Egyptian Journal of Aquatic Biology & Fisheries
Zoology Department, Faculty of Science,
Ain Shams University, Cairo, Egypt.
ISSN 1110 –6131
Vol. 28(5): 331– 354 (2024)
www.ejabf.journals.ekb.eg

Spatial Resilience of a Lagoon Ecosystem: The Case of the El Mellah Lagoon (Northeastern Algeria)

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ARTICLE INFO

Article History:
Received: March 27, 2024
Accepted: April 21, 2024
Online: Sep. 9, 2024

Keywords:
Ecosystem functioning,
Eutrophication,
Resilience,
Spatial structure,
STATIS

ABSTRACT

Mediterranean lagoons face a significant threat due to the prevalent risks of eutrophication and dystrophy, particularly in sectors with limited water renewal. The El Mellah Lagoon in northeastern Algeria represents a crucial ecosystem. Our study focused on assessing its operational state by examining the seasonal variability of spatial patterns indicative of eutrophication. Our primary hypothesis posited that a lack of fluctuation in spatial pattern expression reflects ecosystem dysfunction in the face of eutrophication-related disturbances. Our objective was to establish that the El Mellah Lagoon maintains robust health, capable of recovering or sustaining dynamic equilibrium following periods of instability induced by external or internal disruptions. To achieve this, we employed a methodology combining multidimensional analysis (utilizing STATIS from the K-TABLE family) and spatial analysis (employing Moran's I and ordinary Kriging interpolation). Statistical analyses of physicochemical and biological measurements revealed seasonal variations in key eutrophication parameters. The first principal components derived from the STATIS analysis underwent spatial analysis techniques. Consequently, the spatial models constructed unveiled the dynamics characterizing the operational states of the El Mellah Lagoon. This comprehensive approach aimed to demonstrate the lagoon's resilience and ability to withstand disturbances, fostering a dynamic equilibrium crucial for its long-term viability.

INTRODUCTION

The Mediterranean lagoons are coastal ecosystems of great importance due to their exceptional biodiversity and crucial role in regulating numerous ecological processes. They are semi-enclosed coastal wetlands characterized by their connection to the sea through narrow inlets. These ecosystems are of great importance as they host a wide variety of animal and plant species adapted to specific environmental conditions, such as variations in salinity, tides, and freshwater inflow **(Kosyan, 2017; El Mahrad *et al*., 2022)**.

The El Mellah Lagoon is located in eastern Algeria. It is part of the El Kala National Park, recognized as a biosphere reserve by UNESCO **(RAMSAR, 2020)**. The lagoon is surrounded by lush vegetation and offers a picturesque landscape of marshes, seagrass beds, and sand dunes. This coastal ecosystem is home to a rich and diverse biodiversity. It is home to various migratory birds, fish, crustaceans, and other marine species. The lagoon also serves as a breeding and nesting site for many bird species, making it a site of ecological and ornithological importance **(Samraoui *et al*., 2011; Telailia *et al*., 2017)**.

Mediterranean lagoons play a crucial role in the functioning of coastal ecosystems. They act as natural filters by retaining sediments and nutrients and regulating water flows between the marine environment and adjacent lands. Moreover, these ecosystems contribute to the protection of coastal areas against storms and erosion. However, these ecosystems face several threats, of which eutrophication is one of the most worrying **(Leone *et al*., 2020; Ligorini *et al*., 2022)**. Eutrophication is when an excess of nutrients such as nitrates and phosphates enter the lagoons, usually from human activities such as intensive agriculture and waste water discharges **(Kennison & Fong, 2014; Padedda *et al*., 2019)**. This leads to excessive proliferation of algae and aquatic plants, disrupting the ecological balance of the lagoon. The decomposition of these excess organisms depletes oxygen levels in the water, causing hypoxia and threatening the survival of other species, including fish and crustaceans **(Jones *et al*., 2022)**.

We have adopted a spatial approach to study the effects of these disturbances on the ecosystem's resilience and stability. By mapping and analyzing the distribution of habitats within an ecosystem, it is possible to identify key areas for biodiversity, understand the relationships between the different habitat compartments, and assess the impact of anthropogenic and environmental changes on their distribution **(Menció *et al*., 2023)**.

The spatial patterns of nutrient cycling within ecosystems are crucial for assessing their overall health and functioning. The spatial connectivity of different habitats determines the availability and accessibility of nutrients to organisms **(Olin *et al*., 2023)**. Studying the spatial distribution of trophic levels can provide insights into nutrient cycling dynamics and its impact on ecosystem productivity. Spatial analysis is a tool for sustainable management of natural resources. It offers the advantage of a global assessment that makes it possible to identify priority areas for conservation, assess the potential impact of human activities on ecosystems, and develop appropriate protection measures.

The spatial approach to ecosystem resilience focuses on understanding and analyzing ecosystems' spatial characteristics, patterns, and processes to assess and enhance their resilience **(Ligorini *et al*., 2022)**. It recognizes that spatial factors, such as landscape structure, connectivity, and heterogeneity, play a crucial role in determining the capacity of ecosystems to withstand and recover from disturbances or environmental changes.

We adopted a strategy based on multidimensional K-table analysis and geostatistical analysis to identify the ecosystem's functionality **(Thioulouse *et al*., 2018; Dray *et al*., 2023)**. These methods provide an opportunity for the study of the dynamic aspect, which reveals the functional aspect that characterizes the spatial resilience of the ecosystem**(Sankaran *et al*., 2019; Masik, 2022; Zhang, 2023)**. The first principal components of the analysis in Table K, which summarizes the expression of eutrophication that characterizeseach season, were used as the basis for the spatial analysis **(Dray *et al*., 2023)**. Based on Moran's I statistics and kriging interpolation, the second stage allowed us to establish the ecosystem organization model as a function of the level of expression of eutrophication **(Legendre, 1993)**. The results show the amplitude of spatial variations per season in the trophic gradient. These variations are evidence that the ecosystem is functioning in a way that promotes stability and resilience.

To delve into the issue addressed in our study, we devised a strategy grounded in the analysis of multidimensional data using the K-Tableaux (K-Tab) method **(Thioulouse *et al*., 2018; Dray *et al*., 2023)**, coupled with spatial analysis techniques **(Dray *et al*., 2023)**. The components derived from the K-Tab analysis were employed as new variables summarizing the various states of eutrophication expression. By mapping these new variables using kriging, we were able to shed light on the spatial expression of resilience. Our findings uncovered the seasonal fluctuations experienced by eutrophication at the spatial scale. Mapping the patterns that symbolize eutrophication expression proved to be a valuable means of tracking the effects of disturbances on the proper functioning of our lagoon ecosystem. We were able to demonstrate these results using two powerful tools: the ArcGIS 10.2.2 software **(ESRI, 2011)** for spatial analysis, and the R software and its ade4 package **(R Core Team, 2022)** for conducting the K-Tab method.

MATERIALS AND METHODS

This study aimed to assess the level of functioning and resilience of a lagoon ecosystem exposed to eutrophication-related disturbances. Physicochemical and phytoplanktonic metrics expressing eutrophication were examined for spatial structure using multidimensional paired K-table analysis and spatial analysis tools.

1. Presentation of the study area

El Mellah Lagoon is located in the El-Kala National Park in the Wilaya of El Tarf in Algeria's far north-east (8° 20'E and 36° 54'N).

El Mellah, also known as "Garaat El-Melha,"extends 4 kilometers north to south and 2 kilometers east to west, covering an area of around 865 hectares (Fig.1). It is a rather deep paralic basin that extends roughly perpendicular to the coast **(Guelorget & Perthuisot, 1983)**. It communicates with the sea by a roughly 870 meters long and 15 meters broad waterway. It also obtains fresh water from the Wadis El Mellah and Bouaroug in the south and the WadiR'kibet in the west. Its swampy extensions are primarily found in the north, toward the channel's origin, and in the south, near the mouth of the Bouarougwadi. The lagoon's bathymetry reveals the presence of an axial gutter with a depth of about 5m. Two shallow plateaus (up to 2m deep) extend along the banks on either side of this depression.

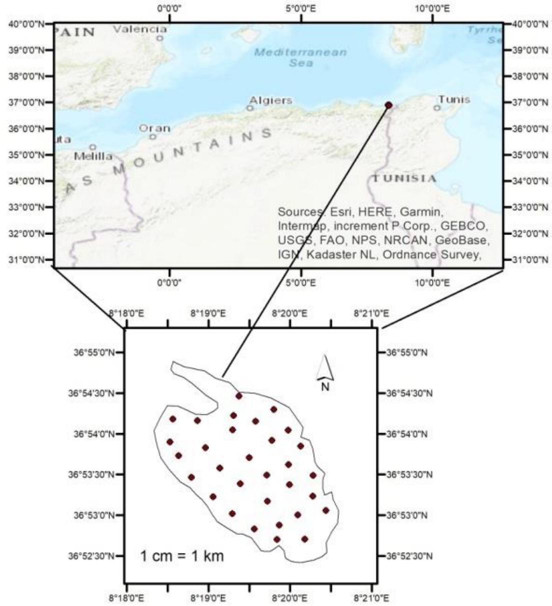

Fig. 1. Location of the study area

2. Methodology

For this study, we adopted a spatial sampling protocol that consists of a systematically dispersed seeding point on a 700m grid **(Baghdadi *et al*., 2018)**. Implementing the sampling plan required considering a certain number of material and scientific constraints, which led us to implement 36 sites (Fig. 1). The fieldwork companions were spread out over the four seasons of 2015/2016. Physical and chemical parameters (temperature, dissolved oxygen, hydrogen potential, electrical conductivity, total dissolved solids, and dissolved oxygen) were measured for each campaign using a multiparametric probe (HoribaU50). We collected one liter (1L) bottle of water in the euphotic zone to research phytoplankton biomass. These samples were again utilized to calculate the trophic level's chemical characteristics (PO_4, NO_3, NO_2, NH_4, SiO_4, Chlorophyll-*a*). The nutrients were determined using an automatic photometer (Hanna Instruments TM Multiparameter Photometer) following the principles of photometric techniques **(Eaton *et al*., 2005)**. After filtration, the spectrophotometric determination of chlorophyll-*a* and concentration calculations were performed using **Lorenzen (1967)** method. We employed the method established by Standard NF EN 15204 **(AFNOR, 2006)** for phytoplankton counting based on Utermöhl's sedimentation methodology.

The obtained data are temporal and spatially organized in two dimensions. This characteristic frequently leads to analysis tools for longitudinal data or repeated measurements over time (seasons) **(Islam & Chowdhury, 2017)**. The observations obtained at different periods on a given individual (station) are dependent and necessitate the inclusion of a "covariance structure" in the analytic models ‘expression. Under these circumstances, an analysis of variance for repeated data or a linear mixed model (MLM) analysis is applicable **(Dagnelie, 2013)**. This model explains the change in the response variable over time using both fixed-effects and random-effects elements (stations).

In order to evaluate the main hypothesis formulated around the dynamics, functioning, and resilience of the El Mellah Lagoon ecosystem in response to pollution and eutrophication phenomena, we utilized the widely known K-Tab methods, well-established in the fields of ecology and hydrology **(Lavit*et al*., 1994)**. Among these methods, we chose the STATIS method. This method provides the opportunity to analyze multiple paired tables jointly. The theoretical foundations of the K-Tab methods were developed by **Escoufier (1973, 1980, 1985)**. The principle of this analysis is based on evaluating the variation of all K-tables relative to an average structure (compromise). The magnitude of discrepancies serves as tangible evidence of the dynamism of resilience and ecosystem functioning. The K-Tab analysis is based on a series of principal component analyses (PCA), and the mapping of the first component of each PCA is the principle that revealed the spatial structure of resilience **(Dray, 2011; Bauman *et al*., 2018; Dray *et al*., 2023)**.

To investigate the dynamics of spatial resilience, a spatial analysis approach was utilized in which the coordinate values of station points were projected onto the plane of the first two components. The process of analysis encompassed the following steps:

- Firstly, a spatial structure analysis was conducted to evaluate the spatial arrangement of the data. This involved examining the autocorrelations and spatial relationships between samples using the Moran's I statistic (IM) **(Legendre & Legendre, 1987)**.
- Next, a variogram model was fitted to estimate the spatial variability and correlation structure.
- Following that, kriging interpolation was applied to predict the values of unsampled points. This technique involved using a linear combination of known values weighted by their distance and spatial covariance.
- Finally, a variable map was created using the values of the estimated points, following the approaches outlined by **Fortin *et al*. (1989)** and **Thioulouse*et al*. (1995)**.

RESULTS

1. Physicochemical and biological parameters of the El Mellah lagoon

The descriptive and inferential results from measurements of physical and chemical parameters are listed in Table (1). The surface water temperature readings vary significantly across seasons. The average seasonal temperature is roughly 21°C, with the maximum (29°C) occurring during the summer season and the minimum (15°C) occurring during the autumn-winter season. This oscillation type is linked to the region's Mediterranean climate, supporting continuous biological activity. The pH value identifies alkaline water, with an average pH=8 that varies between minimum values in the autumn (pH=7.16) and highest values (8.75) in the summer. The pH changes reflect the importance of photosynthetic activity, which reduces CO_2 concentrations and favors pH increases.

Table 1. Descriptive and inferential statistics of physicochemical parameters characterizing the surface waters of the El Mellah Lagoon

Physicochemical parameter	Mean	P test	Median	Min	Max	CV
T°C	21	<2.2e-16 ***	20.78	14.1	28.7	24.53
pH	8	<2.4e-16 ***	8.0165	7.16	9.615	3.27
EC (µs/cm^2)	48	<2.2e-16 ***	48.65	42.8	54.2	7.98
DO (mg/L)	6.68	<2.3e-16 ***	6.635	3.44	10.63	32.83
TDS (mg/L)	44.48	<2.2e-16 ***	48.65	26.1	54.12	23.37
Salinity (g/L)	31.77	<2.2e-16 ***	31.8	27.3	35.5	8.79
NO_3 (mg/L)	21	<2.2e-16 ***	24	21	40	11.93
NO_2(mg/L)	1,01	<2.2e-16 ***	0.22	0.07	6.5	139.56
PO_4 (mg/L)	1,8	<2.2e-16 ***	1.2	0.2	8.2	88.49
NH_4 (mg/L)	1,28	<2.2e-16 ***	1.22	0.33	2.6	35.59
SiO_2 (mg/L)	2,23	<2.2e-16 ***	1.875	0.48	5.00	50.58
Chlr-*a* (µg/L)	2,6	<2.2e-16 ***	1.869	0.14	12.282	96.2

Temperature (T°C), dissolved oxygen (DO), hydrogen potential (pH), electrical conductivity (EC), total dissolved solids (TDS), dissolved oxygen (DO), nitrate (NO_3), nitrite (NO_2),phosphate(PO4), ammonium (NH_4), silicate (SiO_2), Chlorophyll-*a* (Chlr-*a*).

As it explains the degree of marinization and confinement, salinity provides key indications on the hydrology of the lagoon analyzed. The seasonal average salinity of the lagoon El Mellah's surface waters is 32.5g/L, with the highest values (35g/L) recorded during the summer-autumn period and minimum values (29g/L) recorded during the winter-spring period. These values indicate the influence of sea-lagoon interactions and differentiate two major haline phases: a decreasing phase from autumn to winter and an increasing phase from spring to summer. A low mineral load and poor mineralization are characterized by seasonal changes in electrical conductivity values around an average of 49µs/cm. Waters with a high concentration of dissolved solids are called highly mineralized because dissolved solids are mostly inorganic. The seasonal average TDS concentration of surface waters (44.5mg/L), as well as its highest and minimum ranges (54.12-27.8mg/L), define low mineralization (Table 1).

Dissolved oxygen is a measure that indicates eutrophication levels. Over saturation is a symptom of excessive primary production. The decomposition of significant amounts of organic materials, such as algae, causes under-saturation. High values define this parameter's seasonal oscillations in the autumn-winter period (9.57 and 7.75mg/L) and low levels in the spring-summer period (4.76 and 4.66mg/L) (Table 1). Temperature and salinity expression levels are associated with these fluctuations.

The three nitrogenous salts required for the growth of the trophic chain producers are included in dissolved inorganic nitrogen. Nitrate is the most common type of dissolved inorganic nitrogen. It varies between 24.7mg/L on a seasonal basis. The first peak (26.7mg/L) was observed in summer, favored by the mineralization conditions, while the second, less important peak (24.1mg/L) appeared in winter. It was favored by external contribution flows. Nitrites have properties comparable to nitrates but are less common. Nitrite expression levels swing around an average of 1.01mg/L. A high summer peak (3mg/L) (Table 1) implies a significant inflow of the main effluents. Ammoniacal nitrogen, often known as ammonium, is a mineral nitrogen source required for aquatic habitats' biological functioning. Phytoplankton and macrophytes use it as a nitrogen source. Ammonium has a significant role in eutrophication processes.

The average seasonal concentration is predicted to be 1.28mg/L, with a peak over the summer-autumn period (2.12-2.6mg/L). These high concentrations are caused by the inflow from the northern region's wadis (OuedReguibet and OuedBoumalek) and the southern region's wadis (Oued El-Aroug and Oued El Mellah), as well as the discharge from the wastewater treatment plant. Phosphate is the most important element in eutrophication processes. Significant seasonal fluctuations characterize El Mellah Lake's dynamics; 1.8mg/L is the seasonal average. During the summer and autumn, phosphorus contents in surface water rise (6.4-8.2mg/L). Temperature and the anoxic conditions that characterize these periods affect these quantities. Furthermore, wastewater treatment station discharges amplify the accumulation effect and accelerate the development of eutrophication.

The role of silica in the eutrophication of lagoons is insignificant. It is a metric that indicates the dominant status of phytoplanktonic groupings **(Beklioglu*et al*., 2007)**. Low silicates at Lake El Mellah can be noted for winter, spring, and autumn seasons, with averages of 2.96-1.88-2.34mg/L. Increased values to approach the maximum (5mg/L) are observed during summer. The most likely source of this rising value is endogenous from diatom frustules destruction **(Osadchyy*et al*., 2016)**. The chlorophyll-*a* parameter measures the level of eutrophication by expressing the intensity of chlorophyll biomass **(Beklioglu *et al*., 2007)**. The values recorded overall and over the study period show fluctuations, with the highest values corresponding to the spring and summer seasons (12.3-8.81g/L) (Table 1). The chlorophyll biomass values of the El Mellah Lagoon are compared to some lagoons of the Mediterranean basin in Table (2).

Table 2. The concentration of chlorophyll biomass values of El Mellah Lagoon and some Mediterranean basin lagoons

Lagoons and Ponds	Chlorophyll-*a* (µg/L)	Reference
Thau (France)	0.01-14.04	DeCasabianca *et al*., 1997
Gialova (Greece)	0.10-11.70	Triantafyllou *et al*., 2000
Mellah (Algeria)	1-3	Semroud, 1983
Mellah (Algeria)	2.5-3	Guelorget *et al*.,1989
Mellah (Algeria)	0.10-8.72	Draredja, 2007
Mellah (Algeria)	0.14- 12.3	This study

Among the 5 classes that compose the phytoplankton of El Mellah Lagoon, only two dominate the seasonal number profile: Bacillariophyceae and Dynophyceae. Cyanophyceae, Chlorophyceae, and Euglenophyceaeare marginally represented.

The diversity of diatoms is mainly represented by species of the genera *Paralia* sp., *Nitzshia* sp., *Navicula* sp.,*Chaetoceros* sp., and *Melosira* sp. The dinoflagellates present a more significant occurrence during the autumn period. The species that predominate this group belong to the genus *Scriptiella* sp., *Gymnodinium* sp., *Prorocentrum* sp., and *Peridinium* sp. The Cyanobacteria encountered in winter are represented mainly by the genus *Oscillatorilla*. Euglenophyceae are mainly represented in the lagoon by the genus *Euglena*. For the Chlorophyceae, their occurrence is noted, especially in summer.

2. Functional aspect: STATIS analysis results

This analysis aims to highlight the dynamics of changes that affect the spatial organization of the eutrophication phenomenon and the intensity of its expression described by the combination of physicochemical and biological variables. In simpler terms, we tried to demonstrate the following:

- Is the spatial expression of eutrophication represented by spatial patterns structured or random?
- Whether the intensity of eutrophication expression is stable or variable across seasons?

The specific organization of the data in this study (Fig. 2) requires a block structure of k-season tables. These tables are paired (dependency) and arranged according to a data cube with three indices: stations (spatial entities), variables, and time (seasons). The reasoning is symmetrical between column pairing and row pairing. This allowed us to perform a STATIS-VQ to study the dynamics of the variables common to all-season tables (the intensity of eutrophication expression) and a STATIS-WD to study the dynamics of the spatial organization of the stations common to all-season tables (the spatial expression of eutrophication). The dynamic and functional aspect is interpreted from the following stages: inter-structure, compromise, and intra-structure.

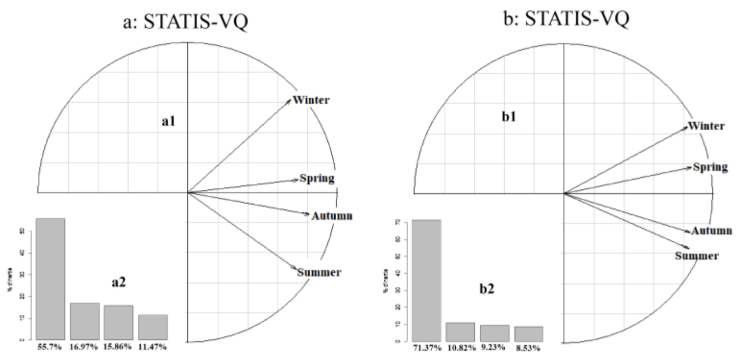

Fig. 2. Correlations circle. Euclidean representation of season tables (a1-b1) and Histograms of the eigenvalues (a2-b2) of the Inter-structure PCA for the case of **(a)** STATIS-WD and **(b)**STATIS-VQ

2.1. Inter-structure

A PCA-type analysis provides the projection of the objects (table periods). The results of this analysis are favorable and reveal the importance of the first component in both cases of inter-structure analysis. Fig. (2) represents the Eigenvectors and gives an Euclidean picture of the level of similarity between tables measured by the RV values resulting from calculating the vector correlations.

- The STATIS-VQ inter-structure distinguishes two levels of similarity (Fig. 2b). The first correlation links summer and autumn (RV: 0.63), and the second links winter and spring (RV: 0.64).
- The STATIS-WD inter-structure reveals three levels of similarities represented by Fig. (2a). The first correlation distinguishes autumn and spring (RV: 0.50), while the second distinguishes the summer structure, which is close to autumn (0.49). The last one is the winter structure which is close to the autumn one.

The Eigenvalues of the first inter-structure PCA components, STATIS-VQ (2.85–71.31%) and STATIS-WD (2.23–55.7%), and the size effect, which is clearly distinguishable on the planes of the two PCAs (Fig. 2), confirm the existence of a mean structure (Compromise). The coordinates of the season tables on the first component provide the weighting coefficients for calculating the average matrices (Compromise).

2.1.1. Compromise (STATIS-VQ)

The first two-axis plane of the compromise PCA explains 29.21% of the total variability (Fig. 3b).

- The first component, with a rate of inertia of 18.67%, represents an expression that opposes on one side the set of variables that express the salinity and conductivity (TDS. Ce. Sal. DO. Dino) to the variables that define the productivity and eutrophication on the other side (PO_4. NH_4. NO_3. Chloro. Diatom. Eugl. Chlr-*a*) (Fig. 3a).

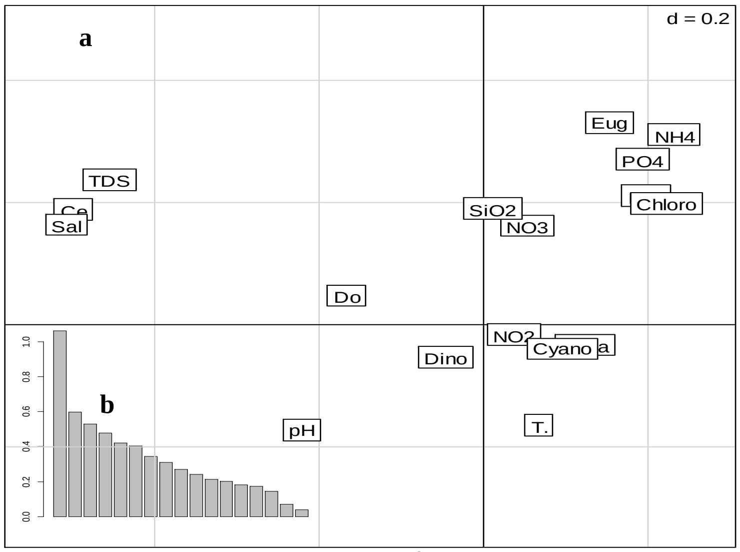

Fig. 3.(a) First plane (Comp1xComp2) of the compromise PCA; **(b)**Eigenvalues barplot.STATIS-VQ

- The second component accumulates a rate of 10.54% of the variability. It defines an expression that opposes mainly phytoplanktonic groups and some physicochemical variables (Eug: Euglenes. Diat: Diatoms. Chloro: Chlorophyceae. NH_4. PO_4) to other phytoplanktonic groups and other physicochemical variables (Cyano: Cyanophyceae. Dino: Dinophyceae.T°. pH. NO_2). (Fig . 3b).Exploration of the first plane of the compromise PCA (variables) reveals the expression of the two gradients globally. On the first axis is the gradient of eutrophication and salinity, and on the second axis is the phytoplankton composition gradient.

2.1.2. Compromise analysis (STATIS-WD)

The first PCA plane of the STATIS-WD compromise matrix analysis explains 26.15% of the total variability. The first component accounts for 16.10% of overall variability and has an expression that contrasts the southern stations (sta28-sta29-sta30) with those in the northern area (sta5-sta6-sta4-sta3).The central zone stations (sta17-sta18-sta22-sta13-sta14) can distinguish these two scenarios. The second component accounts for 10.05% of total variability and has an expression that contrasts the central region (sta18-sta17-sta14) with the southern and northern regions (Fig. 4).

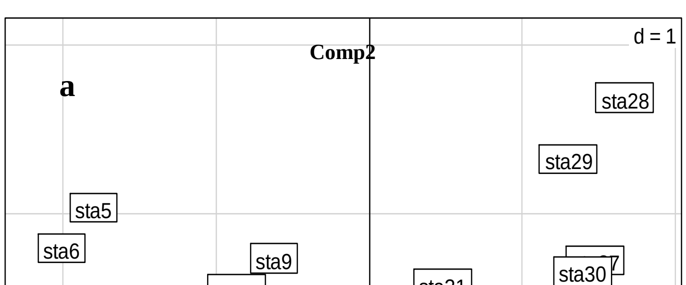

Fig. 4.(a) The first plane (Comp1xComp2) of the compromise PCA and **(b)** Eigenvalues barplot**)**.STATIS-WD.

Using Moran's I statistic, a geostatistical investigation was done on the data of the PCA compromise's first component (STATIS-WD) to determine this component's spatial structuring level. The test result is highly significant (I: 0.737 Pr: 0.00***) and validates the type of spatial structure gradient in the expression of this component. This finding enabled the creation of a spatial reference model to investigate the dynamic aspect.

Table 3. Statistics of error from selected spatial model

Mean	Root-mean-square	Mean standardized	Root-mean-square standardized	Average standard error
0.00020439	0.452	- 0.00081836	0.905	0.522

The cross-validation and errorstatistics results (Table 3) indicate that the spherical model, frequently employed in this environment, is the best. The standard kriging interpolation allows us to generalize the empirical model's statement. The mapping of the model defined by the first component displays the patterns that structure the eutrophication gradient's organization. This geographical reference pattern distinguishes four zones; the degree of production and salinity in two extreme zones (north and south) and two intermediate zones of moderate expression are shown in (Fig. 4). The results of the following intra-structure analysis, which discloses the deviations and variability of the functional component of resilience, are used to examine seasonal oscillations within this average typology.

2.2. Intra-structure

The structural framework applied in this part of the analysis to measure levels of fluctuation showcases a trade-off. Every table reproduces the mean typology, with variations in the reproduction observed across different time periods. The variability in the seasonal frameworks encompassing the compromised structure is characterized by two metrics, illustrating the dynamics of expression. Specifically, these metrics are the Table Weight (TabW) and the Cosine squared (Cos2) values presented in Table (4), indicating the extent of resemblance between each seasonal table and the compromised table.

Table 4. Typology parameters values

	STATIS-VQ		**STATIS-WD**	
	Cos2	TabW	Cos2	TabW
Autumn	0.73	0.55	0.66	0.51
Spring	0.55	0.50	0.67	0.51
Summer	0.50	0.49	0.63	0.50
Winter	0.55	0.46	0.69	0.49

- The inter-structure analysis (STATIS-VQ) results (Table 4) suggest a typology with three structures: autumn, spring, winter, and summer. The output of the inter-structure (STATIS-WD) (Table 4) displays a typology that distinguishes three structures: winter, autumn-spring, and summer.

The distortion elements characterizing the variability of the point clouds are illustrated by the trajectory-type k-plot representation of the stations (STATIS-VQ) and variables (STATIS-WD) for each season table (Fig. 5).

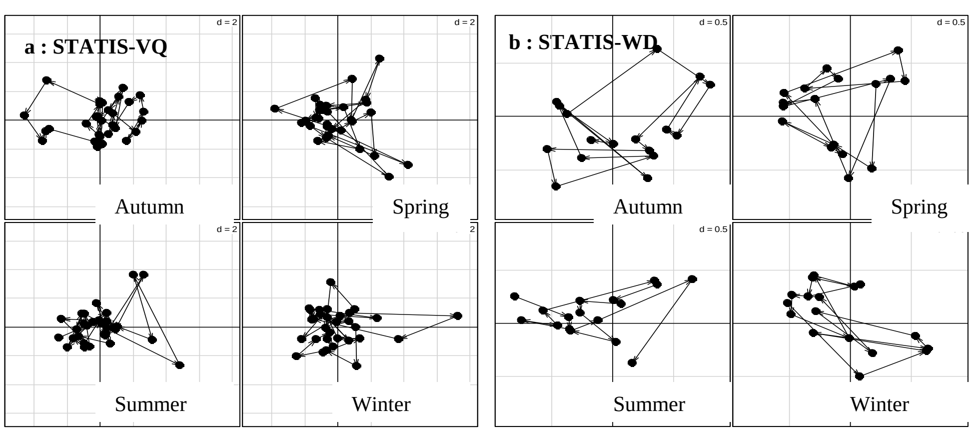

Fig. 5. Trajectory-type k-plot of the intra-structure analysis. **(a)** STATIS-VQ and **(b)** STATIS-WD representation of point cloud deformations over seasons

The eutrophication-salinity gradient's expression dynamics are characterized by distortions of the variable point cloud (Fig.5a. STATIS-VQ). The fluctuation in the spatial structure of the eutrophication-salinity gradient is characterized by distortions of the station point cloud (Fig. 5b. STATIS-WD). The two analyses, STATIS-WD infrastructure and STATIS-VQ infrastructure, facilitate the examination of both spatial variation and fluctuations in eutrophication intensity across different seasons. The kriging mapping of the first components relative to each season best exemplifies this result.

Through the emergence of spatial patterns that characterize the spatial models, analysis of seasonal interpolation maps indicates the dynamic cyclicality of the eutrophication phenomena. The pattern shape, dispersion, and connection offer evidence of this variability, quantified by Moran's I parameter values (Fig. 6). The eutrophication gradient's pattern level is at its highest during the summer and autumn phases and then lowers throughout the winter and spring phases. These cycles also represent features of functioning and resilience to the disruption problem.

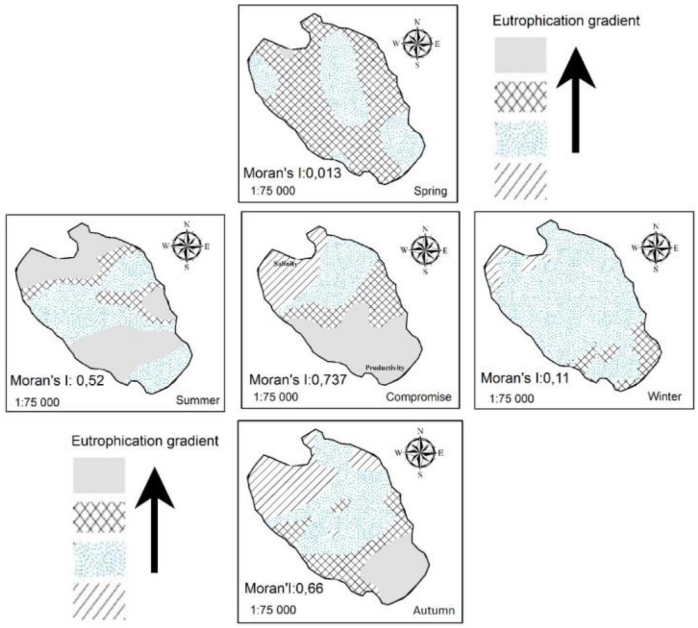

Fig. 6. Seasonal variations in spatial structure indicate spatial resilience in response to eutrophication

DISCUSSION

In most cases, the seasonal changes in the parameters that indicate the trophic level of the El Mellah Lagoon are typical Mediterranean, especially for the temperature, salinity, and dissolved oxygen variables. Temperature changes with strong seasonal thermal amplitudes of roughly 20°C influence specific taxonomic groups' biological processes. Salinity is an essential indicator of the lagoon's hydrology, precisely its degree of marinization and confinement. According to **Venice classification (1958)**, El Mellah Lagoon is one of the mixpolyhalline lakes **(Semroud, 1983)**. The exchanges with the sea and the freshwater influx of the various affluents directly influence haline changes in El Mellah Lagoon. The lagoon's accumulation basin receives limited external input due to water variations for agricultural uses. The channel's management in 1988 enabled it to be widened to 20m (wetted portion) and deepened to 2m to facilitate water exchanges. In comparison to some Mediterranean lagoons, this action has favored an average salinity (31.77g/L) comparable to that of the sea and a wide range of viability **(Tuchkovenko *et al*., 2019)**.

Fluctuations in the dissolved oxygen saturation level are caused by biological activities involved in production and consumption and are primarily determined by climatic conditions, particularly during the warm season. El Mellah Lagoon has a lower amplitude of fluctuation in dissolved oxygen (10.66 - 3.44mg/L) than other lagoons such as Thau

Lagoon (3.10 and 16mg/1) **(Laugier *et al*., 1999)**. This is likely due to the lagoon's poor hydrodynamics and water exchange **(Osadchyy *et al*., 2016)**.

The Mellah Lagoon receives fresh water from a watershed with little anthropogenic activity. The terrain is dominated by a forest cover, regressing due to clearing and urbanization. This has saved the lagoon from the severe eutrophication that most lagoons are experiencing in the Mediterranean region **(IFREMER, 2000; Padedda *et al*., 2019)**. Nevertheless, seasonal changes in the concentrations of the main parameters are concerning.

Nitrate concentrations surpass during the summer due to the remineralization activity of the benthic biomass damaged by anoxia, which defines this hot season **(Altieri & Diaz, 2019)**. Exogenous inflows are more critical in the winter and spring and are represented by the waters of the Wadis Souk Reguibet and Wadis El Mellah on the western side. The southern section receives wastewater treatment plant waters containing significant mineral and organic loads. During the summer-autumn season, ammonium concentrations rise. They benefit from the conditions of a reductive environment **(Padedda*et al*., 2019)**.

During the summer, the primary phosphorus inputs into the lagoon are connected to the particle phase, primarily from surface leaching or runoff during heavy rainfall. Phosphates concentrate in sediments, primarily mixed in mineral and particle forms. When reductive circumstances set up and/or occur, sediments can release many phosphates into the water (disappearance of dissolved oxygen and drop in pH). It happens specifically during the summer when the water temperature is high, thus causing the sediment to rise **(Osadchyy*et al*., 2016; Berthold & Schumann, 2020)**. The sewage treatment station also contributes to the enrichment of this parameter, which increases the risk of lagoon eutrophication. According to various quality grids, chlorophyll biomass swings with seasonal values indicating low to medium trophic levels **(Ofori *et al*., 2022)**.

Silicates are a source of nutrition for siliceous phytoplankton (Diatoms,Chrysophyceae, and Silicoflagellates). In general, silicates originate in both watershed inputs and sediments. Diatom frustules, which dissolve at the interface of water and sediment, constitute a significant source of silicates, especially when the temperature is high. Deep lagoons act as excellent particle traps, and silted lagoons generally create significant silicate fluxes during the summer **(IFREMER, 2000)**.

The chlorophyll biomass is an integrating parameter that restores the lagoon's prize status. According to the **OECD (1982)** classification, the lagoon oscillates between two states. An eutrophic state characterizes the spring-summer season, while an oligotrophic state characterizes the autumn-winter period. Some authors **(Semroud, 1983; Draredja, 2007; Draredja *et al.*, 2019)** believe that the degree of chlorophyll biomass expression is not alarming compared to some Mediterranean lagoons. Our findings, however, indicate a trend toward an increase in the values of eutrophication indices that should not be underestimated.

Diversity is critical for maintaining ecosystem resilience **(Lake, 2013)**. This role is due to functional groups, which are specific groups that perform numerous ecological activities. Diversity can provide some protection against pollution risk, while its loss can make particular ecological services more vulnerable **(Loreau *et al*., 2001)**.

The results of the second part of this study attempted to demonstrate whether seasonal fluctuations in physicochemical and biological characteristics represent the functionality and resilience of the El Mellah Lagoon to disturbances. The combination of multidimensional statistical techniques and spatial statistical tools enabled us to highlight the dynamic and functional aspects that characterize the lagoon ecosystem in the face of eutrophication issues. Using the STATIS approach, we established that the functioning is a set of dynamic states that characterize a gradient. It brings together all physicochemical and biological variables. The resilience mechanisms are revealed by fluctuations in the expression of this gradient compared to the mean (compromise). The resilience of a regime is the difference between its average and its limit **(Carpenter *et al*., 2006)**. Resilience is a dynamic trait of ecosystems that has experienced many perturbations in ecology. It is commonly characterized as the ability to absorb changes generated by a disturbance without causing the system's structure and functioning to change **(Davoudi *et al*., 2016; Liu *et al*., 2018)**.

The trophic level is mainly indicated by the water's phosphate and nitrogen concentration **(Sfriso *et al*., 2021)**. It is governed by functions of assimilation and decomposition, which restore and sustain a configuration that delivers ecological services. Exceeding the critical level results in a configuration change: the system is placed in a new dynamic that no longer allows it to reconstruct itself later **(Liu *et al*., 2018; Wang *et al*., 2018)**. This was found in the current yearly and in the face of critical thresholds. The lagoon's resilience reaction is good since it allows the transition from a eutrophic to an oligotrophic state.

Geographical indicators are grouped similarly to temporal indicators at global spatial scales spanning the entire ecosystem **(Sheffer & Van Nes, 2007)**. Seasonal fluctuations in geochemical, hydrological, and biological disturbance variables affect the spatial patterns that determine gradient organization. The move from an anisotropic north-south gradient spatial organization that tries to dominate the lake to a random, unstructured organization is a good resilience response.

The response time or reactivity to an environmental perturbation distinguishes the primary parameters that impact resilience. The loss of resilience is caused mainly by factors with low reactivity in lakes' ecosystems. The progressive increase in nutrient loading in the sediment (mainly phosphorus loading) is the primary force causing loss of resistance **(Oujidi *et al*., 2021)**. The response time to eutrophication is determined by nutrient exchange with the sea and the watershed **(Tamborski *et al*., 2019)**. The watershed is predominantly a dune and mountainous area occupied by oak forests. It is sparsely urbanized, and agriculture is minimally represented **(RAMSAR, 2020)**. The agricultural domain makes little contribution to the flow of nutrient burdens. The surface area of the lagoon's watershed is covered by the principal municipality (El-Kala) and other neighboring municipalities, which are currently undergoing intense urbanization activity, endangering the water quality in this body of water without effective urban discharge treatment devices. The contact with the sea on the south side (effect of salt) influences the north-south orientation of the spatial gradient of eutrophication. In contrast, the discharges of the wastewater treatment plant influence the south side (impact of the trophic load).

The uniformity of the distribution pattern of the expression level parameters that determine eutrophication varies throughout seasons. We found that the spatial distribution of eutrophication changes from a random structure to a more structured gradient with a south-north orientation, in contrast to prior works **(Semroud, 1983; Draredja, 1992; Messerer, 1999)**. This outcome is intriguing from the lagoon water quality management and maintenance standpoint. It allows us to choose the location of monitoring points for long-term monitoring.

CONCLUSION

In this study, we demonstrated that the spatial expression of eutrophication is a crucial indicator of lagoon ecosystem resilience. In the El Mellah Lagoon, variations in biotic and abiotic factors create spatial gradients that fluctuate seasonally, impacting multiple trophic levels. Eutrophication's distribution within the lagoon is uneven, with some areas more affected than others. A resilient ecosystem would show a more uniform distribution, suggesting its capacity to mitigate and manage eutrophication.

The size and extent of eutrophic zones are key resilience indicators, with smaller zones reflecting better ecosystem functionality despite disturbances. Additionally, a resilient lagoon maintains biodiversity and productivity, even in eutrophicated areas, showcasing its ability to recover from perturbations.

Protecting Mediterranean lagoons from eutrophication requires preserving habitat diversity, enhancing connectivity, and supporting self-regulation. By assessing spatial expression, we gain insights into lagoon resilience, guiding effective management and conservation strategies.

Looking ahead, remote sensing offers significant potential for studying lagoon resilience, enabling large-scale monitoring and providing valuable data for conservation efforts.

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