrient cycle: Nitrates: Maximum in spring (5-7 mg/L), minimum in summer (<1 mg/L), NTK: peaks in summer (0.8-0.9 mg/L), stable during the other seasons while OrtoP is relatively stable from one season to another. For the biological activity parameters, Chl-a: Maximum in summer (15-17 µg/L), minimum in winter (5-6 µg/L). DO records peaks in summer (8-11 mg/L), however the MES present a maximum variability in spring. These results suggest a correlation between photosynthetic activity (Chl a) and these explanatory variables; Tair&Twater, Nitrates, NTK, pH, MES and OD (Moura et al., 2021).

Analysis of the distribution and seasonal profile of chl-a

Seasonal variability in phytoplankton biomass is well established (Zhao et al., 2016; Cheraghpour-Ahmadmahmoodi et al., 2024), hence the interest in exploring this variability at the level of this water reservoir and drawing up its seasonal profile (figure 3).

The seasonal profile of chlorophyll a (Chl-a) shows distinct characteristics, with higher mean values in summer, indicating an increase in algal biomass during the warmer months (Anderson et al., 2022). Variability, as indicated by the standard deviation, is highest in spring and summer, suggesting greater fluctuation in algal concentrations during these seasons. This pattern is consistent with typical ecological responses to temperature and nutrient availability (Gerhard et al., 2019).

Multivariate statistical analysis

Correlation between chl-a and explanatory variables

An analysis of correlations between environmental variables measured in the surface waters of the reservoir (Figure 4 and 5) shows a strong positive correlation between phytoplankton biomass and NTK ($r = 0.656$ $p < 0.01$) as well as with water temperature ($r = 0.514$, $p < 0.05$). In

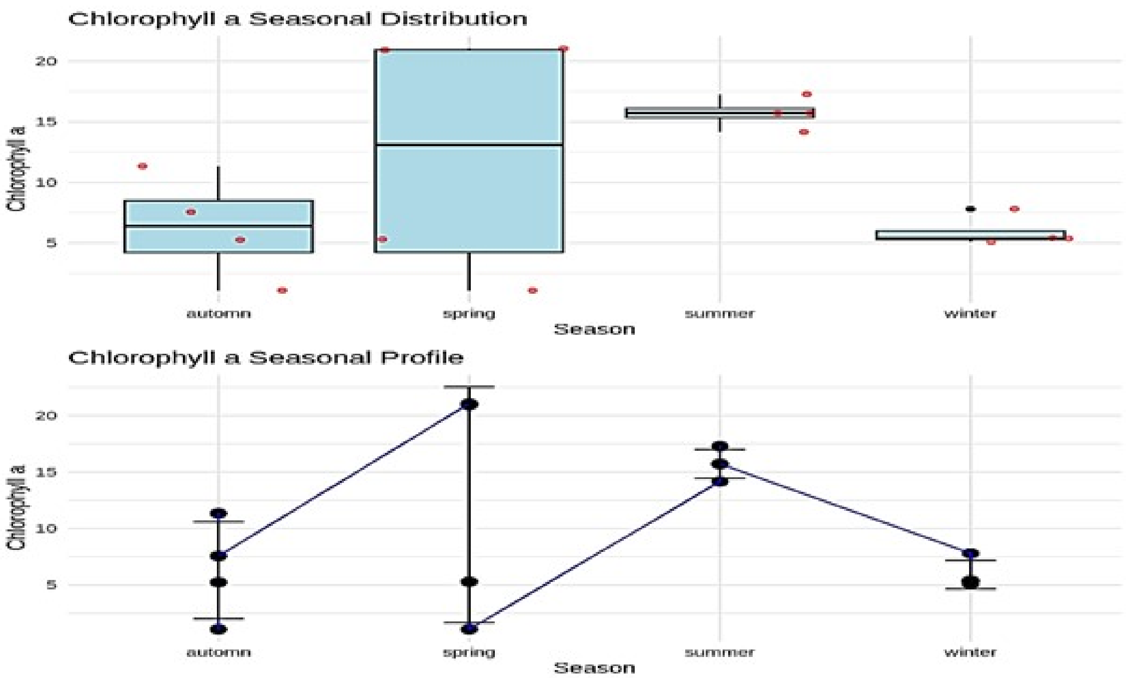

Fig. 3. Distribution and seasonal profile of chl-a at the surface water level of the dam Ahmed ELhansali.

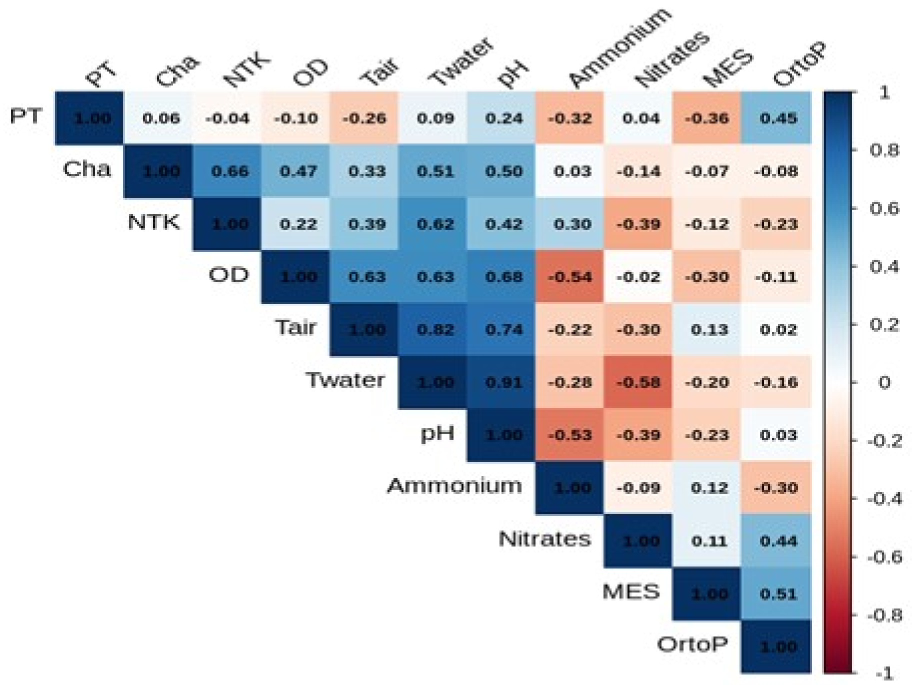

Fig. 4. Correlation matrix between chl-a and explanatory variables

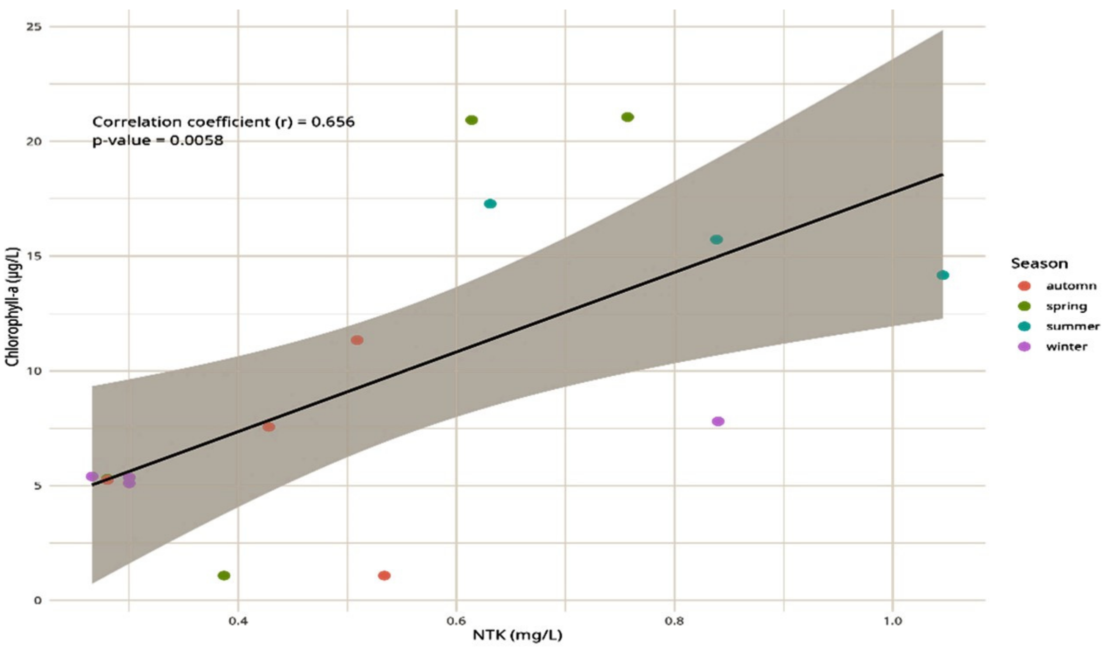

Fig. 5. Correlation between Chlorophyll-a and NTK

addition, there is a moderate correlation with pH and OD. These results suggest that enrichment of the dam waters with nitrogen nutrients promotes phytoplankton growth, resulting in higher biomass and chl-a levels. Furthermore, increasing water temperature appears to improve the ability of phytoplankton to use available nutrients more efficiently, thereby stimulating their proliferation (Fernández González et al., 2022).

Table 1. Multiple linear regression model statistics

Regression Coefficients				
term	**estimate**	**std.error**	**statistic**	**p.value**
(Intercept)	-43,6770062	41,571763	-1,05064118	0,31595766
NTK	20,0225193	7,16483431	2,79455441	0,01744386
Twater	-0,70897839	0,64104042	-1,1059808	0,29233644
pH	6,21531106	6,3831011	0,9737134	0,35112507
OD	0,91401803	0,66823438	1,36781055	0,19866496
Model Fit Statistics			**Variance Inflation Factors**	
Statistic	Value		Variable	VIF
R-squared	0,59133389		NTK	1,97559736
Adjusted R-squared	0,44272803		Twater	8,91249691
F-statistic	3,97920979		pH	7,1416606
p-value	0,03098525		OD	1,93382101

Table 2. Scale model statistics

Regression		Coefficients		
Term	**Estimate**	**Std_Error**	**t_value**	**p_value**
(Intercept)	-7,0495	25,3609	-0,278	0,786
NTK	15,1562	5,707	2,656	0,021*
pH	0,3471	3,5814	0,097	0,924
OD	0,8225	0,6692	1,229	0,243

Significant. Codes : 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Multiple Linear Regression Model

To quantify the influence of environmental variables positively correlated with the dependent variable chl-a, we performed a multiple regression model to identify the most significant predictors and their relative contributions to the development of phytoplankton biomass (chl-a), which allows us to better understand the dynamics of the dam water quality (Table1).

The results, indicate the contributions of NTK, Twater, pH and OD to the variance of Chl-a. Variance inflation factors (VIF) were also calculated to check for multicollinearity (Mcelreath, 2020).

Based on the analysis of these results, our model is efficient and significant, given that the R^2= 0.59 (59% of the variance of chl-a is explained) and that p value of the F statistic = 0.031. The NTK has a strongest positive effect (β = 20.02, p = 0.017) while the VIF value of the Twater and pH variables suggests a problem of multicollinearity between these two variables. To solve this problem, we removed the highly correlated variable (Twater) (James et al., 2013), the summary of the reduced model is generated (Table2). The outputs of the reduced model reveal that the overall model is significant (p-value = 0.02008) and explains a large part of the variance of Chl-a (54.59%). NTK is the most significant predictor and has a positive impact on Chl-a in the surface waters of the dam (for each unit increase in NTK, the concentration of Chl-a increases by 15.16 µg/L), while pH and DO have minimal and nonsignificant effects. To account for the remaining 45.41% of the chlorophyll-a (Chl-a) variance, future investigations should explore alternative modeling approaches. The Kolmogorov-Arnold Network, which has demonstrated superior accuracy in capturing trends and dynamic fluctuations in Chl-a

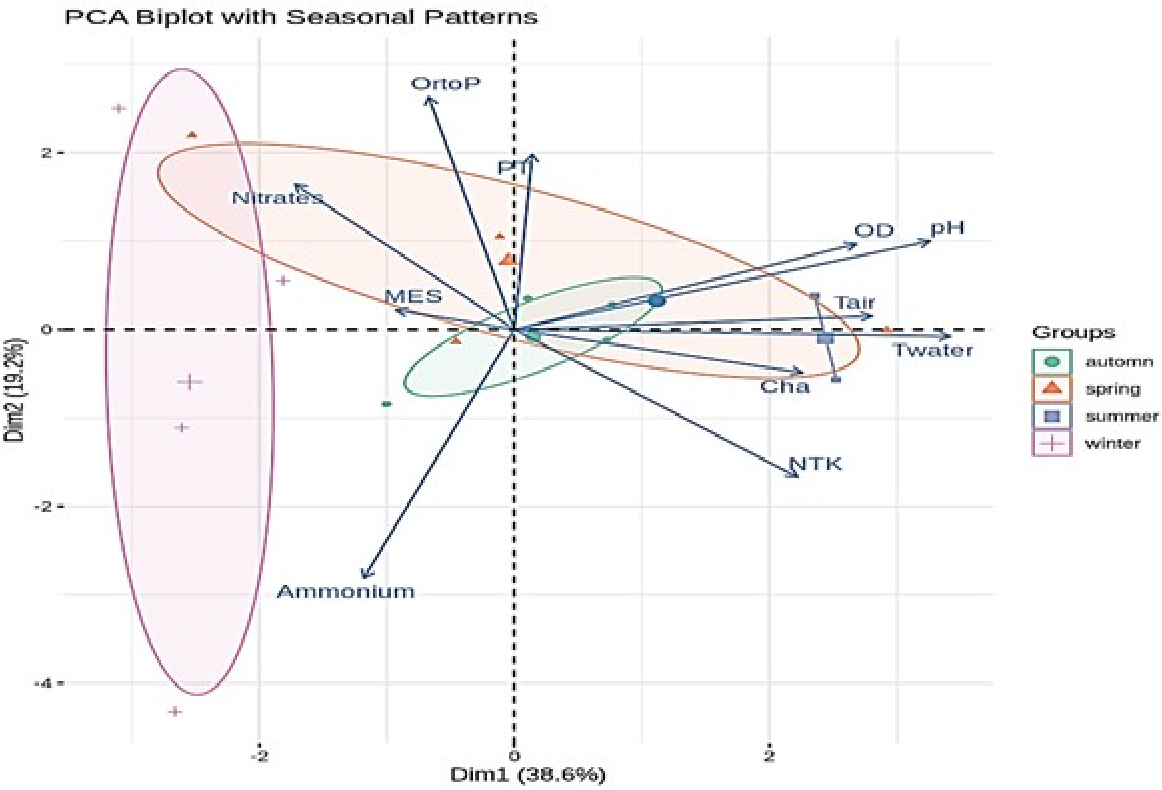

Fig. 6. Graph of variables (ACP)

concentrations (Saravani et al., 2025), warrants consideration. Furthermore, the integration of additional environmental covariates, such as light availability, hydraulic retention time and zooplankton grazing pressure, may provide a more complete understanding of Chl-a dynamics in the waters of the Ahmed el Hansali dam.

Principal Component Analysis (PCA)

The PCA biplot and summary statistics provide insight into the relationships between physicochemical parameters and seasonal variations (Figure 5).

An estimate of the relevant number of axes to be interpreted suggests restricting the analysis to the description of the first two axes. These components reveal a higher rate of inertia than the 0.95-quantile of random distributions (57.8% versus 49.2%). This observation suggests that only these axes carry real information. Consequently, the description of the analysis will be restricted to these axes only.

Spatial distribution

Principal component analysis (PCA) highlighted several interesting relationships between the variables studied. First, strong positive correlations were observed between water temperature (Twater), air temperature (Tair), pH, DO and Chl-a. The latter is correlated with NTK, these results corroborate with the work of Anderson et al (2022);Fernández-González et al (2022) who in their respective studies, revealed that the increase in water temperature and the availability of nutrients significantly influenced the growth of phytoplankton, on the other hand, the increase in algal synthetic activity, leads to an increase in DO and pH levels (Wallace et al., 2016). Analysis of seasonal patterns reveals a clear separation between summer and winter samples. Summer samples are associated with higher temperatures and pH, suggesting significant

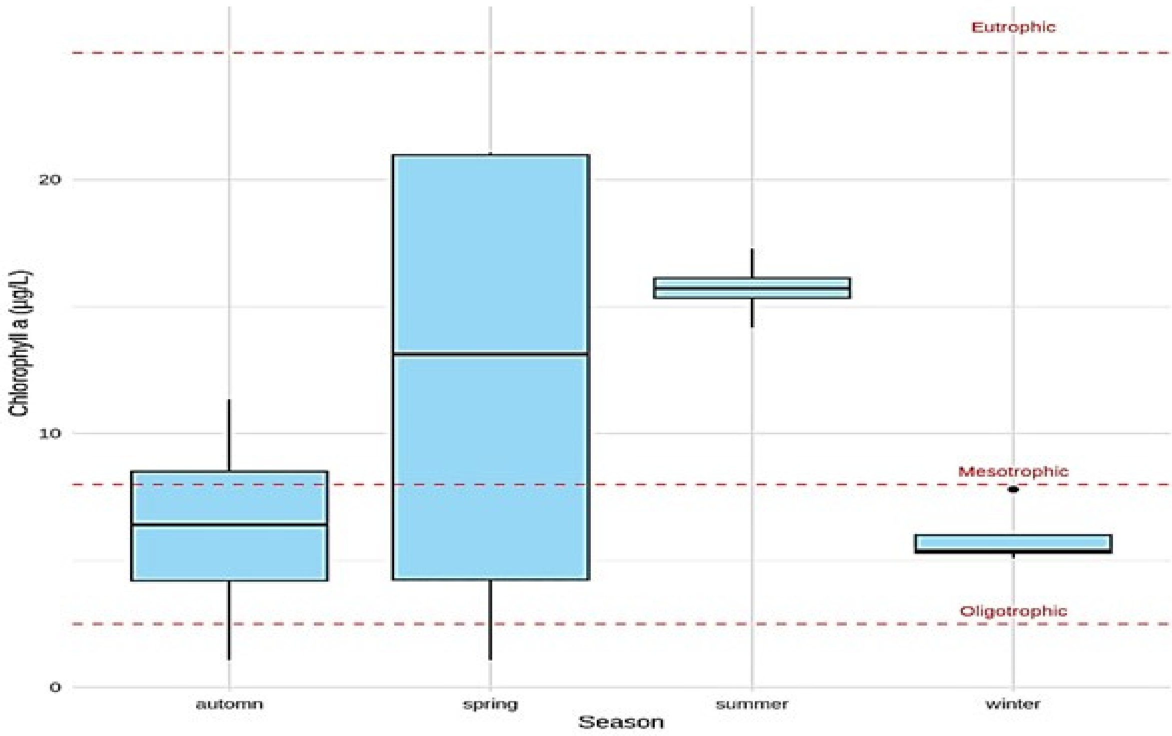

Fig. 7. Seasonal distribution of chl-a with OECD trophic limits

remineralization of organic matter in the dam waters during this season (Григорьева, 2023; Kim et al., 2024), while winter samples are correlated with higher nutrient levels, probably due to excessive nutrient input from agricultural runoff from areas surrounding the reservoir during the rainy season (Chen et al., 2018). Orthophosphate and total phosphorus (TP) show opposite variations with temperature, which could be attributed to fluctuations of the concentration of dissolved alkaline phosphatase, thus revealing a possible limitation of phosphorus in the dam waters (Kobayashi et al., 1984).

Trophic status analysis

Classification of the trophic status of aquatic ecosystems is essential for understanding water quality and ecosystem health. (Rahmawati et al., 2022). The trophic status of the surface waters of the dam was assessed based on the classification criteria of the Organization for Economic Co-operation and Development (OECD) (Ryding&Rast., 1994). There figure7 shows the seasonal distribution of chl-a with OECD trophic limits.

The trophic status of the surface waters of the ELhansali reservoir varies seasonally, with oligotrophic conditions in winter and autumn, and mesotrophic conditions in spring and summer. The maximum productivity is reached in summer (chl-a concentration 15.73 µg/L), while the lowest productivity is observed in winter (chl-a concentration 5.92 µg/L). These results stipulate that nutrient monitoring is essential during the periods of maximum productivity (spring and summer) to combat potential eutrophication of the dam waters.

Recommendations for combating eutrophication of dam waters

Comparing the results of the analysis of the surface water of the dam with the Moroccan standards of water quality (https://www.environnement.gov.ma/PDFs/grille_de_qualite_des_eaux_de_surface.pdf)

and by referring to monitoring strategies based on established standards and methodologies

Table 3. Recommendations for NTK Management

Priority	Action	Timeline_Months	Expected_Impact	Resources_Required
Immediate	Install automated NTK monitoring	1	Real-time monitoring capability	Equipment + Training
Short-term	Implement nutrient reduction measures	3	20% reduction in NTK loads	Infrastructure + Staff
Medium-term	Establish treatment protocols	6	Consistent compliance	Technical expertise
Long-term	Develop watershed management	12	Sustainable improvement	Multi-stakeholder effort

(World Health Organization, 2022) we were able to develop seasonal management recommendations for NTK whose compliance with Moroccan standards is high except for the summer season, which indicates the need for targeted management strategies during this season (Table 3).

CONCLUSION

This study allowed us to better understand the dynamics of surface water quality of the Ahmed El Hansali dam. The study revealed a significant correlation between phytoplankton biomass and nutrient levels, particularly total Kjeldahl nitrogen (NTK). The multiple regression model confirms the importance of NTK as a major factor influencing algal growth. We observed a marked seasonal variability in water quality, with conditions ranging from oligotrophy to mesotrophy. The summer period is characterized by maximum productivity, highlighting the vulnerability of the dam to eutrophication due to excessive nutrient input from agricultural runoff from areas surrounding the reservoir during the rainy season. To prevent this phenomenon, we recommend continuous monitoring of nutrient concentrations, including NTK. Measures to reduce external nutrient inputs, such as optimizing agricultural practices in the watershed, should also be considered. These results highlight the importance of integrated water resource management to preserve the ecological quality of the Ahmed el Hansali dam and ensure the sustainability of these ecosystem services.

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The authors declare that no funding has been used for the study.

CONFLICT OF INTEREST

The authors declare that there is not any conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and falsification, double publication and/or submission, and redundancy, has been completely observed by the authors

LIFE SCIENCE REPORTING

No life science threat was practiced in this research.

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